METHODS FOR EVALUATING THE EFFECTS OF UPSTREAM FLOOD CONTROL MEASURES ON WATERSHED YIELD

by

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ABSTRACT

Methods of determining the effects of upstream flood prevention measures on watershed yield are required for optimum water resources development. This report presents the results and analyses of studies conducted since 1952 to define these effects. The studies were conducted in seven study areas in Texas having diverse physical and climatic characteristics. Reductions in annual yield ranged from 100 percent in dry years to 4 percent in a very wet year. Average reductions in yield for an 8-year period common to all seven study areas ranged from 54 percent in an area having an average annual runoff of 1.37 inches to 11 percent in an area having average annual runoff of 6.64 inches.

A mathematical model for monthly consumption by reservoirs was developed. The model consists of a linear multiple regression equation relating monthly consumption to combinations of variables considered to be representative of the physical processes involved in evaporation from the free water surface and wetted peripheral soil, transpiration, and seepage away from the pools. These prediction equations have standard errors of estimate ranging from 11 percent to 16 percent.

A computer program which models the hydrologic response of a system of upstream floodwater-retarding reservoirs was developed also utilizing the mathematical model for monthly consumption. Necessary parameters may be determined from soil maps, and reservoir design. Climatic variables are computed from existing first order climatological data stations. The program is suggested for use in water yield studies to adjust historical streamflow records for the effects of upstream flood control programs.

An annual inflow-outflow relationship was developed based on data collected in all areas. This relation may be used as a reasonable first approximation of the depletion of annual runoff from the controlled area of a watershed.

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INTRODUCTION

General Considerations

Congress, in the Flood Control Acts of 1936 and 1944 and by the Watershed Protection and Flood Prevention Act of 1954, all as amended and supplemented, authorized the construction of flood control and water-conservation structures on small watersheds. These projects, which are the responsibility of the U. S. Soil Conservation Service, entail the initiation of appropriate land management practices to reduce erosion and sedimentation damage and the installation of structural measures to temporarily store flood runoff.

Local Soil Conservation Districts request the Soil Conservation Service to make a survey of flood damages on a problem watershed and recommend remedial measures. If benefit-cost analysis indicates economic feasibility, standard practice is to construct a series of floodwater-retarding structures in headwater areas to reduce damage in downstream reaches. Structures generally control runoff from 0.5 to 10.0 square miles and provide sediment storage for 50 to 100 years. Water is stored in the sediment pools until storage is eliminated by sediment. Flood runoff temporarily stored in the floodwater-retarding pool is automatically released through fixed openings and the emergency spillway. A section of a typical structure is shown in Figure 1.1.

Although the projects are initiated at the local level, the Federal Government, through the Soil Conservation Service, pays almost the entire cost. Local Districts are required only to provide right-of-way and agree to maintain the structures. The floodwater-retarding structures are not to be confused with the familiar farm pond, for which financial and

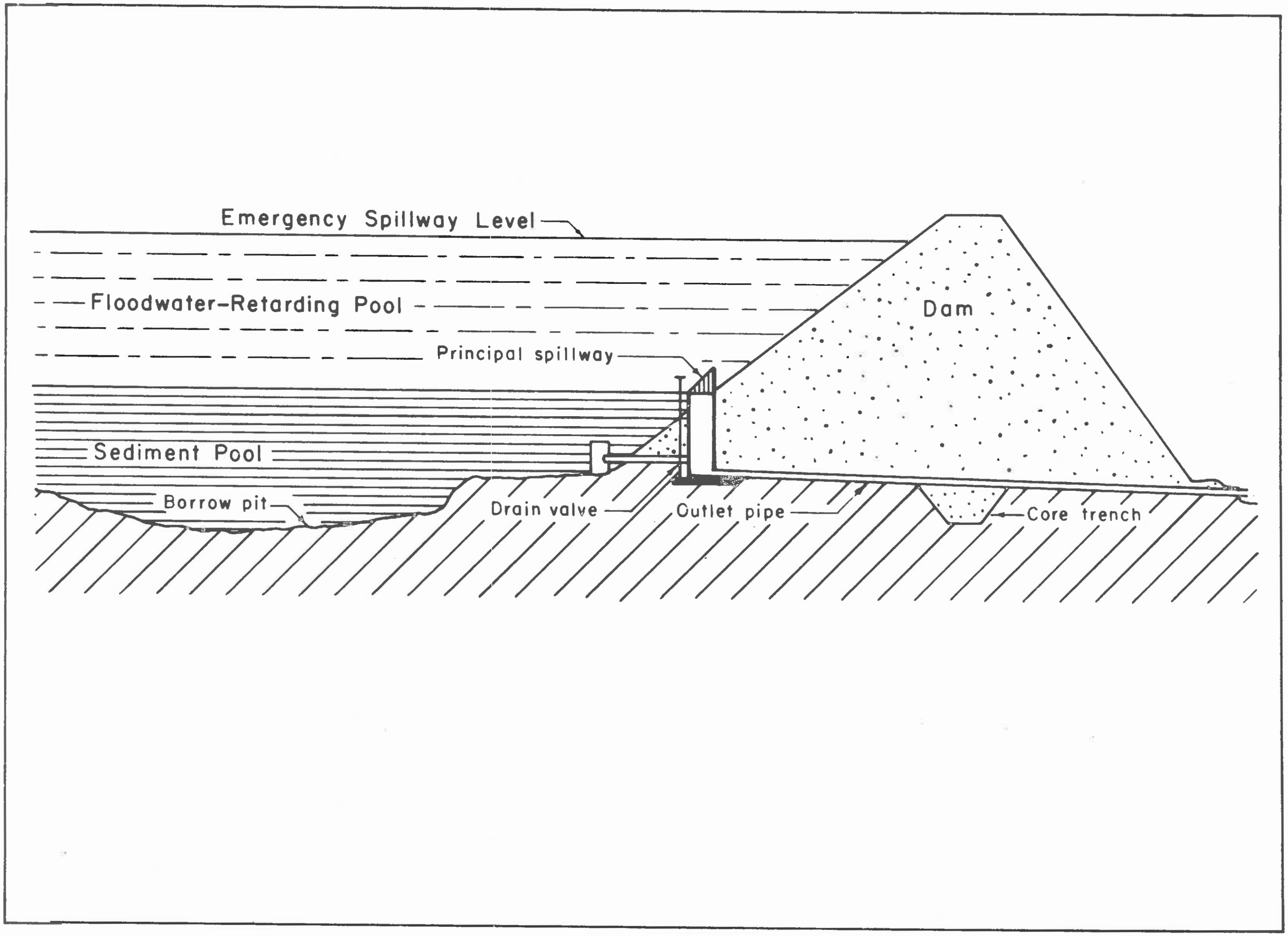


FIGURE 1.1 - Section of typical floodwater-retarding structure with outlet works

technical assistance is also provided by the U. S. Department of Agriculture. These two types of structures differ in size by approximately two orders of magnitude. According to figures compiled by the Soil Conservation Service (1957), the 342,000 farm ponds in place in Texas had an average contributing drainage area of 37 acres. The floodwater-retarding structures in place as of 1969 have an average contributing drainage area of approximately 4 square miles or 2,560 acres.

The magnitude of the Soil Conservation Service program is large. In Texas alone, over 1,300 structures controlling runoff from approximately 5,200 square miles have been constructed since 1950. The Soil Conservation Service estimates that approximately 3,500 structures are economically feasible in Texas (U. S. Study Commission-Texas, 1962 and U. S. Soil Conservation Service, 1963). Obviously a program of this magnitude will affect the hydrologic characteristics of the watersheds involved.

The Texas District of the U. S. Geological Survey initiated hydrologic data-collection programs in Texas as early as 1951 to define the effects of the floodwater-retarding structures on downstream yield and to acquire hydrologic knowledge under the new condition. The first floodwater-retarding structures were instrumented in 1952. Eleven watersheds were selected for study by the U. S. Geological Survey and its cooperating agencies (Texas Water Development Board, U. S. Soil Conservation Service, the City of Dallas, and others), to obtain samples from a broad spectrum of hydrologic environments, including different soils, geology, vegetation, and climate. The data-collection program provides basic hydrologic information sufficient to determine the water budget of the floodwater-retarding pools.

Purpose and Scope

The purpose of this study was to develop relationships for determining the consumptive use attributable to the structural measures used in implementing the upstream flood-damage prevention program. In this study, consumptive use is defined as the reduction in watershed yield due to evaporation, transpiration, and seepage losses due to impoundment. These relationships may be used in adjusting historical streamflow for the effects of present and future development of structural flood-damage prevention measures. These adjustments are necessary for the proper evaluation and planning for utilization of the water resources of Texas.

Monthly and annual relationships are developed based on data collected in Texas but may be applicable to other areas. In the first approach, monthly consumptive losses are related to climatic parameters and physical characteristics of the structures, including the underlying soils. These relationships were derived based on multiple linear regression analysis. Based on these relationships, a mathematical model for the hydrologic response of a system of reservoirs was developed which is useful in evaluating monthly losses due to watershed development and for adjusting historical records. In a second approach, using only annual values, a direct inflow-outflow relationship was developed. This relationship may be used for preliminary or reconnaissance type studies where annual values are sufficient. However, the annual relationships will not be valid after appreciable quantities of sediment have been deposited in the pools.

Justification for Study

The upstream floodwater-retarding structures in place at present affect the runoff from most major streams in the State to varying degrees.

Upon completion of the program, the Trinity, Brazos, Colorado, Guadalupe, and San Antonio River basins will be heavily developed. The planned expansion of the program will result in some 15,000 square miles of Texas watersheds being partially controlled. Based on data collected by the U.S. Geological Survey in watersheds throughout the State, this ultimate development would result in a net annual at site water loss in excess of 600,000 acre-feet. It is therefore necessary to accurately define the effects of the flood-damage prevention program in all areas of the State by appropriate adjustments to historical streamflow.

Chapter 2

EXPLANATION OF DATA

In any analysis of hydrologic data where accurate areal extrapolation is the goal, data collected over a long and common period are desirable. For this study, data from 7 of the 11 study areas previously mentioned were used. This chapter contains descriptions of data used as well as related hydrologic parameters. Locations of the seven study areas, six climatological data stations, and areas in Texas developed or currently being developed by the Soil Conservation Service are shown in Figure 2.1. For the purpose of analysis, data for each study area were "lumped", and all structures were assumed to act as a unit.

Most data are given on a water year basis. A water year is defined as the 12-month period ending on September 30 and designated by the calendar year in which it ends. Thus the period October 1, 1959 through September 30, 1960 is designated as the 1960 water year.

Reservoir Surface-Water Budget Data

Data on the surface-water budget for each floodwater-retarding site were collected by the U. S. Geological Survey. The number of reservoirs instrumented and drainage area controlled at the beginning of the water year in each of the seven study areas is shown in Table 2.1.

Data were collected to define the following parameters for each reservoir site on a monthly basis:

1. Inflow from land drainage, I, designated also as net inflow.
2. Outflow from reservoir, O.
3. Rainfall on pool, R.
4. Pool consumption, C.
5. Pool change-in-volume, ΔS
6. Mean pool surface area, A.

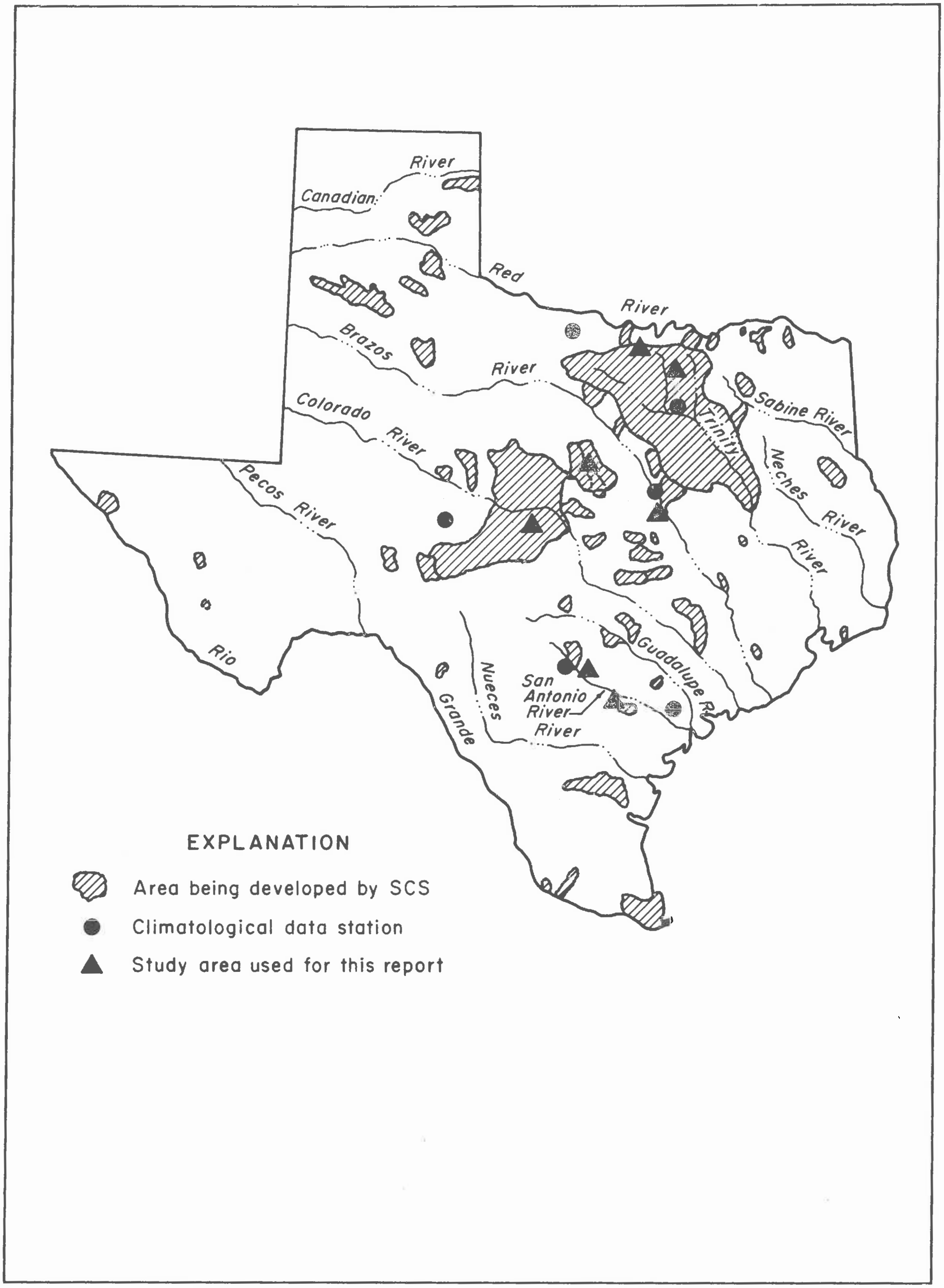


FIGURE 2.1- Location of areas being developed by SCS, and climatological data stations and study areas used for this report

Table 2.1.--Number of reservoirs instrumented and drainage area (in square miles) controlled at beginning of water year in seven study areas.

Water Year	Calaveras Creek		Cow Bayou 1/		Deep Creek		Elm Fork 2/ Trinity River		Escondido Creek		Green Creek		Honey Creek	
	Number	Drainage Area	Number	Drainage area	Number	Drainage area	Number	Drainage area	Number	Drainage area	Number	Drainage area	Number	Drainage area
1953	-	-	-	-	-	-	-	-	-	-	-	-	2	3.40
1954	-	-	-	-	-	-	-	-	-	-	-	-	2	3.40
1955	-	-	-	-	6	24.21	-	-	1	3.29	-	-	6	7.82
1956	4	14.17	-	-	6	24.21	-	-	3	8.33	-	-	8	13.23
1957	6	18.46	-	-	6	24.21	10	29.88	4	11.02	7	16.03	10	17.51
1958	7	25.47	-	-	6	24.21	11	31.00	9	29.59	8	22.29	12	20.90
1959	7	25.47	9	28.03	6	24.21	11	31.00	11	44.92	8	22.29	12	20.90
1960-66	9	37.07	9	28.03	6	24.21	11	31.00	11	44.92	8	22.29	12	20.90

1/ 17 additional sites controlling 14.70 sq mi established 1964-65, not included in analyses.

2/ 3 additional sites controlling 2.53 sq mi established 1966, not included in analyses.

All terms except consumption are self-explanatory. Consumption at the reservoirs is defined as the residual of inflow, rainfall on pool, outflow, and change in volume. In equation form (units generally in acre-feet):

$$C = I + R - O \pm \Delta S \tag{2.1}$$

Consumption is composed of evaporation from the free pool surface, evaporation from the soil surface peripheral to the pool, transpiration by plants surrounding the pool, and seepage away from the pool. Water that percolates from the pools to the ground-water table is not consumed in the strict sense of the word. However, unless the water table intersects the surface stream at some downstream point, this water is "lost" insofar as surface-water yield to a downstream water supply is concerned.

These data are compiled annually by study area. Most of these data have been distributed by the Texas District of the Geological Survey in booklet form in their "Compilation of Hydrologic Data" series. Data are available for inspection in the files of the Geological Survey at Austin, Texas. In addition, data for some of the study areas for various time periods have been included in reports by Gilbert et al. (1962, 1964), Kennon et al. (1967), Mills et al. (1965), and Mills (1969).

A summary of the annual water budget for the system of reservoirs in each study area, computed in "lumped" fashion as a sum of the water budget for the individual sites, is given in Table 2.2. For each study area monthly values of equivalent consumption, defined as the quotient of consumption in acre-feet divided by the average surface area in acres, were also computed. From the outset of the data collection program, it became apparent that losses were generally in excess of those attributable to evaporation from the free water surface alone. A comparison of equivalent annual consumption and

Table 2.2.--Annual water budget for reservoirs in seven study areas.

(Symbols: C, pool consumption; R, rainfall on pools; O, outflow from pools; I, net inflow to pools; all units expressed as equivalent inches distributed over controlled area.)

Water year		Calaveras Creek				Cow Bayou				Deep Creek				Elm Fork Trinity River				Escondido Creek				Green Creek				Honey Creek			
		C	R	O	I	C	R	O	I	C	R	O	I	C	R	O	I	C	R	O	I	C	R	O	I	C	R	O	I
1953		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.33	0.51	1.03	2.51
1954		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.86	.71	.72	2.63
1955		-	-	-	-	-	-	-	-	0.88	0.33	6.38	7.50	-	-	-	-	-	-	-	-	-	-	-	-	1.85	.58	1.37	2.76
1956		-	-	-	-	-	-	-	-	.83	.08	.23	.73	-	-	-	-	-	-	-	-	-	-	-	-	1.38	.19	.28	1.14
1957		-	-	-	-	-	-	-	-	.79	.29	5.62	6.17	0.97	0.53	11.90	12.96	-	-	-	-	0.85	0.31	3.76	4.49	1.71	1.77	23.76	24.74
1958		1.61	0.58	[a]6.50	5.68	-	-	-	-	.80	.34	2.48	2.88	1.00	.39	8.71	9.32	2.14	0.79	7.23	7.88	.98	.39	1.00	1.68	1.77	.92	10.75	11.68
1959		.87	.27	.24	.64	0.91	0.31	1.65	2.48	.71	.17	.77	1.31	.62	.16	.02	.35	1.10	.38	.63	.98	.60	.18	.12	.47	1.47	.45	.05	1.18
1960		.82	.21	.29	.87	1.13	.44	8.83	9.25	.80	.26	1.15	1.60	1.16	.38	5.45	6.55	.96	.32	.19	.91	1.10	.43	2.93	3.60	1.48	.69	2.44	3.71
1961		1.19	.37	1.52	2.63	1.25	.62	14.28	15.19	.74	.28	.94	1.35	1.00	.27	3.26	3.78	1.44	.56	5.71	6.49	.90	.29	.40	1.07	1.52	.65	4.56	5.41
1962		1.10	.22	.30	.88	1.22	.28	1.59	2.28	.55	.09	.01	.37	1.16	.40	7.06	7.98	.92	.19	.11	.68	.94	.28	.63	1.51	1.57	.82	7.99	8.92
1963		.48	.07	.03	.30	.67	.12	.04	.26	.73	.13	.38	1.17	1.09	.21	3.87	4.24	1.37	.28	.27	1.56	1.02	.23	.76	1.26	1.57	.49	5.72	6.25
1964		1.28	.26	.90	2.08	.80	.25	1.04	1.78	.92	.27	2.08	3.08	.86	.26	1.43	2.83	1.46	.39	.58	2.08	1.09	.40	2.41	3.78	1.46	.60	3.14	4.98
1965		1.35	.35	1.57	2.65	1.12	.44	9.73	10.69	.87	.21	.98	1.21	1.13	.45	9.16	9.45	1.53	.42	2.27	3.18	1.16	.39	3.20	3.29	1.50	.80	10.35	10.36
1966		1.02	.33	.23	.91	1.23	.58	10.33	11.23	.63	.13	.12	.88	1.17	.36	8.10	8.86	1.10	.36	.09	.74	.78	.26	.36	1.14	1.56	.92	10.29	11.21
Period of record	Total	9.72	2.66[a]	11.58	16.64	8.33	3.04	47.49	53.16	9.25	2.58	21.14	28.25	10.16	3.41	58.96	66.32	12.02	3.69	17.08	24.50	9.42	3.16	15.57	22.29	22.03	10.10	82.45	97.48
	Average	1.08	.30	1.29	1.85	1.04	.38	5.94	6.64	.77	.22	1.76	2.35	1.02	.34	5.90	6.63	1.34	.41	1.90	2.72	.94	.32	1.56	2.23	1.57	.72	5.89	6.96
Period 1959-66	Total	8.11	2.08	5.08	10.96	8.33	3.04	47.49	53.16	5.95	1.54	6.43	10.97	8.19	2.49	38.35	44.04	9.88	2.90	9.85	16.62	7.59	2.46	10.81	16.12	12.13	5.42	44.54	52.02
	Average	1.01	.26	.64	1.37	1.04	.38	5.94	6.64	.74	.19	.80	1.37	1.02	.31	4.79	5.50	1.24	.36	1.23	2.08	.95	.31	1.35	2.02	1.52	.68	5.57	6.50

[a] Includes 1.59 carryover from 1957 wateryear.

gross lake evaporation for 1959 through 1965 water years is shown in Figure 2.2. Gross lake evaporation is taken from Kane (1967).

Climatological Data

For this study monthly values of the following climatological data were used: wind speed, relative humidity, and temperature. Since the proposed methodology was to be used to adjust historical streamflow, one criteria for selecting a first order U. S. Weather Bureau Station was a long and continuous record. Another criteria was proximity to the seven study areas. The six stations selected were Dallas, San Angelo, San Antonio, Victoria, Waco, and Wichita Falls. Data for these stations are published by the Department of Commerce, Weather Bureau, in the annual series "Climatological Data - Texas Section". Subjective weight factors for each study area were assigned to weather stations primarily based on distance, with consideration also being given to elevation. These weight factors are shown in Table 2.3.

Related Physical and Climatic Data

Climate and Physiography.--A summary of the more important climatic and physiographic parameters of the seven developed study areas is given in Table 2.4. Average annual precipitation and temperature for the period 1931-60 were taken from Carr (1967). Values of average annual gross lake evaporation, 1940-65, were taken from Kane (1967).

