# Hydrologic Effects of Floodwater-Retarding Structures on Garza-Little Elm Reservoir, Texas

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1984

*Prepared in cooperation with the city of Dallas and the Texas Water Development Board*

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By C. R. GILBERT and S. P. SAUER

## ABSTRACT

The Texas District of the Water Resources Division of the U.S. Geological Survey has collected and analyzed hydrologic data since 1953 to define the effects of systems of floodwater-retarding structures on downstream water and sediment yield. The district project includes 11 study areas ranging from 18 to 80 square miles in size and from 0 to 67 in percent of study area controlled by floodwater-retarding structures. The 11 study areas are within that part of Texas where the west-to-east average annual runoff ranges from about 2 to 7 inches. This report presents results of analyses, development of methodolgy, and results of application of methods for defining the downstream effects of systems of floodwater-retarding structures.

Annual inflow to and outflow from the system of floodwater-retarding reservoirs in seven of the 11 study areas were found to be related by the equation: $O=0.98I-0.68$, where $O$ is annual outflow, in inches, and $I$ is annual net inflow, in inches. Transmission loss of structure outflow to the downstream study-area stream-gaging station was determined and compared with the transmission loss of natural flood flow between tandem stream-gaging stations on Denton Creek, a tributary to Elm Fork Trinity River above Dallas.

Trap efficiency of most floodwater-retarding structures was found by the U.S. Soil Conservation Service to be about 97 percent. Downstream increases in suspended-sediment concentration in the outflow were found to be large in a study area with mostly silt and clay sediments, but even a large increase in suspended-sediment concentration did not represent a significant quantitative pickup of sediment by the outflow water.

Water consumption in floodwater-retarding reservoirs from the combined actions of evaporation, evapotranspiration, and seepage was found to be as much as twice the average annual consumption attributable to evaporation alone. Average annual consumption in reservoirs in the seven study areas analyzed ranged from 1.57 inches of equivalent runoff in the easternmost study area, where annual runoff averaged 6.96 inches, to 0.77 inch of equivalent runoff in the westernmost study area, where the average annual runoff was 2.35 inches. The effect of consumption on downstream flow is partially offset by rainfall on pool surface. Studies covering as much as 15 years of streamflow record at the stream-gaging stations that gage outflow from the Deep and Honey Creek study areas indicated no increase in base flow.

Multiple-linear-regression techniques were used in developing methodology to determine reservoir consumption in seven study areas. The physical and climatic factors influencing consumption were grouped as variables in regard to their relative effect on the actions of evaporation, evapotranspiration, and seepage. The resulting generalized equation was then used in synthesizing the consumptive effects of a planned system of 162 floodwater-retarding reservoirs controlling 26 percent of a 1,660-square-mile drainage basin upstream from a major water-supply reservoir. The analyses were based on the assumption that all water consumed at the floodwater-retarding reservoirs would have reached the downstream water-supply reservoir. Water-sediment discharge relationships were derived for the runoff into the structures as well as for the runoff through and below the structures. A mathematical response model of the floodwater-retarding reservoir systems and the entire drainage basin was computer programed to yield monthly water and sediment inflow to the water-supply reservoir.

Results of the response model showed that with full development, depletion of annual yield to the large reservoir would be as much as 10 percent in the early years; but after the permanent pools of the floodwater-retarding structures had mostly filled with sediment, depletion of annual yield would be generally less than 1 percent. The depletion of yield to Garza–Little Elm Reservoir during the 39-year synthesized period of study was estimated as 296,800 acre-feet out of 18,256,000 acre-feet total yield. During the same period, the floodwater-retarding structures were estimated to have kept 19,700 acre-feet of sediment from being deposited in the reservoir.

"Firm"- or "critical"-yield studies were made of the large reservoir on the basis of two sets of conditions: with floodwater-retarding structures in the drainage basin, and without such structures. Results of the firm-yield studies indicated that with full development, annual firm yield would be initially reduced by 10 percent. After 30 or more years, when the permanent pools of the floodwater-retarding reservoirs would be mostly filled with sediment, the firm yield would be almost the same with or without the upstream development.

## INTRODUCTION

In 1950, the U.S. Soil Conservation Service began construction of floodwater-retarding structures in Texas under authorities granted by the Congress. These authorities provide that, where economically feasible, land- and water-conservation programs be applied to tributary watersheds.

One phase of the programs has been to control flood runoff from the watersheds by a system of floodwater-retarding structures located on headwater subwatersheds of generally less than 10 square miles. In June 1968, the U.S. Soil Conservation Service estimated approximately 3,500 structures to be economically feasible for installation in Texas. As of January 1, 1968, 1,275 structures were under contract or had been completed. During the period 1961–67, floodwater-retarding structures were completed in Texas at an average of 108 per year. The scope of the planned program of development in June 1968 is illustrated on plate 1. However, the program is subject to change as needs change. Definition and consideration of the hydrologic effects of floodwater-retarding structures on downstream water-resources development is requisite to sound water planning and management.

### PURPOSES OF THIS REPORT

The purposes of this report are: (1) To analyze hydrologic data collected during the period 1953–67 in watersheds developed with floodwater-retarding structures and to define the effects of these structures on downstream water and sediment yield, (2) to develop methodology for synthesizing the effects of floodwater-retarding structures on downstream water and sediment yield in ungaged areas, and (3) to apply this methodology to show the effects of the structures on inflow to reservoirs in a basin that is being extensively developed.

### ACKNOWLEDGMENTS

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Assistance to the U.S. Geological Survey in the form of funds and (or) services for hydrologic-data collection in the statewide small-watershed project was provided by the U.S. Soil Conservation Service, the Texas Water Development Board, the city of Dallas, the San Antonio River Authority, and the Tarrant County Water Control and Improvement District No. 1.

## HYDROLOGIC-DATA COLLECTION

### TEXAS DISTRICT SMALL-WATERSHEDS PROJECT

The U.S. Geological Survey, cooperating with the U.S. Soil Conservation Service and the Texas Water Development Board (the Texas Board of Water Engineers), began hydrologic studies of to-be-developed watersheds in 1951 in the upper Trinity and middle Colorado River basins. Later requests from cities, river authorities, and other water-management agencies needing data on the hydrologic effects of the floodwater-retarding programs resulted in the present Texas District studies in 11 study areas. These areas and their respective drainage areas are given in table 1.

TABLE 1.—*Small-watershed study areas in Texas, September 30, 1967*

| Study area | Drainage area (sq mi) | Hydrologic data collection began | Floodwater-retarding structures in study area | |
|---|---|---|---|---|
| | | | Number | Year completed |
| Trinity River basin: | | | | |
| North Creek near Jacksboro | 21.6 | Aug. 1956 | 0 | |
| Elm Fork Trinity River near Muenster | 46.0 | July 1956 | 11, 3 | 1954–57, 1963 |
| Little Elm Creek near Aubrey | 75.5 | June 1956 | 8 | 1966 |
| Honey Creek near McKinney | 39.0 | July 1951 | 12 | 1951–57 |
| Pin Oak Creek near Hubbard | 17.6 | Sept. 1956 | 6 | 1962–64 |
| Brazos River basin: | | | | |
| Green Creek near Alexander | 46.1 | Oct. 1954 | 8 | 1954–56 |
| Cow Bayou near Mooreville | 79.6 | Sept. 1954 | 9, 17 | 1955–58, 1964–65 |
| Colorado River basin: | | | | |
| Mukewater Creek near Trickham | 70.0 | Aug. 1951 | 5, 1 | 1961–62, 1965 |
| Deep Creek near Mercury | [1] 43.9 | June 1951 | 5 | 1951–53 |
| San Antonio River basin: | | | | |
| Calaveras Creek near Elmendorf | 77.2 | Aug. 1954 | 9 | 1954–58 |
| Escondido Creek at Kenedy | [2] 72.4 | July 1954 | 10 | 1954–58 |

[1] 8.31 sq mi above Dry Prong Deep Creek near Mercury not included in this total.
[2] 8.43 sq mi above Escondido Creek subwatershed 11 (Dry Escondido Creek) near Kenedy not included in this total.

Basic-data collection programs were begun while the areas were being developed because of the acute need to obtain and publish small-watershed hydrologic data. After complete development of structures in a study area, investigations of downstream effects of the structure system were begun.

In some areas where development was supposedly complete, changes in the U.S. Soil Conservation Service program resulted in the construction of additional floodwater-retarding structures.

Information on each of the 11 study areas within the statewide small-watershed project is given in table 1. Study-area locations are shown on plate 1. The areas were chosen to collect data on watersheds having different climate, topography, geology, and soils.

On four watersheds (Little Elm, Mukewater, North, and Pin Oak Creeks), collection of rainfall and downstream-runoff records was started to get at least 6 years of record before construction of floodwater-retarding structures. Hydrologic investigations of these four study areas made using records of rainfall and runoff under drought, flood, and average climatic conditions after construction, are expected to define some hydrologic effects of the system of structures more accurately than investigations in those areas that were developed throughout the data-collection periods. By June 1968, structures had been built on streams in three of these four study areas—Little Elm, Mukewater, and Pin Oak Creeks. A summary of the status of construction in each area, to September 30, 1967, is given in table 1. Figure 1 is a section view of a typical floodwater-retarding structure.

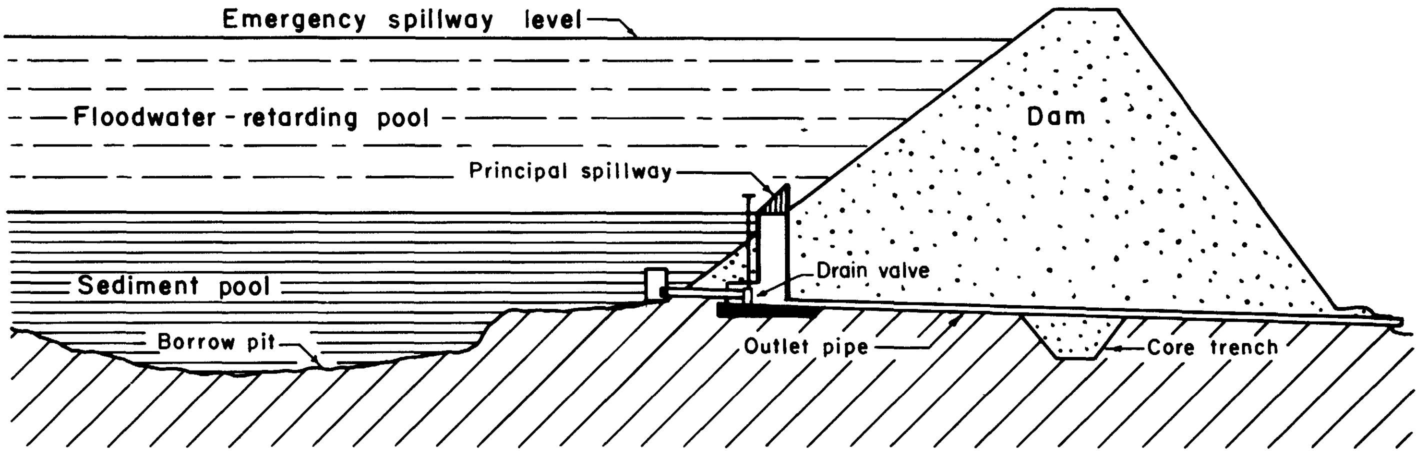


FIGURE 1.—Section of typical floodwater-retarding structure.

## OBJECTIVES OF THE PROJECT

The initial broad purpose of these investigations was to collect sufficient data to make needed intepretations, as then recognized, and to record data for future analyses.

In 1961, a committee of engineers and hydrologists representing the U.S. Geological Survey, the Texas Board of Water Engineers (now the Texas Water Development Board), the city of Dallas, the San Antonio River Authority, and the U.S. Soil Conservation Service reviewed the district small-watershed project and determined the following desirable specific objectives:

1. Obtain basic data which will aid in determining the net effect of systems of floodwater-retarding structures on the regimen of streamflow at downstream points, and publish annually a compilation of the data collected at each of the 11 study areas within the data-collection network.
2. Determine, where possible, the effect of the structures on the underlying ground-water reservoir.
3. Determine the effect of the structures on the sediment yield of the basin and determine the trap efficiency of the structures.
4. Develop computation techniques that will give more accurate estimates of runoff resulting from a given amount of rainfall on small watersheds.
5. Develop relationships between maximum rates of runoff and rainfall in small watersheds that will enable more accurate design of small storm-drainage structures.
6. Check the applicability of flood-routing procedures and techniques for small watersheds.
7. Determine the minimum instrumentation necessary for making reliable estimates of total storm inflow to the structures.
8. Determine the chemical quality of the water with respect to suitability for possible uses, and determine the flocculation characteristics of the water with respect to sediment trap efficiency of the pools.
9. Prepare, as data becomes sufficient for the purpose, interpretive reports on individual areas that will fulfill as many of the stated objectives as possible.

These are the objectives of the statewide project. They do not apply, as a whole, to each particular study area within the project.

Details regarding physiography and scope of hydrologic- and climatic-data collection in each of the 11 study areas are given on plate 2.

## PROJECT DATA COLLECTED

The scope of the hydrologic and climatic data collected in the 11 study areas of the Texas District small-watershed project can best be seen in table 1 and on plate 2. Most of the data were collected to define the effects of floodwater-retarding structures on natural downstream streamflow and sediment yield. To this end much of the data collection was in the form of research to establish procedures and guidelines necessary for isolation of the many factors that make up the study-area water budget. For example, evaporation and ground-water data were collected at some study areas to afford more accurate procedures for determining pool losses (consumption), especially during periods of simultaneous inflow to and outflow from the floodwater-retarding structures (reservoirs). Also, extensive rainfall data were necessary, not only for hydrologic studies of small watersheds, but as a term in the surface-water budgets of the reservoirs.

For those structures shown as gaged on plate 2, data were collected to define the following parameters for each reservoir site on a monthly basis:

Inflow to reservoir from land drainage, $I$.
Outflow from reservoir, $O$.
Rainfall on pool, $R$.
Pool consumption, $C$.
Pool change-in-contents, $\Delta S$.
Mean pool surface area, $A$.
Weighted mean rainfall on site drainage area, $WMR$.

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

$$C=I+R-O\pm\Delta S. \qquad (1)$$

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 recharge the ground water is not consumed in the strict sense of the word. However, unless this recharge causes the water table to intersect the surface stream at some downstream point, this water is lost insofar as surface-water yield to a downstream water supply is concerned. Streamflow records in each developed study area show no ground-water effluent to channels downstream from floodwater retarding structures.

Data on total surface runoff from each study area were collected at downstream stream-gaging stations to afford total runoff computations and, under certain hydrologic conditions, an index of transmission loss of outflow from the system of reservoirs. Beginning in February 1966, tandem stream-gaging stations provided more accurate data for computation of transmission loss of outflow from reservoirs in the Little Elm Creek study area.

Daily suspended-sediment data were collected at the stream-gaging station and one reservoir station in the Elm Fork Trinity River study area (from October 1956), at the stream-gaging station in the Pin Oak Creek study area (from September 1956 to September 1960, and from September 1962), and at the two stream-gaging stations in the Little Elm Creek study area (from February 1966). In addition, reservoir-sedimentation surveys were made by the U.S. Soil Conservation Service for at least one reservoir in each study area developed with floodwater-retarding structures, except Pin Oak Creek and Little Elm Creek.

## SMALL-WATERSHED PROJECT DATA USED FOR THIS REPORT

### RESERVOIR SURFACE-WATER BUDGET DATA

Surface-water budgets of systems of floodwater-retarding reservoirs are available in seven of the 11 study areas for a sufficient common period to afford analyses that form the basis for this report. These seven study areas are shown on plate 1 as areas 2, 4, 6, 7, 9, 10, and 11. Consumption was determined by the water-budget method (eq. 1). Techniques for determining the various components of consumption and the physical parameters to which they are related are covered in a later section of this report. An indication of the amount of water-budget data available for analysis is given in table 2, which shows the number of structures instrumented and the drainage area controlled at the beginning of each water year (the year beginning October 1) of the period of study.

### SUSPENDED-SEDIMENT-DISCHARGE DATA

Daily suspended-sediment-discharge data collected at the stream-gaging station and trap-efficiency data collected at reservoir site 6–O since October 1956 in the Elm Fork Trinity River study area were used in defining sediment pickup by the outflow from reservoirs. Because the sediment-data collection was under complete development conditions throughout the period, the water-sediment discharge relationship at the stream-gaging station was useful only in a relative manner—that is, the sediment data collected when there was only

TABLE 2.—*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 Trinity River [2] | | 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.

structure outflow could be used in water-sediment discharge relationships to indicate the relative magnitude of sediment pickup.

Suspended-sediment-discharge data collected in the Little Elm Creek study area from February 1966 to September 1967 were used to define sediment pickup in a 9-mile reach by the relatively clear water discharged from upstream floodwater-retarding structures.

The daily suspended-sediment-discharge data collected at the stream-gaging station for the Pin Oak Creek study area from September 1956 to September 1960 and from September 1962 to September 1967 were used in analyses involving the relationship of water discharge to sediment discharge and in analyses involving changes in suspended-sediment discharge resulting from watershed development with floodwater-retarding structures (which were built 1962–64).

All suspended-sediment samples were taken with a depth-integrating sampler, except at reservoir site 6–O in the Elm Fork Trinity River study area where samples of the outflow from the 17-inch-diameter discharge pipe were taken by passing a bottle through the discharging nappe.

### GROUND-WATER DATA

Data on ground-water levels and movement collected in the Elm Fork Trinity River study area from January 1957 to October 1959 (Gilbert and others, 1962) and in the Calaveras Creek study area from March 1955 to August 1960 (J. T. Smith and W. B. Mills, unpub. data) were used in regression analysis involving pool consumption in support of the assumption that no significant ground-water inflow occurred.

### EVAPORATION DATA

A minimum of 2 years of mass-transfer and (or) energy-budget evaporation data for all study areas except North Creek, Little Elm Creek, and Pin Oak Creek were used in this report to aid in the grouping of variables in the multiple-regression analysis involving pool consumption. The evaporation data were also used for calibration and verification of monthly values for evaporation determined by the climatic-factor concept (McDaniels, 1960).

## RELATED PHYSICAL AND CLIMATIC DATA

### CLIMATE AND PHYSIOGRAPHY

A summary of the important climatic and physiographic parameters of the seven developed study areas is given in table 3. 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).