Surface Area, Storage, and Discharge.--The surface area-storage relationships for the system of reservoirs in each study area also vary depending upon topography. Discharge characteristics and amounts of water stored at various designated elevations depend upon design. Table 2.5 and 2.6 summarize the surface area, storage, and discharge characteristics found in the seven developed study areas. A comparison of surface area-storage

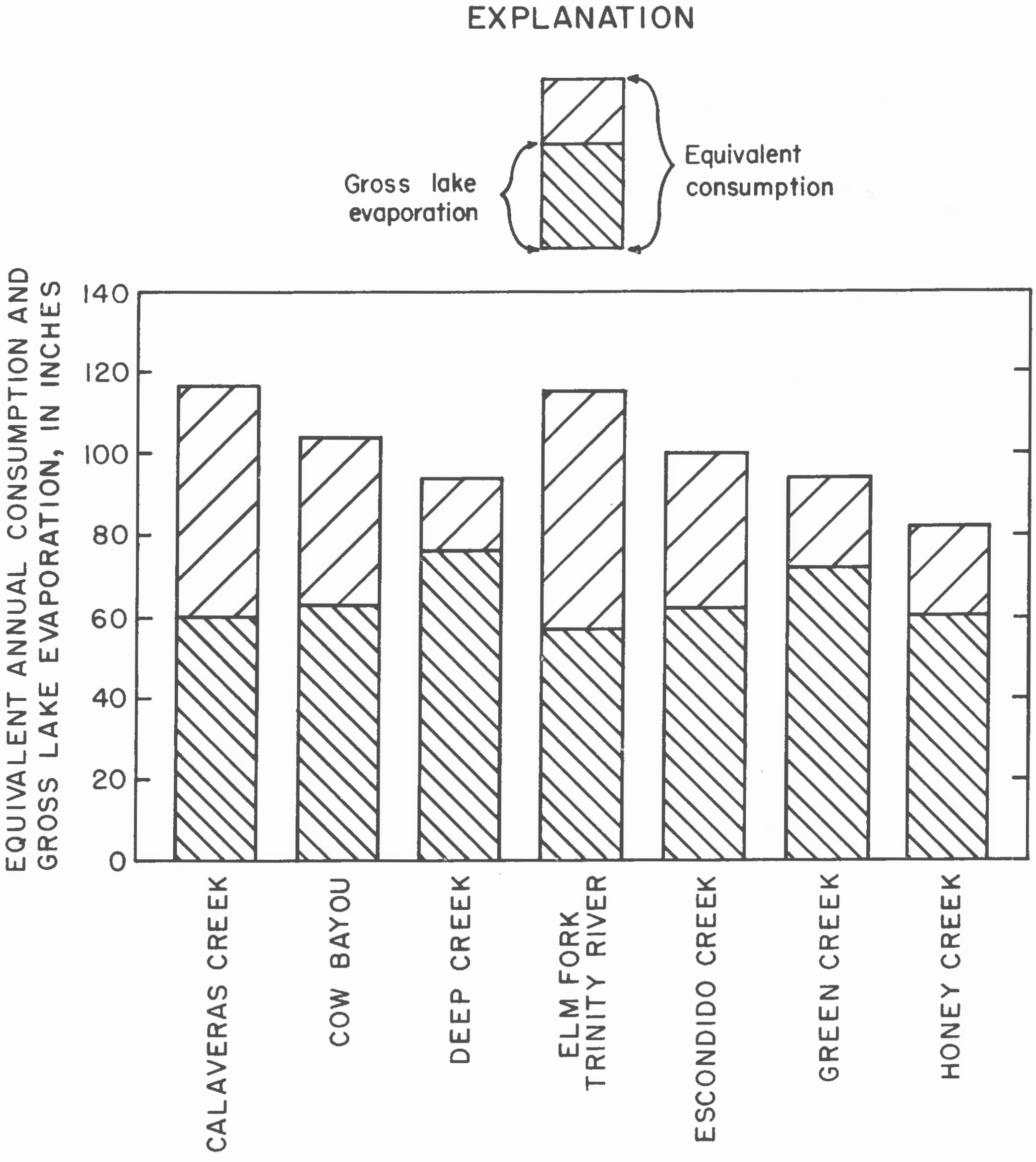


FIGURE 2.2 - Comparison of equivalent annual consumption in study areas and gross lake evaporation, 1959-65.

Table 2.3 Weather station and weight factor used for each study area.

Study area	Station					
	Dallas	San Angelo	San Antonio	Victoria	Waco	Wichita Falls
Calaveras Creek	0	0	90%	10%	0	0
Cow Bayou	0	0	0	0	100%	0
Deep Creek	0	60%	0	0	40%	0
Elm Fork Trinity River	40%	0	0	0	0	60%
Escondido Creek	0	0	50%	50%	0	0
Green Creek	0	25%	0	0	50%	25%
Honey Creek	100%	0	0	0	0	0

Table 2.4.--Climate and physiography of seven developed study areas.

Study area	Average elevation, feet above (msl)	Latitude	Longitude	Average annual precipitation, inches 1931-60	Average annual temperature, °F 1931-60	Average annual gross lake evaporation, inches 1940-65
Calaveras Creek	505	29°19'	98°18'	29	69	64
Cow Bayou	600	31°21'	97°15'	33	67	64
Deep Creek	1,490	31°20'	99°09'	27	65	76
Elm Fork Trinity River	985	33°38'	97°25'	33	65	68
Escondido Creek	360	28°49'	97°54'	30	70	62
Green Creek	1,370	32°07'	98°17'	31	65	74
Honey Creek	660	33°20'	96°42'	38	65	64

Table 2.5. -- Surface area charteristics of floodwater-retarding reservoirs in seven study areas.

Study area	Surface Area, acres								
	Lowest uncontrolled outlet			Sediment pool			Emergency spillway		
	Total	Per sq. mi. controlled	Average per reservoir	Total	Per sq. mi. controlled	Average per reservoir	Total	Per sq. mi. controlled	Average per reservoir
Calaveras Creek	321	8.67	35.7	386	10.42	42.9	1,265	34.16	140.5
Cow Bayou	223	7.96	24.8	319	11.39	35.4	837	29.88	93.0
Deep Creek	164	6.77	27.3	164	6.77	27.3	756	31.22	126.0
Elm Fork Trinity River	169 1/209	5.46 1/6.74	15.4 1/19.0	216	6.98	19.6	786	25.39	71.4
Escondido Creek	411	9.16	37.4	593	13.22	53.9	1,774	39.56	161.3
Green Creek	188 2/197	8.55 2/8.97	23.5 2/24.6	226	10.28	28.2	798	36.31	99.8
Honey Creek	277	13.24	23.1	279	13.33	23.4	772	36.90	64.3

1/ Beginning April 1959.

2/ Beginning March 1958.

Table 2.6.--Storage and discharge data for floodwater-retarding reservoirs in seven study areas.

Study area	Storage, acre-feet									Maximum combined outflow rate principal spillway acre-feet per day		
	Lowest uncontrolled outlet			Sediment pool			Emergency spillway					
	Total	Per sq. mi. controlled	Average per reservoir	Total	Per sq. mi. controlled	Average per reservoir	Total	Per sq. mi. controlled	Average per reservoir	Total	Per sq. mi. controlled	Average per reservoir
Calaveras Creek	1,426	38.4	158	1,869	50.4	208	12,040	324	1,338	393	10.6	43.7
Cow Bayou	1,420	50.7	158	2,366	84.5	263	10,490	375	1,168	599	21.4	66.6
Deep Creek	845	34.9	141	845	34.9	141	7,080	293	1,180	446	18.4	74.3
Elm Fork Trinity River	1,384 1/1,728	44.6 1/55.7	126 1/157	1,798	58.0	163	11,550	373	1,050	625	20.2	56.8
Escondido Creek	1,938	43.2	176	3,432	76.4	312	16,240	362	1,476	970	21.6	88.2
Green Creek	929 2/1,012	42.2 2/46.0	116 2/126	1,118	50.8	140	7,500	341	938	341	15.5	42.6
Honey Creek	1,959	93.7	163	1,974	94.5	164	7,850	376	654	559	26.7	46.6

1/ Beginning April 1959.

2/ Beginning March 1958.

characteristics may be seen in Figure 2.3.

Soils.--The hydrologic properties of soils in a study area are important parameters. The amount of water lost from floodwater-retarding pools other than by evaporation from the free water surface is to some degree dependent upon the soil adjacent to and underlying the pools. Soil maps were prepared for each of the seven watersheds. Soil series were determined from county soil maps compiled by the Soil Conservation Service (USDA) and the Texas Agricultural Experiment Station. The maps are published by the Texas Agricultural Extension Service. The county soil maps show delineations for the dominant soil series and the approximate percentages of each soil. These maps are useful for reconnaissance purposes and are available for most counties in the State.

Soils have been classified as to hydrologic properties (primarily as to runoff potential) by the Soil Conservation Service (National Engineering Handbook, Hydrology, SCS, 1957), and are classified into four major groups. Soils are classified as A, B, C, and D, with definitions as follows:

Group A: (Low runoff potential). Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of sands and gravel that are deep and well to excessively drained.

Group B: Soils having moderate infiltration rates when thoroughly wetted, chiefly moderately deep to deep, moderately well to well drained, with moderately fine to moderately coarse textures.

Group C: Soils having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water, or of moderately fine to fine texture and a slow infiltration rate.

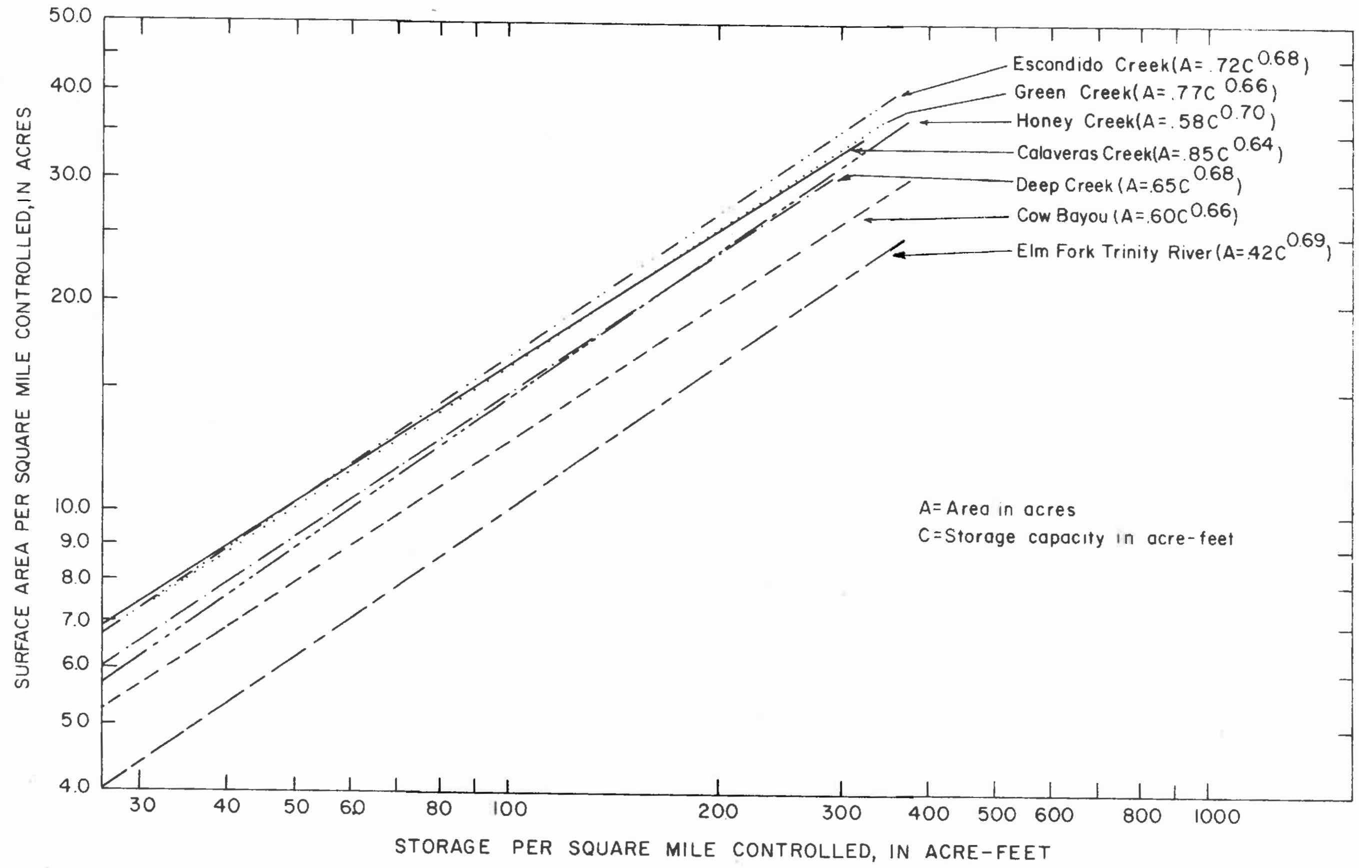


FIGURE 2.3–Relationship of surface area to storage for systems of reservoirs in seven study areas

Group D: (High runoff potential). Soils having very slow infiltration rates when thoroughly wetted, chiefly clay soils with a high swelling potential; soils with a high permanent water table; soils with a clay pan or clay layer at or near the surface; and shallow soils over nearly impervious materials.

Although soils were classified for runoff potential, this classification will also serve as an index of seepage potential. Musgrave and Holtan (1964) give the following minimum infiltration rates by soil groups; SCS soil classification:

Soil Group	Minimum infiltration rate, inches per hour
A	0.30 to 0.45
B	.15 to .30
C	.05 to .15
D	0 to .05

An abbreviated description of soils, along with their hydrologic classification and approximate percentage found in each study area, are shown in Table 2.7. Only those soils underlying floodwater-retarding structures are listed. The computed percentage of each soil is based partly on total area and partly on surface area of individual pools at sediment-pool elevation.

Table 2.7.--Description of soils in seven study areas.

Study area	Soil series	Description	Hydrologic soil group	Approximate percentage
Calaveras Creek	Miguel	Friable sandy loam to loamy sand surface, 8-18 inches thick, grading to firm sandy clay or sandy clay loam 25-40 inches below the surface.	D	16
do	San Antonio	Weakly granular to massive fine sandy loam to clay loam surface, 6-12 inches thick, grading to very firm blocky clay 24 inches below the surface.	D	7
do	Stidham	Weakly granular very friable fine sandy loam to loamy fine sand surface, 6-18 inches thick, grading into a friable blocky sandy clay.	B	43
do	Webb	Friable sandy loam to loam surface, 8-12 inches thick, with very firm plastic clay subsoil over calcareous sandy clay with thin strata of sandstone at depths of 30-45 inches.	C	34
Cow Bayou	Austin	Friable calcareous silty clay to clay surface, 10-14 inches thick, over friable strongly granular highly calcareous silty clay to clay. Chalky marl or chalk at depths of 15-30 inches.	B	30
do	Eddy	Very friable calcareous silty clay or clay 3-15 inches thick, over soft chalky marl.	C	24
do	Houston	Crumbly calcareous clay surface, 6-15 inches thick, over blocky highly calcareous clay at 20-36 inches depth.	D	20
do	Houston-Black	Crumbly and friable calcareous clay surface, 10-25 inches thick, over firm blocky calcareous clay with strongly calcareous clay at 30-60 inches depth.	D	26
Deep Creek	Kirkland	Friable silt loam to clay loam surface, 7-10 inches thick, over very firm and compact blocky clay that grades into weakly calcareous clay or shaly clay below about 36 inches depth.	D	40
do	Owens	Calcareous clay surface, 5-10 inches thick, over very firm blocky to massive calcareous clay that grades into calcareous shaly clay 15-30 inches beneath the surface.	D	60
Elm Fork Trinity River	Denton	Crumbly granular calcareous clay surface, 8-12 inches thick, over crumbly plastic strongly calcareous clay over substrata of limestone interbedded with soft marl, or broken fragments of limestone mixed with marl at depths of about 12-36 inches.	C	65
do	Tarrant	Friable highly calcareous clay surface, 4-8 inches thick, over broken or partly weathered limestone or limestone bedrock at less than 12 inches beneath the surface.	D	35

Table 2.7.--Description of soils in seven study areas-Continued

Study area	Soil Series	Description	Hydrologic soil group	Approximate percentage
Escondido Creek	Monteola	Calcareous clay surface, 12 to 30 inches thick, over angular blocky calcareous clay.	D	26
do	Runge	Fine sandy loam, 8 to 16 inches thick, over calcareous sandy clay loam that grades to a calcareous sandstone 4 to 7 feet below the surface.	B	24
do	Unnamed	(Similar to Engle soil series). Calcareous loam, 10 to 18 inches thick over calcareous fine subangular blocky loam to sandy clay loam that grades to sandy clay loam and interbedded partially weathered calcareous sandstone.	B	44
do	Zapata	Calcareous sandy loam to loam 4 to 14 inches thick, over strongly cemented to indurated caliche, several feet thick.	D	6
Green Creek	Denton (shallow phase)	Crumbly granular and subangular blocky calcareous silty clay loam to clay surface, 4-8 inches thick, over crumbly plastic strongly calcareous clay over substrata of limestone, largely strongly cemented caliche, grading into unaltered marine limestone at depths of 10-20 inches.	C	25
do	Stephenville	Friable sandy loam to loamy sand surface, 8-15 inches thick, over friable sandy clay loam.	B	13
do	Tarrant	Friable highly calcareous clay surface, 4-8 inches thick, over broken or partly weathered limestone or limestone bedrock at less than 12 inches beneath the surface.	D	11
do	Windthorst	Friable fine sandy loam to loam surface, 8-12 inches thick, over very firm sandy clay.	C	51
Honey Creek	Austin	Friable calcareous silty clay to clay surface, 10-14 inches thick, over friable strongly granular highly calcareous silty clay to clay. Chalky marl or chalk at depths of 15-30 inches.	B	35
do	Houston-Black	Crumbly and friable calcareous clay surface, 10-25 inches thick, over blocky strongly calcareous clay at 30-60 inches depth.	D	65

Chapter 3

REVIEW OF COMPONENTS OF WATER LOSS IN IMPOUNDMENTS

Results previously cited amply illustrate that losses from floodwater-retarding pools are considerably in excess of losses commonly associated with the surface storage of water in large reservoirs. It seems appropriate to consider the reasons for the losses. Once the underlying physical reasons are established, design procedures can be developed in order to minimize undesirable losses. Additionally, design agencies can make appropriate allowances for any existing or proposed upstream flood prevention programs.

For an analysis of the response of a floodwater-retarding pool to various inputs, it is necessary to know the water budget. By the nature of its design, the change in storage of the reservoir is zero over a long period of time. For this study, inflow, rainfall on pools, outflow, and total consumption are known. A conceptual model of the floodwater-retarding reservoir is shown in Figure 3.1.

Obviously evaporation from free water surface, evaporation from soil adjacent to the pool, and transpiration are depletions insofar as downstream water use is concerned. In none of the study areas has there been evidence of significant quantities of seepage under and through the dam. Therefore, this quantity is assumed to be zero. In addition, unless the ground-water table intersects the stream channel below the system of reservoirs, percolation to ground water is a loss for a downstream surface water user. In none of the study areas has there been an increase in base flow, therefore percolation to the ground water table is considered as a loss. Hence the problem is to separate the four components of consumption,

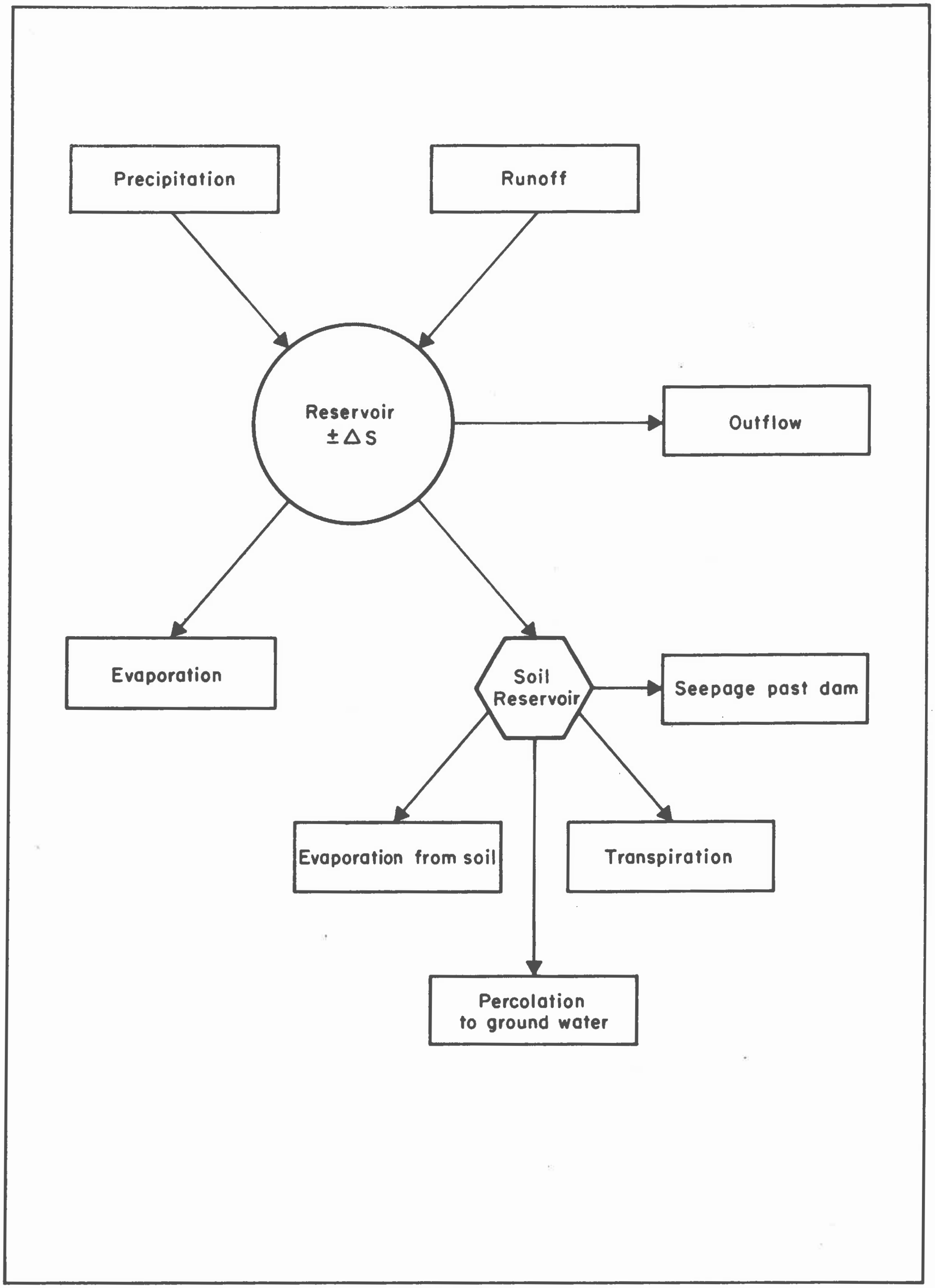


FIGURE 3.1 – Conceptual model of water budget for a floodwater-retarding reservoir

evaporation from free water surface, evaporation from adjacent soil, transpiration, and seepage, based on sound physical principles. In addition, to make the methodology of general use, it should incorporate parameters which are reasonably easy to obtain. A discussion of the four components of consumption is given in the following sections.