TABLE 3.—*Climate and physiography of seven developed study areas*

| Study area | Average elevation (ft above msl) | Latitude north | Longitude west | Average annual precipitation, 1931–60 (inches) | Average annual temperature, 1931–60 (°F) | Average annual gross lake evaporation, 1940–65 (inches) | Drainage area (sq mi) | | Number of structures |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Controlled | Total | |
| Calaveras Creek | 505 | 29°19′ | 98°18′ | 29 | 69 | 64 | 37. 1 | 77. 2 | 9 |
| Cow Bayou | 600 | 31°21′ | 97°15′ | 33 | 67 | 64 | 28. 0 | 79. 6 | 9 |
| Deep Creek | 1, 490 | 31°20′ | 99°09′ | 27 | 65 | 76 | 24. 2 | 52. 2 | 6 |
| Elm Fork Trinity River | 985 | 33°38′ | 97°57′ | 33 | 65 | 68 | 31. 0 | 46. 0 | 11 |
| Escondido Creek | 360 | 28°49′ | 97°54′ | 30 | 70 | 62 | 44. 9 | 80. 7 | 11 |
| Green Creek | 1, 370 | 32°07′ | 98°17′ | 31 | 65 | 74 | 22. 3 | 46. 1 | 8 |
| Honey Creek | 660 | 33°20′ | 96°42′ | 38 | 65 | 64 | 20. 9 | 39. 0 | 12 |

### SURFACE AREA, STORAGE, AND DISCHARGE

The surface-area–storage relationships for the system of reservoirs in each study area vary depending upon topography. Discharge characteristics and amounts of water stored at various designated elevations depend upon design. Tables 4 and 5 summarize the surface area, storage, and discharge characteristics in the seven developed study areas. A comparison of surface-area–storage characteristics can be seen in figure 2.

### 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. In addition, sedimentation characteristics depend on soils. Soil maps were prepared for each of the seven watersheds. Soil series were determined from county soil maps compiled by the U.S. Soil Conservation Service (U.S. Dept. Agriculture) 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 U.S. Soil Conservation Service (1957). Soils are classified as A, B, C, or D, with definitions as follows:

*Group A* (Low runoff potential): Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of sands or 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.

*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 are classified for runoff potential, this classification also serves as an index of seepage potential. Musgrave and Holtan

TABLE 4.—*Surface-area characteristics of floodwater-retarding reservoirs in seven study areas*

[Surface area, in acres]

| Study area | Lowest uncontrolled outlet | | | Sediment pool | | | Emergency spillway | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | Per square mile controlled | Average per reservoir | Total | Per square mile controlled | Average per reservoir | Total | Per square mile 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 | 5.46 | 15.4 | 216 | 6.98 | 19.6 | 786 | 25.39 | 71.4 |
| | [1] 209 | [1] 6.74 | [1] 19.0 | | | | | | |
| Escondido Creek | 411 | 9.16 | 37.4 | 593 | 13.22 | 53.9 | 1,774 | 39.56 | 161.3 |
| Green Creek | 188 | 8.55 | 23.5 | 226 | 10.28 | 28.2 | 798 | 36.31 | 99.8 |
| | [2] 197 | [2] 8.97 | [2] 24.6 | | | | | | |
| 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 5.—*Storage and discharge data for floodwater-retarding reservoirs in seven study areas*

| Study area | Storage (acre-ft) | | | | | | | | | Maximum combined outflow rate, principal spillway (acre-ft per day) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lowest uncontrolled outlet | | | Sediment pool | | | Emergency spillway | | | | | |
| | Total | Per square mile controlled | Average per reservoir | Total | Per square mile controlled | Average per reservoir | Total | Per square mile controlled | Average per reservoir | Total | Per square mile 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 | 44.6 | 126 | 1,798 | 58.0 | 163 | 11,550 | 373 | 1,050 | 625 | 20.2 | 56.8 |
| | [1] 1,728 | [1] 55.7 | [1] 157 | | | | | | | | | |
| 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 | 42.2 | 116 | 1,118 | 50.8 | 140 | 7,500 | 341 | 938 | 341 | 15.5 | 42.6 |
| | [2] 1,012 | [2] 46.0 | [2] 126 | | | | | | | | | |
| 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.

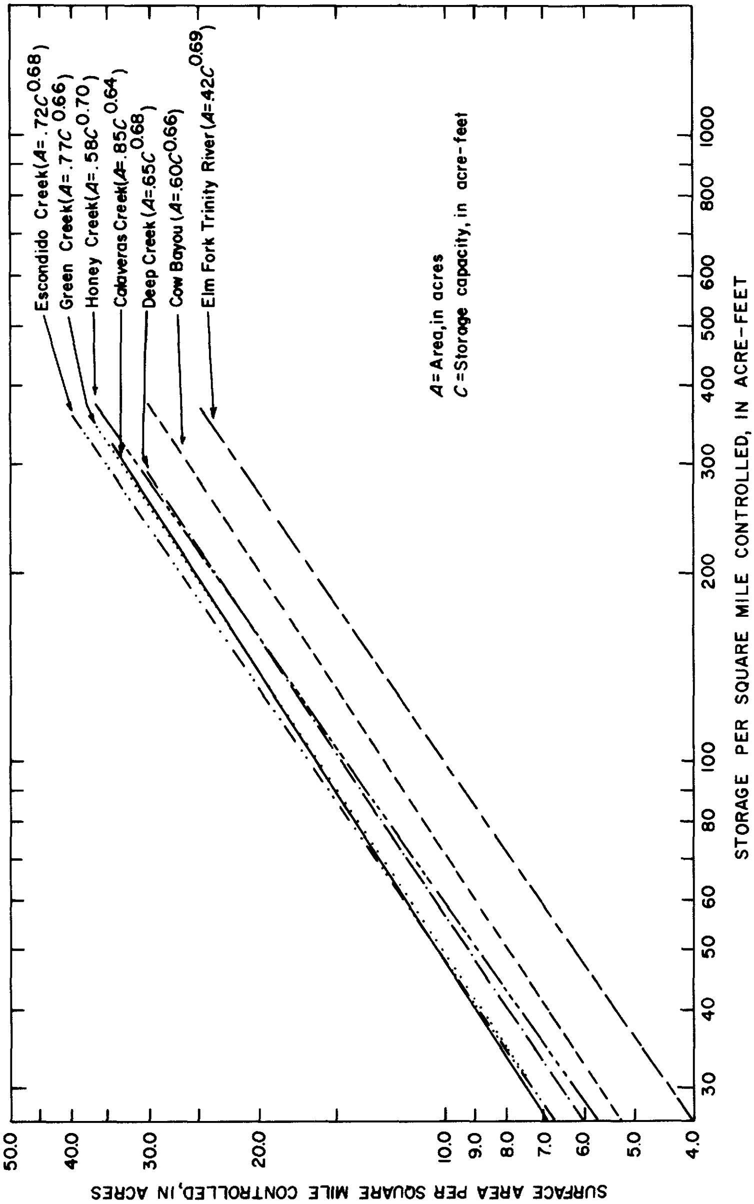


FIGURE 2.—Relationship of surface area to storage for systems of reservoirs in seven study areas.

(1964) gave the following minimum infiltration rates by soil groups (U.S. Soil Conservation Service 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, is shown in table 6. 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 6.—*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 in. thick, grading to firm sandy clay or sandy clay loam 25–40 in. below the surface. | D | 16 |
| | San Antonio | Weakly granular to massive fine sandy loam to clay loam surface, 6–12 in. thick, grading to very firm blocky clay 24 in. below the surface. | D | 7 |
| | Stidham | Weakly granular very friable fine sandy loam to loamy fine sand surface, 6–18, in. thick, grading into a friable blocky sandy clay. | B | 43 |
| | Webb | Friable sandy loam to loam surface, 8–12 in. thick, with very firm plastic clay subsoil over calcareous sandy clay with thin strata of sandstone at depths of 30–45 in. | C | 34 |
| Cow Bayou | Austin | Friable calcareous silty clay to clay surface, 10–14 in. thick, over friable strongly granular highly calcareous silty clay to clay. Chalky marl or chalk at depths of 15–30 in. | B | 30 |
| | Eddy | Very friable calcareous silty clay or clay 3–15 in. thick, over soft chalky marl. | C | 24 |
| | Houston | Crumbly calcareous clay surface, 6–15 in. thick, over blocky highly calcareous clay at 20–36 in. depth. | D | 20 |
| | Houston-Black | Crumbly and friable calcareous clay surface, 10–25 in. thick, over firm blocky calcareous clay with strongly calcareous clay at 30–60 in. depth. | D | 26 |
| Deep Creek | Kirkland | Friable silt loam to clay loam surface, 7–10 in. thick, over very firm and compact blocky clay that grades into weakly calcareous clay or shaly clay below about 36 in. depth. | D | 40 |
| | Owens | Calcareous clay surface, 5–10 in. thick, over very firm blocky to massive calcareous clay that grades into calcareous shaly clay 15–30 in. beneath the surface. | D | 60 |
| Elm Fork Trinity River. | Denton | Crumbly granular calcareous clay surface, 8–12 in. 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 in. | C | 65 |
| | Tarrant | Friable highly calcareous clay surface, 4–8 in. thick, over broken or partly weathered limestone or limestone bedrock at less than 12 in. beneath the surface. | D | 35 |

TABLE 6.—*Description of soils in seven study areas*—Continued

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

# HYDROLOGIC-DATA COMPILATION AND ANALYSIS

## RUNOFF CONSUMPTION BY SYSTEMS OF FLOODWATER-RETARDING RESERVOIRS

It is a stated purpose of this report to present methodology and analyses useful in the evaluation of the effect of floodwater-retarding structures on downstream runoff. Intuitively, one would expect that losses resulting from storage of water are functionally related to surface-area characteristics, amount of controlled storage, characteristics of the soil, geology, amount of inflow, rate of release of floodwaters, riparian vegetation, and climatic factors. As described in previous sections of this report, these factors differ considerably in the seven study areas.

When water is impounded for any purpose, there is a reduction in the amount of water passing the point of impoundment, except in areas where rainfall on the pool surface exceeds the amount of losses from the pool. In Texas, only in the extreme eastern part of the State does rainfall exceed lake evaporation on an average basis. In the study areas used for this report, there is always a net loss due to evaporation on an annual basis, although at times monthly rainfall exceeds monthly evaporation.

From the viewpoint of planning agencies and design engineers, knowledge of the total quantity of water consumed at a particular site is useful only in determining the resultant reduction in yield at some downstream point, such as a water-conservation reservoir. Hence, the problem is twofold:

1. Determine the inflow-outflow relations on site.
2. Analyze the change in regimen of flows between the site and the downstream point.

Inflow as used here is net inflow (runoff from land surface) because only this value is indicative of the flow that would occur under natural conditions.

Analyses of runoff depletion and conclusions presented in this section of the report apply only to the hydrologic and physical conditions prevailing during the relatively short period of data collection. Physical changes in the system of floodwater-retarding reservoirs with time will alter the analyses presented. A later section of the report presents an estimate of some of these physical changes and relates them to the maximum probable long-term depletion of runoff that could be expected.

## INFLOW-OUTFLOW RELATIONS

Study of a simple inflow-outflow relationship on a monthly basis is not feasible because change in storage and carryover effects are significant factors in this short time interval. For preliminary planning and approximation for design purposes, a time period of 1 year is generally satisfactory. For this reason, an analysis of the annual inflow-outflow relation was made for the system of floodwater-retarding reservoirs in all seven study areas. The base period used was the 8-year period 1959–66. During this period, no adjustments were made for carryover and storage effects, physical characteristics of the structures and study areas, or climatic factors. Linear least-squares regression analysis yielded the following equation:

$$O=0.98I-0.68, \qquad (2)$$

where

$O$=annual outflow, in inches, from the system of floodwater-retarding structures; and

$I$=annual net inflow, in inches, into the system of floodwater-retarding structures.

For the period 1959–66, the standard error of estimate in use of the equation is 0.31 inch. The data and analyses for this relationship were included in a report by Sauer and Masch (1969). A plot of the values used for this regression is shown in figure 3. A comparison of the estimated and observed outflows and of the standard errors of estimate resulting from use of equation 2 for the period 1959–66 are shown in table 7.

The derived relation between outflow and inflow is surprisingly consistent throughout the seven areas studied when the variations in physical and climatic characteristics are considered. The relation indicates that, in general, annual runoff (net inflow) values of less than 0.7 inch will result in no outflow passing the floodwater-retarding site. The relation also indicates that the total amount of pool consumption increases and that the ratio of this consumption to inflow decreases as runoff increases. This relation is suggested for general

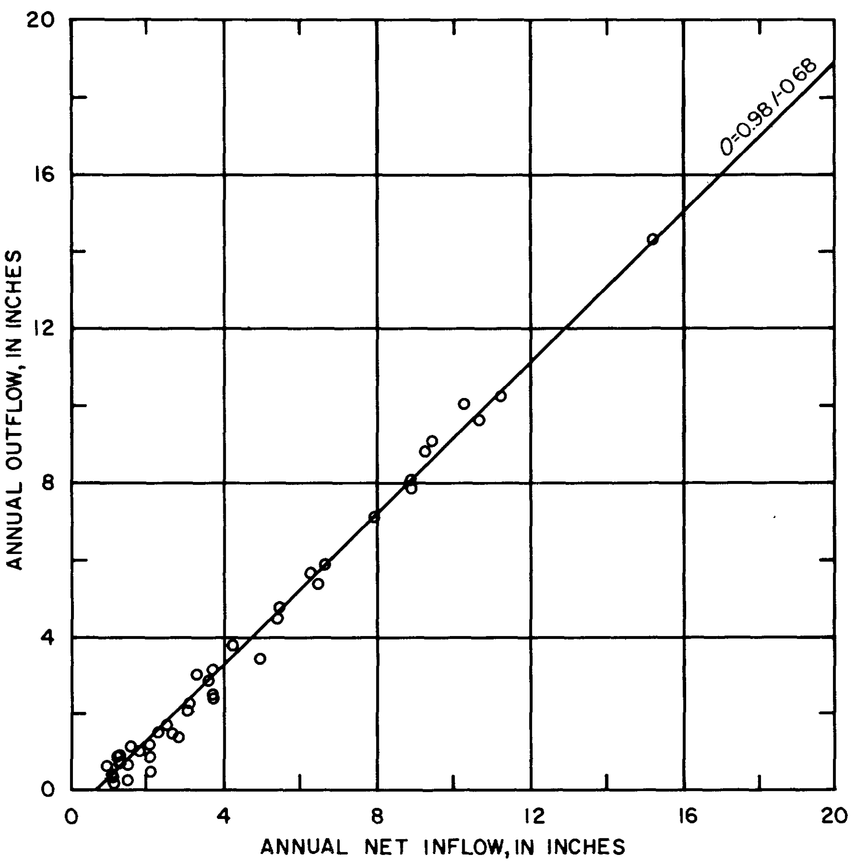


FIGURE 3.—Annual outflow versus net inflow for seven study areas, 1959–66. Data plotted are from table 9.

TABLE 7.—*Comparison of observed reservoir outflow and outflow estimated from equation 2, for period 1959–66*

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

usage in preliminary studies to determine the effect of floodwater-retarding structures on watershed yield in the area bounded by the seven study areas. This relation probably represents the maximum reduction in outflow to be expected. As the sediment pools fill with sediment, the floodwater-retarding structures will cause less reduction in flow, particularly as the surface area at the lowest uncontrolled outlet is decreased.

A simpler presentation of effects of floodwater-retarding structures on yield (based on eq 2) is tabulated below:

| *Annual runoff (inches)* | *Reduction in yield (percentage)* |
|---|---|
| <0.7 | 100 |
| 1.0 | 70 |
| 2.0 | 36 |
| 5.0 | 16 |
| 10.0 | 9 |

This tabulation shows that reduction in yield increases rapidly with decreasing average annual runoff.

## CHANNEL TRANSMISSION LOSS OF FLOOD FLOW

Floodwater-retarding structures modify natural flood waves by impounding the floodwater and then later releasing the water into stream channels at a rate of discharge that is only a fraction of the natural rate—usually a maximum of 5–10 cubic feet per second per square mile of the area controlled. The much longer in-channel exposure of the flood discharge to seepage and evapotranspiration has been conjectured by some hydrologists to cause transmission losses greater than those that occur with the passage of natural flood flow. If transmission losses are greater with the floodwater-retarding structures, these greater losses should be considered in analyses of the downstream effects of structures. However, if transmission losses are greater under natural conditions of flood flow, the downstream depletion of runoff attributable to the structures would be less than the on-site reservoir losses. Analyses were made to determine transmission losses under both conditions.

### OUTFLOW FROM STRUCTURES

Inflow, outflow, and downstream streamflow data collected in the study areas developed with floodwater-retarding structures (see table 1) were used in determining the transmission loss of outflow from the structures. For each period of outflow analyzed, a transmission loss in acre-feet was computed as gaged outflow from structures plus estimated runoff below structures plus estimated release from channel storage minus gaged runoff at downstream streamflow station. The resulting value was divided by days in period of outflow and river miles in reach for convenience of expression. Runoff from the area below the structures was estimated on the basis of gaged inflow to the structures and adjusted for any rainfall difference on the respective drainage basins. The values used for river miles were computed by weighting the outflow and distance above the gaging station for each reservoir in the study area.

Although the computations sometimes gave a transmission loss greater than the outflow from the structures, the outflow was used as a maximum loss. For most periods analyzed, runoff below structures was small relative to outflow. Some periods of outflow with recurring storm runoff below the structures indicated a gain in flow rather than a loss. Although the transmission loss computed from these rather selective dry periods is probably more accurate because the relative error in estimating the runoff below the structures is diminished, the loss should be considered as the maximum. The values computed for average daily transmission loss per mile were plotted against values for average daily outflow rate (fig. 4). In view of the wide variation in the factors causing transmission loss, the scatter of the plot is not surprising. The plot improves when the data for only one study area are considered. However, owing to the small number of periods of extended flood outflow from the structures when little or no runoff was occurring below the structures, the statistical sample in each study area is not considered sufficient to make individual analyses.