Evaporation from Free Water Surface

Generally the major cause of depletion of impounded water is evaporation from the free water surface. Evaporation is the process whereby water is changed from the liquid state to the vapor state. The evaporation process has been researched quite extensively, yet some of the processes involved are not fully understood. An excellent summary and development of evaporation processes is given by Anderson, Anderson, and Marciano (1950).

Evaporation occurs when water molecules in the liquid state attain sufficient energy to eject themselves from the water surface. Water vapor exerts a partial pressure termed vapor pressure. When a parcel of air contains the maximum amount of water vapor it can hold without condensation occurring, the partial pressure exerted by the water vapor is termed saturation vapor pressure.

Evaporation from a free water surface is highly dependent upon the difference between the saturation vapor pressure and the actual vapor pressure of the thin layer of air adjacent to the water surface. This is the basis for the many empirical evaporation equations based on Dalton's Law:

$$E = K (e_s - e_a)$$

where E = rate of evaporation

K = a constant of proportionality

e_s = saturation vapor pressure of air at water surface temperature

e_a = actual vapor pressure of air.

A large number of studies have been concerned with defining the constant of proportionality, K, which is generally partly dependent on air movement. A summary of selected evaporation equations based on Dalton's Law is given by Veihmeyer (1964).

Basically there are four methods of estimating evaporation from lake surfaces. These four methods are discussed separately in the following sections.

Pan-to-Lake Coefficients.--Pan-to-lake coefficients are by far the most widely used method of estimating lake evaporation. They are simple to use, necessary data are generally available, and results are reasonably accurate on an annual basis. An annual pan-to-lake coefficient of 0.7 is commonly used. Monthly values of pan-to-lake coefficients vary considerably depending on local climate and on lake characteristics. The development of improved methods for estimating annual lake evaporation from pan observations and related meteorological data has been a primary objective of U. S. Weather Bureau evaporation studies. Values of average annual Class A pan and lake evaporation and Class A pan-to-lake coefficients for the conterminous United States are given by Kohler, Nordenson, and Baker (1959). The use of the customary 0.7 coefficient can lead to appreciable error unless the effects of advected energy into the lake and heat transfer through the pan are taken into account. In U. S. Weather Bureau Research Paper No. 38 (Kohler, Nordenson, and Fox, 1955) techniques are presented to adjust for advected energy and heat transfer. This paper gives the following equation as being best suited for the computation of annual lake evaporation from pan data:

$$E_L = 0.70\,[E_p + .00051\,P_a\,\alpha_p(0.37 + .0041\,U_p)\,(T_o - T_a)^{0.88}]$$

where E_L = lake evaporation, inches/day

E_p = pan evaporation, inches/day

P_a = atmospheric pressure in inches of mercury

α_p = proportion of advected energy (Class A pan) used for evaporation

U_p = wind movement 6 inches above Class A pan in miles/day

T_a = air temperature, °F

T_o = water surface temperature, °F.

Total annual evaporation is then obtained by accumulating daily values and solving the equation graphically. Lamoreaux (1962) has developed a formula suitable for computer operations which replaces the graphical solution of the above equation. This method has been successfully applied by Roberts and Stall (1966) in Illinois.

Empirical Equations.--Most empirical equations are based on Dalton's Law and an empirical definition of the constant of proportionality. Generally, the most important factor other than vapor pressure differential is wind movement. Many of the formulas agree well with data from which they are derived, but frequently are not readily applicable to other areas.

Energy-Budget Method.--In the energy-budget method, incoming, outgoing, and stored energy are measured during some finite period and related to the amount of energy required for the evaporation process. Utilizing the energy budget, evaporation from a lake surface can be expressed as follows

(Anderson, 1954):

$$E = \frac{Q_s - Q_r - Q_b + Q_v - Q_z}{\rho L\ (1 + R)}$$

where E = evaporation

Q_s = incident solar radiation

Q_r = reflected solar radiation

Q_b = net energy lost by the body of water through the exchange of long-wave radiation between the atmosphere and the body of water.

Q_v = net advected energy into the body of water

Q_z = increase in stored energy in the body of water

ρ = mass density of water

L = latent heat of vaporization

R = ratio of energy conducted to or from the air as sensible heat to the energy lost through evaporation, generally referred to as Bowen's ratio.

From a physical point of view, it appears the energy budget method is the most accurate method of computing evaporation if the terms in the equation can be measured with sufficient accuracy. Accurate measurements require costly and elaborate instrumentation, therefore, the method is generally used only for calibration purposes.

Mass-Transfer Method.--Mass transfer theory has been developed to derive evaporation equations, based on the concepts of discontinuous and continuous mixing applied to the transfer of mass in the boundary layers. A physical and mathematical review of mass-transfer equations is given by Anderson, Anderson, and Marciano (1950). Two approaches are taken in mass transfer theory. One group of equations is based on the concept of discontinuous mixing as developed in Prandtl's mixing length theory. The other group of equations is based on the continuous mixing concept.

In the Lake Hefner studies, Marciano and Harbeck (1954), reported the following:

> From the practical point of view of obtaining an evaporation equation suitable for field use -
>
> 1. Two theoretical equations, Sverdrup (1937) form and Sutton's form gives good results.
>
> 2. The Thornwaite-Holzman equation would probably give satisfactory results with proper instrumentation but instrument requirements are exacting.
>
> 3. All other theoretical evaporation equations based on existing models and methods were found to be unsatisfactory.

As an outgrowth of the Lake Hefner and other studies, Harbeck (1962) has presented a quasi-empirical mass transfer equation of the form:

$$E = Nu\ (e_s - e_a) \qquad (3.1)$$

where E = evaporation in inches/day

N = a mass-transfer coefficient, coefficient of proportionality

u = wind speed in miles per hour at some height above the water surface

e_s = saturation vapor pressure in millibars corresponding to the water surface temperature

e_a = vapor pressure of air in millibars.

The mass transfer coefficient N represents a combination of many variables in the published mass transfer equations, including manner of variation of wind with height, size of lake, roughness of the water surface, atmospheric stability, barometric pressure, and density and kinematic viscosity of air. Harbeck found

$$N = \frac{0.00338}{A^{0.05}}$$

with A in acres and u = wind speed in miles per hour at 2 meters above water surface as used in equation (3.1).

The results of Harbeck's mass-transfer equation are generally reasonably accurate. The method requires only water-surface temperature, air temperature, relative humidity, and wind movement observations for application. Observations of climatic factors at nearby weather stations may be used for estimating purposes. The method has gained wide acceptance in the U. S. Geological Survey.

Evaporation from Peripheral Soil Surface

Evaporation from the soil surface peripheral to the pool is generally not considered to be a significant source of water loss in reservoirs. In general, this is a valid assumption for large reservoirs because the soil area subject to evaporation loss is small compared to the area of the free water surface.

For small reservoirs, this may be a significant factor since perimeter is exponentially related to area. Perimeters and surface areas at the sediment pool and emergency spillway elevations were measured and these values were averaged for each of the 7 study areas. The results are shown in Figure 3.2.

A linear least-square regression indicates the perimeter-surface area relation to be

$$P = 1{,}660\ A^{0.44} \qquad (3.2)$$

where P = perimeter in feet

A = surface area in acres.

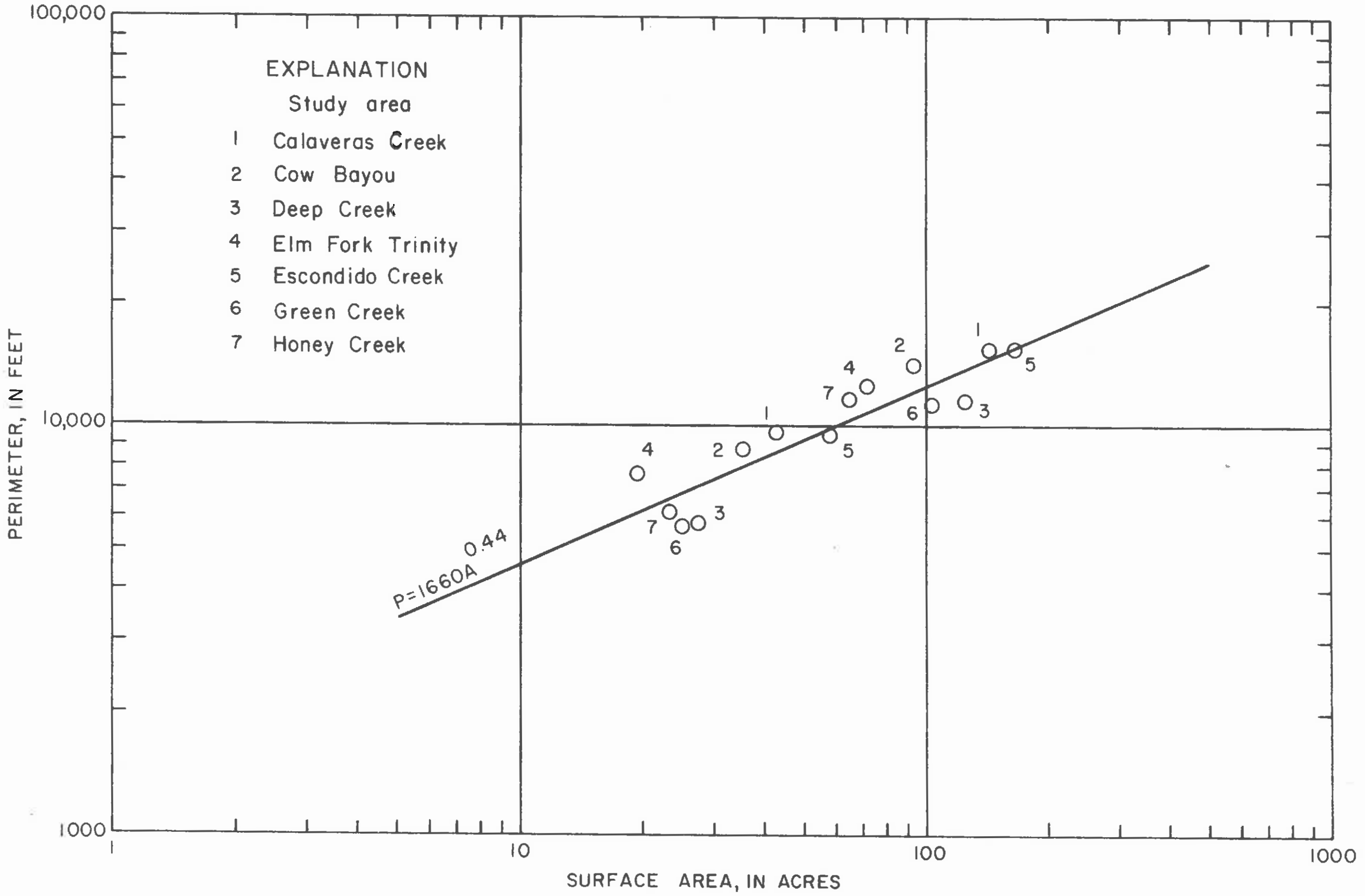


FIGURE 3.2.-Relationship of perimeter to surface area for floodwater — retarding reservoirs in seven study areas

This relationship will vary depending upon topography and the number of tributaries flowing directly into the pool, however, the trend is apparent. If geometric scale is maintained, the exponent would be 0.5 rather than 0.44. For this report, the exponent is assumed to be a constant (0.44) and the coefficient is varied. This yields the following relationships for the seven study areas:

Calaveras Creek	Escondido Creek
$P = 1800\ A^{0.44}$	$P = 1640\ A^{0.44}$
Cow Bayou	Green Creek
$P = 1900\ A^{0.44}$	$P = 1450\ A^{0.44}$
Deep Creek	Honey Creek
$P = 1400\ A^{0.44}$	$P = 1800\ A^{0.44}$
Elm Fork Trinity River	
$P = 2000\ A^{0.44}$	

To illustrate the effect of size on relative peripheral area, a hypothetical example is taken:

Assume $P = 1660\ A^{0.44}$ and effective evaporating band of soils is 20 feet wide

For A = 10 acres,

Evaporating soil area = $\dfrac{20 \times 1660(10)^{0.44}}{43{,}560} = 2.1$ acres or 21 percent of surface area

For A = 1,000 acres,

Evaporating soil area = $\dfrac{20 \times 1660(1000)^{0.44}}{43{,}560} = 16.0$ acres or 1.6 percent of surface area.

This hypothetical example illustrates that for small pools evaporation from the contiguous soil surface can be a significant factor.

Obviously a pool of water creates a very shallow water table adjacent to the pool. Evaporation from a shallow water table has been well documented in research reported in various scientific media. For example, van Hylckama (1966), reporting on field investigations in southern Arizona, found significant amounts of evaporation from bare soils with water table at a depth of 1.2 meters (3.9 feet). Information given by van Hylckama, based on the assumption that soil porosity was 40 percent, showed that during two periods in June evaporation from the soil surface was 0.25 inch per day. McDonald and Hughes (1968) in field experiments conducted in Arizona, found that for depth to water table of 2 feet, evaporation in the 1964 calendar year was equal to about 23 inches of water applied to the surface. Assuming soil porosity of 40 percent, this would require the equivalent of 58 inches evaporation, slightly over 50 percent of U. S. Weather Bureau Class A pan evaporation of 115 inches. In a 125 centimeter (49 inches) soil column initially saturated and allowed to evaporate under constant potential evaporation rates, Gardner and Hillel (1962) found evaporation was at an approximately constant rate to a water table depth of 10 inches, then continued at a decreasing rate to a depth of 25 inches. The soil was loam with a porosity of 40 percent. Nixon and Lawless (1960), in tests on a bare soil, found that evaporation noticeably reduced soil moisture in the upper two feet, but found no evaporation loss below four feet. Fritchen and van Bavel (1962) found the rate of evaporation from a wet soil surface to be higher than from a free water surface, which they attributed to more energy being used in heating the air over shallow open water than over a wet soil surface.

Physical phenomena governing the rate of evaporation from the soil surface are complex. Research by Schleusner and Corey (1959) and King and Schleusner (1961) demonstrated conclusively that evaporation from the soil surface proceeds at a rate very nearly equal to the rate of evaporation from a free water surface until a critical point is reached, after which evaporation from the soil becomes very small. This critical point occurs when the evaporation rate exceeds the upward transport rate and the upper soil dries out. The critical point is determined by soil characteristics, rate of evaporation, and depth to water table.

Based on a purely theoretical concept, Liakopoulas (1966) developed a partial differential equation for representing evaporation loss from ground water. Assuming an initially saturated column and considering the equations of motion, continuity, and state, Liakopoulas solved the equation by finite difference approximations. He found that the evaporation rate reduces rather quickly, then levels off. The lower level of evaporation was found to be determined by the unsaturated moisture conductivity of the soil.

Transpiration by Riparian Vegetation

Transpiration by vegetation can also be a significant quantity in areas with shallow water table. Unless preventive steps are taken, phreataphytes will flourish around the pools. Robinson (1952) found that generally the greater the depth to the water table, the lower the rate of water used by phreatophytes.

Transpiration depends primarily on temperature if the water table is shallow and it virtually ceases during the dormant season. Various methods have been presented to estimate consumptive use by crops (McDaniels, 1960). Perhaps the most widely known and used methods are the Blaney-Criddle formula (Blaney and Criddle, 1945), and the Penman type equations (Penman, 1948). Most methods relate consumptive use to pan evaporation.

Percolation to the Ground Water Reservoir

The rate of seepage from a reservoir to the underlying soil depends primarily on the hydraulic conductivity of the underlying soil and geologic formation. Hydraulic conductivity is the proportionality constant K in the well known Darcy's equation flow in porous media

$$Q = K A \frac{dh}{dl}$$

where Q = rate of flow

A = gross cross-sectional area

$\frac{dh}{dl}$ = hydraulic gradient.

The term K is also frequently defined as the coefficient of permeability. The value of K depends upon both the permeability of the porous media and the viscosity of the fluid.

The U. S. Geological Survey has adopted two definitions of the coefficient of permeability.

1. Laboratory or standard coefficient of permeability K_s is defined as the flow of water at 60°F in gallons per day through a medium having a cross-sectional area of 1 square foot under a hydraulic gradient of unity.
2. Field coefficient of permeability K_f is defined as the flow of water in gallons per day through a cross section of aquifer 1 foot thick and 1 mile wide under a hydraulic gradient of 1 foot per mile at field temperature.

It is noted that K_s and K_f differ only in consideration of temperature. If the difference in density due to temperature is neglected, the only difference necessary to consider is the viscosity. Hence,

$$\frac{K_s}{K_f} = \frac{\mu_f}{\mu_{60}}$$

where μ_f and μ_{60} are viscosity of water at field temperature and at 60°F, respectively. Laboratory coefficient of permeability K_s for various soils on an order of magnitude basis are given by Todd (1959) as follows:

Soil Class	Range of K_s, gal/day/ft
Clean gravel	10^6 -- 10^4
Clean sands; mixture of clear snad and gravels	10^4 -- 10
Very fine sands; silts, mixtures of sand, silt, and clay, glacial till, stratified clays, etc.	10 -- 10^{-3}
Unweathered clays	10^{-3} - 10^{-4}

Percolation to the ground-water table for an individual pool depends upon the wetted soil area, permeability of the soil and underlying formations, viscosity of the water, and relative position and slope of the ground-water table.

Chapter 4

MATHEMATICAL MODEL FOR MONTHLY CONSUMPTION

Multiple Linear Regression Analysis

A multiple linear regression study was undertaken to define relationships for consumption attributable to floodwater-retarding structures. Measurements of all physical parameters necessary to define all segments of the four components of consumption are not available, nor would it be economically feasible to make the necessary measurements. It appears then, that the best method of analyzing consumptive losses is by multiple linear regression. Multiple linear regression is useful in developing prediction equations although the prediction equations may or may not have physical significance. This method has been found to be quite useful in many areas of research where it is not feasible to define and measure all the processes involved.

The multiple linear regression equation is of the general form

$$Y = a_o + \sum_{i=1}^{n} a_i X_i + E$$

where Y is the dependent variable

a_o and a_i are regression constants

X_i are independent variables

n is the number of independent variables

E is the error due to regression

The dependent variable, consumption, is dependent upon evaporation from the free water surface, evaporation from peripheral soil surface, transpiration by vegetation, and seepage. The four factors comprising consumption are partially interrelated, being to some degree dependent upon the same physical parameters. This is often the case in hydrology; however, statistical techniques can still be very useful.

Two basic approaches may be taken in multiple linear regression. In one approach, all variables which are thought to be important are used and tested for statistical significance. This frequently leads to regression equations which bear no resemblance to the physical processes involved. The second approach is to formulate the individual variables into new variables or expressions which are considered to be representative of the physical processes involved. The second approach was taken for this study.

Variables Used in Analysis.--For use in the multiple linear regression study, data on the following were available for use either as measured or observed values:

1. C = monthly consumption, acre-feet.
2. A = monthly average surface area, acres.
3. $\overline{D}$ = monthly mean depth, feet.
4. u = monthly average wind speed, miles per hour.
5. e_s = saturation vapor pressure at surface temperature of water.
6. e_a = actual vapor pressure at average monthly air temperature and relative humidity, millibars.
7. $\Delta e = e_s - e_a$, vapor pressure deficit, millibars.
8. P = perimeter of pools at average surface area, in feet.
9. S = average side slope, feet per foot.
10. ν = kinematic viscosity of water at average monthly water surface temperature, feet^2 per second x 10^5.
11. T_a = average monthly air temperature, °F.
12. T_w = average monthly water surface temperature, °F.

13. DA = drainage area controlled by floodwater-retarding structures, square miles.

The first variable, consumption C, is considered to be dependent upon the remaining 12 variables.

Using these 13 variables, equations which were thought to be representative of the physical processes were formulated and analyzed by multiple linear regression. The equations have three parts which were considered to be representative of consumption by evaporation, transpiration, and seepage. The basis for formulation is as follows:

1. Evaporation was considered to have two components.
    a. Free water-surface evaporation was assumed to be a function of surface area, vapor pressure deficit, and wind speed. This is patterned after the mass-transfer method (Harbeck, 1962).
    b. Peripheral soil-surface evaporation was assumed to be a function of vapor pressure deficit, wind speed, depth to water table, capillary rise, hydraulic conductivity of soil, effective evaporating area, and porosity of soil. For a given study area, permeability and soil porosity is constant and height of capillary rise varies only slightly. The effective evaporating area is directly proportional to perimeter of the pool and inversely proportional to the side slope. Hydraulic conductivity varies inversely with viscosity.

For each study area, the following expressions for the independent variables representative of evaporation were computed for each month:

$X_1 = \Delta e\ u\ (A + K_1\ P/S\nu)$

or $X_1 = \Delta e\ u\ (A + K_1\ P/S)$

or $X_1 = \Delta e\ (A + K_1\ P/S\nu)$

or $X_1 = \Delta e\ (A + K_1\ P/S)$

where K_1 = a constant to convert the term to acres. For this study, it was assumed the maximum effective depth for evaporation from the soil was one foot. Under this assumption, when only P and S are used, $K_1 = 1/43{,}560$.

In the initial processing of the data, combinations of Δe, u, ν and A, and Δe, u, P, S, and ν were considered as separate variables. The greatest variation of the evaporation expressions was attributable to Δe, therefore the two expressions were highly correlated. High simple correlation between variables often leads to somewhat unreasonable and erratic results. This happened in this study, therefore, A, P, S, Δe, and ν were combined as shown in the above expressions for X_1.

2. Transpiration depends upon the amount of vegetation around pools and the length of the growing season. For a given amount of growth, transpiration is primarily a function of temperature. It was assumed that the transpiration process is linearly related to temperature and that transpiration ceases when mean monthly temperature falls below a given level. For comparability between study areas of various sizes, a scale factor equal to the drainage area upstream from the structures was added. The two expressions used for the second independent variable were

$$X_2 = (T_a - 40)\ DA$$

$$\text{or } X_2 = (T_a - 32)\ DA$$

with the qualification that X_2 could not be less than zero.

3. Seepage away from reservoir was assumed to be directly proportional to pool surface area and the product of mean depth and perimeter, and inversely proportional to the kinematic viscosity of water. Therefore, the expression used for the third independent variable was

$$X_3 = (K_3\ \overline{D}P + A)\ /\nu$$

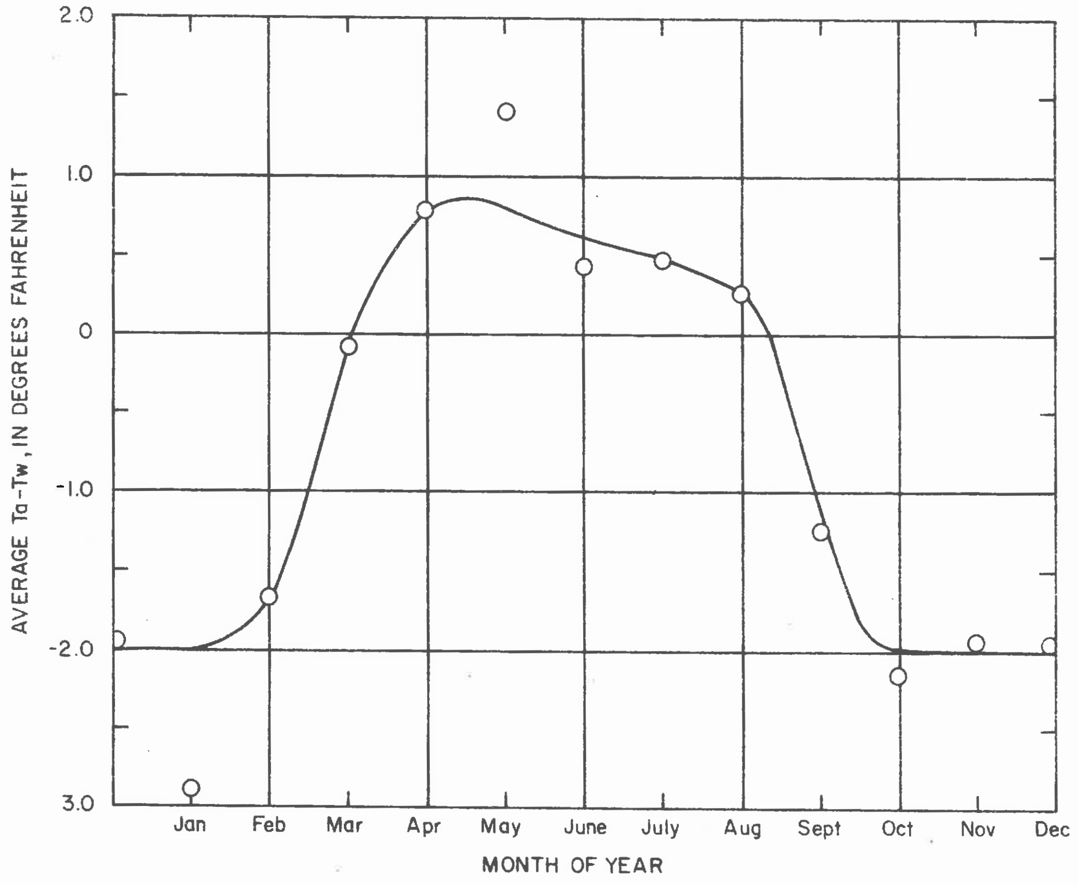
where $K_3 = 1/43{,}560$ to convert $\overline{D}P$ to acres.

The basic regression equation then is of the form:

$$C = a_o + a_1\ X_1 + a_2\ X_2 + a_3\ X_3 \qquad (4.1)$$

For each study area, monthly values of consumption C, average surface area A, and mean reservoir depth $\overline{D}$, were available from U.S. Geological Survey data. The mean depth, $\overline{D}$, was computed as the quotient of average monthly content and surface area. Mean monthly air temperature, wind movement, and relative humidity were computed using appropriate first order weather station data as shown in Table 2.3.

A general relationship of difference in water surface temperature and air temperature was developed based on average values of observations taken in the study areas. This relationship is shown in Figure 4.1 and was used to correct from air temperature to water temperature. The relation indicates that water temperatures do not deviate greatly from air temperature on an average basis. This is characteristic of shallow lakes which are well mixed and because of their small size cannot store large amounts of heat energy.



NOTE:

Ta = Average monthly air temperature, °F
Tw = Average monthly water surface temperature, °F

FIGURE 4.1.—Relation of water-surface temperature to air temperature for floodwater-retarding reservoirs in Texas

Saturation vapor pressure e_s was computed using water surface temperature. For all practical purposes, saturation vapor pressure is a function of temperature only. Since it is desirable to have an equation for saturation vapor pressure rather than using a table look-up procedure, an interpolating polynomial was developed using finite differences and the Gregory-Newton formula for forward interpolation as outlined in Kunz (1957). The Gregory-Newton formula for forward interpolation is:

$$x = \sum_{j=0}^{n} \frac{u^{[j]}}{j!} \Delta^j x_o + R$$

where x = dependent variable

x_o = x at initial value of independent variable

y = independent variable

$u = \frac{y-y_o}{h}$

$u^{[j]} = \prod_{j=o}^{n} (u-j)$

Δ^j = j^{th} difference in finite difference table

h = increment of independent variable in difference table $(y_{j+1}-y_j)$

n = degree of interpolating polynomial

R = remainder (difference between tabulated value and polynomial).

For the polynomial, temperature in degrees centigrade and corresponding saturation vapor pressure in millibars were tabulated from 0°C to 30°C (32°F to 86°F). Neglecting the remainder in R, the fourth degree polynomial of e_s

in terms of T is:

$$e_s = 6.1 + 0.4180555\ T + 0.0190971\ T^2$$
$$-0.0000386\ T^3 + 0.0000096\ T^4$$

where e_s = saturation vapor pressure in millibars

T = temperature in °C.

This gives e_s between 0°C and 30°C with a maximum error of 0.5 percent. The temperature used to compute e_s is water surface temperature. To compute air vapor pressure e_a, saturation vapor pressure is computed at air temperature and multiplied by relative humidity, since relative humidity $= e_a/e_s$.

To compute kinematic viscosity, ν, the relationship of ν to water temperature is used, since ponds are shallow and little stratification would be expected. Soundings taken in Honey Creek site 12 in September and November 1957 and February, March, and August 1958 (Gilbert et al. 1964) illustrate the uniformity of water temperature profiles in the pools. An interpolating polynomial was developed for viscosity in terms of water temperature, using the Gregory-Newton difference formula. Results are:

$$\nu = [1.93 - 0.0630556T + 0.0009955T^2 + 0.0000154T^3$$
$$- 0.0000006T^4] \times 10^{-5}$$

where ν = kinematic viscosity in ft^2 / sec

T = water temperature in °C.

This equation gives values of ν within ±1 percent accuracy in the range of temperature 0 - 30°C (32-86°F).

Average side slopes at the sediment pool elevation were computed for each study area, based on rate of increase of surface area - capacity relation and pool perimeter. Values of side slope computed and used were as follows:

Calaveras Creek	0.034
Cow Bayou	.061
Deep Creek	.021
Elm Fork Trinity River	.098
Escondido Creek	.033
Green Creek	.052
Honey Creek	.065

For the regression study, the water years 1959-66 were used as the base period. Numerical values of the independent variables were computed for each watershed and analyzed. Various combinations of different X_1 and X_2 were used, making a total of 12 regression equations for each watershed. As is often the case in research, the path from initial conception to final formulation was at times a tortuous road. A number of other formulations were attempted and discarded. Only the 12 which presently seem most reasonable are included in this text. If the reasoning used is correct, the regression coefficients should have the following characteristics:

a_o should be zero as C should be zero when X_1, X_2, and X_3 are zero.

a_1 should be reasonably similar in the seven study areas.

a_2 should be a measure of growth around pools.

a_3 should vary amoung the watersheds depending upon soil type and geology and should reflect the hydraulic properties of the underlying soils and geologic formations.

The independent variables for each watershed were processed by digital computer using the observations of hydrologic and climatic data and the physical properties of the structures.

Description of Computer Program.--Data for each study area were analyzed using a standardized program developed by the Biomedical Sciences Department at the University of California at Los Angeles and modified to some extent by personnel of the Civil Engineering Department of the University of Texas at Austin. The program is quite flexible and can accommodate up to 99,999 samples. For this study, 7 sub-samples (study areas) with 96 observations (months) were used. Output of the program included the following:

1. Sums and sums of squares.
2. Cross products of deviations.
3. Correlation matrix.
4. Inverse of correlation matrix.
5. Means and standard deviations.
6. Regression coefficients, their standard errors and t-values and deviation about regression, with degrees of freedom and F-values.
7. Sums of squares due to regression for each variable.
8. Standard error of estimate.
9. Intercept.
10. Partial correlation coefficients.
11. Multiple correlation coefficients and coefficient of determination.
12. Table of residuals.
13. Analyses of extreme residuals.

For a complete description of the program and computation procedure, see Dixon (1964). For a thorough treatment of theory and methodology of multiple regression analysis, see Ezekiel and Fox (1959), or Fisher (1950).

<u>Results of Regression Analysis</u>.--As stated previously, 12 regression equations for different combinations of variables thought to be significant were used for each study area. These 12 regression equations are as follows:

1. $C = a_o + a_1 u (e_s-e_a)(A+K_1P/S\nu)+a_2(T_a-40)(DA)+a_3(K_3\overline{D}P+A)/\nu$
2. $C = a_o + a_1 u (e_s-e_a)(A+K_1P/S)+a_2(T_a-40)(DA)+a_3(K_3\overline{D}P+A)/\nu$
3. $C = a_o + a_1 (e_s-e_a)(A+K_1P/S\nu)+a_2(T_a-40)(DA)+a_3(K_3\overline{D}P+A)/\nu$
4. $C = a_o + a_1 (e_s-e_a)(A+K_1P/S)+a_2(T_a-40)(DA)+a_3(K_3\overline{D}P+A)/\nu$
5. $C = a_o + a_1 u (e_s-e_a)(A+K_1P/S\nu)+a_2(T_a-32)(DA)+a_3(K_3\overline{D}P+A)/\nu$
6. $C = a_o + a_1 u (e_s-e_a)(A+K_1P/S)+a_2(T_a-32)(DA)+a_3(K_3\overline{D}P+A)/\nu$
7. $C = a_o + a_1 (e_s-e_a)(A+K_1P/S)+a_2(T_a-32)(DA)+a_3(K_3\overline{D}P+A)/\nu$
8. $C = a_o + a_1 (e_s-e_a)(A+K_1P/S\nu)+a_2(T_a-32)(DA)+a_3(K_3\overline{D}P+A)/\nu$
9. $C = a_o + a_1 u (e_s-e_a)(A+K_1P/S)+a_3(K_3\overline{D}P+A)/\nu$
10. $C = a_o + a_1 u (e_s-e_a)(A+K_1P/S\nu)+a_3(K_3\overline{D}P+A)/\nu$
11. $C = a_o + a_1 (e_s-e_a)(A+K_1P/S\nu)+a_3(K_3\overline{D}P+A)/\nu$
12. $C = a_o + a_1 (e_s-e_a)(A+K_1P/S)+a_3(K_3\overline{D}P+A)/\nu$

A summary of the results of the regression analysis is given in Table 4.1.

These results indicate that several different equations yield similar multiple regression coefficients and standard errors of estimate. All twelve equations yielded reasonably good results. On an average basis, the inclusion of wind speed as a factor did not improve the estimate. This may be due to the fact that although wind is a significant factor in the evaporation process in a short time interval, other factors dominate for a period as long as a month. Only in the Cow Bayou and Elm Fork Trinity River study areas were results improved by the inclusion of wind movement. The inclusion of viscosity in the evaporation term did not improve results.

Table 4.1.--Statistical results of regression analysis of reservoir consumption.

Study area	Regression equation number																							
	1		2		3		4		5		6		7		8		9		10		11		12	
	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e	r	S_e
Calavaras Creek	.925	16.5	.924	16.6	.935	15.4	.935	15.4	.925	16.5	.924	16.6	.935	15.4	.935	15.4	.924	16.6	.925	16.5	.934	15.4	.934	15.4
Cow Bayou	.984	8.6	.984	8.6	.981	9.2	.981	9.2	.984	8.6	.984	8.6	.981	9.2	.981	9.2	.976	10.2	.977	10.1	.974	10.6	.974	10.6
Deep Creek	.942	16.3	.941	16.5	.958	14.0	.958	14.0	.942	16.3	.941	16.5	.958	14.0	.958	14.0	.929	18.0	.932	17.5	.957	14.0	.957	14.0
Elm Fork Trinity River	.983	9.5	.983	9.4	.981	9.9	.981	9.9	.983	9.5	.983	9.4	.981	9.9	.981	9.9	.973	11.7	.973	11.6	.975	11.4	.975	11.3
Escondido Creek	.914	13.0	.914	13.1	.916	12.9	.916	12.9	.914	13.0	.914	13.1	.916	12.9	.916	12.9	.911	13.1	.912	13.1	.916	12.8	.916	12.8
Green Creek	.954	13.3	.954	13.3	.960	12.4	.959	12.5	.954	13.3	.954	13.3	.959	12.5	.960	12.4	.936	15.5	.938	15.3	.955	13.0	.954	13.1
Honey Creek	.957	12.9	.956	13.0	.966	11.5	.966	11.5	.956	13.0	.956	13.0	.966	11.5	.966	11.5	.931	16.0	.933	16.0	.958	12.7	.957	12.8
Average	.951	12.9	.951	12.9	.957	12.2	.957	12.2	.951	12.9	.951	12.9	.957	12.2	.957	12.2	.940	14.4	.941	14.3	.953	12.8	.952	12.9

r = Multiple correlation coefficient

S_e = Standard error of estimate, percent

From the above study, the equation selected as the best estimator of monthly consumption for the seven study areas was:

$$C = a_o + a_1\ (e_s - e_a)(A + K_1P/S) + a_2(T_a - 40)(DA) + a_3(K_3\bar{D}P + A)/\nu \qquad (4.2)$$

A summary of statistical parameters for each of the seven study areas using equation (4.2) is given in Table 4.2. From this table, the following is noted:

1. a_1 is significantly different from zero for all study areas except Escondido Creek for a 99 percent confidence interval. For Escondido Creek a_1 is significantly different from zero for a 90 percent confidence interval.
2. a_2 is significantly different from zero at 99 percent confidence level in all study areas except Calaveras Creek, Deep Creek, and Escondido Creek.
3. a_3 is significantly different from zero at 99 percent confidence level in all study areas.

The results did not show a clear trend for any of the regression coefficients, and several of the study areas had intercept (a_o) values significantly different from zero. As the purpose of this study was to develop methodology which could be extrapolated to ungaged areas, the least square-multiple linear regression equations were not deemed to be satisfactory because of the variation in regression coefficients.

Development of General Equations for Monthly Consumption

The multiple linear regression study was used to identify the combination of variables which provide the best estimate of consumption. Using these variables (equation 4.2) another program was developed in which the intercept (a_o) was fixed at 0 and the other three regression coefficients

Table 4.2.--Summary of statistical parameters for regression study using best fit equation in each of seven study areas.

Study area	a_o	F	a_1	t_1	a_2	t_2	a_3	t_3	r	S_e percent
Calaveras Creek	4.21	212	.028	5.33	-.008	- .91	.594	9.06	.935	15.4
Cow Bayou	-17.7	786	.012	5.42	.031	5.70	.601	21.17	.981	9.2
Deep Creek	- 2.7	340	.023	8.39	.007	1.10	.384	7.18	.958	14.0
Elm Fork Trinity River	-56.7	793	.016	5.36	.034	5.46	.868	17.36	.981	9.9
Escondido Creek	-23.7	159	.008	1.69	.002	.23	.714	12.15	.916	12.9
Green Creek	-11.6	355	.017	5.71	.023	3.29	.500	11.15	.960	12.4
Honey Creek	8.6	428	.019	6.69	.063	4.81	.236	4.52	.966	11.5

were varied in a stepwise manner to determine the least square estimator when $a_o = 0$. This program, designated as Program MINMIZ, along with an example of output is included in the appendix. The object was to optimize the results with a given set of constraints. The regression coefficient a_1 should be relatively constant for all seven study areas. Initial testing indicated the value of a_1 which best fit all seven study areas was 0.026. This value of a_1 was then fixed for each study area and a_2 and a_3 were varied in a stepwise manner. The values of a_2 and a_3 should vary depending upon the amount of vegetal growth and the type of soil in each study area. A summary of the resulting equations which best fit the data is tabulated below:

Calaveras Creek:

$$C = .026\ (e_s - e_a)(A + K_1 P/S) + .59\ (K_3 \overline{D}P + A)/\nu \qquad (4.3)$$

Cow Bayou:

$$C = .026\ (e_s - e_a)(A + K_1 P/S) + .004\ (T_a - 40)(DA) + .47\ (K_3 \overline{D}P + A)/\nu \qquad (4.4)$$

Deep Creek:

$$C = .026\ (e_s - e_a)(A + K_1 P/S) + .004\ (T_a - 40)(DA) + .34\ (K_3 \overline{D}P + A)/\nu \qquad (4.5)$$

Elm Fork Trinity River:

$$C = .026\ (e_s - e_a)(A + K_1 P/S) + .020\ (T_a - 40)(DA) + .50\ (K_3 \overline{D}P + A)/\nu \qquad (4.6)$$

Escondido Creek:

$$C = .026\ (e_s - e_a)(A + K_1 P/S) + .49\ (K_3 \overline{D}P + A)/\nu \qquad (4.7)$$

Green Creek:

$$C = .026\ (e_s - e_a)(A + K_1 P/S) + .004\ (T_a - 40)(DA) + .40\ (K_3 \overline{D}P + A)/\nu \qquad (4.8)$$

Honey Creek:

$$C = .026\ (e_s - e_a)(A + K_1 P/S) + .012\ (T_a - 40)(DA) + .32\ (K_3 \overline{D}P + A)/\nu \qquad (4.9)$$

In those equations having no $(T_a-40)(DA)$ term, the best fit regression coefficient was 0. A comparison of the standard error of estimate using the derived equations and the least square regression study equations is shown in Figure 4.2. In two cases, the standard error of estimate was apparently slightly improved, no doubt a result of machine rounding. The largest difference was found in the Elm Fork Trinity River and Escondido Creek study areas, the two areas having the largest values of intercept, a_o.

Relation of Seepage Regression Coefficient to Soil.--The regression coefficient postulated to be functionally related to the rate of movement of water away from the reservoir through the underlying soil is termed a_3. The range of values of the coefficient a_3 found in this investigation was approximately two-fold. This range must be related to the relative permeability of the underlying soil and rock units. A description of soils found in the study areas was given in Table 2.7.

Experience would indicate that a fixed value of permeability cannot be related to any particular soil series; however, a range of values can be assigned. In order that results of this investigation may be extrapolated to other areas, a range of values for the regression coefficient a_3 for each of the three hydrologic soil groups was developed. The range of values were developed as follows:

Let B, C, and D each represent a range of values of the regression coefficient a_3 for the respective hydrologic soil group in each study area. Then the weighted average of a_3 for each study area must equal the regression coefficient a_3 found in the analysis for each study area. Based on this assumption, the following equations can be written:

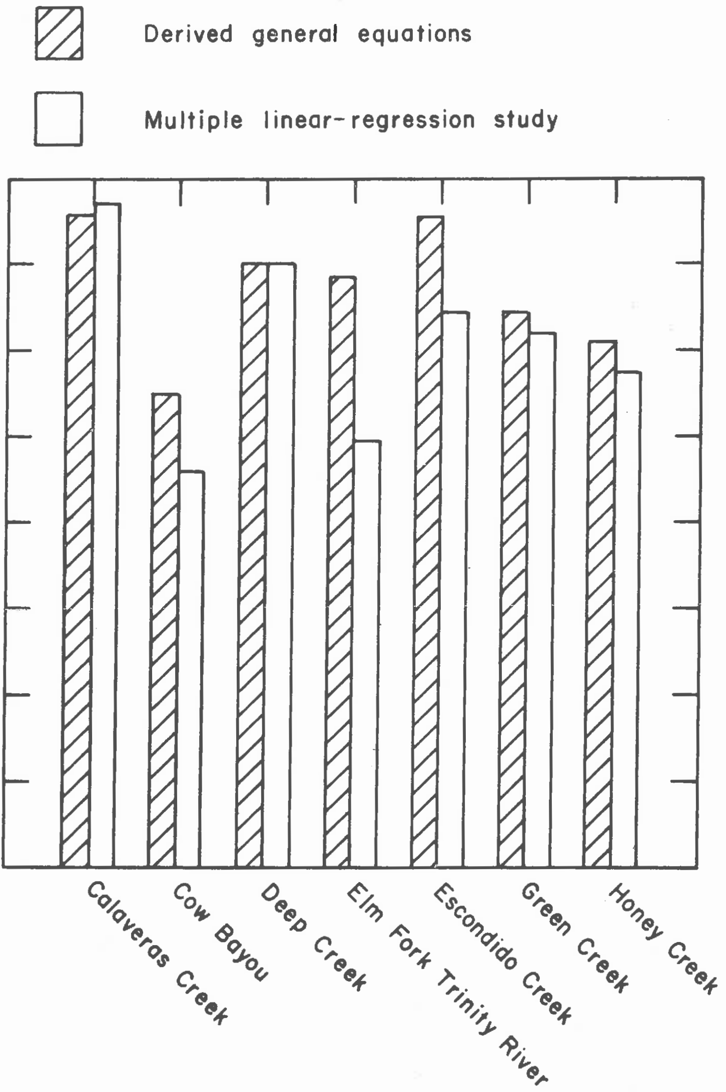


FIGURE 4.2.–Comparison of standard error of estimate of monthly consumption, best-fit multiple linear-regression equations, and derived general equations, 1959-66

Study Area	Equation
Calaveras Creek	$.43\ B + .34\ C + .23\ D = .59$
Cow Bayou	$.30\ B + .24\ C + .46\ D = .47$
Deep Creek	$D = .34$
Elm Fork Trinity River	$.65\ C + .35\ D = .50$
Escondido Creek	$.68\ B + .32\ D = .49$
Green Creek	$.13\ B + .76\ C + .11\ D = .40$
Honey Creek	$.35\ B + .65\ D = .32$

A range of values of B, C, and D which can simultaneously satisfy all seven equations of the above equations is:

$B = .49$ to $.72$

$C = .36$ to $.56$

$D = .23$ to $.40$

An average of these values is suggested for use in other areas, with adjustments within the indicated range based on the relative permeability of the underlying geologic formations. The range in values with soil group is shown graphically in Figure 4.3. In the seven study areas, the maximum proportion of consumption accounted for by the term $a_3\ (\overline{D}P+A)/\nu$ was approximately 65 percent, in an area with a high percentage of B type soils. The maximum error to be expected by using the mean value of a_3 would be ±12 percent, since the range of values of a_3 for the B type soil is ±19 percent from the mean.

Sensitivity Analysis.--The sensitivity of derived parameters and accuracy of results is always an important consideration in hydrologic studies.