The curve relating daily values of transmission loss and outflow rate for the small-watershed studies (fig. 4) shows that at a daily outflow rate of 10 acre-feet, about 7 percent of the outflow would be lost in each mile of channel; whereas, with a daily outflow rate of 100 acre-feet, about 4 percent of the outflow would be lost per mile. As previously stated, because of hydrologic conditions during the outflow periods selected for analysis of transmission losses, the above values are considered maximums.

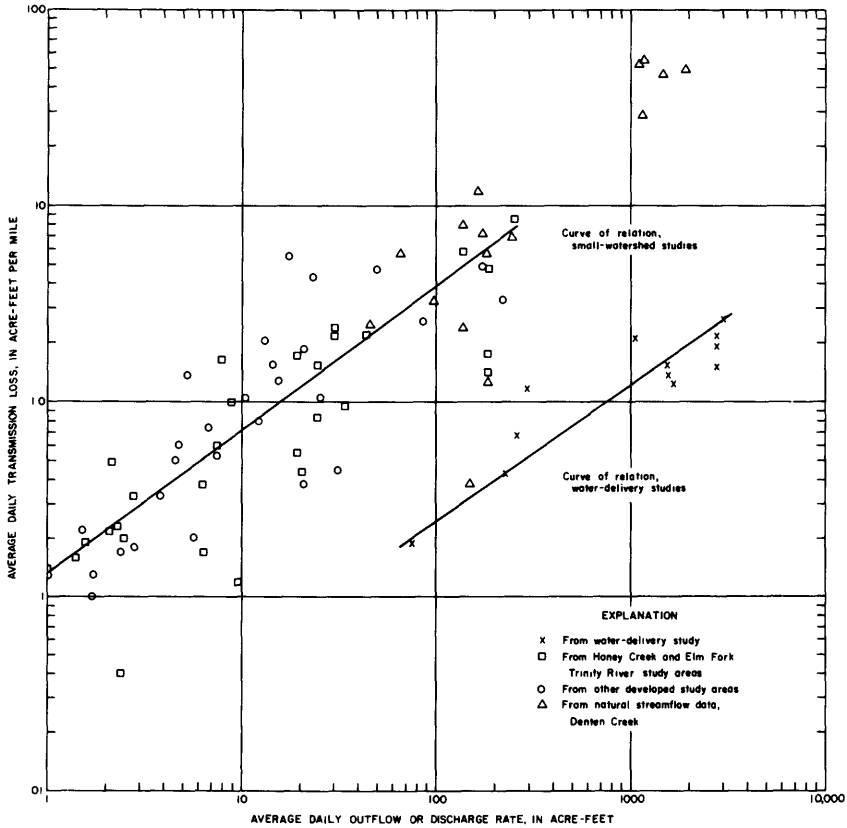


FIGURE 4.—Relation between outflow transmission loss and outflow rate.

## NATURAL FLOOD FLOW

Figure 4 shows a plot of the results of water-delivery studies made by the U.S. Geological Survey on reaches of the Elm Fork Trinity, Brazos, Colorado, Nueces, and Pecos Rivers and their tributaries in Texas. The results of these water-delivery studies were published by the Texas Board of Water Engineers (1960), Sauer and Blakey (1965), and Grozier, Albert, Blakey, and Hembree (1966). The transmission-loss–discharge-rate relation for the water-delivery studies was initially derived to accurately illustrate the channel losses that take place with the passage of a natural flood wave. However, when the hydraulics of these two conditions of streamflow are compared, it is understandable that transmission losses for natural flow should be higher. The primary reason for this is that for a given average daily rate of flow, the range in discharge is much greater for a natural flood wave than it is for the regulated discharge measured in a water-delivery study. Thus, there is much more exposure of the river bank to seepage (also to evaporation on recession) in the passage of a natural flood wave.

The much higher transmission loss indicated in figure 4 for the small-watershed studies can also be accounted for qualitatively. Outflow from floodwater-retarding structures travels down many tree-lined channels before entering the main channel upstream from the gaging station. Because the flow in these small channels is ephemeral, the channel seepage loss is probably high, even after the channel has been wetted with storm rainfall. The combined-channel wetted perimeter per unit volume of outflow is much higher for the structure discharge than for the single large-channel discharge involved in water-delivery studies. Also, the streams used for the water-delivery studies are generally perennial (flow sustained by continuous reservoir release). For water-delivery studies, outflow is released from the bottom of the reservoir and is colder and less conducive to evaporation than discharge from the drop-inlet-type outlet of the floodwater-retarding structures.

The transmission losses indicated by the water-delivery studies were reasoned to be incomparable with those in natural streamflow. Therefore, to illustrate losses of streamflow that take place under natural conditions, the continuous streamflow records for two gaging stations 11.5 miles apart on the same stream were analyzed. The two gaging stations are Denton Creek near Justin, Tex. (drainage area: 400 sq mi; operated from October 1949 to the present) and Denton Creek near Roanoke, Tex. (drainage area: 621 sq mi, operated from October 1923 to December 1927 and from March 1939 to September 1955). Streamflow data for the period of concurrent record, October 1949 to September 1955, were used in the analysis. Annual rainfall for the period averaged about 75 percent of normal. Only two storms during the period caused streamflow that exceeded the channel capacity.

For the analyses, 25 storm events with isolable runoff during the 6-year period of common record were used. Streamflow loss in the 11.5-mile reach between the two gaging stations was computed as gaged runoff at the upstream station (400 sq mi drainage area) plus estimated runoff from the intervening 221 square miles of drainage area (estimated on the basis of upstream station runoff adjusted for drainage area and rainfall difference) minus gaged runoff at the downstream station. This computation procedure is consistent with that used in determining transmission loss of outflow from floodwater-retarding structures. Of the 25 storms analyzed, 16 indicated a channel transmission loss, whereas nine indicated a gain between the two gaging stations. Included among the nine storms that indicated a gain were the only two storms that exceeded the channel capacity during the 6-year period of record.

For purposes of comparison, the streamflow losses in Denton Creek are also plotted in figure 4. Although the statistical sample is small, the results indicate that natural streamflow transmission loss is about the same order of magnitude as transmission loss of outflow from floodwater-retarding structures during similar dry hydrologic conditions.

The foregoing analyses of channel transmission loss of flood flow emphasize that only during mostly dry hydrologic conditions can transmission losses be computed with any degree of accuracy. Even then, the hypothesis that there is a transmission loss was rejected nine out of 25 times in the Denton Creek analyses. For the average, or wet, hydrologic condition, it is doubtful that channel transmission loss is quantitatively significant in most streams. For the 6-year period of concurrent record, the average annual unit runoff was 78.8 acre-feet per square mile for the upper station and 87.6 acre-feet per square mile for the lower station. If there is no channel transmission loss, the average annual unit runoff for the 221 square-mile intervening drainage can be computed as 103.4 acre-feet per square mile. The avearge annual rainfall for the period was about 10 percent greater for drainage above the upper station than for the intervening drainage. The fact that the intervening drainage is a gaining reach tends to discount significant transmission loss between the gaging stations.

On the basis of the analyses of channel transmission losses of flood flow under mostly dry hydrologic conditions, the analyses presented in later sections of this report are made with the assumption that these losses are the same with and without floodwater-retarding reservoirs in the watershed.

## ANALYSIS OF SEDIMENT DISCHARGE AND DEPOSITION

To aid in determining the effects of floodwater-retarding structures on the downstream total sediment yield, analyses were made of all sediment data collected in the State project. The following sections describe these analyses and present the results.

### SUSPENDED-SEDIMENT DISCHARGE

#### PIN OAK CREEK STUDY AREA

Suspended-sediment-discharge data collected in the Pin Oak Creek study area during the period October 1956 to September 1960 (prior to construction of floodwater-retarding reservoirs) were compiled and analyzed by Smith and Welborn (1967). They found the sediment yield for this 17.6-square-mile watershed to average 2.8 acre-feet per square mile per year for the 4-year period. This watershed is in the Blackland Prairie land-resource area. Analyses of size distribution of the sediment indicated an initial specific weight of 35 pounds per cubic foot. Average annual rainfall for the period was about 20 percent greater than the 37-inch normal.

Floodwater-retarding structures were completed in the watershed as follows: Two structures controlling 1.51 square miles were completed in December 1962; three structures controlling 5.78 square miles were completed in April 1963; and one structure controlling 2.39 square miles was completed in November 1964. The total controlled drainage in the study area is 9.68 square miles, or 55 percent. Inflow, change-in-contents, or outflow was not gaged at any of these reservoirs. (See pl. 2.)

For this report, analyses were made of the suspended-sediment regimen before and after reservoir construction to define the sediment trapped in the reservoirs and the sediment pickup by the relatively clear outflow from the reservoirs. Monthly sediment- and water-discharge data collected through September 1967 were used. Unfortunately, the period after completion of the structures was generally dry; therefore, comparative data were not plentiful. During some of the months with runoff, the effects of upstream soil-disturbing construction activities biased the sediment-discharge data and made it unusable. Figure 5 is a plot of usable monthly water- and sediment-discharge data from the beginning of data collection through September 1967. Mean curves were graphically fitted to the data to represent the "before structures" relationship and the "maximum effect" relationship. If the water-sediment discharge relation is the same for runoff above and below the structures, a comparison of the equations for the two curves gives some measure of the trap efficiency of the structures and the sediment pickup by the relatively sediment-free outflow from the structures. The equations indicate a 92-percent decrease (difference in coefficients) in suspended sediment in runoff passing through the structures. On the basis of a trap efficiency of 97 percent for the structures, which is later shown to be a realistic value for this land-resource area, a 5-percent pickup in sediment by the outflow is indicated. The stream channel at the gaging station is known to be degrading.

For storms causing uniform runoff from the study area, if all inflow to structures is assumed to become outflow and to pass the gaging station, the theoretical maximum reduction in sediment load would be about 51 percent (92 percent of the 55-percent-controlled area).

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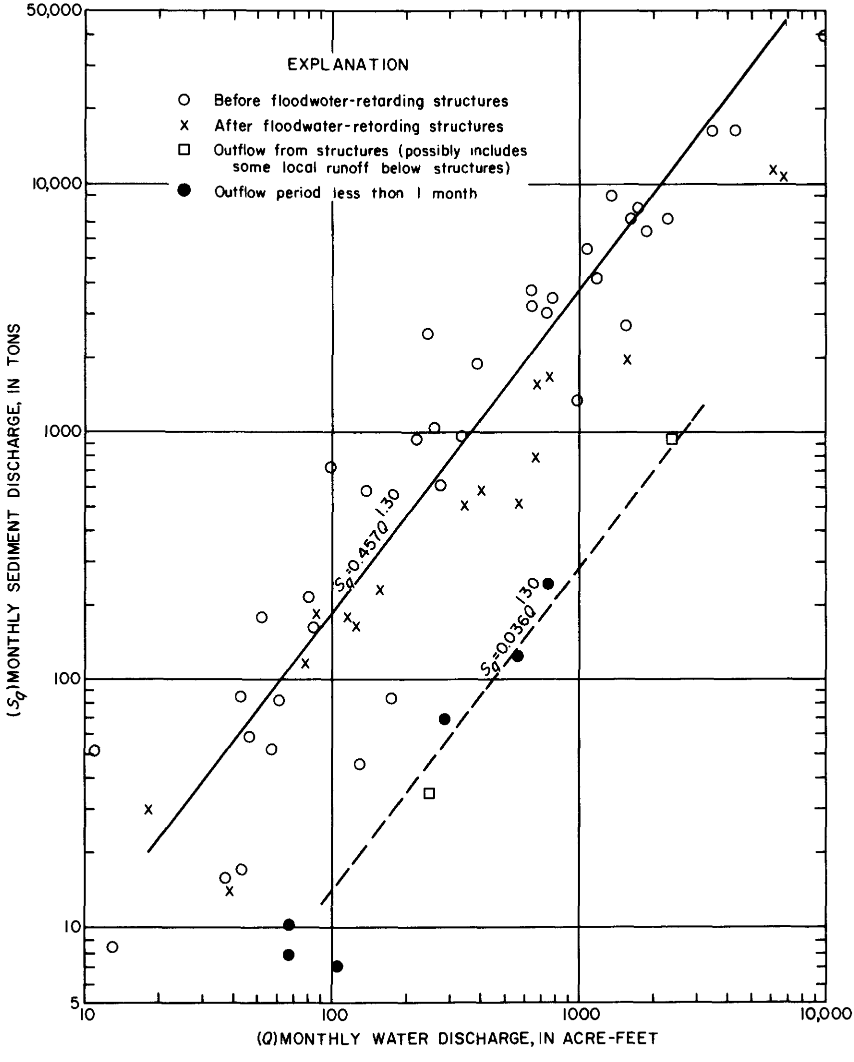


FIGURE 5.—Relationship of monthly water discharge to monthly sediment discharge, Pin Oak Creek near Hubbard, Tex., 1956–67.

### ELM FORK TRINITY RIVER STUDY AREA

Suspended-sediment discharge data collected in the Elm Fork Trinity River study area during the period October 1956 to September 1960 were compiled and analyzed by Gilbert, Myers, Leggat, and Welborn (1962). The initial specific weight of a deposit resulting from suspended sediment passing this station was found to be 52 pounds per cubic foot. About 30 percent of the study area is in the Grand Prairie land-resource area, and the remainder is in the West Cross Timbers land-resource area.

Because 30 to 33.5 square miles of the 46-square-mile study area (see pl. 2) was controlled by floodwater-retarding reservoirs throughout the period October 1956 to September 1967 for which sediment data were available, analyses to define changes in sediment regimen because of the structures could not be made without the assumption that the water-sediment discharge relation for the drainage below the structures is applicable to the entire study area. Most of the sediment discharge from this study area probably originates upstream from the floodwater-retarding structures; therefore, the undeveloped condition of sediment discharge cannot be determined from the data collected.

For the sediment and water discharge which passes through the structures and is gaged at the downstream stream-gaging station, the curve of relation was found to have the equation $S_q=0.00331Q^{1.39}$, where $S_q$ is monthly sediment discharge, in tons, and $Q$ is monthly water discharge, in acre-feet. The average annual outflow for the period October 1956 to September 1966 was 314 acre-feet per square mile controlled by structures. The curve for the conditions, if only outflow from the structures is considered, is well defined. The extremely low sediment discharge attainable from the above equation with known outflow supports the conjecture that only a very small amount of sediment runoff above the structures passes them and that sediment pickup by the outflow is insignificant. Observations of the channel at the stream-gaging station indicated only minor degradation.

### LITTLE ELM CREEK STUDY AREA

Data collection by the U.S. Geological Survey (depth-integrated sampling) for suspended sediment began February 1966 in the Little Elm Creek study area. (See pl. 2.) The Texas Water Development Board has collected daily suspended-sediment samples approximately 1 foot below the water surface near the center of the channel since July 1964 at the gaging station, Little Elm Creek near Aubrey, Tex. (downstream gaging station). The percentage of sediment by weight of sample was multiplied by 1.102 to obtain the suspended sediment for the observed water discharge. Sediment loads computed from

Texas Water Development Board data were available only for the period prior to September 1964.

Because of lack of data, monthly water- and sediment-discharge relationships could not be well defined for this study area for the before and after conditions of development. However, since simultaneous suspended-sediment data were collected at two gaging stations on Little Elm Creek beginning in February 1966, sediment pickup in the channel between stations by outflow from structures could be defined. During periods when streamflow was entirely outflow from the eight upstream floodwater-retarding reservoirs, concurrent daily streamflow and suspended-sediment concentration was plotted for each of the two gaging stations. These plots are shown in figure 6. From the least-squares fitted curves of relation, a sediment pickup is indicated in the 9 miles of river channel between the two stations. At 100 cubic feet per second daily discharge, a pickup of 96 percent in daily concentration, or 63 tons per day, is indicated, whereas at 1.0 cubic foot per second daily discharge, a sediment pickup of 39 percent, or 0.5 ton per day, is indicated. Channel degradation has been observed at each of the gaging stations since the floodwater-retarding structures were built.

## SEDIMENT DEPOSITION IN FLOODWATER-RETARDING RESERVOIRS

The U.S. Soil Conservation Service has made several sedimentation surveys of floodwater-retarding reservoirs in the developed study areas of the State project. The results of these surveys are summarized in table 8. Because of the wide variation in effectiveness of land-management practices, the unit sediment yield shown in the table can be misleading. For example, in the Escondido Creek study area, site 1 drainage had an average annual sediment yield of 3.43 acre-feet per square mile, whereas site 11, with more storm runoff, had an annual sediment yield of only 0.73 acre-foot per square mile. Because the site 1 drainage is about 75 percent cultivated and the site 11 drainage is only about 10 percent cultivated, the respective sediment yields appear consistent. However, in the Honey Creek study area, the drainage for site 11 is about 20 percent cultivated, whereas the site 12 drainage is about 80 percent cultivated; yet, the sediment yields in the watershed are only about 10 percent different.

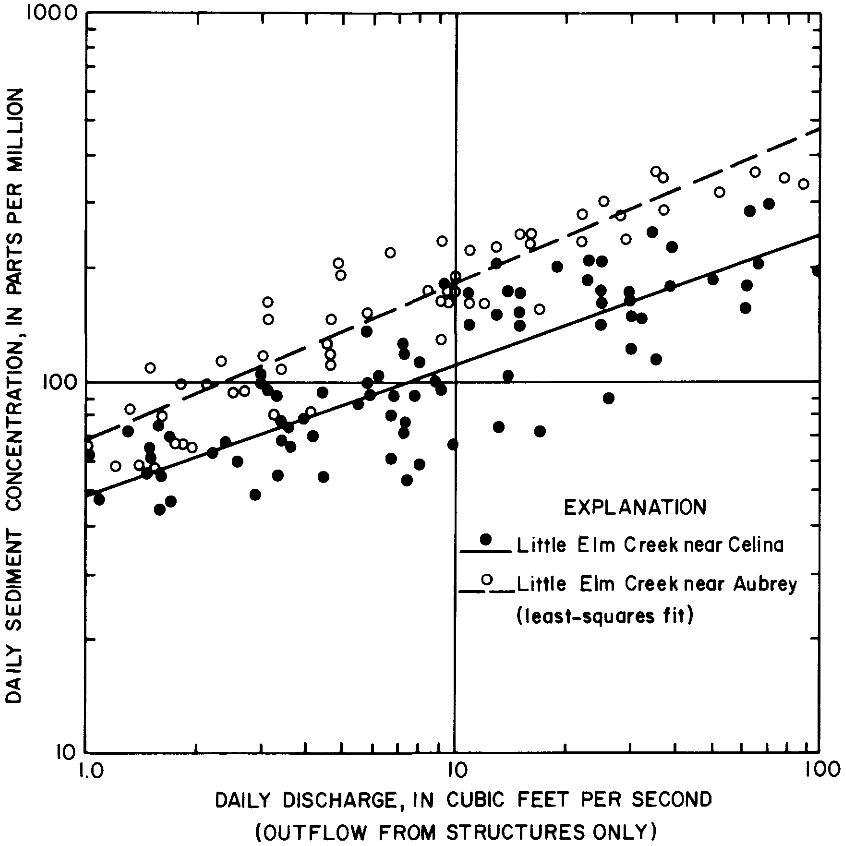


FIGURE 6.—Concurrent daily discharge and suspended-sediment concentration at two gaging stations, Little Elm Creek study area.