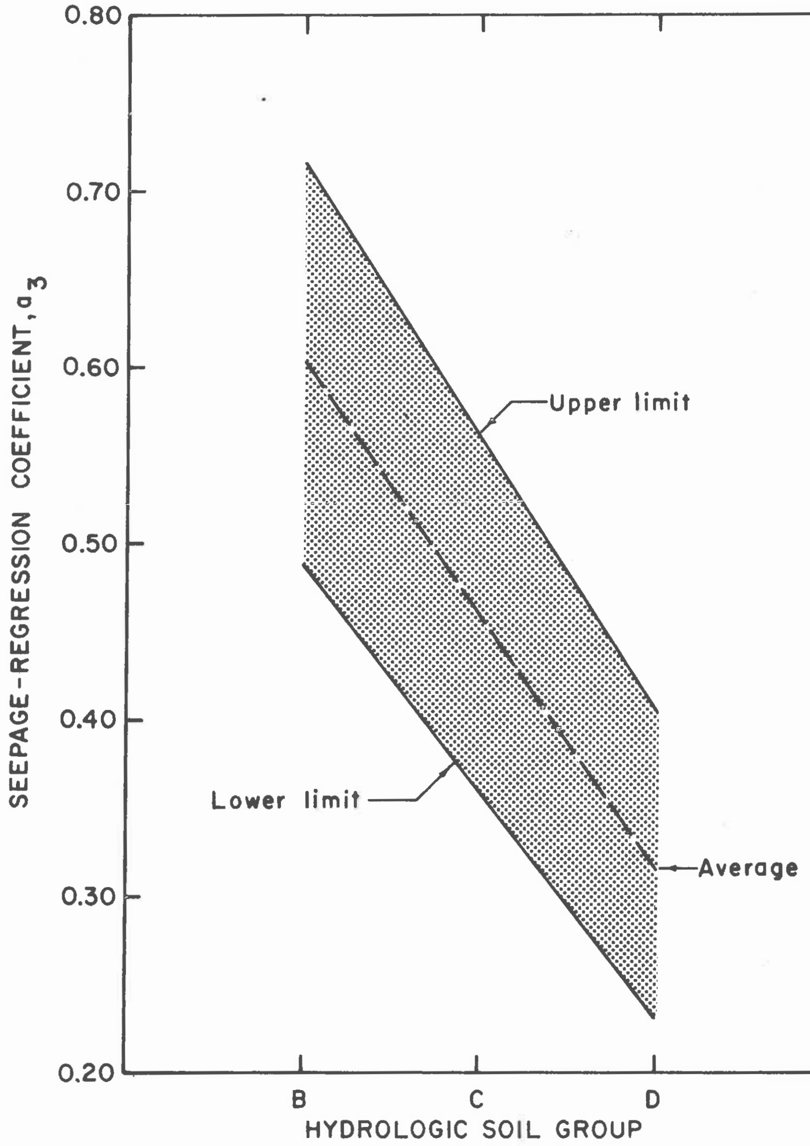


FIGURE 4.3 - Range of values of seepage-regression coefficient (a_3) with hydrologic soil group

For agencies engaged in hydrologic data collection, it is necessary to determine the incremental "information" gained by additional periods of data collection. Obviously when the value of the incremental knowledge gained is less than the cost, data collection should be discontinued or shifted to areas in which hydrologic knowledge is deficient.

The values given previously are certainly not absolute values. In fact, the three regression coefficients can vary over considerable limits and still provide reasonably accurate predictions. As an example of this phenomena, see the output of the minimization program for Calaveras Creek in the appendix. The "best estimator" yielded a standard error of estimate of 15.2 percent. However, it may be noted from the results that a considerable variation of the regression coefficients could be effected within the limits of an additional one (1) percent standard error of estimate.

A second item studied was the sensitivity of regression coefficients and standard errors of estimate to length of period studied. For this study, the data was divided into 4-two year periods, 2-four year periods, and of course the original eight year period. The results indicated generally the same values for the regression coefficients. Standard errors of estimate for each study area for each of the time periods is shown in Figure 4.4.

Each of the individual periods studied indicated a value for a_1 of 0.026 to best fit all the data. In order to test the sensitivity of the regression coefficients to lengths of time of data collection, a comparison was made of the seepage regression coefficient, holding a_1 and a_2 constant and equal to values obtained for the 8-year period. The seepage regression coefficient is the largest contributor to estimated consumption. The results are shown in Figure 4.5. These results indicate in general the

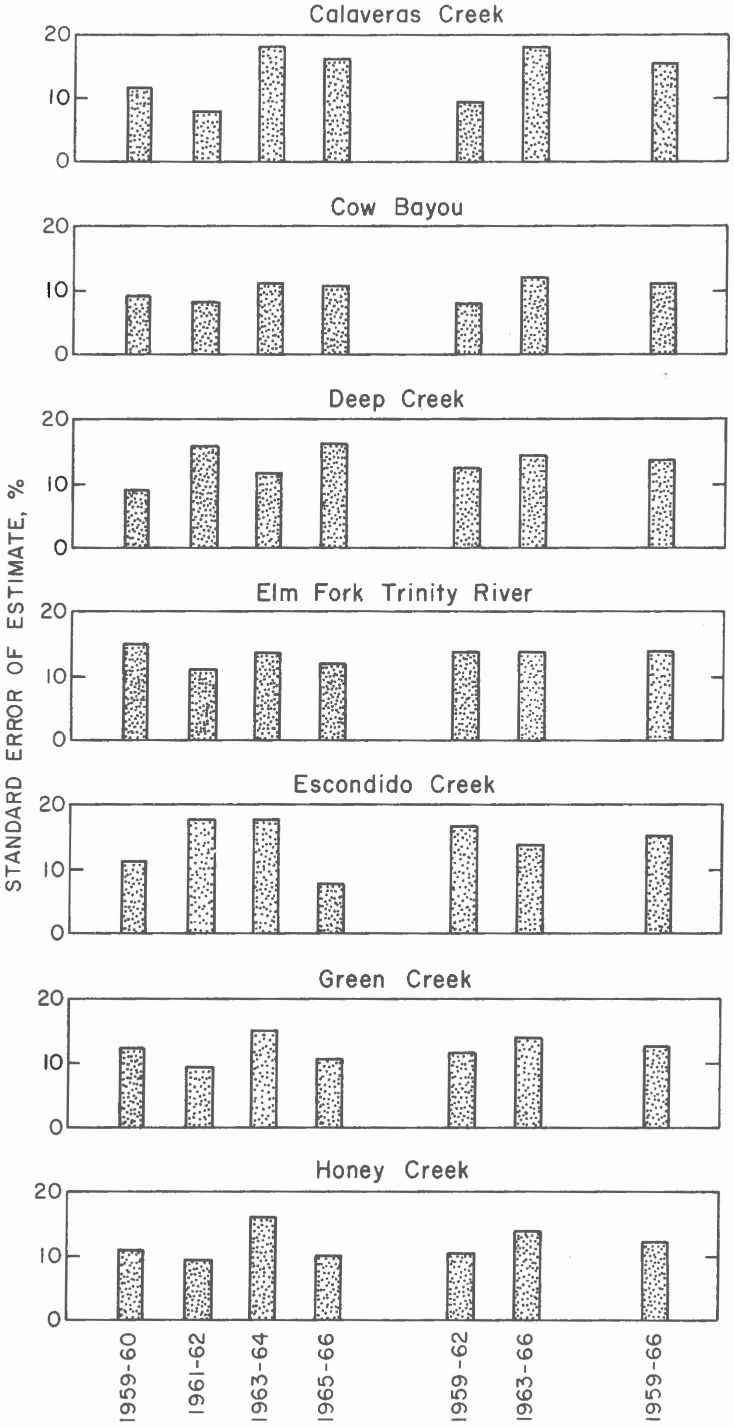


FIGURE 4.4.- Comparison of standard errors of estimate for different time periods

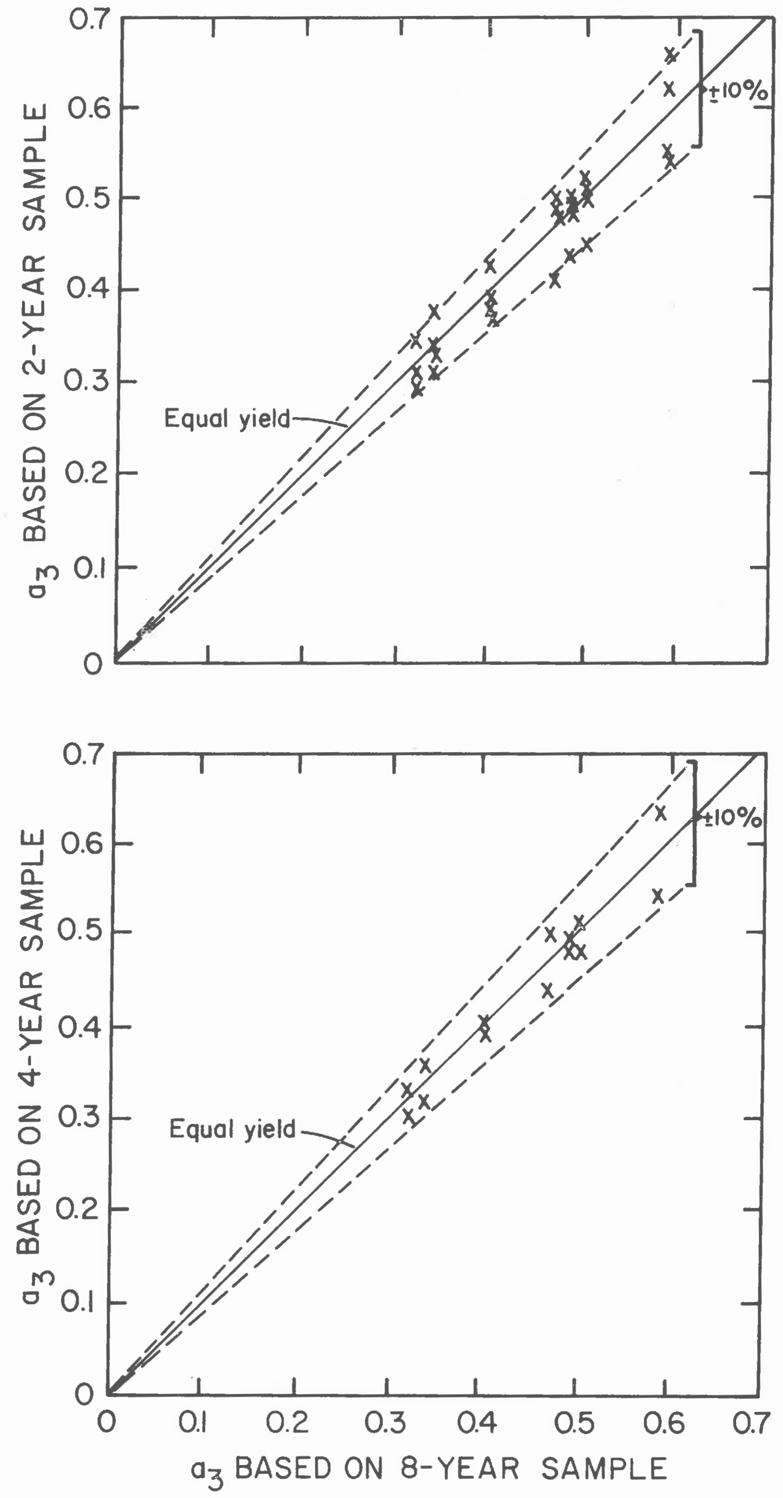


FIGURE 4.5.– Comparison of seepage regression coefficients for various time periods

seepage regression coefficients would have been no more than 10 percent different for a two year period than for the eight year period. This would result in a maximum difference of 6 percent in consumption computed by 2-years and 8-years record.

Comparison of Observed and Estimated Monthly Consumption.--The utility of any method of prediction is determined by the accuracy with which results can be predicted outside the period used for calibration. This study used the period 1959-66 for calibration. The regression equation was optimized on volume of consumption (acre-feet) rather than equivalent consumption (acre-feet/acre of surface area). To test the validity of the prediction equations, they were used to predict monthly values of consumption and equivalent consumption for the entire period of record available for each study area. This covers the period of construction on several of the study areas. A summary of the results is shown in Table 4.3 and in Figure 4.6. To illustrate more clearly the magnitude of the individual monthly variations, the results for the Cow Bayou study area are shown in Figure 4.7.

The results were better than frequently attainable in hydrology, indicating the equations developed could be used to predict monthly values of consumption using physical characteristics of a study area and climatic parameters from nearby first order weather stations. The regression equations shown are by no means unique solutions. Other combinations of parameters could yield equally accurate estimates. The value of a_1 was fixed as a constant best fitting all the study areas partly for convenience and partly by intuitive reasoning. Values used for a_2 can vary appreciably percentage wise without seriously reducing the accuracy of estimator. The so-called transpiration term $a_2(T_a-40)(DA)$ accounted for approximately 11 percent of

Table 4.3--Comparison of estimated and observed consumption, estimated using optimum equation for each study area.

Study area	Period	Number of years	Total consumption				Standard error of estimate of monthly values			
			Acre-feet		Equivalent feet		Acre-feet		feet	
			Estimated	Observed	Estimated	Observed	a.f.	%	feet	%
Calaveras Creek	1958-66	9	17,970	18,020	87.35	86.88	24.4	14.6	.119	14.8
Cow Bayou	1959-66	8	12,430	12,440	69.08	68.95	14.3	11.1	.079	11.0
Deep Creek	1955-66	12	12,040	11,900	94.70	93.28	12.1	14.6	.100	15.4
Elm Fork Trinity River	1957-66	10	16,840	16,830	96.55	95.06	20.2	14.4	.112	14.1
Escondido Creek	1958-66	9	27,010	27,320	74.49	74.80	42.2	16.7	.110	15.8
Green Creek	1957-66	10	10,870	11,000	76.76	77.79	11.7	12.8	.081	12.5
Honey Creek	1953-66	14	19,280	19,410	98.06	99.15	16.5	14.3	.082	13.9

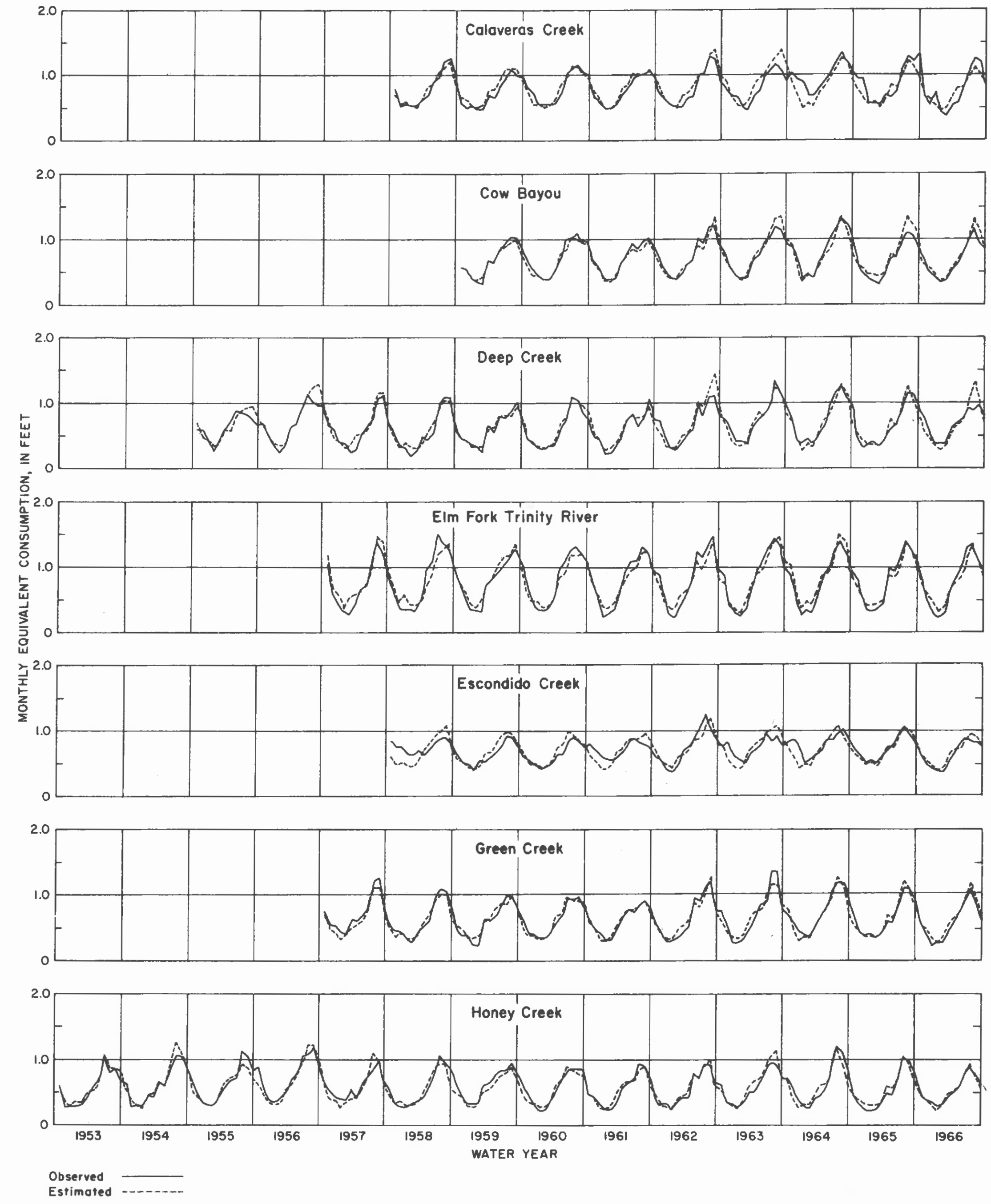


FIGURE 4.6 – Comparison of observed and estimated monthly equivalent consumption

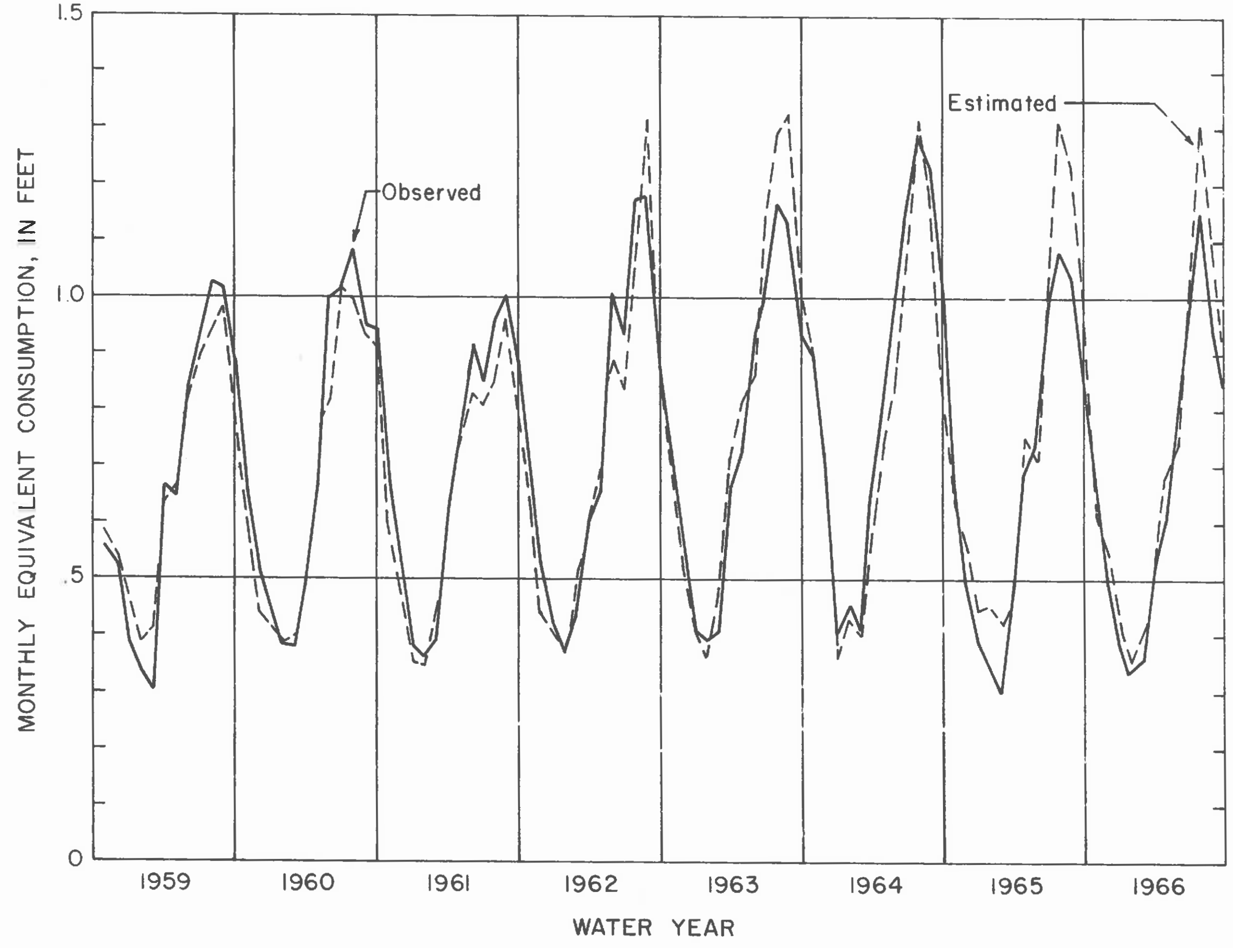


FIGURE 4.7.–Comparison of observed and estimated monthly equivalent consumption for Cow Bayou study area

the total loss in the Elm Fork study area, the maximum percentage of all study areas. Monthly consumption in the 7 study areas was also computed using a value of 0.010 for a_2 rather than the optimized value found for each area; this resulted in very little change in the standard errors of estimate given in Table 4.3. Therefore, a reasonable value of a_2 for use in ungaged study areas would be 0.010.

General Monthly Consumption Model

Based on the preceding analyses and results, it is suggested the following procedure be used in adjusting historical streamflows for the effects of consumption at upstream floodwater-retarding structures:

1. Compute monthly values of consumption using the formula:

$$\text{Consumption} = .026(e_s - e_a)(A + K_1 P/S) + .010(T_a - 40)(DA) + a_3(A + K_3\overline{D}P)/\nu \tag{4.10}$$

2. With all parameters computed as previously outlined, values of a_3 should be chosen based on county soils maps and Figure 4.3.
3. The value of a_2 may be adjusted upward or downward from 0.010 depending upon the degree of vegetal cover likely to be found in the study areas. Generally, areas with highest mean annual rainfall would tend to have the largest values of a_2. The value of a_2 would be expected to increase with time due to the increase in vegetation around the pools.

To verify the applicability of the suggested equation using average values of a_1 and a_2 and a value of a_3 from soils maps and Figure 4.3, consumption at three individual floodwater-retarding sites was estimated. Individual reservoirs used were in the Elm Fork Trinity River, Honey Creek, and Mukewater Creek study areas. Drainage areas for these sites are 0.77, 2.14, and 4.02 square miles, respectively. The Mukewater Creek study area is located in West Central Texas, and is described in Sauer (1963). A summary of the results of this verification study is shown in Table 4.4. The results for Mukewater Creek site 9 are also illustrated in Figure 4.8.

Table 4.4.--Comparison of estimated and observed consumption in seven study areas and at individual reservoirs, estimated using single generalized form of equation (4.10) with a_1 and a_2 constant and a_3 from Figure 4.3.

Study area	Number of years	Period, water year	a_3	Estimated consumption, acre-feet	Observed consumption, acre-feet	Ratio of estimated and observed consumption
Calaveras Creek	9	1958-66	0.49	16,910	18,020	0.94
Cow Bayou	8	1959-66	.44	12,350	12,440	.99
Deep Creek	12	1955-66	.32	12,180	11,900	1.02
Elm Fork Trinity River	10	1957-66	.41	14,190	16,830	.84
Escondido Creek	9	1958-66	.51	29,160	27,320	1.07
Green Creek	10	1957-66	.46	12,280	11,000	1.12
Honey Creek	14	1953-66	.42	22,440	19,410	1.16
Elm Fork Trinity River Site 6-0	8	1959-66	.41	450	410	1.10
Honey Creek Site 11	8	1959-66	.42	2,530	2,170	1.16
Mukewater Creek Site 9	5	1962-66	.32	840	820	1.02
Total	93	--	--	123,330	120,320	1.02

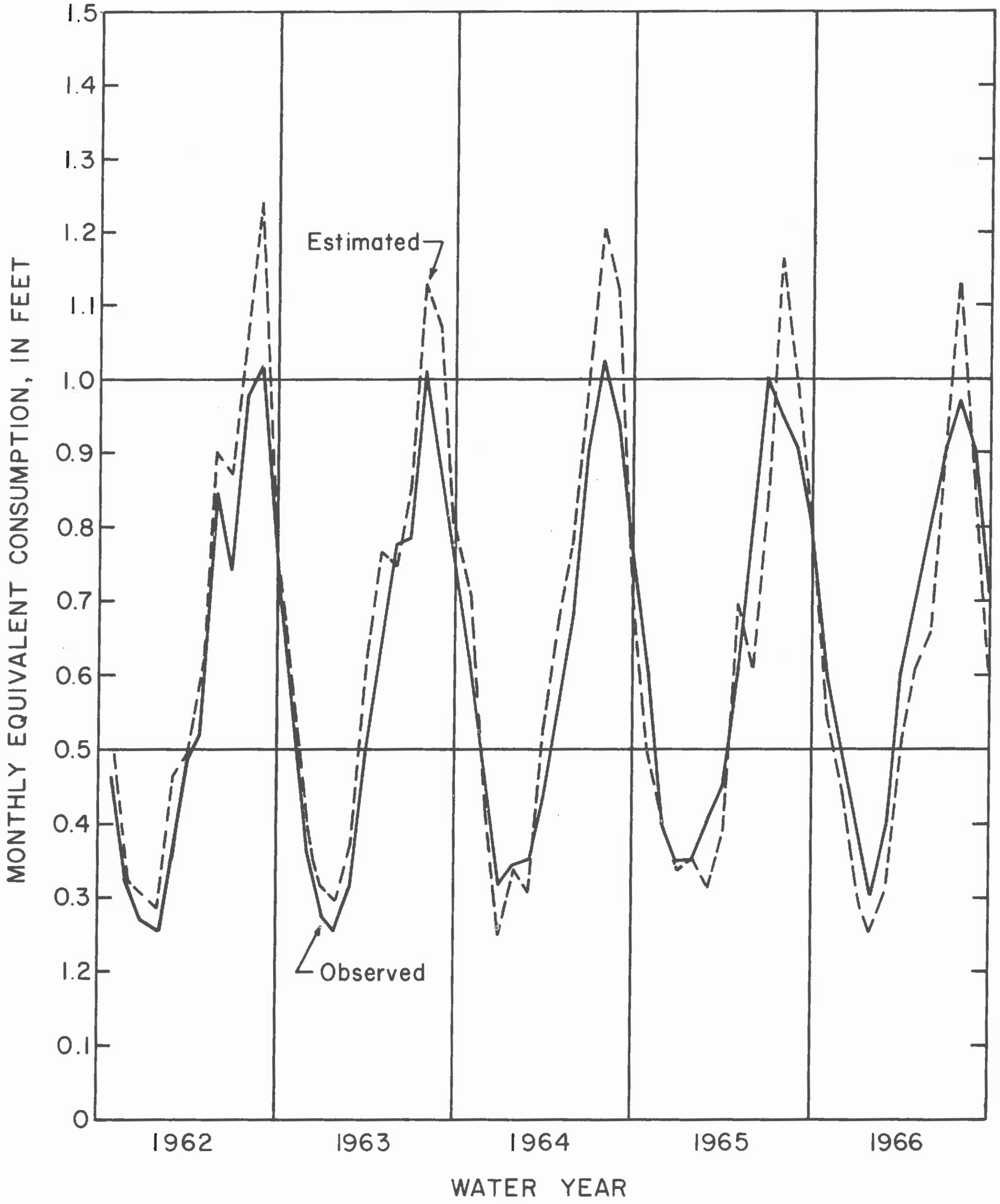


FIGURE 4.8.-Comparison of observed and estimated monthly equivalent consumption for Mukewater Creek Site 9

Chapter 5

MATHEMATICAL MODEL OF HYDROLOGIC RESPONSE OF A SYSTEM OF UPSTREAM RESERVOIRS

If the results of previous sections are to be utilized in adjusting historical streamflow for the effects of upstream development, it is necessary to develop a mathematical model which simulates the response of a system of reservoirs to historical hydrologic sequences. In this way, the effects on streamflow of various degrees of development can be tested. With computer simulation, a vast array of possible sequences can be tested at a relatively reasonable cost.

A computer program was written to simulate the response of the system of floodwater-retarding structures for time periods of one month. Input for the program consists of the following:

1. Monthly values of:
    a. Rainfall.
    b. Runoff.
    c. Temperature.
    d. Relative humidity.
2. Watershed parameters:
    a. Number of floodwater-retarding structures.
    b. Drainage area.
    c. Surface area-storage relation.
    d. Surface area-perimeter relation.
    e. Design outflow rate from principal spillway.
    f. Regression coefficients for consumption equation.
    g. Total storage at lowest uncontrolled outlet.

h. Total storage at beginning of period of interest, may be assumed any value from zero to full pool.

A simplified flow diagram of the program is shown in Figure 5.1. Essentially, the program is an iterative procedure to determine the mean monthly surface area, as all computations of depletion are based on this parameter. The procedure is to assume a value for average monthly surface area and compute net depletion from the regression equations. Average monthly content is then computed based on storage at the beginning of the month, inflow during the month, time required for the pool to drain to the lowest uncontrolled spillway, and net depletion. A value of average surface area is then computed based on the average content. This value of surface area is compared with the assumed value and if the difference is greater than one-tenth of one percent, the assumed value of surface area is incremented by one-half the difference. This procedure is continued until the surface areas agree within one-tenth of one percent tolerance limits. The procedure converges quite rapidly, generally within 7 or 8 iterations. For the program, the following simplifying assumptions are made:

1. Total monthly inflow occurs on first day of month.
2. Outflow rate is 80 percent of maximum design discharge.
3. Rainfall is applied to 95 percent of the average surface area for the month in computing rainfall on pool.
4. Reservoir surface area is exponentially related to capacity, with capacity adjusted for sedimentation.
5. Side slope = .055, the median value found in the seven study areas.

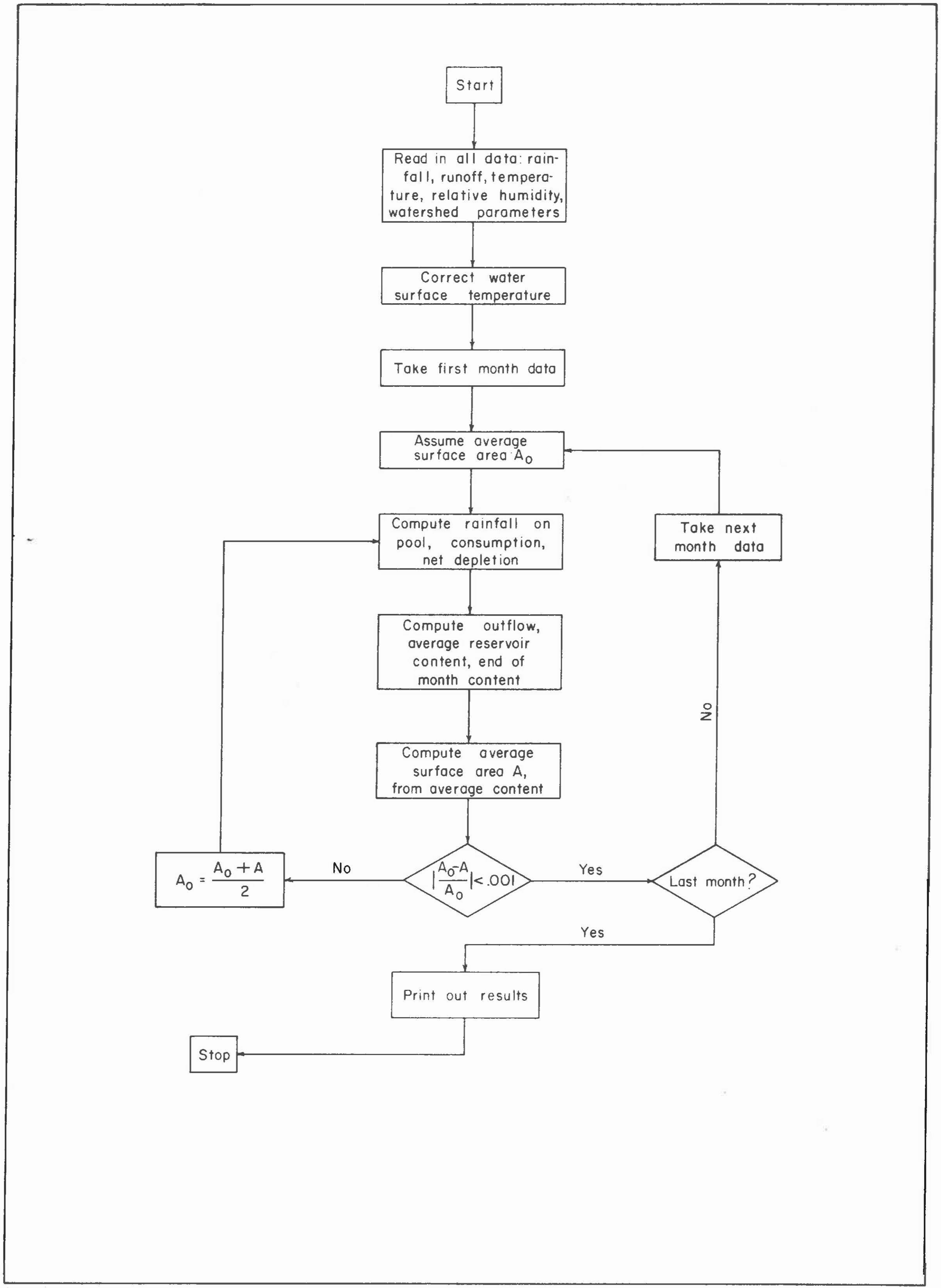


FIGURE 5.1.-Simplified flow chart of the computer program for a mathematical model of the hydrologic response of a system of floodwater-retarding reservoirs

The first assumption was made for ease of computation since the time distribution of inflow is not critical for a monthly water budget for long term studies. The remaining three assumptions were based on consideration of existing study area data. The program allows for a variable surface-area and storage relation. Surface area-storage relation and capacity at lowest uncontrolled outlet are read in for each year. As the program is set up, no variation in degree of development is permitted. However, with minor variation, the degree of development could be varied from year to year. This could be accomplished very simply by using drainage area, number of structures, and rate of outflow as dimensioned variables to be read in for each year rather than being read in once as a watershed parameter. A complete program documentation is given in the appendix.

The response model was applied to the Cow Bayou and Deep Creek study areas. The various physical features of the watersheds have been previously cited. For this run, surface area-storage and surface area-perimeter relations, design outflow rate, and total storage at uncontrolled outlet were taken from study area data. Regression coefficients a_1 and a_2 were taken as those average values shown in equation (4.10). Seepage regression coefficients a_3 were computed from soils maps. The storage at the beginning of the period was taken from study area data. A summary of the results is given in Tables 5.1 and 5.2 and illustrated in Figure 5.2. The entire output for the program is included in the program documentation in the appendix.

These results illustrate the reliability of the model as a tool for adjusting historic streamflow records for the effects of systems of floodwater-retarding structures. The model is simple to apply and any

Table 5.1 Summary of results of mathematical model of hydrologic response of a system of upstream reservoirs applied to Cow Bayou study area.

Values shown in acre-feet.

Water Year	Net Inflow	Rainfall on Pool		Consumption		Net Depletion		Outflow	
		Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual
1959	3720	490	470	1330	1360	850	890	2290	2460
1960	13830	700	650	1870	1680	1180	1030	12790	13200
1961	22710	960	920	1870	1880	910	960	21560	21360
1962	3400	450	410	1880	1820	1420	1410	2390	2370
1963	390	200	180	1170	1000	970	810	0	70
1964	2670	390	380	1420	1190	1030	810	1010	1550
1965	15980	740	660	1900	1670	1160	1010	14760	14540
1966	16790	860	860	1960	1840	1100	980	15360	15440
TOTAL	79490	4800	4530	13410	12440	8610	7900	70140	70990

Table 5.2. Summary of results of mathematical model of hydrologic response of a system of upstream reservoirs applied to Deep Creek study area.

Values shown are in acre-feet.

Water Year	Net Inflow	Rainfall on Pool		Consumption		Net Depletion		Outflow	
		Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual
1955	9680	420	430	1150	1140	730	710	8260	8230
1956	950	110	100	1200	1080	1090	980	0	300
1957	7960	380	370	1090	1020	710	650	7290	7260
1958	3710	430	440	1030	1030	600	590	3190	3200
1959	1680	270	220	900	890	630	670	1020	990
1960	2060	350	340	1060	1030	710	690	1400	1480
1961	1740	400	360	1050	960	650	600	970	1210
1962	380	160	110	910	710	750	600	0	20
1963	1510	220	170	1020	940	800	770	470	490
1964	3980	380	350	1180	1180	800	830	2840	2680
1965	1560	300	280	1130	1120	830	840	1160	1260
1966	1140	230	170	830	810	600	640	140	150
TOTAL	36350	3550	3340	12550	11910	8900	8570	26730	27270

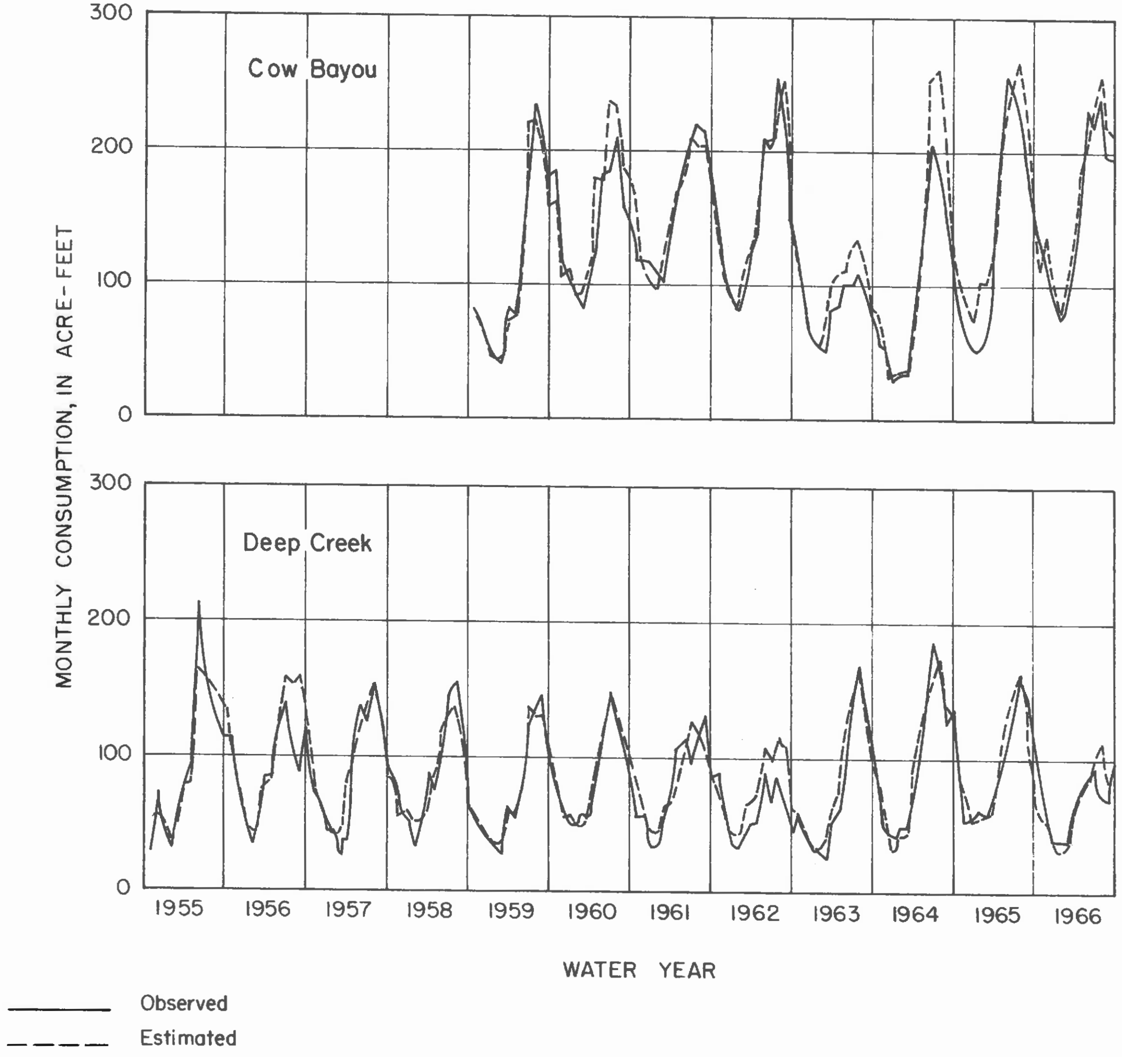


FIGURE 5.2.- Comparison of observed and estimated monthly consumption using hydrologic response model, Cow Bayou and Deep Creek study areas

number of sequences can be "run through" the model at one time by the use of one DO loop. Requirements are to obtain the physical parameters of the systems of reservoirs and monthly values of unit runoff (acre-feet/square mile), rainfall, relative humidity, and temperature. The last three terms may be interpolated from long term Weather Bureau stations.

Chapter 6

INFLOW-OUTFLOW RELATION

The hydrologic response model as outlined in Chapter 5 is suggested as the best means for adjusting historical runoff records for the effects of systems of floodwater-retarding structures. In some cases, such as reconnaissance type studies, it is probable that hydrologists may not wish to expend the funds necessary to develop all the data required for the model. The procedure set forth in this Chapter was developed with preliminary studies in mind.

In determining the effect of a system of floodwater-retarding structures on the yield of a watershed for downstream uses, the simplest approach is to compare outflow with inflow and analyze downstream channel losses under varying conditions. In this report, only "on site" losses are analyzed. No analysis of differences in channel losses attributable to flow regulation is undertaken.

A simple relationship of outflow to inflow is not feasible on a monthly basis for two primary reasons. First, rate of loss varies by month, with the greatest losses expected during the summer. Second, the amount of water stored at the end of the month frequently varies from month to month. For these reasons, a comparison of outflow and inflow was developed on an annual basis since, in general, storage and the rate of loss do not vary greatly from year to year.

The base period used for the annual inflow-outflow relation was the period 1959 through 1966 water years, inclusive. This period was common to all seven study areas. A linear least-square regression equation was developed for data from all seven watersheds. The equation resulting from this analysis was:

$$\underline{0} = 0.98I - 0.68 \qquad (6.1)$$

where $\underline{0}$ = annual outflow in inches

I = annual net inflow in inches.

Equation (6.1) applies only when annual net inflow is equal or greater than 0.7 inch. For annual net inflow less than 0.7 inch, annual net outflow is zero. Figure 6.1 is a plot of points used for this regression equation. Data are shown in Table 2.2.

The relation between inflow and outflow is surprisingly consistent in view of the variations in physical and climatic characteristics found in the seven study areas. An indication of the overall accuracy of this equation is shown in Table 6.1. This equation is suggested for use in adjusting annual values of historical streamflow records for effects of upstream development in watersheds where conditions are similar to those found in the seven study areas.

Another manner of presenting the inflow-outflow relation is on a depletion basis, that is, the proportion of a specified annual runoff that will be lost due to upstream development. From equation (6.1), it follows that:

For $I > 0.7$

$$D = 2 + \frac{68}{I}$$

and for $I < 0.7$

$$D = 100$$

where D = percent of annual runoff depleted due to floodwater-retarding structures.

The proportionate effects of upstream development on yield diminish with

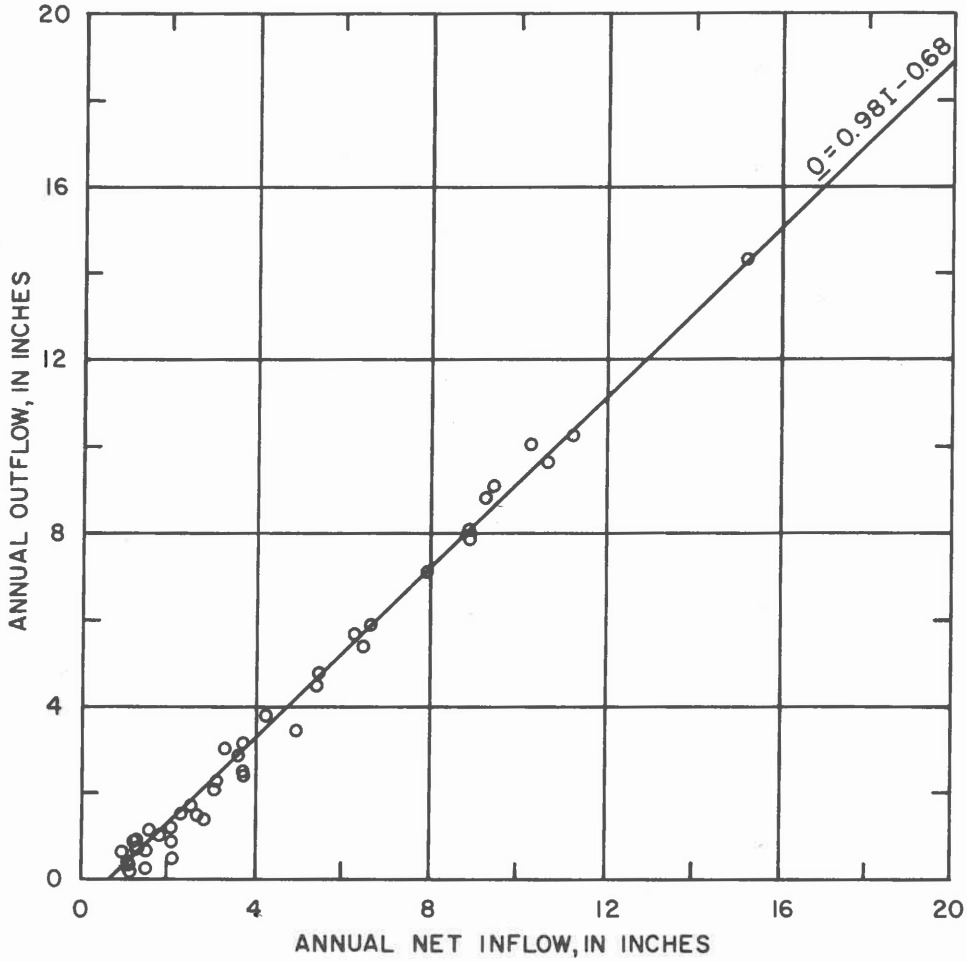


FIGURE 6.1-Annual outflow versus net inflow for seven study areas, 1959-66.

Table 6.1.--Comparison of estimated and observed outflow and standard error of estimate, in inches, for period 1959-66 using $\underline{O} = .98I - 0.68$.

	Calaveras Creek	Cow Bayou	Deep Creek	Elm Fork Trinity River	Escondido Creek	Green Creek	Honey Creek
Estimated outflow, inches	5.74	47.09	5.63	38.05	10.87	10.57	45.54
Observed outflow, inches	5.08	47.49	6.43	38.35	9.85	10.81	44.54
Ratio of estimates to observed outflow	1.13	.99	.88	.99	1.10	.98	1.02
Standard error of estimate in inches	.27	.16	.25	.37	.37	.26	.43

increasing runoff. A comparison of average reduction in runoff and annual runoff is shown below:

Annual runoff, inches	Reduction in yield, %
< 0.7	100
1.0	70
2.0	36
5.0	16
10.0	9

This illustrates how the depletion due to upstream development increases drastically with decreasing average annual runoff.