Owing to the drop-inlet type of outlet (orifice or pipe flow) at floodwater-retarding reservoirs, the sediment trap efficiency should remain high for all inflow to the detention pools even after the permanent pools are filled with sediment. Therefore, the structures should effect a considerable reduction in downstream sediment discharge as long as the dam remains in place.

TABLE 8.—*Summary of sedimentation surveys of floodwater-retarding reservoirs in Texas small-watersheds project*

| Study area | Reservoir surveyed | | Date of survey | Date storage began | Sediment deposition | | | Initial permanent pool capacity (acre-ft) | Trap efficiency (percent) | Annual sediment yield (acre-ft per sq mi) | Land-resource area |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Site | Net land-area drainage (sq mi) | | | Permanent pool (acre-ft) | Detention pool (acre-ft) | Total | | | | |
| Elm Fork Trinity River | 6–O | 0.76 | July 1964 | August 1956 | 8.9 | 2.4 | 11.3 | 84.0 | 98 | 1.92 | West Cross Timbers and Grand Prairie. |
| Honey Creek | 11 | 2.08 | July 1967 | February 1952 | 66.9 | 37.4 | 104.3 | 501.4 | 95 | 3.40 | Blackland Prairie. |
| Do | 12 | 1.24 | April 1964 | January 1952 | 37.8 | 17.8 | 55.6 | 141.5 | 97 | 3.80 | Do. |
| Green Creek | 1 | 3.11 | June 1967 | April 1955 | 19.0 | 13.0 | 32.0 | 239.0 | 98 | 0.86 | West Cross Timbers. |
| Cow Bayou | 4 | 5.20 | June 1963 | July 1956 | 80.6 | 17.8 | 98.4 | 223.0 | 97 | 2.76 | Blackland Prairie. |
| Deep Creek | 8 | [1] 4.03 | September 1966 | December 1951 | 30.3 | 11.7 | 42.0 | 214.6 | 98 | 0.72 | Palo Pinto. |
| Escondido Creek | 1 | 3.24 | May 1959 | September 1954 | 35.3 | 17.0 | 52.3 | 196.0 | 98 | 3.43 | Rio Grande Plain. |
| Do | 11 | 8.39 | September 1965 | July 1960 | 20.8 | 10.2 | 31.0 | 156.7 | 98 | 0.73 | Do. |

[1] Deep Creek does not include 1.38 sq mi above diversion dam.

## ANALYSIS OF FLOODWATER-RETARDING RESERVOIR CONSUMPTION

As stated previously, data were collected in the seven developed study areas to determine the monthly water budget, and also reservoir consumption, at individual reservoir sites by standardized techniques. Results for various time intervals in several of the study areas were reported in progress reports by the U.S. Geological Survey—Gilbert, Commons, Koberg, and Kennon (1964), Gilbert, Myers, Leggat, and Welborn (1962), Mills, McGill, and Flugrath (1965), Kennon, Smith, and Welborn (1967), and Mills (1969). Some of the data and analyses included in this report regarding on-site consumptive losses in the seven developed study areas were presented in whole or in part by Sauer and Masch (1969).

It became apparent soon after data collection began that reservoir consumption was considerably larger than could be attributed to evaporation from the free water surface. For example, Kennon, Smith, and Welborn (1967) reported that evaporation in the Escondido Creek study area accounted for 51 percent of consumption during water years 1955–63. Gilbert, Myers, Leggat, and Welborn (1962) reported that evaporation accounted for 49 percent of consumption in the Elm Fork Trinity River study area during water years 1957–60.

For this report, monthly reservoir consumption and other hydrologic variables were computed for each study area on a composite basis—that is, total consumption, inflow, and outflow were computed for each reservoir in the study area and summed to yield a value used in all analyses. By this procedure, variations at individual sites were averaged over the study area. In the following sections, values given for hydrologic variables in each study area represent the average value for all reservoirs in the study area.

For each study area, values for the following hydrologic variables were computed on a monthly basis in terms of equivalent depth on the controlled drainage area:

Consumption, $C$;
Rainfall on pool, $R$;
Outflow, $O$; and
Net inflow, $I$.

A summary of the results is given in table 9. Results for the Escondido Creek and Calaveras Creek study areas in water years 1956–57 are not included because initial filling losses in some of the reservoirs were abnormally high and, hence, not representative of the general condition. The algebraic difference of the four items for each study

TABLE 9.—*Annual water-budget terms*

[Symbols: *C*, pool consumption; *R*, rainfall on pools; *O*, outflow from pools; *I*, net

| Water year | Calaveras Creek | | | | Cow Bayou | | | | Deep Creek | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *C* | *R* | *O* | *I* | *C* | *R* | *O* | *I* | *C* | *R* | *O* | *I* |
| 1953 | | | | | | | | | | | | |
| 1954 | | | | | | | | | | | | |
| 1955 | | | | | | | | | 0.88 | 0.33 | 6.38 | 7.50 |
| 1956 | | | | | | | | | .83 | .08 | .23 | .73 |
| 1957 | | | | | | | | | .79 | .29 | 5.62 | 6.17 |
| 1958 | 1.61 | 0.58 | [1] 6.50 | 5.68 | | | | | .80 | .34 | 2.48 | 2.88 |
| 1959 | .87 | .27 | .24 | .64 | 0.91 | 0.31 | 1.65 | 2.48 | .71 | .17 | .77 | 1.31 |
| 1960 | .82 | .21 | .29 | .87 | 1.13 | .44 | 8.83 | 9.25 | .80 | .26 | 1.15 | 1.60 |
| 1961 | 1.19 | .37 | 1.52 | 2.63 | 1.25 | .62 | 14.28 | 15.19 | .74 | .28 | .94 | 1.35 |
| 1962 | 1.10 | .22 | .30 | .88 | 1.22 | .28 | 1.59 | 2.28 | .55 | .09 | .01 | .37 |
| 1963 | .48 | .07 | .03 | .30 | .67 | .12 | .04 | .26 | .73 | .13 | .38 | 1.17 |
| 1964 | 1.28 | .26 | .90 | 2.08 | .80 | .25 | 1.04 | 1.78 | .92 | .27 | 2.08 | 3.08 |
| 1965 | 1.35 | .35 | 1.57 | 2.65 | 1.12 | .44 | 9.73 | 10.69 | .87 | .21 | .98 | 1.21 |
| 1966 | 1.02 | .33 | .23 | .91 | 1.23 | .58 | 10.33 | 11.23 | .63 | .13 | .12 | .88 |
| 1953–66 total | 9.72 | 2.66 | [1] 11.58 | 16.64 | 8.33 | 3.04 | 47.49 | 53.16 | 9.25 | 2.58 | 21.14 | 28.25 |
| Average | 1.08 | .30 | 1.29 | 1.85 | 1.04 | .38 | 5.94 | 6.64 | .77 | .22 | 1.76 | 2.35 |
| 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 |
| Average | 1.01 | .26 | .64 | 1.37 | 1.04 | .38 | 5.94 | 6.64 | .74 | .19 | .80 | 1.37 |

[1] Includes 1.59 carryover from 1957 water year.

area is equal to the change in storage in the reservoirs in the study area during the water year—that is,

$$R+I-O-C=\pm\Delta S.$$

Values given are for controlled drainage areas prevailing at the time (see table 2) and are not adjusted for carryover inflow or outflow unless so indicated.

Because it is more easily extrapolated to ungaged areas, an equivalent depth value of reservoir consumption was also computed. This equivalent consumption, $C_e$, was determined by the equation:

$$\text{Consumption (equivalent depth)}=\frac{\text{volume consumed}}{\text{monthly mean water surface area}}.$$

Equivalent consumption is also more useful when a direct comparison is made with lake evaporation, because both reflect lake-level recession.

As expected, equivalent consumption was found to respond to seasonal climatic variations. Results also showed that factors other than climate were involved in the cause and effect relation for pool consumption. A more detailed analysis of the relation between consumption and other factors is given in a later section of this report which deals with the development of the mathematical model for consumption.

Table 10 is a summary of values of annual equivalent consumption found in the seven study areas. Annual equivalent consumption is the sum of the monthly values. Table 10 shows that there are no significant differences between averages for the period of record and the average *for reservoirs in seven study areas*

inflow to pools; all units expressed as equivalent inches distributed over controlled area]

| 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* |
| | | | | | | | | | | | | 1.33 | 0.51 | 1.03 | 2.51 |
| | | | | | | | | | | | | 1.86 | .71 | .72 | 2.63 |
| | | | | | | | | | | | | 1.85 | .58 | 1.37 | 2.76 |
| | | | | | | | | | | | | 1.38 | .19 | .28 | 1.14 |
| 0.97 | 0.53 | 11.90 | 12.96 | | | | | 0.85 | 0.31 | 3.76 | 4.49 | 1.71 | 1.77 | 23.76 | 24.74 |
| 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 |
| .62 | .16 | .02 | .35 | 1.10 | .38 | .63 | .98 | .60 | .18 | .12 | .47 | 1.47 | .45 | .05 | 1.18 |
| 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 |
| 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 |
| 1.16 | .40 | 7.06 | 7.98 | .92 | .19 | .11 | .68 | .94 | .28 | .63 | 1.51 | 1.57 | .82 | 7.99 | 8.92 |
| 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 |
| .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 |
| 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 |
| 1.17 | .36 | 8.10 | 8.86 | 1.10 | .36 | .09 | .74 | .78 | .26 | .36 | 1.14 | 1.56 | .92 | 10.29 | 11.21 |
| 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 |
| 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 |
| 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 |
| 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 |

for the 8-year period 1959–66. The period 1959–66 was chosen as a correlative period primarily because records were available in all seven study areas. Additionally, all structures were in place at the beginning of the 1959 water year, except two in the Calaveras Creek study area which were placed in operation during the 1959 water year.

Average monthly values of equivalent consumption during the base period 1959–66 are given in table 11. These values are shown graphically in figure 7. For reservoir-operation studies where monthly values are necessary but where funds do not permit computations based on

TABLE 10.—*Annual equivalent reservoir consumption, in feet, in seven study areas*

[Equivalent reservoir consumption is volume of consumption divided by average surface area]

| Water year | Calaveras Creek | Cow Bayou | Deep Creek | Elm Fork Trinity River | Escondido Creek | Green Creek | Honey Creek |
|---|---|---|---|---|---|---|---|
| 1953 | | | | | | | 6.86 |
| 1954 | | | | | | | 7.42 |
| 1955 | | | 7.58 | | | | 7.54 |
| 1956 | | | 8.39 | | | | 8.83 |
| 1957 | | | 7.35 | 8.94 | | 8.60 | 7.16 |
| 1958 | 9.49 | | 6.89 | 9.77 | 8.95 | 7.46 | 6.68 |
| 1959 | 8.55 | 8.10 | 7.20 | 9.26 | 7.58 | 7.17 | 7.48 |
| 1960 | 9.63 | 8.55 | 7.23 | 9.79 | 7.47 | 7.41 | 6.72 |
| 1961 | 9.11 | 8.36 | 6.87 | 9.38 | 8.37 | 7.26 | 6.59 |
| 1962 | 9.51 | 8.89 | 7.88 | 9.68 | 8.72 | 7.74 | 6.50 |
| 1963 | 9.65 | 9.07 | 9.03 | 9.89 | 8.70 | 8.44 | 6.97 |
| 1964 | 11.68 | 9.97 | 8.97 | 9.43 | 9.14 | 8.84 | 7.59 |
| 1965 | 10.43 | 8.03 | 7.71 | 9.60 | 8.50 | 7.82 | 6.35 |
| 1966 | 8.83 | 8.02 | 7.96 | 9.22 | 7.35 | 7.07 | 6.41 |
| Average, 1953–66 | 9.65 | 8.62 | 7.76 | 9.50 | 8.31 | 7.78 | 7.08 |
| Average, 1959–66 | 9.67 | 8.62 | 7.86 | 9.53 | 8.23 | 7.72 | 6.83 |

climatic data, the relationships shown in figure 7 are suggested for use in areas that have climate and soils similar to those in the study areas. This permits reasonable estimates of losses without the lengthy computations required for relating losses to climatic factors.

Table 12 is a comparison of annual consumption and gross lake evaporation, as published by the Texas Water Development Board (Kane, 1967). Losses ranged from 24 percent greater than evaporation in the Deep Creek study area to 102 percent greater than evaporation in the Elm Fork study area.

## MATHEMATICAL MODEL OF EQUIVALENT MONTHLY CONSUMPTION

The foregoing analyses show that consumptive losses from floodwater-retarding pools are considerably in excess of losses commonly associated with the surface storage of water. Once the underlying physical reasons for the losses are known, design procedures can be developed to minimize undesirable losses. Additionally, design agencies can

TABLE 11.—*Average monthly equivalent reservoir consumption, in feet, in seven study areas, 1959–66*

| Month of water year | Calaveras Creek | Cow Bayou | Deep Creek | Elm Fork Trinity River | Escondido Creek | Green Creek | Honey Creek | Average of 7 study areas |
|---|---|---|---|---|---|---|---|---|
| October | 0.77 | 0.70 | 0.60 | 0.82 | 0.71 | 0.63 | 0.56 | 0.68 |
| November | .67 | .54 | .44 | .50 | .62 | .45 | .42 | .52 |
| December | .61 | .40 | .34 | .30 | .52 | .35 | .33 | .41 |
| January | .51 | .37 | .34 | .29 | .45 | .31 | .27 | .36 |
| February | .51 | .38 | .35 | .35 | .48 | .32 | .28 | .38 |
| March | .65 | .58 | .52 | .59 | .56 | .48 | .44 | .55 |
| April | .70 | .70 | .63 | .88 | .66 | .60 | .51 | .67 |
| May | .90 | .90 | .82 | 1.04 | .76 | .76 | .64 | .83 |
| June | 1.05 | .97 | .90 | 1.18 | .87 | .88 | .77 | .95 |
| July | 1.20 | 1.12 | 1.04 | 1.32 | .93 | 1.07 | .94 | 1.09 |
| August | 1.12 | 1.06 | 1.04 | 1.26 | .89 | 1.07 | .92 | 1.05 |
| September | .98 | .90 | .84 | 1.00 | .78 | .80 | .75 | .87 |
| Annual | 9.67 | 8.62 | 7.86 | 9.53 | 8.23 | 7.72 | 6.83 | 8.36 |
| Ratio to average for all sites | 1.16 | 1.03 | .94 | 1.14 | .98 | .92 | .82 | ---------- |

TABLE 12.—*Comparison of equivalent annual reservoir consumption and gross lake evaporation in seven study areas, 1959–65*

| Study area | Calaveras Creek | Cow Bayou | Deep Creek | Elm Fork Trinity River | Escondido Creek | Green Creek | Honey Creek |
|---|---|---|---|---|---|---|---|
| Quadrangle [1] | H-9 | F-10 | F-8 | D-10 | I-10 | E-9 | D-11 |
| Average annual consumption inches | 117 | 104 | 94 | 115 | 100 | 94 | 82 |
| Average annual evaporation [1] do | 60 | 63 | 76 | 57 | 62 | 72 | 60 |
| Ratio of equivalent consumption to gross lake evaporation | 1.95 | 1.65 | 1.24 | 2.02 | 1.61 | 1.31 | 1.37 |

[1] From Kane (1967).

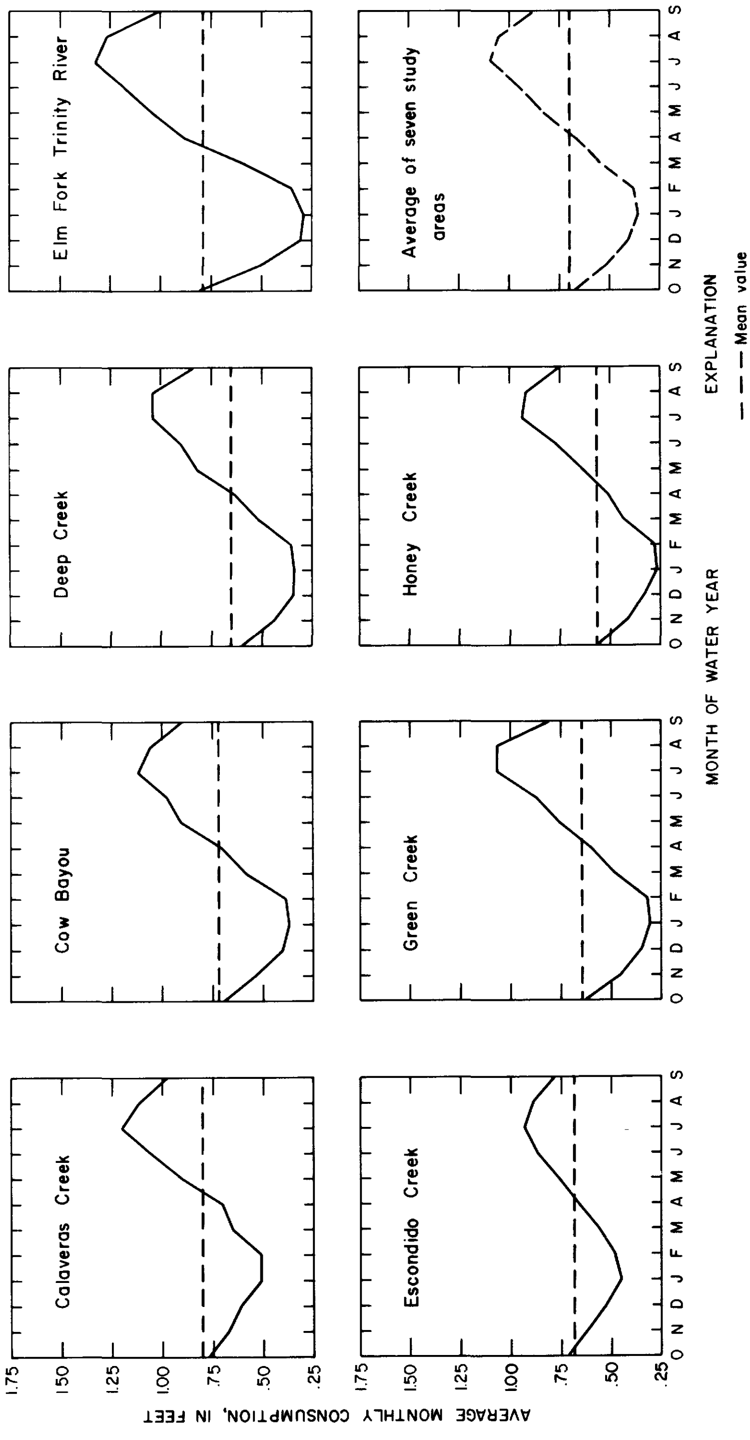


FIGURE 7.—Average monthly reservoir consumption in seven study areas, 1959–66.

make appropriate allowances for any existing or proposed upstream systems of floodwater-retarding reservoirs.

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 detention reservoir is zero over a period of time. For this study, inflow, rainfall on pools, outflow, and total consumption are known. Figure 8 is a conceptual model of the floodwater-retarding reservoir as conceived by the writers.

Evaporation from the free water surface, evaporation from soil adjacent to the pool, transpiration, and percolation to the ground-water reservoir are considered herein as depletions insofar as down-

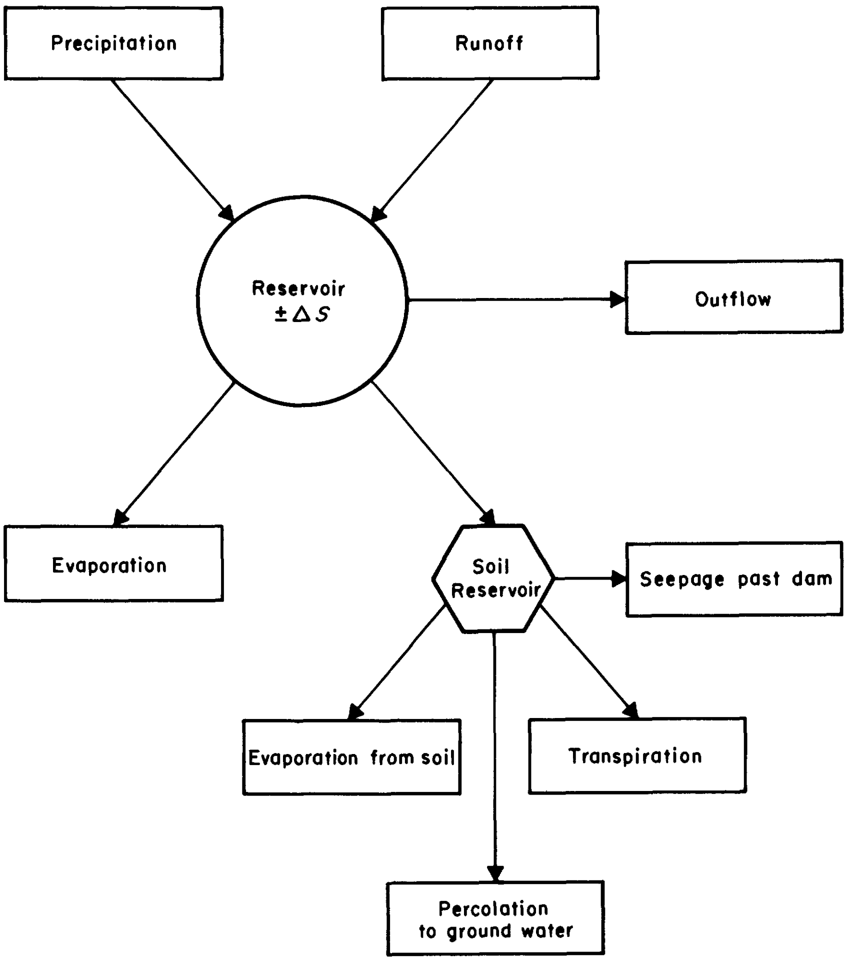


FIGURE 8.—Conceptual model of water budget for a floodwater-retarding reservoir.

stream water use is concerned. Significant quantities of seepage under and through the dam have not been measured in any channels of the study areas. Therefore, this quantity is assumed to be zero. Hence, the problem is to separate the four components of consumption on the basis of sound physical principles. In addition, to make the methodology of general use, it should incorporate parameters that are reasonably easy to obtain. A discussion of the four components of consumption is given in the following sections.

## COMPONENTS OF RESERVOIR CONSUMPTION

### EVAPORATION FROM FREE WATER SURFACE

Generally, the major cause of depletion of impounded water is evaporation from the free water surface. An excellent summary of the evaporation process is given in a report on water losses in Lake Hefner (U.S. Geol. Survey, 1954).

There are primarily four methods of estimating evaporation from lake surfaces. These four methods are discussed briefly in the following sections to indicate their utility in hydrologic model studies.

#### Pan-to-Lake Coefficients

Application of pan-to-lake coefficients is by far the most widely used method of estimating lake evaporation. It is simple to use, necessary data are generally available, and results are reasonably accurate on an annual basis. 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 were given by Kohler, Nordenson, and Baker (1959). Monthly values of pan-to-lake coefficients vary considerably depending on local climate and on-lake characteristics. The use of the customary 0.7 annual 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 and others, 1955), techniques are presented to adjust for advected energy and heat transfer.

#### Empirical Equations

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 reason most empirical evaporation equations are based on Dalton's law. A summary of selected evaporation equations based on

Dalton's law was given by Veihmeyer (1964). Generally, the most important factor in the equations, other than vapor-pressure differential, is wind movement. Many of the formulas agree well with data from which they are derived, but frequently they 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 method, Anderson (1954) computed evaporation from Lake Hefner.

From a physical point of view, the energy-budget method is apparently 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 was given by Marciano and Harbeck (1954).

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

$$E=Nu(e_s-e_a),$$

where

$E$=evaporation, in inches per day;

$N$=a mass-transfer coefficient, coefficient of proportionality;

$u$=wind speed, in miles per hour, at some height above water surface;

$e_s$=saturation vapor pressure, in millibars, corresponding to water-surface temperature; and

$e_a$=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 water surface, atmospheric stability, barometric pressure, and density and kinematic viscosity of air. Harbeck found that when the humidity of the air was measured at some distance from the lake and when wind movement was measured 2 meters above the lake surface, the mass-transfer coefficient could be related as

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

where $A$ is lake area, in acres.

The results of Harbeck's mass-transfer equation are 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 basic principles of Harbeck's mass-transfer equation are used in this report in multiple-linear-regression analyses for modeling the evaporation portion of reservoir consumption. For the range of individual reservoir surface area in the seven study areas, the equation would yield a maximum variation of mass-transfer coefficient of less than 20 percent.

### EVAPORATION FROM PERIPHERAL SOIL SURFACE

Evaporation from the soil surface peripheral to the pool is generally not considered 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 with the area of the free water surface.

For small reservoirs, this may be a significant factor because perimeter is exponentially related to pool area. Perimeters and surface areas at the sediment pool and emergency spillway elevations were measured for each reservoir, and these values were averaged in each of the seven study areas. The results are shown in figure 9.

A linear least-squares regression indicates the perimeter–surface area relation to be:

$$P=1{,}660A^{0.44} \tag{3}$$

where

$P$ = perimeter of pool, in feet, and
$A$ = surface area of pool, in acres.

The coefficient in this relationship will vary depending upon topography and the number of tributaries flowing directly into the pool, however, the exponent should be constant. In fact, theoretically, the exponent should be 0.5 for any shape of surface. However, because of the manner in which perimeter is used in the multiple-linear-regression analyses which follow, the use of 0.44 for the exponent tends to yield a more factual and (or) effective value for perimeter. Because of shore-

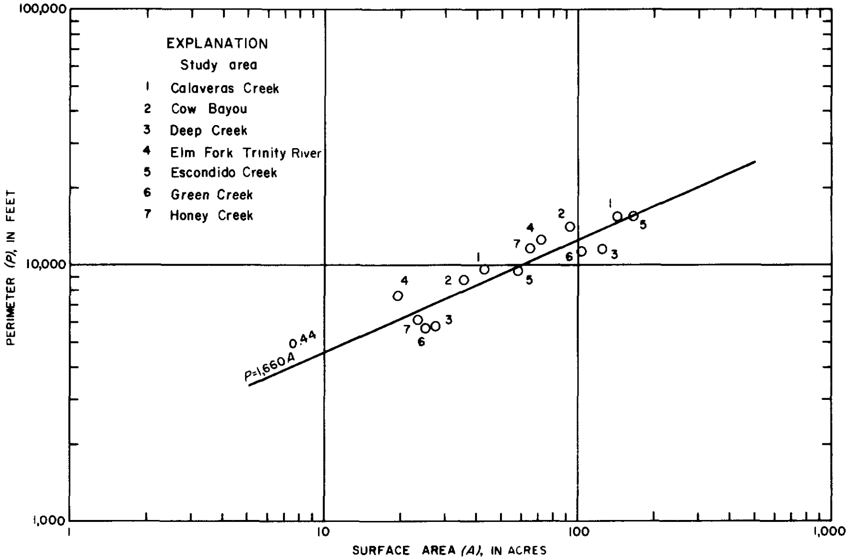


FIGURE 9.—Relationship of perimeter to surface area for floodwater-retarding reservoirs in seven study areas.

line configuration, there is some overlap in the peripheral area when computed from perimeter and a distance normal to the shoreline. Therefore, the use of 0.44 instead of 0.5 for the exponent should compensate for this overlap. The following relationships were used for the seven study areas:

| | |
|---|---|
| Calaveras Creek | $P=1{,}800A^{0.44}$ |
| Cow Bayou | $P=1{,}900A^{0.44}$ |
| Deep Creek | $P=1{,}400A^{0.44}$ |
| Elm Fork Trinity River | $P=2{,}000A^{0.44}$ |
| Escondido Creek | $P=1{,}640A^{0.44}$ |
| Green Creek | $P=1{,}450A^{0.44}$ |
| Honey Creek | $P=1{,}800A^{0.44}$ |

To illustrate the effect of pool size on relative peripheral area, assume that $P$ is equal to $1{,}660A^{0.44}$ and that the effective evaporating band of soil is 20 feet wide. For a pool area of 10 acres, the evaporating soil area is $\frac{20\times 1{,}660(10)^{0.44}}{43{,}560}$, which is equal to 2.1 acres, or 21 percent of the surface area. For a pool area of 1,000 acres, the evaporating soil area is $\frac{20\times 1{,}660(1{,}000)^{0.44}}{43{,}560}$, which is equal to 16.0 acres, or 1.6 percent of the surface area. This hypothetical example illustrates that evaporation from the contiguous soil surface can be a significant factor for small pools.

A pool of water generally creates a very shallow water table adjacent to the pool. Evaporation from a shallow water table has been well documented. For example, Hylckama (1966), reporting on investigations in southern Arizona, found significant amounts of evaporation from bare soils with a water table at a depth of 1.2 meters (3.9 ft). Fritschen and Bavel (1962) found a higher rate of evaporation from a wet soil surface than from a free water surface. They attributed this to more energy being used to heat air over shallow open water than was used to heat air over a wet soil surface. Research by Schleusener and Corey (1959) and King and Schleusener (1961) demonstrated conclusively that evaporation from the soil surface occurs at a rate almost equal to the rate of evaporation from a free water surface until a critical point is reached; after which, evaporation from the soil is very small. The critical point is determined by soil characteristics, rate of evaporation, and depth to water table.

### TRANSPIRATION BY RIPARIAN VEGETATION

Transpiration by vegetation can be significant in areas with a shallow water table. Unless preventive steps are taken, phreatophytes will flourish around pools formed by floodwater-retarding structures. An example of progressive growth around a floodwater-retarding reservoir is shown in figure 10. Of the 65 floodwater-retarding reservoirs studied, only a few experienced progressive vegetal encroachment similar to that shown in figure 10. Robinson (1952) found that generally the depth to the water table determines the amount of water used by phreatophytes.

Transpiration by phreatophytes depends primarily on air temperature, if the water table is shallow and will virtually cease during the dormant season. Various methods have been presented to estimate consumptive use of water by vegetation (McDaniels, 1960). 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 equation for Darcy's law for flow in porous media:

$$Q=-KA\frac{dh}{dl},$$

where

$Q$=rate of flow,

$A$=gross cross-sectional area, and

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

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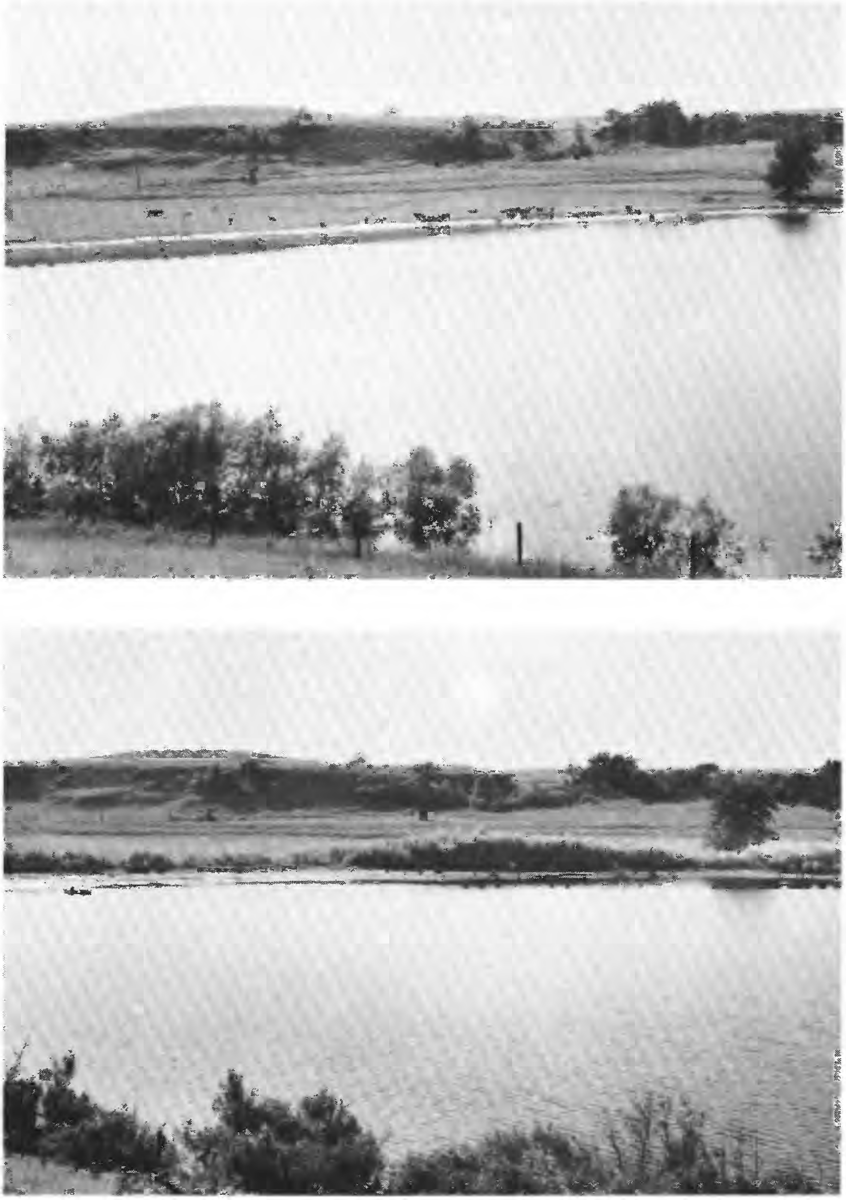


FIGURE 10.—Progressive growth of vegetation on right upstream shoreline at site 5, Elm Fork Trinity River study area. Upper: July 28, 1960. Lower: September 28, 1966. Storage in reservoir began May 1955.

A porous medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing kinematic viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow. Laboratory values of hydraulic conductivity for various materials on an order of magnitude basis (adapted from Todd, 1959) are shown below:

| *Soil Class* | *Range of* K (*ft per day*) |
|---|---|
| Clean gravel | $10^5$–$10^3$ |
| Clean sands; mixture of clean sands and gravels | $10^3$–$10^{-1}$ |
| Very fine sands; silts, mixtures of sand, silt, and clay, glacial till, stratified clays | $10^{-1}$–$10^{-4}$ |
| Unweathered clays | $10^{-4}$–$10^{-5}$ |

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.

## MULTIPLE-LINEAR-REGRESSION ANALYSIS

Measurements of all physical parameters necessary to define all segments of the four presumed components of consumption are not available, and it would not 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:

$$Y=a_o+\sum_{i=1}^{n}(a_iX_i)+E_i,$$

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, and
$E_i$ 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 composing consumption are somewhat interrelated, being to some degree dependent upon the same physical parameters. Although this is often true in hydrology, statistical techniques can still be very useful.

Two basic approaches may be taken in multiple-linear regression. In one approach, all variables 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 which are considered to be representative of the physical processes involved. The second approach was taken for this report.

### VARIABLES USED IN ANALYSIS

Data for each study area used for regression analysis included monthly values of the following: Consumption, average monthly water-surface area, mean depth of water in reservoirs, average air temperature, average relative humidity, and average wind speed. Average side slopes at the sediment-pool elevation were computed for each study area. A general relationship of difference in water-surface temperature and air temperature was developed on the basis of average values of observations taken during mass-transfer studies in the study areas. This relationship is shown in figure 11 and may be used to determine water-surface temperature. The relation indicates that water-surface 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.

Mean monthly air temperature, wind movement, and relative humidity were computed using appropriate first-order weather stations. Locations of weather stations used and study areas are shown in figure 12. Station names and weight factors used are shown in table 13. Interpolating polynomials for saturation vapor pressure and kinematic viscosity in terms of water temperature were developed using finite differences as outlined by Kunz (1957).