It must be borne in mind the above relations represent the maximum effects on yield to be expected. The relations are derived from data collected under the initial condition where the total sediment pool is available for storage of water. As the sediment pool fills with sediment, effects will be diminished.

To provide a comparison of the monthly hydrologic response model and the annual inflow-outflow relation, Table 6.2 and 6.3 are presented. For the Cow Bayou and Deep Creek study areas, the hydrologic response model generally gives better results because variations in storage, soil types, and climatic conditions are accounted for but the inflow-outflow relation also gives satisfactory results over a longer period of time.

Table 6.2 Comparison of annual depletion of runoff as estimated by hydrologic response model and annual inflow-outflow relation with actual study findings, Cow Bayou study area.

Water Year	Net Inflow, inches	Outflow, inches			Reduction in Yield, %		
		Model	$Q=.98I-.68$	Actual	Model	$Q=.98I-.68$	Actual
1959	2.48	1.53	1.75	1.65	38.3	29.4	33.5
1960	9.25	8.56	8.38	8.83	7.5	9.4	4.5
1961	15.19	14.42	14.20	14.28	5.1	6.5	6.0
1962	2.28	1.60	1.55	1.59	29.8	32.0	30.3
1963	.26	0	0	.04	100.0	100.0	84.6
1964	1.78	.68	1.06	1.04	61.8	40.4	41.6
1965	10.69	9.87	9.78	9.73	7.7	8.5	9.0
1966	11.23	10.27	10.33	10.33	8.5	8.0	8.0
Total	53.16	46.93	47.05	47.49	11.7	11.5	10.7

Table 6.3 Comparison of annual depletion of runoff as estimated by hydrologic response model and annual inflow-outflow relation with actual study findings, Deep Creek study area.

Water Year	Net Inflow, inches	Outflow, inches			Reduction in Yield, %		
		Model	Q=.98I -.68	Actual	Model	Q=.98I -.68	Actual
1955	7.50	6.40	6.67	6.38	14.7	11.1	14.9
1956	.73	0	.04	.23	100.0	94.5	68.5
1957	6.17	5.65	5.37	5.62	8.4	13.0	8.9
1958	2.88	2.47	2.14	2.48	14.2	25.7	13.9
1959	1.31	.79	.60	.77	39.7	54.2	41.2
1960	1.60	1.08	.89	1.15	32.5	44.4	28.1
1961	1.35	.75	.64	.93	44.4	52.6	31.1
1962	.37	0	0	.01	100.0	100.0	97.3
1963	1.17	.36	.47	.38	69.2	59.8	67.5
1964	3.08	2.20	2.34	2.08	28.6	24.0	32.5
1965	1.21	.90	.51	.98	25.6	57.9	19.0
1966	.88	.11	.18	.12	87.5	79.5	86.4
Total	28.25	20.71	19.85	21.13	26.7	29.7	25.2

Chapter 7

SUMMARY AND CONCLUSIONS

Results of studies conducted by the U. S. Geological Survey since 1952 to define the effects of systems of upstream flood control measures on watershed yield are summarized and presented. The studies were conducted in seven areas in Texas having diverse physiographic and climatic characteristics. These studies adequately define the"on site" losses to be expected. For the 8-year period common to all seven study areas considered, average reductions in yield ranged from 54 percent in an area where average annual runoff was 1.37 inches to 11 percent in an area where average annual runoff was 6.64 inches. Total losses recorded were as much as twice that attributed to evaporation from the free water surface alone. In none of the areas was there evidence of an increase of base flow following reservoir construction, therefore all water lost at the site was assumed to be a depletion of downstream surface water yield.

Multiple linear regression analysis was used in an attempt to develop regression equations relating monthly consumptive losses to physical characteristics of the study areas and variation of climatic parameters including relative humidity, temperature, and wind speed. A combination of variables approach was used wherein variables considered to be representative of the physical processes involved were formulated from individual variables. The most important physical processes involved were assumed to be evaporation from the free water surface and from the peripheral soil area, transpiration, and seepage away from the pool. This analysis indicated the combination of variables yielding the smallest average standard error of estimate for all seven study areas included difference in vapor pressure of water surface and air, surface area, air temperature, viscosity of water, drainage area, perimeter, side slope, and mean depth of pool. The inclusion of wind speed did not increase the accuracy of the prediction equations.

The results of the multiple linear regression analysis were deemed to be unsatisfactory for extrapolation purposes primarily because intercept values in some cases were significantly different from zero and there was no clear trend of regression coefficients. Since the purpose of the study was to develop general relationships applicable to ungaged areas, another study was undertaken to develop a general mathematical model of monthly consumption. The combination of variables identified by the multiple linear regression analysis as providing the best estimator was used. A computer program was developed wherein the intercept of the multiple linear regression was fixed at zero and the other regression coefficients were varied in a stepwise manner to determine the least square of errors estimator. Using this technique, general equations were developed with a constant evaporation regression coefficient and a seepage regression coefficient related to underlying soils. Using these equations, standard errors of estimate of monthly consumption ranged from 11 percent to 16 percent. Sensitivity analysis indicated regression coefficients based on 2-years of data would not have differed more than 10 percent from those based on 8-year record.

A computer program which is a mathematical model of the hydrologic response of a system of upstream reservoirs was developed in order to utilize the general relationships for watershed yield analysis. Watershed parameters and monthly values of runoff and climatic parameters are input data. The program output includes total inflow, rainfall on pool, consumption, net depletion of flow, and outflow from the system of reservoirs.

The program was tested on two watersheds with satisfactory results and is suggested for use in water yield studies requiring monthly values of runoff.

A simple relationship of annual outflow from a system of reservoirs to annual net inflow was developed for use in reconnaissance type studies requiring only adjustments to annual values of runoff. This study resulted in a simple linear relation between outflow and inflow. This relation applies to systems of reservoirs having hydrologic characteristics similar to those studied and will change as the permanent pools become filled with sediment. Despite its shortcomings, this relation provides an accurate first approximation of runoff reductions attributable to upstream flood prevention programs. Reductions in yield from controlled areas studied were approximately as follows:

Annual runoff, inches	Reduction in yield, percent
< 0.7	100
1.0	70
2.0	36
5.0	16
10.0	9

As would be expected, effects during low runoff years and in areas with lower average annual runoff are much more drastic than in areas of high runoff.

APPENDIX

APPENDIX

Description of Program MINMIZ

Computer programs were written in Fortran IV program language and run on the Control Data 6600 computer at the University of Texas at Austin Computation Center. Program MINMIZ was used to develop the general mathematical model of monthly consumption as a function of climatic variables and watershed parameters. Descriptions of the program along with sample output are given in Tables A.1 and A.2 and in Figures A.1, A.2, and A.3.

Table A.1 - Notation and Conversion for Program MINMIZ.

Fortran Notation	General Notation	Description
A1	a_1	Regression coefficient in equations 4.3 - 4.9 times 10
A2	a_2	Regression coefficient in equations 4.3 - 4.9 times 5
A3	a_3	Regression coefficient in equations 4.3 - 4.9
B1	b_1	Same as a_1
B2	b_2	Same as a_2
CONS	Consumption	Monthly reservoir consumption in acre-feet
I	i	An index variable
J	j	An index variable
K	k	An index variable
LK	lk	An index variable
NAME	Name	Name of study area
RES	Residual	Standard error of estimate
S	Sum	A variable for summing residual errors
X	x	$X_1 = (e_s - e_a)(A+P/S)/10$ $X_2 = (T_a - 40)(DA)/5$ $X_3 = (\overline{D}P+A)/\nu$ $X_4 = Y =$ Consumption in acre-feet
X1BAR	$\overline{X}_1$	Average value of X_1
X2BAR	$\overline{X}_2$	Average value of X_2
X3BAR	$\overline{X}_3$	Average value of X_3
YBAR	$\overline{Y}$	Average value of consumption

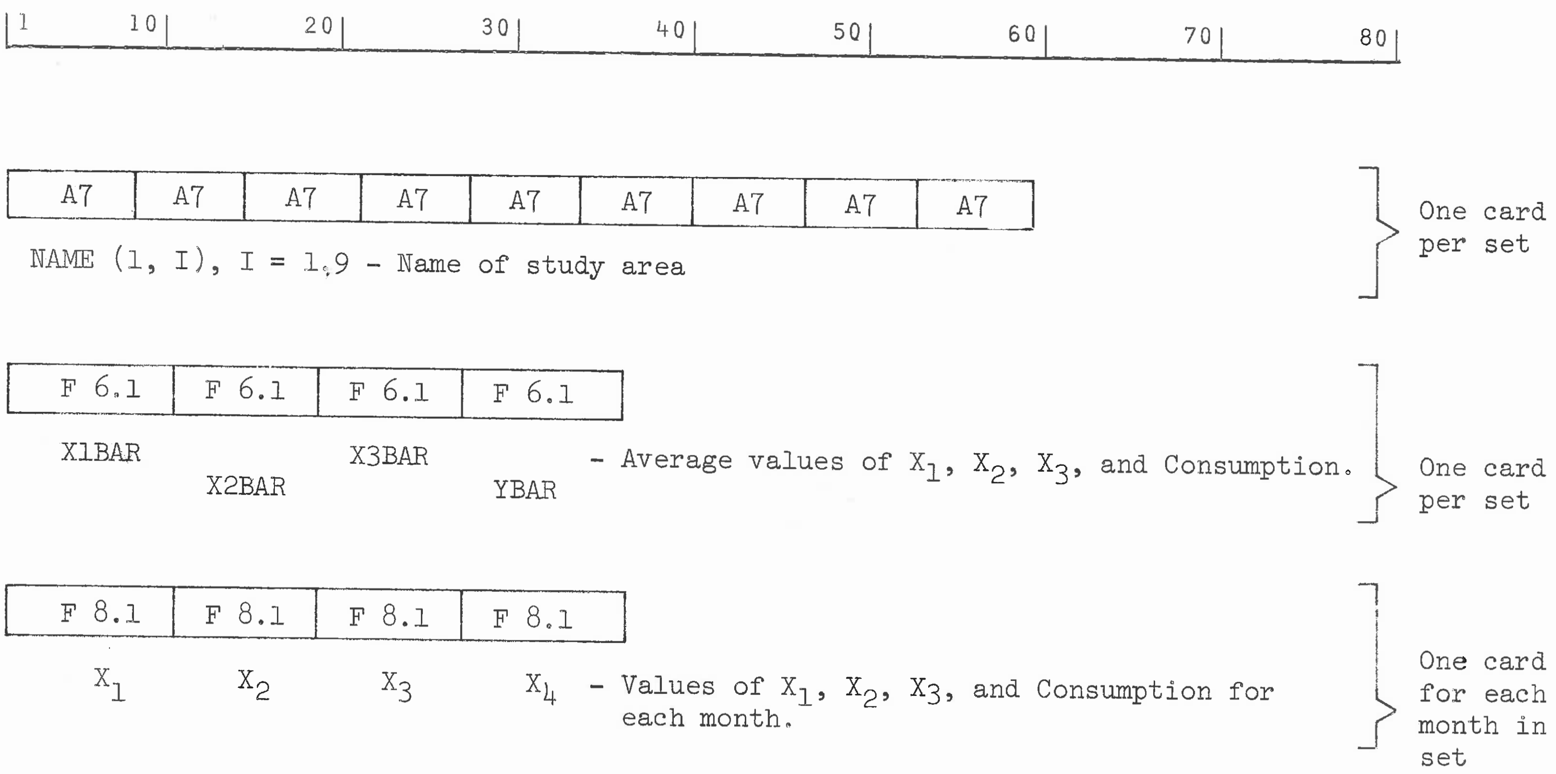


FIGURE A.1. Guide for data input - Program MINMIZ.

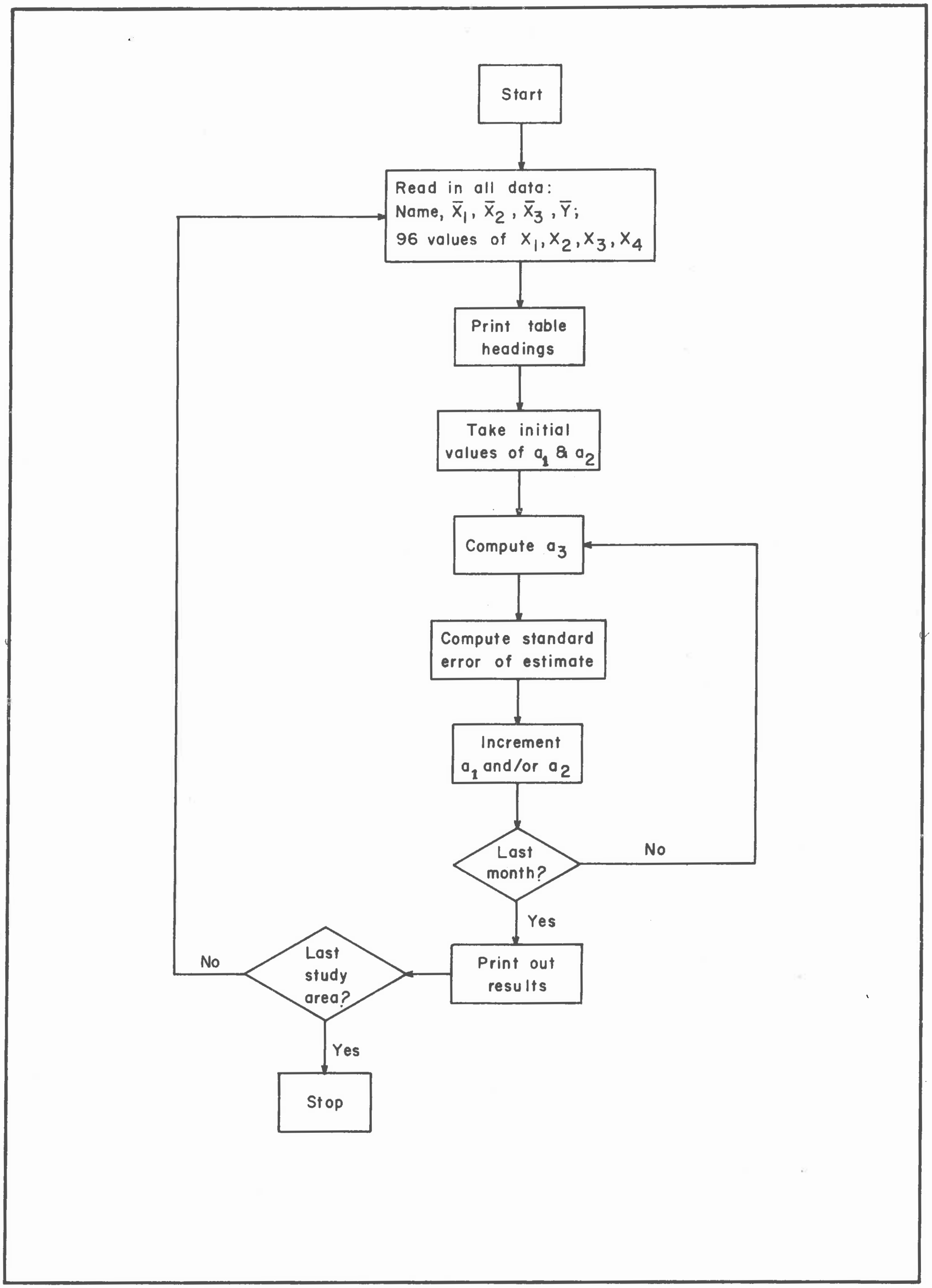


FIGURE A.2. - Program MINMIZ flow diagram

```
                 PROGRAM MINMIZ(INPUT,OUTPUT)
000002           DIMENSION X(96,4),NAME(1,9),CONS(96),A3(16,11),RES(16,11),A1(16),
                1A2(16,11)
000002         1 FORMAT(4F6.1)
000002        10 FORMAT(9A7)
000002        11 FORMAT(1H1,/////,43X,9A7,//)
000002        12 FORMAT(1H0,*A(2)=     0.00        0.02        0.04        0.06        0.08
                1     0.10        0.12        0.14        0.16        0.18        0.20*)
000002        13 FORMAT(1H0,*A(1)   SE    A(3)  SE    A(3)  SE    A(3)  SE    A(3)  SE    A(3
                1)  SE    A(3)  SE    A(3)  SE    A(3)  SE    A(3)  SE    A(3)*)
000002        14 FORMAT(1H0,23F5.3)
000002       230 FORMAT(4F8.1)
000002             READ 10,(NAME(1,I),I=1,9)
000014             READ 1,X1BAR,X2BAR,X3BAR,YBAR
000030             READ 230,((X(I,J),J=1,4),I=1,96)
000047             PRINT 11,(NAME(1,I),I=1,9)
000061             PRINT 12
000065             PRINT 13
000071             B1=.10
000073             DO 405 I=1,16
000074              B2=0.0
000075               DO 404 J=1,11
000100                 A1(I)=B1
000101                 A2(I,J)=B2
000103                 A3(I,J)=(YBAR-A1(I)*X1BAR-A2(I,J)*X2BAR)/X3BAR
000110                 S=0.0
000112                   DO 403 K=1,96
000127                     CONS(K)=A1(I)*X(K,1)+A2(I,J)*X(K,2)+A3(I,J)*X(K,3)
000134       403           S=S+(CONS(K)-X(K,4))**2
000140                 RES(I,J)=((S/96.0)**0.5)/YBAR
000147       404       B2=B2+.02
000153       405     B1=B1+.02
000156             PRINT 14,(A1(I),(RES(I,J),A3(I,J),J=1,11),I=1,16)
000203           END


PROGRAM LENGTH INCLUDING I/O BUFFERS
006424

FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS
1        -  000214     10       -  000216     11       -  000220     12       -  000224
13       -  000242     14       -  000260     230      -  000263

BLOCK NAMES AND LENGTHS

VARIABLE ASSIGNMENTS
A1       -  002046     A2       -  002066     A3       -  001306     B1       -  002354
B2       -  002355     CONS     -  001146     I        -  002346     J        -  002353
K        -  002357     NAME     -  001135     RES      -  001566     S        -  002356
X        -  000335     X1BAR    -  002347     X2BAR    -  002350     X3BAR    -  002351
YBAR     -  002352
```

FIGURE A.3 Printout of Program MINMIZ source deck.

TABLE A.2. Sample output for Program MINMIZ.

CALAVERAS CREEK 1959-66

A(2)=	0.00		0.02		0.04		0.06		0.08		0.10		0.12		0.14		0.16		0.18		0.20	
A(1)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)	SE	A(3)
.100	.168	.745	.167	.723	.166	.701	.166	.679	.167	.658	.169	.636	.172	.614	.175	.592	.180	.570	.185	.548	.191	.527
.120	.164	.725	.163	.703	.162	.681	.163	.660	.164	.638	.167	.616	.170	.594	.174	.572	.179	.550	.185	.529	.191	.507
.140	.161	.705	.160	.684	.160	.662	.161	.640	.163	.618	.166	.596	.169	.574	.174	.553	.179	.531	.185	.509	.192	.487
.160	.158	.686	.157	.664	.158	.642	.159	.620	.162	.598	.165	.576	.169	.555	.174	.533	.180	.511	.186	.489	.193	.467
.180	.155	.666	.155	.644	.156	.622	.158	.600	.161	.578	.165	.557	.169	.535	.175	.513	.181	.491	.187	.469	.195	.447
.200	.154	.646	.154	.624	.155	.602	.158	.580	.161	.559	.165	.537	.170	.515	.176	.493	.182	.471	.189	.449	.197	.428
.220	.152	.626	.153	.604	.155	.582	.158	.561	.162	.539	.167	.517	.172	.495	.178	.473	.185	.452	.192	.430	.200	.408
.240	.152	.606	.153	.585	.156	.563	.159	.541	.163	.519	.168	.497	.174	.475	.180	.454	.187	.432	.195	.410	.203	.388
.260	.152	.587	.154	.565	.157	.543	.161	.521	.165	.499	.171	.477	.177	.456	.183	.434	.191	.412	.198	.390	.207	.368
.280	.153	.567	.155	.545	.159	.523	.163	.501	.168	.479	.173	.458	.180	.436	.187	.414	.194	.392	.202	.370	.211	.348
.300	.155	.547	.157	.525	.161	.503	.166	.481	.171	.460	.177	.438	.184	.416	.191	.394	.199	.372	.207	.350	.215	.329
.320	.157	.527	.160	.505	.164	.484	.169	.462	.174	.440	.181	.418	.188	.396	.195	.374	.203	.353	.211	.331	.220	.309
.340	.160	.507	.163	.486	.168	.464	.173	.442	.179	.420	.185	.398	.192	.376	.200	.355	.208	.333	.216	.311	.225	.289
.360	.163	.488	.167	.466	.172	.444	.177	.422	.183	.400	.190	.378	.197	.357	.205	.335	.213	.313	.222	.291	.231	.269
.380	.167	.468	.171	.446	.176	.424	.182	.402	.188	.380	.195	.359	.203	.337	.211	.315	.219	.293	.228	.271	.237	.249
.400	.171	.448	.176	.426	.181	.404	.187	.383	.194	.361	.201	.339	.208	.317	.216	.295	.225	.273	.234	.252	.243	.230

Note: SE = standard error of estimate, percent of mean.

Description of Program DEPLETE

Program DEPLETE is a mathematical model which simulates the response of a system of floodwater-retarding structures to sequences of hydrologic events. The program is written in Fortran IV program language. Descriptions of the program along with sample output are given in Tables A.3 and A.4 and Figures A.4 and A.5. The flow diagram for this program was previously shown (Figure 5.1).

Table A.3 - Notation and Conversion for Program DEPLETE.

Fortran Notation	General Notation	Description
A	Area	Average monthly surface area computed from average contents, acres
AAA	-	Total quantity of water available for consumption, acre-feet
ACONS	-	Accumulated total consumption, acre-feet
ANET	-	Accumulated total net depletion, acre-feet
AQ	-	Accumulated total net inflow from surface runoff, acre-feet
AQOUT	-	Accumulated total outflow, acre-feet
ARAIN	-	Accumulated total rainfall on pool, acre-feet
ASA	-	Average monthly surface area per structure, acres
A1	a_1	Regression coefficient
A2	a_2	Regression coefficient
A3	a_3	Regression coefficient
C	-	End-of-month contents, acre-feet
CA	-	Average monthly contents, acre-feet
CAP	Capacity	Capacity of system of structures at lowest uncontrolled outlet, acre-feet
CK	-	Coefficient in surface area-perimeter relation
CONS	Consumption	Monthly consumption, acre-feet
C1	c_1	Coefficient in surface area-capacity relation
C2	c_2	Coefficient in surface area-capacity relation
C3	c_3	Coefficient in surface area-capacity relation
D	$\overline{D}$	Monthly mean depth, feet

Table A.3 - Notation and Conversion for Program DEPLETE - (con't).