Using these data and relationships, the following variables were developed:

$C$= monthly consumption, in acre-feet;
$A$= monthly average water-surface area, in acres;
$\overline{D}$= monthly mean depth, in feet;
$u$= monthly average wind speed, in miles per hour;
$e_s$= saturation vapor pressure at surface temperature of water, in millibars;
$e_a$= actual vapor pressure at average monthly air temperature and relative humidity, in millibars;
$\Delta e = e_s - e_a$, vapor pressure deficit, in millibars;
$P$= perimeter of pools at average surface area, in feet;
$S$= average side slope, in feet per foot;

$\nu$= kinematic viscosity of water at average monthly water-surface temperature, in square feet per second $\times 10^5$;
$T_a$= average monthly air temperature, in degrees Fahrenheit; and
$T_w$= average monthly water-surface temperature, in degrees Fahrenheit.

By use of the above variables, equations which were thought to be representative of the physical processes in pool consumption were formulated and analyzed by multiple-linear regression. The equations

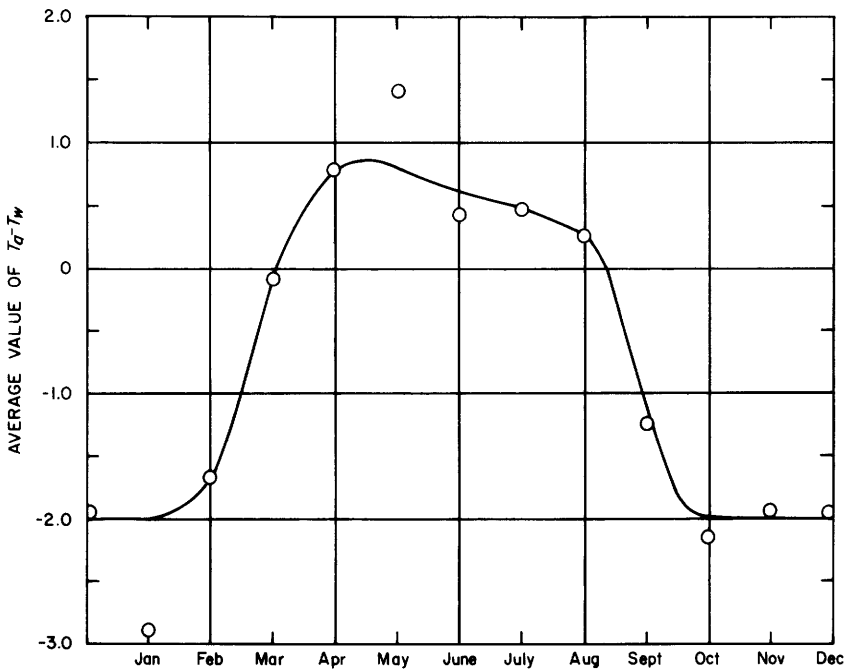



FIGURE 11.—Relation of water-surface temperature to air temperature for floodwater-retarding reservoirs in Texas. $T_a$, average monthly air temperature; $T_w$, average monthly water-surface temperature. All temperatures recorded in degrees Fahrenheit.

TABLE 13.—*Weather station and weight factor used for each study area*

| Study area | Dallas | San Angelo | San Antonio | Victoria | Waco | Wichita Falls |
|---|---|---|---|---|---|---|
| Calaveras Creek | 0 | 0 | 0.90 | 0.10 | 0 | 0 |
| Cow Bayou | 0 | 0 | 0 | 0 | 1.00 | 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 | 1.00 | 0 | 0 | 0 | 0 | 0 |

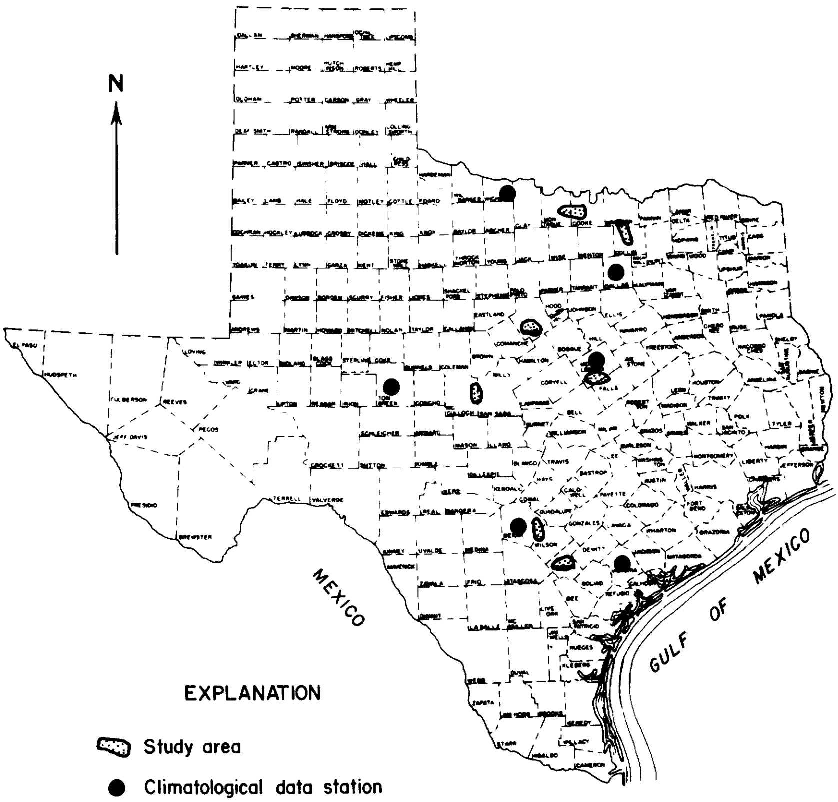



FIGURE 12.—Location of weather stations and study areas used in multiple-linear-regression analysis.

have three parts which were considered to be representative of consumption by evaporation, transpiration, and seepage. Basis for formulation is as follows:

1. Evaporation
   - a. Free water-surface evaporation was assumed to be a function of surface area, vapor-pressure deficit, and wind speed.
   - 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 are 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 values were computed for each month and assumed to be the independent variable representative of evaporation:

$$X_1=\Delta eu\left[A+K_1\left(\frac{P}{Sv}\right)\right],$$

or

$$X_1=\Delta eu\left[A+K_1\left(\frac{P}{S}\right)\right],$$

or

$$X_1=\Delta e\left[A+K_1\left(\frac{P}{Sv}\right)\right],$$

or

$$X_1=\Delta e\left[A+K_1\left(\frac{P}{S}\right)\right],$$

where $K_1$ = a constant to convert the term to acres. For computational purposes, the maximum depth at which significant amounts of evaporation from the soil contiguous to the pool was assumed to be 1 foot. For this case, $K_1$=ft/43,560, when only $P$ and $S$ are used.

2. Transpiration

Transpiration depends upon the amount of growth 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 size, a scale factor, *S.F.*, equal to the drainage area upstream from the structures was added. The two values used for the second independent variable were:

$$X_2=(T_a-40)S.F.$$

or

$$X_2=(T_a-32)S.F.$$

3. Seepage

Seepage away from reservoirs 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 value used for the third independent variable was:

$$X_3=\frac{(K_3\,\bar{D}P+A)}{\nu},$$

where $K_3$=1/43,560 to convert square feet to acres.

The basic regression equation for pool consumption is then of the form:

$$C=a_o+a_1X_1+a_2X_2+a_3X_3.$$

For the regression study, the base period, water years 1959–66, was used. Values of variables were computed for each watershed using hydrologic and climatic data and physical properties of the structures and were used for regression analysis. Various combinations of different $X_1$ and $X_2$ variables were used, making a total of 12 regression equations for each watershed. If this reasoning 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 because of consistency in mass-transfer coefficient for small areas;

$a_2$ should be a measure of growth around pools;

$a_3$ should vary among the watersheds depending upon soils and geology and should reflect the hydraulic properties of the underlying soils and (or) geologic formations.

### RESULTS OF REGRESSION ANALYSIS

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. 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).

As stated previously, 12 regression equations for different combinations of variables considered to be significant were used for each study area. These 12 regression equations are as follows:

1. $C=a_o+a_1u[e_o-e_a]\ [A+K_1(P/S\nu)]+a_2[T_a-40]\ [S.F.]+a_3[(K_3\overline{D}P+A)/\nu]$,
2. $C=a_o+a_1u[e_o-e_a]\ [A+K_1(P/S)]+a_2[T_a-40]\ [S.F.]+a_3[K_3\overline{D}P+A)/\nu]$,
3. $C=a_o+a_1[e_o-e_a]\ [A+K_1(P/S\nu)]+a_2[T_a-40]\ [S.F.]+a_3[(K_3\overline{D}P+A)/\nu]$,
4. $C=a_o+a_1[e_o-e_a]\ [A+K_1(P/S)]+a_2[T_a-40]\ [S.F.]+a_3[(K_3\overline{D}P+A)/\nu]$,
5. $C=a_o+a_1u[e_o-e_a]\ [A+K_1(P/S\nu)]+a_2[T_a-32]\ [S.F.]+a_3[(K_3\overline{D}P+A)/\nu]$,
6. $C=a_o+a_1u[e_o-e_a]\ [A+K_1(P/S)]+a_2[T_a-32]\ [S.F.]+a_3[(K_3\overline{D}P+A)/\nu]$,
7. $C=a_o+a_1[e_o-e_a]\ [A+K_1(P/S)]+a_2[T_a-32]\ [S.F.]+a_3[(K_3\overline{D}P+A)/\nu]$,
8. $C=a_o+a_1[e_o-e_a]\ [A+K_1(P/S\nu)]+a_2[T_a-32]\ [S.F.]+a_3[(K_3\overline{D}P+A)/\nu]$,
9. $C=a_o+a_1u[e_o-e_a]\ [A+K_1(P/S)]+a_3[(K_3\overline{D}P+A)/\nu]$,
10. $C=a_o+a_1u[e_o-e_a]\ [A+K_1(P/S\nu)]+a_3[(K_3\overline{D}P+A)/\nu]$,
11. $C=a_o+a_1[e_o-e_a]\ [A+K_1(P/S\nu)]+a_3[(K_3\overline{D}P+A)/\nu]$,
12. $C=a_o+a_1[e_o-e_a]\ [A+K_1(P/S)]+a_3[(K_3\overline{D}P+A)/\nu]$.

A summary of the results of the regression analysis is given in table 14 and is illustrated in figure 13.

TABLE 14.—*Statistical results of regression analysis of reservoir consumption*

[$r$=multiple correlation coefficient; $S_e$=standard error of estimate, in percent]

| Regression equation number | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ |
| *Study area* | | | | | | | | | | | | |
| Calaveras Creek | 0.925 | 16.5 | 0.924 | 16.6 | 0.935 | 15.4 | 0.935 | 15.4 | 0.925 | 16.5 | 0.924 | 16.6 |
| Cow Bayou | .984 | 8.6 | .984 | 8.6 | .981 | 9.2 | .981 | 9.2 | .984 | 8.6 | .984 | 8.6 |
| Deep Creek | .942 | 16.3 | .941 | 16.5 | .958 | 14.0 | .958 | 14.0 | .942 | 16.3 | .941 | 16.5 |
| Elm Fork Trinity River | .983 | 9.5 | .983 | 9.4 | .981 | 9.9 | .981 | 9.9 | .983 | 9.5 | .983 | 9.4 |
| Escondido Creek | .914 | 13.0 | .914 | 13.1 | .916 | 12.9 | .916 | 12.9 | .914 | 13.0 | .914 | 13.1 |
| Green Creek | .954 | 13.3 | .954 | 13.3 | .960 | 12.4 | .959 | 12.5 | .954 | 13.3 | .954 | 13.3 |
| Honey Creek | .957 | 12.9 | .956 | 13.0 | .966 | 11.5 | .966 | 11.5 | .956 | 13.0 | .956 | 13.0 |
| Average | .951 | 12.9 | .951 | 12.9 | .957 | 12.2 | .957 | 12.2 | .951 | 12.9 | .951 | 12.9 |

| Regression equation number | 7 | | 8 | | 9 | | 10 | | 11 | | 12 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ | $r$ | $S_e$ |
| *Study area* | | | | | | | | | | | | |
| Calaveras Creek | 0.935 | 15.4 | 0.935 | 15.4 | 0.924 | 16.6 | 0.925 | 16.5 | 0.934 | 15.4 | 0.934 | 15.4 |
| Cow Bayou | .981 | 9.2 | .981 | 9.2 | .976 | 10.2 | .977 | 10.1 | .974 | 10.6 | .974 | 10.6 |
| Deep Creek | .958 | 14.0 | .958 | 14.0 | .929 | 18.0 | .932 | 17.5 | .957 | 14.0 | .957 | 14.0 |
| Elm Fork Trinity River | .981 | 9.9 | .981 | 9.9 | .973 | 11.7 | .973 | 11.6 | .975 | 11.4 | .975 | 11.3 |
| Escondido Creek | .916 | 12.9 | .916 | 12.9 | .911 | 13.1 | .912 | 13.1 | .916 | 12.8 | .916 | 12.8 |
| Green Creek | .959 | 12.5 | .960 | 12.4 | .936 | 15.5 | .938 | 15.3 | .955 | 13.0 | .954 | 13.1 |
| Honey Creek | .966 | 11.5 | .966 | 11.5 | .931 | 16.0 | .933 | 16.0 | .958 | 12.7 | .957 | 12.8 |
| Average | .957 | 12.2 | .957 | 12.2 | .940 | 14.4 | .941 | 14.3 | .953 | 12.8 | .952 | 12.9 |

These results indicate that several different equations yield similar multiple-regression coefficients and standard errors of estimates. All 12 equations yielded reasonably good results. On an average basis, the inclusion of wind movement as a factor did not improve the estimate. This may be due to the fact that although wind movement 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. The use of $T_a$—40 and $T_a$—32 yielded the same results. From the above study, the equation selected as the best estimator of monthly consumption for the seven study areas was:

$$C=a_o+a_1[e_o-e_a][A+K_1(P/S)]+a_2[T_a-40][S.F.]+a_3[(K_3\bar{D}P+A)/\nu]. \quad (4)$$

A summary of statistical parameters for each of the seven study areas using equation 4 is given in table 15. The $t$ values for the regression coefficients were computed as the ratio of the regression coefficient to the standard deviation of the regression coefficient. Values of Student's $t$ distribution using 92 degrees of freedom for 99 percent and 95 percent confidence limits are $\pm 2.64$ and $\pm 1.99$, respectively. From table 15, the following are noted:

1. $a_1$ is significantly different from zero for all study areas except Escondido Creek for a 99-percent confidence interval. For Es-

condido 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 $a_0$ values significantly different from zero. Because the purpose of this study was to develop methodolgy which could be extrapolated to ungaged

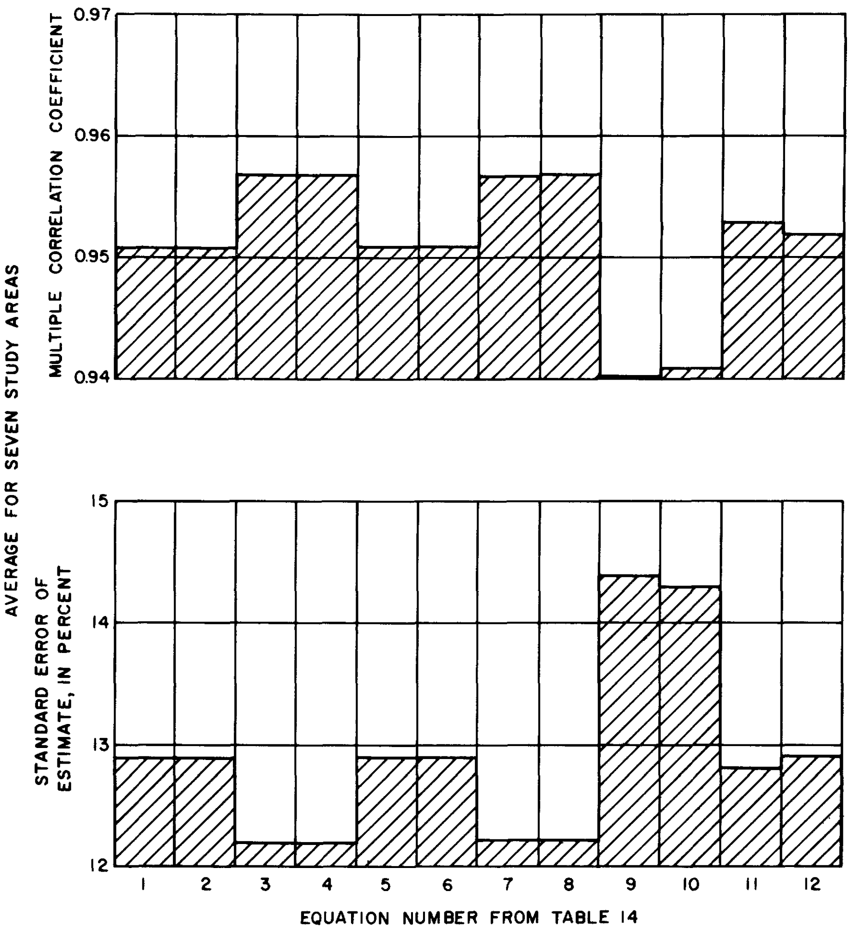



FIGURE 13.—Summary of regression analysis for reservoir consumption.

TABLE 15.—*Summary of statistical parameters for regression study, computed using best-fit equation in each of seven study areas*

| Study area | $a_o$ | $a_1$ | $t_1$ | $a_2$ | $t_2$ | $a_3$ | $t_3$ | $r$ | $S_e$ (percentage) |
|---|---|---|---|---|---|---|---|---|---|
| Calaveras Creek | 4.21 | 0.028 | 5.33 | −0.008 | −0.91 | 0.594 | 9.06 | 0.935 | 15.4 |
| Cow Bayou | −17.7 | .012 | 5.42 | .031 | 5.70 | .601 | 21.17 | .981 | 9.2 |
| Deep Creek | −2.7 | .023 | 8.39 | .007 | 1.10 | .384 | 7.18 | .958 | 14.0 |
| Elm Fork Trinity River | −56.7 | .016 | 5.36 | .034 | 5.46 | .868 | 17.36 | .981 | 9.9 |
| Escondido Creek | −23.7 | .008 | 1.69 | .002 | .23 | .714 | 12.15 | .916 | 12.9 |
| Green Creek | −11.6 | .017 | 5.71 | .023 | 3.29 | .500 | 11.15 | .960 | 12.4 |
| Honey Creek | 8.6 | .019 | 6.69 | .063 | 4.81 | .236 | 4.52 | .966 | 11.5 |

areas, the least-squares 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 (eq 4), another program was developed in which the intercept $a_o$ was fixed at zero, and the other three regression coefficients were varied in a stepwise manner to determine the least-squares estimator, when $a_o=0$. 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. Details of the computer program, along with a program documentation, were given by Sauer and Masch (1969).

A summary of the resulting equations which best fit the data is tabulated below:

Calaveras Creek:

$$C=0.026[e_o-e_a]\,[A+K_1(P/S)]+0.59[(K_3\overline{D}P+A)/\nu].$$

Cow Bayou:

$$C=0.026[e_o-e_a]\;[A+K_1(P/S)]+0.004[T_a-40]\;[S.F.]\\+0.47[(K_3\overline{D}P+A)/\nu].$$

Deep Creek:

$$C=0.026[e_o-e_a]\;[A+K_1(P/S)]+0.004[T_a-40]\;[S.F.]\\+0.34[(K_3\overline{D}P+A)/\nu].$$

Elm Fork Trinity River:

$$C=0.026[e_o-e_a]\ [A+K_1(P/S)]+0.020[T_a-40]\ [S.F.]\ +0.50[(K_3\overline{D}P+A)/\nu].$$

Escondido Creek:

$$C=0.026[e_o-e_a]\ [A+K_1(P/S)]+0.49[(K_3\overline{D}P+A)/\nu].$$

Green Creek:

$$C=0.026[e_o-e_a]\ [A+K_1(P/S)]+0.004[Ta-40]\ [S.F.]\ +0.40[(K_3\overline{D}P+A)/\nu].$$

Honey Creek:

$$C=0.026[e_o-e_a]\ [A+K_1(P/S)]+0.012[T_a-40]\ [S.F.]\ +0.32[(K_3\overline{D}P+A)/\nu].$$

In those equations having no $(T_a-40)$ $(S.F.)$ term, the best-fit regression coefficient ($a_2$) was zero. A comparison of the standard error of estimate computed using the derived equations and the least-squares regression-study equations is shown in figure 14. For two areas, the standard error of estimate was slightly improved, probably owing to rounding errors. 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 $a_o$, in the initial trial correlations.

In using multiple-regression equations, it is desirable to know how much improvement in the estimate results from the addition of each variable. A study was made using equation 4 and $a_o=0$ to determine the significance of each variable. In each case, the order of the variables in explaining the variance of consumption was $X_3$, $X_1$, $X_2$. The results of this study are tabulated below:

| Study area | Standard deviation of consumption, in percentage of mean | Standard error of estimate, in percentage of mean, computed using indicated variables | | |
|---|---|---|---|---|
| | | $X_3$ | $X_1, X_3$ | $X_1, X_2, X_3$ |
| Calaveras Creek | 42. 8 | 19. 6 | 15. 3 | 15. 3 |
| Cow Bayou | 46. 7 | 18. 6 | 11. 2 | 11. 1 |
| Deep Creek | 48. 0 | 26. 7 | 13. 9 | 13. 8 |
| Elm Fork Trinity River | 50. 2 | 26. 0 | 15. 5 | 14. 0 |
| Escondido Creek | 31. 5 | 13. 8 | 15. 1 | 15. 1 |
| Green Creek | 43. 6 | 23. 5 | 13. 1 | 13. 0 |
| Honey Creek | 43. 8 | 23. 5 | 12. 7 | 12. 3 |

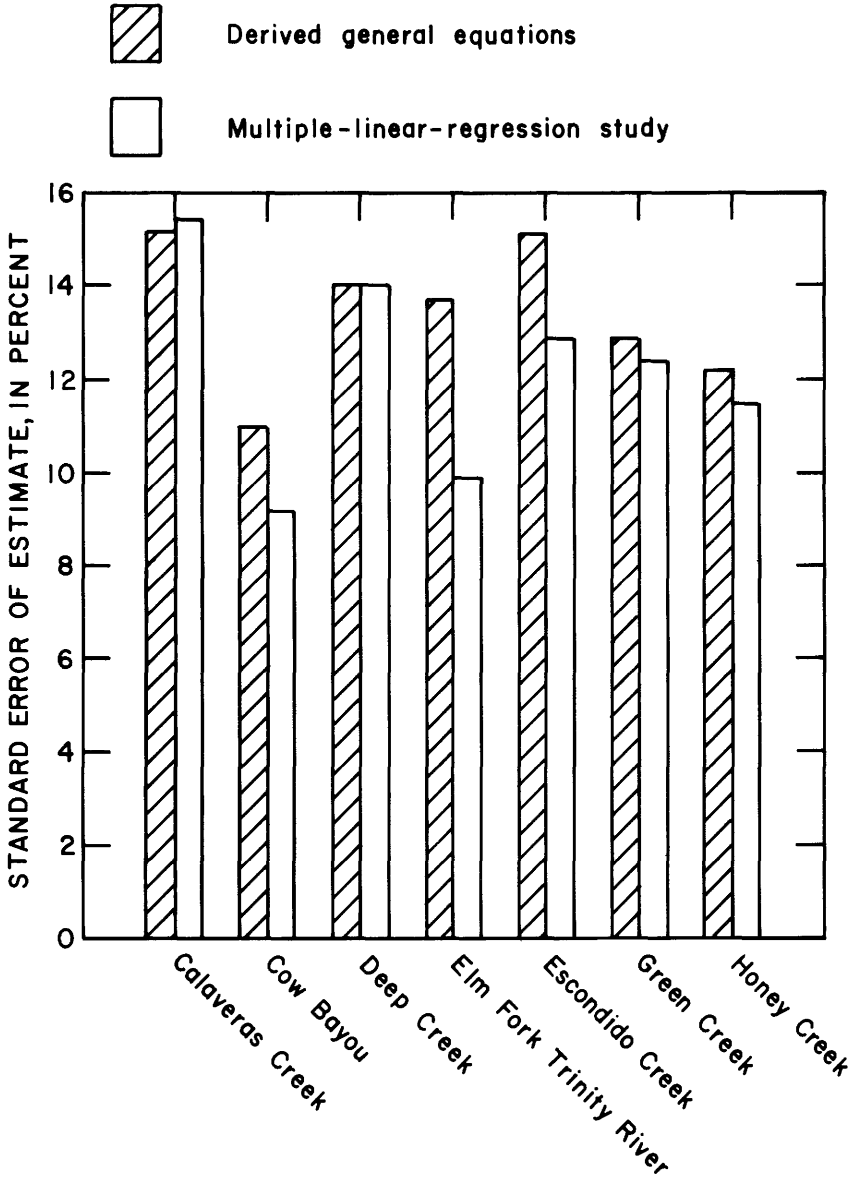



FIGURE 14.—Comparison of standard error of estimate of monthly consumption, best-fit multiple-linear-regression equations, and derived general equation, 1959–66.

## 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 (feet). 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 period covers the period of construction in several of the study areas. A summary of the results is shown in table 16 and in figure 15.

The results were better than those normally attainable in hydrology, which indicates that the equations developed could be used to predict useful monthly values of consumption on the basis of 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. Like most multiple-regression equations, the regression coefficients have no relative significance. The value of $a_1$ was fixed as the constant best fitting all the study areas, partly for convenience and partly by intuitive reasoning. Values used for $a_2$ can vary appreciably in percentage without seriously reducing the accuracy of estimation. Monthly consumption in the seven study areas was 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 16. Therefore, a reasonable value of $a_2$ for use in ungaged study areas would be 0.010.

TABLE 16.—*Comparison of observed consumption with consumption estimated using optimized equation 4 for seven study areas*

| Study area | Period | Number of years | Total consumption: Acre-feet: Estimated | Total consumption: Acre-feet: Observed | Total consumption: Equivalent feet: Estimated | Total consumption: Equivalent feet: Observed | Standard error of estimate of monthly values: Acre-feet | Standard error of estimate of monthly values: Percentage | Standard error of estimate of monthly values: Feet | Standard error of estimate of monthly values: Percentage |
|---|---|---|---|---|---|---|---|---|---|---|
| Calaveras Creek | 1958–66 | 9 | 17,970 | 18,020 | 87.35 | 86.88 | 24.4 | 14.6 | 0.119 | 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 |

Values of $a_3$ ranged from 0.315 to 0.589, depending on soil type and underlying geologic formations. The relation of $a_3$ to soil type is discussed in the next section.

## 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 found for $a_3$ in this investigation was approximately twofold. This range in values must be related to the relative permeability of the underlying soil and rock units. A description of soils found in the study areas is given in table 6.

Experience indicates that a fixed value of permeability cannot be related to any particular soil series; however, a range of values can be assigned. To extrapolate results of this investigation 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 was developed as follows:

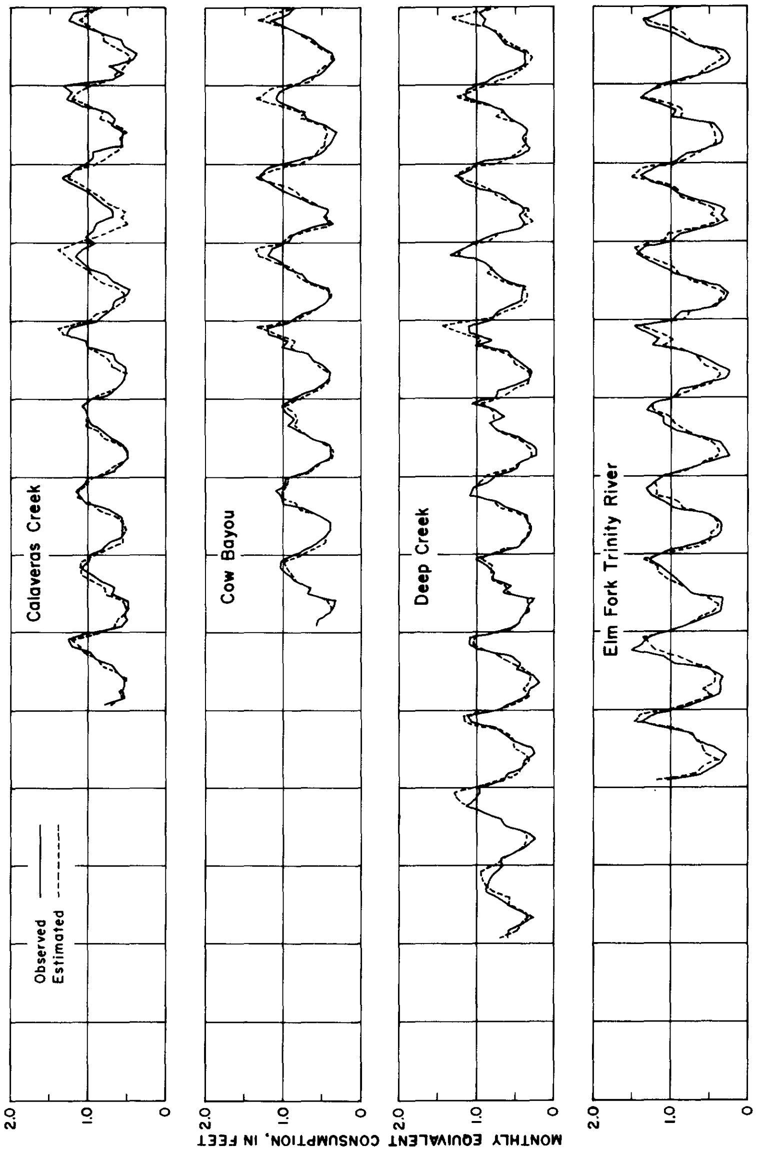
Let $B$, $C$, and $D$ each represent a range of values of the regression coefficient $a_3$ for the respective hydrologic soil group in each study area. Then the weighted average of $a_3$ for each study area (using the percentage of each hydrologic soil group shown in table 6) must equal the regression coefficient $a_3$ found in the analysis for each study area. On the basis of this assumption, the equation for each study area can be written as follows:

| *Study area* | *Equation* |
|---|---|
| Calaveras Creek | $0.43B+0.34C+0.23D=0.59$ |
| Cow Bayou | $0.30B+0.24C+0.46D=0.47$ |
| Deep Creek | $D=0.34$ |
| Elm Fork Trinity River | $0.65C+0.35D=0.50$ |
| Escondido Creek | $0.68B+0.32D=0.49$ |
| Green Creek | $0.13B+0.76C+0.11D=0.40$ |
| Honey Creek | $0.35B+0.65D=0.32$ |

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

$$B=0.49 \text{ to } 0.72$$
$$C=0.36 \text{ to } 0.56$$
$$D=0.23 \text{ to } 0.40$$

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 16.



Calaveras Creek
Cow Bayou
Deep Creek
Elm Fork Trinity River
Observed
Estimated
2.0
1.0
0
MONTHLY EQUIVALENT CONSUMPTION, IN FEET

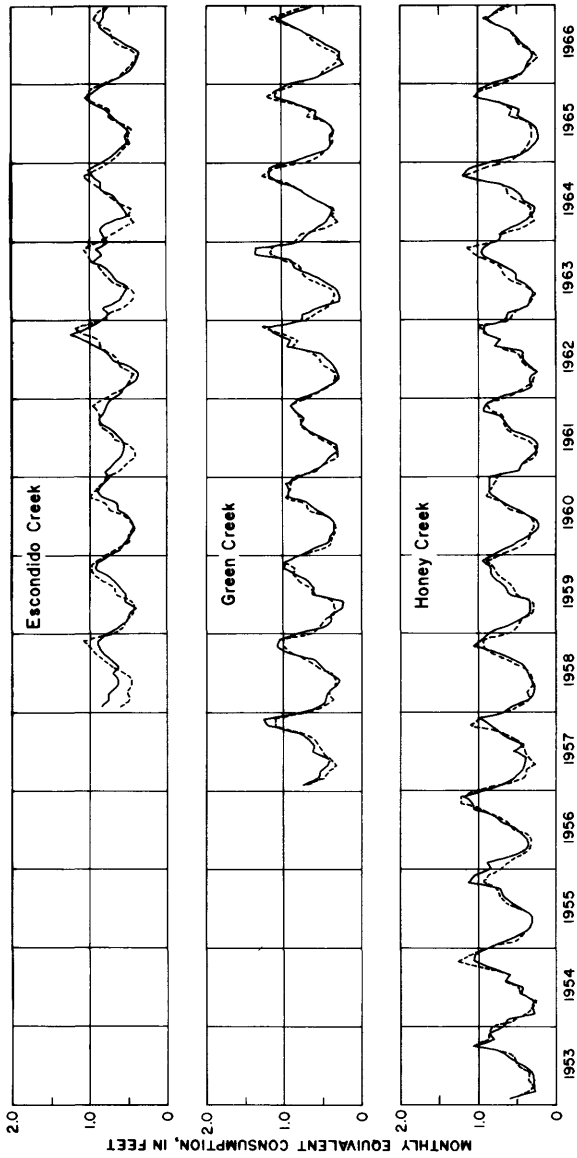



FIGURE 15.—Comparison of observed and estimated monthly equivalent consumption.

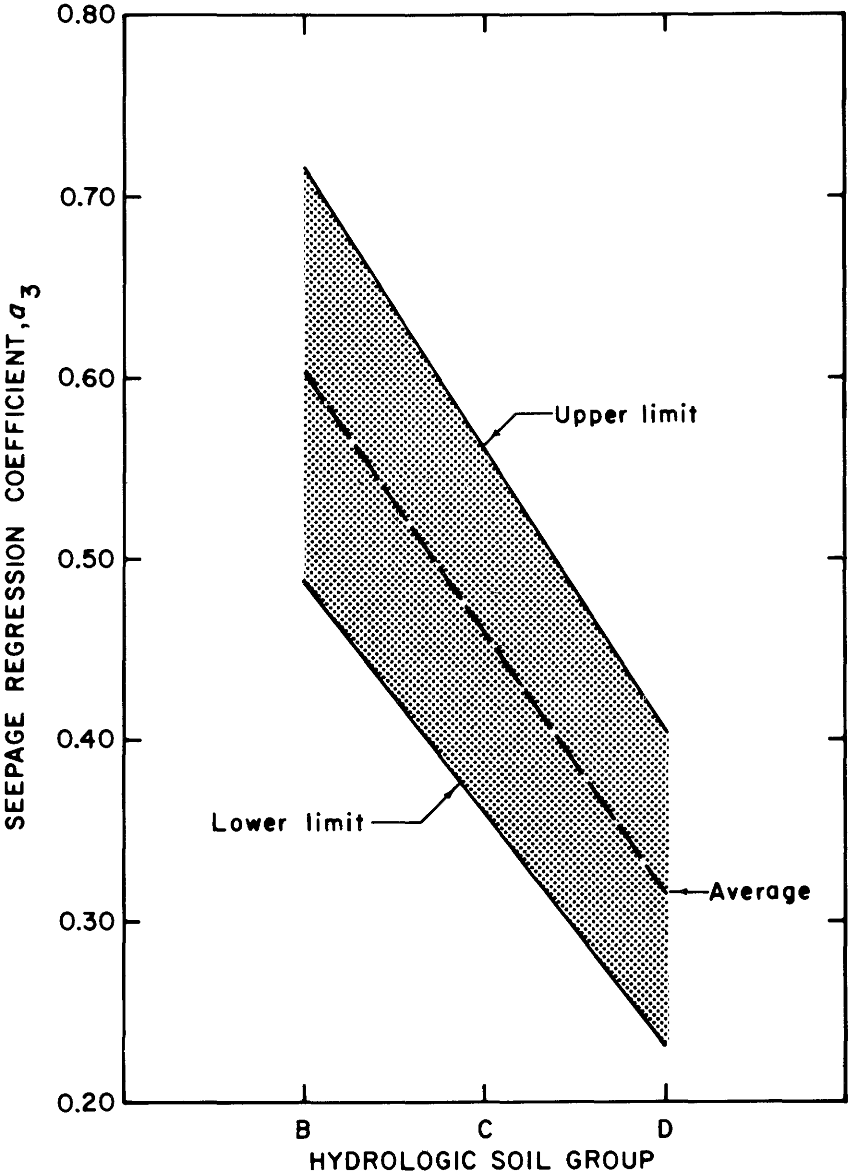



FIGURE 16.—Range of values of seepage regression coefficient $a_3$ with hydrologic soil group.