Fortran Notation	General Notation	Description
DA	-	Drainage area controlled by structures, square miles
EA	e_a	Average monthly vapor pressure of air above water surface, millibars
ES	e_s	Saturated vapor pressure at average monthly water surface temperature, millibars
I	-	An index variable
J	-	An index variable
KOUNT	-	An index variable
MOD	-	An index variable
NAME	Name	Name of watershed being used
NO	Number	Number of years to be processed
NYEAR	Water year	Water year designation
P	P	Perimeter, feet
PCT	-	Percent of month water is above lowest uncontrolled outlet
PCT1	-	Percent of month water is below lowest uncontrolled outlet
Q	q	Monthly surface runoff, acre-feet/square mile or acre-feet
QOUT	Outflow	Monthly outflow, acre-feet
R	-	Monthly average rainfall in watershed, inches
RAIN	-	Monthly rainfall on pool, acre-feet
RATE	Rate	Design principle spillway outflow rate, acre-feet/day
RH	-	Monthly average relative humidity, percent

Table A.3 - Notation and Conversion for Program DEPLETE - (con't).

Fortran Notation	General Notation	Description
SA	-	Assumed monthly average surface area, acres
SET	-	Monthly net depletion, acre-feet
SN	-	Number of structures in watershed
S1 thru S10	S_1 thru S_{10}	Used to compute various totals and accumulated totals
T	T	Monthly average temperature, °F
TAC	T_a	Monthly average air temperature, °C
TCONS	-	Annual total consumption, acre-feet
TIME	Time	Time required to drain pool to lowest uncontrolled outlet, days
TNET	-	Annual net depletion, acre-feet
TQ	-	Annual net inflow from surface runoff, acre-feet
TQOUT	-	Annual outflow, acre-feet
TRAIN	-	Annual rainfall on pool, acre-feet
TRANS	-	Monthly loss due to transpiration, acre-feet
TWC	T_w	Monthly average water surface temperature, °C
TWF	T_w	Monthly average water surface temperature, °F
T1	-	First estimate of time pool is above lowest uncontrolled outlet, days
V	ν	Kinematic viscosity of water at monthly average water surface temperature, ft^2/sec $x10^{-5}$

```
 1        10        20        30        40        50        60        70        80

|   A9   |   A9   |   A9   |   A9   |   A9   |   A9   |                          ┐ One card
  NAME (1, I), I = 1,6 - Name of study area                                       ├ for each
                                                                                  ┘ data set

|12| F6.0 | F6.0 | F6.0 | F6.0 | F6.0 | F6.0 | F6.0 | F6.0 |                       ┐
 NO   SN     DA     CK     C     RATE    A1     A2     A3   -Number of years to be ├    "
                                                             processed, watershed  │
                                                             parameters.           ┘
Water
Year        Oct   Nov   Dec   Jan   Feb   Mar   Apr   May   June  July  Aug   Sept   ┐ One card
| I4 | 4X | F6.2| F6.2| F6.2| F6.2| F6.2| F6.2| F6.2| F6.2| F6.2| F6.2| F6.2| F6.2   │ for each
NYEAR  (1)  R(1,1)---------Monthly average rainfall, in inches---------- R(1,12)    ├ year of
  :           :                                                              :      │ data
NYEAR (NO)  R(NO,1)------------------------------------------------------ R(NO,12) ┘
        Same procedure for T, monthly mean temperature, °F                         ┐
        Same procedure for RH, monthly mean relative humidity, %                   ├    "
        Same procedure for Q, monthly unit surface runoff, acre-feet/square mile   ┘


| I4 | F6.1 | F6.1 | F6.1 | F6.1 |                                                  ┐
NYEAR  C1     C2     C3     CAP - Water year, coefficients of surface area-capacity ├    "
                                  relation, and capacity at lowest uncontrolled     │
                                  outlet.                                           ┘
```

FIGURE A.4. Guide for data input - Program DEPLETE.

```
                    PROGRAM DEPLETE(INPUT,OUTPUT)
              C     PROGRAM IS MATHEMATICAL MODEL WHICH SIMULATES THE RESPONSE OF A
              C     SYSTEM OF FLOODWATER RETARDING STRUCTURES TO MONTHLY HYDROLOGIC
              C     SEQUENCES. INPUT IS RAINFALL,RUNOFF,TEMPERATURE,RELATIVE HUMIDITY,
              C     AND PHYSICAL CHARACTERISTICS  OF THE SYSTEM.
000002              DIMENSION T(50,12),NYEAR(50)    ,RH(50,12),R(50,12),Q(50,12),C1(50)
                   1,C2(50),C3(50),CAP(50)  ,SA(50,12),ASA(50,12),P(50,12),TWC(50,12),
                   2TWF(50,12),TAC(50,12),ES(50,12),EA(50,12),V(50,12),RAIN(50,12),
                   3SET(50,12),CONS(50,12),QOUT(50,12),TQOUT(50),TCONS(50),TNET(50),
                   4TRAIN(50),TQ(50),AQOUT(50),ACONS(50),ARAIN(50),ANET(50),AQ(50),
                   5D(50,12),NAME(1,6)
000002            1 FORMAT(I4,4X,12F6.2)
000002            3 FORMAT(I4,4F6.1)
000002            4 FORMAT(I2,8F6.0)
000002            5 FORMAT(1H0,37X*  RUNOFF ABOVE STRUCTURES IN ACRE-FEET*)
000002            6 FORMAT(1H0,38X* INFLOW FROM RAINFALL ON POOL IN ACRE FEET*)
000002            7 FORMAT(1H0,46X* CONSUMPTION IN ACRE-FEET*)
000002            8 FORMAT(1H0,    * YEAR    OCT      NOV      DEC      JAN      FEB      MAR
                   1   APRIL      MAY      JUNE     JULY     AUGUST    SEPT    W.Y. TOTAL   ACC
                   2UMULATED TOTAL*)
000002            9 FORMAT(I5,12F8.1,F11.1,F20.1)
000002           10 FORMAT(1H0,45X* NET DEPLETION IN ACRE-FEET*)
000002           13 FORMAT(1H0,48X* OUTFLOW IN ACRE-FEET*)
000002           22 FORMAT(6A9)
000002           25 FORMAT(1H1,46X,6A9)
              C     READ IN ALL DATA
000002              READ 22,(NAME(1,I),I=1,6)
000014              READ 4,NO,SN,DA,CK,C,RATE,A1,A2,A3
000042              READ 1,(NYEAR(I),(R(I,J),J=1,12),I=1,NO)
000065              READ 1,(NYEAR(I),(T(I,J),J=1,12),I=1,NO)
000110              READ 1,(NYEAR(I),(RH(I,J),J=1,12),I=1,NO)
000133              READ 3,(NYEAR(I),C1(I),C2(I),C3(I),CAP(I),I=1,NO)
000156              READ 1,(NYEAR(I),(Q(I,J),J=1,12),I=1,NO)
000201              DO 75 I=1,NO
000203              DO 75 J=1,12
000212           75 Q(I,J)=Q(I,J)*DA
              C     CORRECT FOR WATER TEMPERATURE DIFFERENCE
000217              DO 103 I=1,NO
000232              TWF(I,1)=T(I,1)-2.0
000235              TWF(I,2)=T(I,2)-2.0
000240              TWF(I,3)=T(I,3)-2.0
000244              TWF(I,4)=T(I,4)-2.0
000247              TWF(I,5)=T(I,5)-1.7
000252              TWF(I,6)=T(I,6)
000254              TWF(I,7)=T(I,7)+0.8
000256              TWF(I,8)=T(I,8)+0.8
000260              TWF(I,9)=T(I,9)+0.6
000262              TWF(I,10)=T(I,10)+0.5
000264              TWF(I,11)=T(I,11)+0.3
000266          103 TWF(I,12)=T(I,12)-1.2
000305              DO 104 I=1,NO
000307              DO 104 J=1,12
000321              TWC(I,J)=(TWF(I,J)-32.0)*(5.0/9.0)
000324              TAC(I,J)=(T(I,J)-32.0)*(5.0/9.0)
000325              ES(I,J)=6.1+(0.4180555*TWC(I,J))+(0.0190971*TWC(I,J)**2)
                   1-(0.0000386*TWC(I,J)**3)+(0.0000096*TWC(I,J)**4)
000336              EA(I,J)=(6.1+(0.4180555*TAC(I,J))+(0.019097*TAC(I,J)**2)
```

FIGURE A.5. Printout of Program DEPLETE source deck.

```
                 1-(0.0000386*TAC(I,J)**3)+(0.0000096*TAC(I,J)**4))*RH(I,J)/100.0
000350            V(I,J)=(1.93-(0.0630556*TWC(I,J))+(0.0009955*TWC(I,J)**2)
                 1+(0.0000154*TWC(I,J)**3)-(0.0000006*TWC(I,J)**4))
000361       104  CONTINUE
000365            DO 200 I=1,NO
000366            DO 200 J=1,12
000367            SA(I,J)=10.0*DA
000373            KOUNT=0
000400       201  CA=((SA(I,J)+C3(I))/C1(I))**(1.0/C2(I))
000407            KOUNT=KOUNT+1
000411            IF(KOUNT-20)290,207,207
000413       290  CONTINUE
000413            IF(SA(I,J))650,650,651
000424       650  SA(I,J)=0.0
000424            D(I,J)=0.0
000425            GO TO 700
000426       651  CONTINUE
000426            D(I,J)=CA/SA(I,J)
000437       700  ASA(I,J)=SA(I,J)/SN
000441            P(I,J)=(SN*CK*(ASA(I,J)**0.44))/43560.0
000447            CONS(I,J)=A1*(ES(I,J)-EA(I,J))*(SA(I,J)+ P(I,J)/.055)+A2*((T(I,J)-
                 140.0)*DA)+A3*(SA(I,J)+D(I,J)*P(I,J))/V(I,J)
000464            RAIN(I,J)=R(I,J)*SA(I,J)*.95/12.0
000467            SET(I,J)=CONS(I,J)-RAIN(I,J)
000470            TRANS=B2*(T(I,J)-40.0)*DA
000474            AAA=C+Q(I,J)
000476            IF(TRANS.LT.AAA)GO TO 444
000504            CONS(I,J)=Q(I,J)+C
000506            SET(I,J)=CONS(I,J)
000506            RAIN(I,J)=0.0
000507            QOUT(I,J)=0.0
000510            GO TO 207
000510       444  CONTINUE
000510            IF(C+Q(I,J)-SET(I,J)- CAP(I))202,202,203
000524       202  CA=(2.*C+Q(I,J)-SET(I,J))/2.0
000530            QOUT(I,J)=0.0
000531            GO TO 250
000532       203  T1=(C+Q(I,J)-SET(I,J))/RATE
000541            IF(T1.GE.30.0)T1=30.0
000544            IF(T1.LE.0.0)T1=0.0
000553            PCT=T1/30.0
000554            PCT1=1.0-PCT
000556            TIME=(C+Q(I,J)- CAP(I)-SET(I,J)*PCT)/RATE
000563            IF(TIME.GE.30.0)TIME=30.0
000567            IF(TIME.LE.0.0)TIME=0.0
000576            QOUT(I,J)=TIME*RATE
000600            CA=(C+Q(I,J)+ CAP(I)-SET(I,J)*PCT-QOUT(I,J))*PCT/2.0+(2.0* CAP(I)
                 1-SET(I,J)*PCT1)/2.0
000612       250  IF(CA.LE.0.0)CA=0.0
000615            A=C1(I)*(CA**C2(I))-C3(I)
000623            IF(A.LE.0.0)A=0.0
000626            IF(ABS(SA(I,J)-A).LT.2.0)GO TO 207
000635            IF(SA(I,J).LT.1.0)GO TO 207
000643            IF(ABS((SA(I,J)-A)/SA(I,J)).LT.0.001)GO TO 207
000652            SA(I,J)=(SA(I,J)+A)/2.0
000657            IF(SA(I,J).LE.0.0)SA(I,J)=0.0
000667            GO TO 201
000670       207  C=C-QOUT(I,J)-SET(I,J)+Q(I,J)
```

FIGURE A.5. Printout of Program DEPLETE source deck - (con't).

```
000700          IF(C)601,601,200
000701      601 C=0.0
000702      200 CONTINUE
000707          S5=0.0
000707          S6=0.0
000710          S7=0.0
000711          S8=0.0
000711          S10=0.0
000712          DO 214 I=1,NO
000714          S1=0.0
000714          S2=0.0
000715          S3=0.0
000715          S4=0.0
000716          S9=0.0
000717          DO 213 J=1,12
000727          S1=S1+QOUT(I,J)
000731          S2=S2+RAIN(I,J)
000733          S3=S3+CONS(I,J)
000734          S4=S4+SET(I,J)
000736      213 S9=S9+Q(I,J)
000742          TQOUT(I)=S1
000743          TRAIN(I)=S2
000744          TCONS(I)=S3
000746          TNET(I)=S4
000747          TQ(I)=S9
000751          AQOUT(I)=S5+TQOUT(I)
000753          S5=AQOUT(I)
000754          ARAIN(I)=S6+TRAIN(I)
000756          S6=ARAIN(I)
000756          ACONS(I)=S7+TCONS(I)
000761          S7=ACONS(I)
000761          ANET(I)=S8+TNET(I)
000764          S8=ANET(I)
000764          AQ(I)=S10+TQ(I)
000767      214 S10=AQ(I)
000772          PRINT 25,(NAME(1,I),I=1,6)
001004          PRINT 5
001010          PRINT 8
001014          PRINT 9,(NYEAR(I),(Q(I,J),J=1,12),TQ(I),AQ(I),I=1,NO)
001043          PRINT 6
001047          PRINT 8
001053          PRINT 9,(NYEAR(I),(RAIN(I,J),J=1,12),TRAIN(I),ARAIN(I),I=1,NO)
001102          PRINT 7
001106          PRINT 8
001112          PRINT 9,(NYEAR(I),(CONS(I,J),J=1,12),TCONS(I),ACONS(I),I=1,NO)
001141          PRINT 10
001145          PRINT 8
001151          PRINT 9,(NYEAR(I),(SET(I,J),J=1,12),TNET(I),ANET(I),I=1,NO)
001200          PRINT 13
001204          PRINT 8
001210          PRINT 9,(NYEAR(I),(QOUT(I,J),J=1,12),TQOUT(I),AQOUT(I),I=1,NO)
001237          END


PROGRAM LENGTH INCLUDING I/O BUFFERS
034253
```

FIGURE A.5. Printout of Program DEPLETE source deck - (con't).

```
FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS
1        -  001250   3        -  001253   4        -  001256   5        -  001261
6        -  001270   7        -  001277   8        -  001304   9        -  001324
10       -  001330   13       -  001335   22       -  001342   25       -  001344
200      -  000703   201      -  000375   202      -  000521   203      -  000533
207      -  000671   250      -  000613   290      -  000414   444      -  000511
601      -  000702   650      -  000421   651      -  000427   700      -  000434

BLOCK NAMES AND LENGTHS

VARIABLE ASSIGNMENTS
A        -  030174   AAA      -  030167   ACONS    -  026502   ANET     -  026646
AQ       -  026730   AQOUT    -  026420   ARAIN    -  026564   ASA      -  007766
A1       -  030157   A2       -  030160   A3       -  030161   B2       -  030166
C        -  030155   CA       -  030164   CAP      -  006554   CK       -  030154
CONS     -  023546   C1       -  006326   C2       -  006410   C3       -  006472
D        -  027012   DA       -  030153   EA       -  017006   ES       -  015656
I        -  030150   J        -  030162   KOUNT    -  030163   NAME     -  030142
NO       -  030151   NYEAR    -  002634   P        -  011116   PCT      -  030171
PCT1     -  030172   Q        -  005176   QOUT     -  024676   R        -  004046
RAIN     -  021266   RATE     -  030156   RH       -  002716   SA       -  006636
SET      -  022416   SN       -  030152   S1       -  030202   S10      -  030201
S2       -  030203   S3       -  030204   S4       -  030205   S5       -  030175
S6       -  030176   S7       -  030177   S8       -  030200   S9       -  030206
T        -  001504   TAC      -  014526   TCONS    -  026110   TIME     -  030173
TNET     -  026172   TQ       -  026336   TQOUT    -  026026   TRAIN    -  026254
TRANS    -  030165   TWC      -  012246   TWF      -  013376   T1       -  030170
V        -  020136

START OF CONSTANTS
001242

START OF TEMPORARIES
001413

START OF INDIRECTS
001470

UNUSED COMPILER SPACE
033500
```

FIGURE A.5. Printout of Program DEPLETE source deck - (con't).

TABLE A.4. Sample output for Program DEPLETE.

```
                                          COW BAYOU STUDY AREA

                                  RUNOFF ABOVE STRUCTURES IN ACRE-FEET

YEAR    OCT      NOV      DEC      JAN      FEB      MAR    APRIL      MAY     JUNE     JULY   AUGUST     SEPT   W.Y. TOTAL   ACCUMULATED TOTAL
1959    15.1     26.9     15.1      7.0     33.9     31.1     71.1     72.0   2798.9    458.1     87.9     99.1       3716.2              3716.2
1960  4711.0    978.9   2572.1   1911.0    852.0    547.1    549.9    219.0    628.9    730.0    101.1     31.1      13832.0             17548.2
1961  1765.1    274.1   6170.1   5563.9   3529.1    908.0    283.1    136.1   2605.1    775.9    110.0    584.9      22705.5             40253.6
1962   201.9    290.1    231.0    247.0     94.1    129.9    241.9    409.1   1391.9    110.0     22.1     31.1       3400.0             43653.7
1963    23.0     29.1     21.0     16.0     19.9     29.1     28.0     30.0     19.9     29.1     19.9    129.9        394.8             44048.5
1964    10.9     45.1     12.9     91.0     45.9    171.9    630.0    187.9   1311.0     38.1     43.1     80.9       2668.7             46717.2
1965    17.9     82.9     70.0    618.0   1139.9   2740.9    737.0   8641.1   1599.1     82.9     38.1    212.0      15979.6             62696.8
1966   124.0   1753.9    894.0    546.0   1827.0    863.0   4432.1   3473.1    330.1     38.1    435.1   2077.0      16793.6             79490.3

                                  INFLOW FROM RAINFALL ON POOL IN ACRE FEET

YEAR    OCT      NOV      DEC      JAN      FEB      MAR    APRIL      MAY     JUNE     JULY   AUGUST     SEPT   W.Y. TOTAL   ACCUMULATED TOTAL
1959    13.2     14.1     11.7      4.8     29.5      7.7     29.8     24.7    179.5     63.8     60.7     47.4        486.9               486.9
1960   194.5     37.1     98.7     34.2     45.1     15.3     40.5     33.3     95.1     48.3     30.3     22.8        695.4              1182.3
1961   148.9     32.3    175.1    114.6     87.3     48.1     14.4     23.8    165.0     58.5     22.0     74.9        965.0              2147.3
1962    34.1     55.8     26.5     17.7     19.1     16.8     62.1     50.8    139.2      1.0      9.0     22.2        454.3              2601.6
1963    32.4     33.1     15.5      4.8     10.7     11.1     19.6     19.9     26.1      3.9      5.8     16.6        199.4              2801.0
1964     1.3     24.5     10.8     23.0     14.6     21.9     44.9     29.3     95.9      2.2     56.7     68.2        393.3              3194.3
1965    17.6     35.9     17.9     72.7     70.3     94.3     14.7    276.8     35.8      8.3     25.0     75.0        744.5              3938.8
1966    38.9    101.4     55.4     33.3     61.9     20.3    174.9    101.6     26.7      3.8     98.1    145.5        861.8              4800.6

                                        CONSUMPTION IN ACRE-FEET

YEAR    OCT      NOV      DEC      JAN      FEB      MAR    APRIL      MAY     JUNE     JULY   AUGUST     SEPT   W.Y. TOTAL   ACCUMULATED TOTAL
1959    76.3     66.9     46.0     43.8     48.0     73.8     76.2     96.9    221.2    221.2    204.5    159.6       1334.5              1334.5
1960   163.6    105.8    111.6     92.9     93.7    114.9    178.4    176.6    239.4    231.6    188.4    176.9       1873.9              3208.3
1961   150.3    117.4    101.5     95.8    115.3    145.4    167.9    174.5    209.0    202.0    203.4    187.6       1870.1              5078.4
1962   136.6    103.7     92.2     83.5    111.6    125.6    160.7    207.8    206.8    238.7    255.9    153.0       1876.1              6954.5
1963   115.9     81.3     62.8     52.9     68.4    101.5    110.5    110.8    130.2    135.5    118.3     85.1       1173.1              8127.6
1964    77.3     46.0     26.9     36.3     36.8     62.3    113.6    160.2    253.1    260.4    207.6    142.5       1422.9              9550.5
1965   105.7     89.3     74.2    103.0    101.5    123.6    179.1    219.6    248.1    266.6    221.6    172.5       1904.8             11455.3
1966   111.9    136.0    100.4     81.1     98.2    126.8    186.8    199.3    233.6    254.7    217.7    212.8       1959.2             13414.6

                                       NET DEPLETION IN ACRE-FEET

YEAR    OCT      NOV      DEC      JAN      FEB      MAR    APRIL      MAY     JUNE     JULY   AUGUST     SEPT   W.Y. TOTAL   ACCUMULATED TOTAL
1959    63.1     52.8     34.3     39.0     18.5     66.1     46.4     72.2     41.7    157.3    143.9    112.2        847.6               847.6
1960   -30.8     68.7     12.9     58.7     48.6     99.5    137.9    143.3    144.2    183.3    158.1    154.1       1178.5              2026.1
1961     1.4     85.1    -73.6    -18.8     28.1     97.3    153.5    150.7     44.0    143.5    181.4    112.7        905.1              2931.1
1962   102.5     47.9     65.7     65.8     92.5    108.8     98.7    157.0     67.5    237.7    246.9    130.7       1421.8              4352.9
1963    83.5     48.1     47.3     48.1     57.7     90.4     90.9     90.9    104.1    131.6    112.5     68.5        973.7              5326.6
1964    76.0     21.4     16.1     13.3     22.3     40.4     68.7    130.9    157.2    258.2    150.9     74.2       1029.7              6356.2
1965    88.1     53.4     56.3     30.3     31.2     29.3    164.5    -57.3    212.2    258.3    196.6     97.5       1160.4              7516.6
1966    73.0     34.6     45.0     47.8     36.3    106.5     11.9     97.7    206.9    250.8    119.6     67.3       1097.4              8614.0

                                          OUTFLOW IN ACRE-FEET

YEAR    OCT      NOV      DEC      JAN      FEB      MAR    APRIL      MAY     JUNE     JULY   AUGUST     SEPT   W.Y. TOTAL   ACCUMULATED TOTAL
1959     0.       0.       0.       0.       0.       0.       0.       0.    1878.1    407.4      0.       0.        2285.5              2285.5
1960  4515.8    985.8   2511.1   1888.3    799.3    493.2    446.3      0.     564.7    580.9      0.       0.       12785.4             15071.0
1961  1425.0    263.5   6133.3   5607.9   3529.1    874.6    185.1      0.    2441.0    723.5      0.     376.9      21560.0             36630.9
1962     0.     284.5    181.6    181.3      0.       0.     195.4    303.6   1239.9      0.       0.       0.        2386.3             39017.2
1963     0.       0.       0.       0.       0.       0.       0.       0.       0.       0.       0.       0.           0.              39017.2
1964     0.       0.       0.       0.       0.       0.       0.       0.    1006.1      0.       0.       0.        1006.1             40023.3
1965     0.       0.       0.     134.4   1107.4   2706.8    693.5   8538.8   1575.0      0.       0.       0.       14756.0             54779.2
1966     0.    1408.2    859.2    501.8   1777.5    818.8   4336.7   3433.5    243.6      0.       0.    1978.4      15357.8             70137.0
```

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