## SUMMARY OF MONTHLY CONSUMPTION MODEL

On the basis of the preceding analyses and results, the following procedure might 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:

$$\text{Consumption}=0.026[e_o-e_a][A+K_1(P/S)] +0.010[T_a-40][S.F.]+a_3[(A+K_3\overline{D}P)/v].$$

2. With all parameters computed as previously outlined, values of $a_3$ should be chosen on the basis of county soils maps and figure 16.
3. The value of $a_2$ may be adjusted upward or downward from 0.010, depending upon the the degree of vegetal cover in the study areas. Generally, areas with highest mean annual rainfall tend to have the largest values of $a_2$. The value of $a_2$ should increase with time owing to the increase in vegetal growth 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 16, consumption was estimated in the seven study areas. As a further check, 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 of these sites are 0.77, 2.14, and 4.02 square miles, respectively. For the location of the Mukewater Creek site, see plates 1 and 2. A summary of the results of this verification study is shown in table 17.

TABLE 17.—*Comparison of observed consumption with consumption estimated using single generalized form of equation 4, with* $a_1$ *and* $a_2$ *constant and* $a_3$ *from figure 16, in seven study areas and at individual reservoirs*

| Study area | Number of years | Water year | $a_3$ | Estimated consumption (acre-ft) | Observed consumption (acre-ft) | 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–O | 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 |

## APPLICATION OF RESULTS AND METHODOLOGY USING RESPONSE MODEL

The foregoing sections of this report have been devoted to presentation of data and analyses and to development of methodology for defining the maximum probable effects of systems of floodwater-retarding reservoirs on downstream water and sediment discharge. Without direct application and testing of the results of the analyses, the relative magnitude of the effects of structures on yield to a downstream water-supply reservoir is lacking. The procedure used in defining the effects of floodwater-retarding structures on watershed yield was to develop a computer program to mathematically model the response of a sample watershed to imposed physical conditions and historic hydrologic conditions. This program is designated as the response model.

The sample drainage basin selected for modeling is that for Garza-Little Elm Reservoir on the Elm Fork Trinity River. (See pl. 1.) This drainage basin was selected because planned floodwater-retarding structures will control about 25 percent of the drainage area (16 percent of drainage area is controlled by structures at this time) and because runoff records since 1928 are available.

The basic procedure to be followed in modeling the previously defined effects of floodwater-retarding structures is to (1) impose known monthly runoff for the period October 1927 to September 1966 on the model of the sample watershed and assume that all structures are in place at the beginning of the period; (2) apply mathematical model (computer programed) of monthly inflow (water and sediment), pool-consumption regression model, and outflow (water and sediment) to the system of floodwater-retarding reservoirs in the sample drainage basin; and (3) compute monthly water and sediment inflow to Garza–Little Elm Reservoir for conditions both before and after construction of upstream structures, the difference in results being the effect of the structures on the yield to Garza–Little Elm Reservoir.

### DESCRIPTION OF SAMPLE DRAINAGE BASIN

Garza-Little Elm Reservoir receives the drainage from 1,660 square miles via the Elm Fork Trinity River and its tributaries (fig. 17). It is in the southeastern part of Denton County about 22 miles northwest of Dallas, Tex. The reservoir was built to provide flood control, recreation, and water supply and to inundate the smaller, sediment-filled Lake Dallas (drainage area: 1,168 sq mi) 4 miles upstream. Deliberate impoundment started November 1, 1954, and Lake Dallas was completely inundated on October 28, 1957. The drainage basin ranges in elevation from about 1,100 feet above mean sea level in the northwest headwaters to about 450 feet above mean sea level at Lewisville Dam, which forms the reservoir. Major physical details regarding the dam and reservoir are given in the following table:

| Designation | Elevation (ft) | Surface area (acres) | Capacity (acre-ft) |
|---|---|---|---|
| Top flood-control pool (spillway crest) | 532.0 | 39,080 | 989,700 |
| Top conservation pool | 515.0 | 23,250 | 464,500 |
| Lowest sluice gate | 448.0 | 12 | 33 |

Topography of the drainage basin is gently rolling. Four major land-resource areas lie within the drainage basin (fig. 17). Average annual runoff over the basin ranges from about 7 inches in the east to about 3 inches in the west, and average annual rainfall ranges from about 38 inches in the east to about 32 inches in the west.

A net land-area drainage of 1,624 square miles (total drainage area less surface area of reservoir) was used for the sample drainage basin in all the response-model computations.

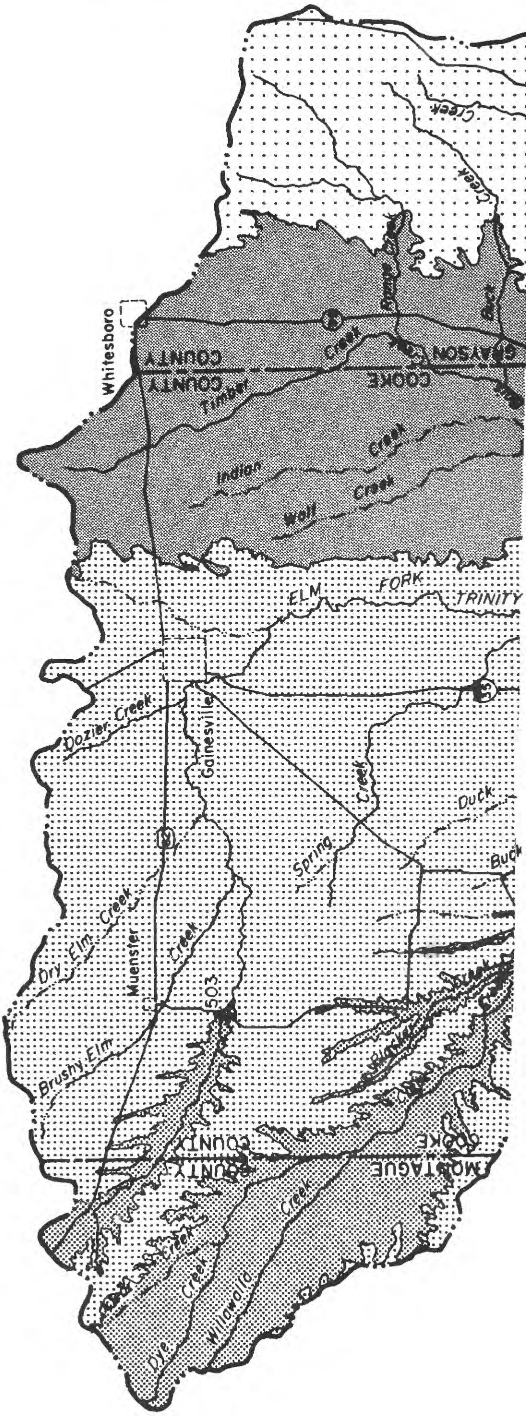
## FLOODWATER-RETARDING RESERVOIRS IN SAMPLE DRAINAGE BASIN

U.S. Soil Conservation Service plans, as of June 1968, were to install 162 floodwater-retarding and sediment-trapping structures in the Garza–Little Elm Reservoir drainage basin. Pertinent data for the system of reservoirs in each of the land-resource areas shown in figure 17 are given in table 18. Note that no structures were to be installed in the East Cross Timbers land-resource area.

The drainage area to some structures was not totally within the assigned land-resource area; however, this should not materially affect the overall results of the response model.

TABLE 18.—*Floodwater-retarding reservoirs in the sample drainage basin*

| Land-resource area | Number of structures | Controlled drainage area (sq mi) | Bottom of detention pool | | Flood-retarding pool | | Maximum discharge rate for principal spillway (acre-ft per day) |
|---|---|---|---|---|---|---|---|
| | | | Surface area (acres) | Capacity (acre-ft) | Surface area (acres) | Capacity (acre-ft) | |
| Blackland Prairie | 24 | 62.57 | 825 | 3,639 | 2,688 | 16,093 | 1,000 |
| East Cross Timbers | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Grand Prairie | 80 | 239.24 | 1,706 | 8,170 | 6,917 | 62,625 | 6,000 |
| West Cross Timbers | 58 | 124.98 | 785 | 4,600 | 2,917 | 32,402 | 3,200 |
| Total | 162 | 426.79 | 3,316 | 16,409 | 12,522 | 111,120 | 10,200 |


Whitesboro
GRAYSON COUNTY
COOKE COUNTY
Timber Creek
Indian Creek
Wolf Creek
ELM FORK TRINITY
Dozier Creek
Gainesville
Spring Creek
Duck
Dry Elm Creek
Muenster
Brushy Elm
503
COOKE COUNTY
MONTAGUE COUNTY
Dye Creek
Willawalla Creek

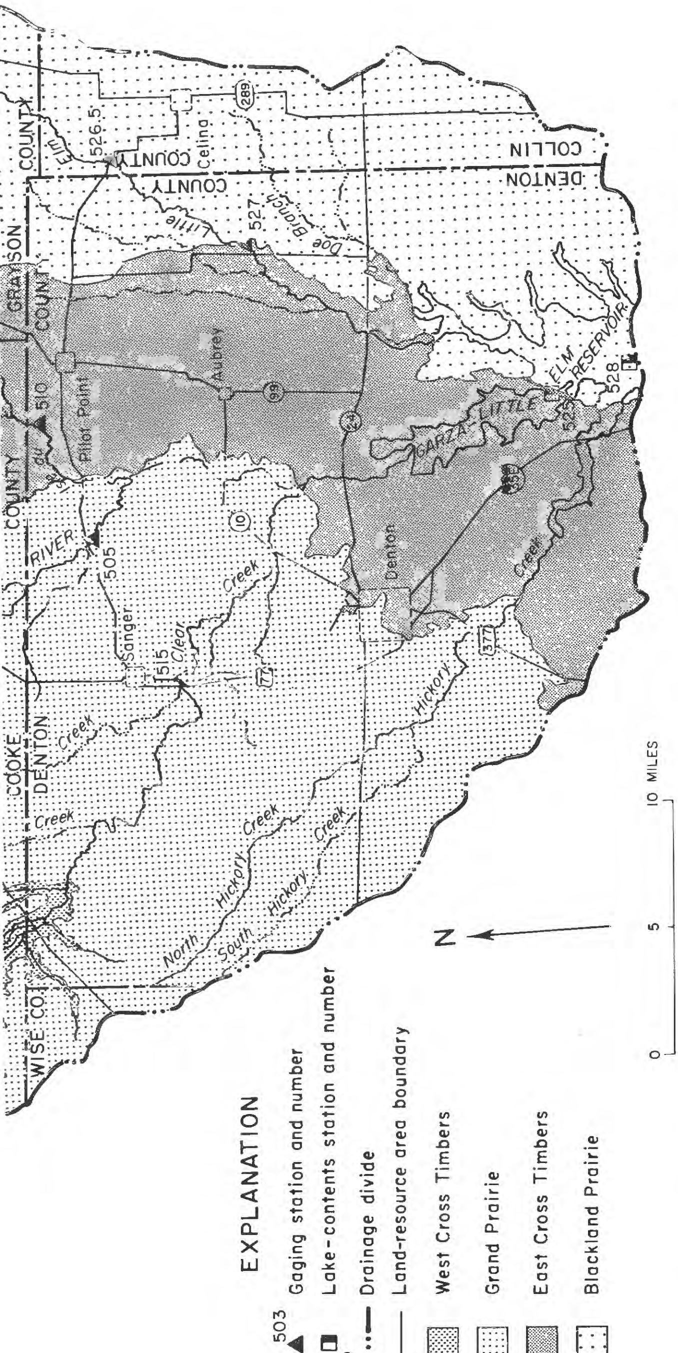



FIGURE 17.—Garza-Little Elm Reservoir drainage basin, showing hydrologic-data network and land-resource areas.

The average surface area and capacity at the bottom of the detention pool (permanent storage) is 20 acres and 101 acre-feet, respectively, for all reservoirs. Similar values for the uncontrolled flood-retarding pool are 77 acres and 686 acre-feet (flood storage only). Because of differences in topography and hydrology, these values differ from one land-resource area to another.

For routing of runoff through the structures programed in the mathematical response model, exponential area-capacity relationships were derived for the system of reservoirs in each land-resource area. The following equations were found to apply before significant sedimentation:

| *Land-resource area* | *Equation* |
| --- | --- |
| Blackland Prairie | $A=2.70C^{0.698}$ |
| Grand Prairie | $A=4.94C^{0.649}$ |
| West Cross Timbers | $A=3.94C^{0.628}$ |

where, $A$ is surface area, in acres, and $C$ is capacity, in acre-feet. Although the relationships are not of high accuracy for very low values of capacity, the accuracy is considered good for the range of capacity used in this report.

## REQUISITE COMPUTATIONS FOR MODEL INPUT

### RUNOFF

Monthly runoff in the Garza–Little Elm Reservoir drainage area (1,660 sq mi) for the period October 1927 to September 1966 was determined as follows and was converted to unit runoff (acre-feet per square mile) for use in the response model to compute net inflow to the reservoir (net drainage area: 1,624 sq mi):

1. October 1927 to December 1940: Drainage-area ratio and weighted-precipitation ratio times gaged runoff Elm Fork Trinity River near Carrollton, Tex., adjusted for change-in-storage in Lake Dallas and upstream diversions. Intervening ungaged drainage area about 800 square miles. (See station 555 on pl. 3.) Runoff data were furnished by U.S. Army Corps of Engineers, Fort Worth District.

2. January 1941 to September 1947: Drainage-area ratio times gaged runoff Elm Fork Trinity River near Carrollton, Tex., as previously adjusted, minus gaged runoff Denton Creek near Roanoke, Tex. Intervening ungaged drainage area about 180 square miles. (See also station 540 on pl. 3.) Runoff data published by U.S. Study Commission—Texas (1962).

3. October 1947 to February 1949: Drainage area ratio times gaged runoff Elm Fork Trinity River near Carrollton, Tex., as previously adjusted, minus gaged runoff Denton Creek near Grapevine, Tex. Intervening ungaged drainage area about 100 square miles. (See also station 550 on pl. 3.) Runoff data published by U.S. Study Commission—Texas (1962).

4. March 1949 to September 1957: Gaged runoff Elm Fork Trinity River near Lewisville, Tex., adjusted for change-in-storage in Lake Dallas and (or) Garza–

Little Elm Reservoir, adjusted for intervening ungaged drainage area of 13 square miles, and adjusted to drainage below gaging stations Clear Creek near Sanger, Elm Fork Trinity River near Sanger, Isle du Bois Creek near Pilot Point, and Little Elm Creek near Aubrey, Tex., and added to their gaged runoff values adjusted where necessary. (See also stations 505, 510, 515, 527, and 530 on pl. 3.) Runoff data published by U.S. Study Commission—Texas (1962).

5. October 1957 to September 1966: Observed inflow to Garza–Little Elm Reservoir adjusted for evaporation and outflow. Observed inflow furnished by U.S. Army Corps of Engineers, Fort Worth District. Furnished data adjusted for rainfall on reservoir surface and runoff depletion by upstream floodwater-retarding reservoirs before use in response model.

Because of the wide variation in runoff in the sample drainage basin, the above described monthly runoff must be apportioned for input to the response model. Surface runoff from the Garza–Little Elm Reservoir drainage basin varies from east to west not only because of rainfall but also because of geology and soils. For this reason and, as later explained, because of variation in sediment discharge, the composite monthly surface runoff from the entire sample drainage basin was apportioned to the four major land-resource areas. The apportionment is based on gaged unit runoff at stations 505, 510, 515, and 527 during the period October 1956 to September 1966. (See fig. 17.) The following is a tabulation of monthly unit-runoff apportionment factors for the four land-resource areas composing the sample drainage basin:

| Land-resource area | Runoff apportionment factor | Effective drainage area (sq mi) |
|---|---|---|
| West Cross Timbers | 0. 539 | 135 |
| Grand Prairie | . 971 | 749 |
| East Cross Timbers | 1. 075 | 433 |
| Blackland Prairie | 1. 168 | 307 |

## SEDIMENT DISCHARGE

Monthly sediment discharge in each of the four land-resource areas was also a necessary input item in the response model. The U.S. Soil Conservation Service (1959) found unit sediment yield to vary with size of drainage area in the four land-resource areas. Although the major cause for variation in sediment yield was found in this report to be due to variation in surface runoff, size of drainage area and type of soil were found to be important factors. Analyses were made both on the basis of individual land-resource areas and on the basis of a composite drainage basin (all land-resource areas are considered as one sediment-discharging unit).

Basic to all water-sediment discharge analyses in this report is the assumption that sediment discharge can be exponentially related to water discharge in the form:

$$S_q = KQ^n, \tag{5}$$

where

$S_q$=sediment discharge, in tons per unit of time;
$K$=a coefficient of proportionality which varies with land-resource area and size of drainage basin;
$Q$=water discharge, in acre-feet per unit of time; and
$n$=an exponent, constant for an individual land-resource area, but different for different units of time.

Colby (1956) demonstrated the validity of the above relationship as well as the change in the relationship with various units of time. The following subsections explain the derivation of the water-sediment discharge relationship for each land-resource area in the Garza–Little Elm drainage basin. Referenced station numbers are shown on plate 3. In the tables listing the stream-gaging station records and type of sediment records available in each land-resource area, the following terminology is implied: Water discharge at all stations is from continuously collected records; daily sediment record is from one or more suspended-sediment samples each day; intermittent sediment record is from one or more suspended-sediment samples each day during mostly high-water periods; periodic sediment record is from suspended-sediment samples collected over a range of water discharge; and reconnaissance sediment record is from a spot suspended-sediment sample taken for areal sediment studies.

Plots of monthly data for each station were made in the manner shown in figure 5. Because of length of record, some plots gave better defined water-sediment discharge relationships than others.

### WEST CROSS TIMBERS WATER-SEDIMENT DISCHARGE RELATIONSHIP

Definition of the exponent $n$ was accomplished from log plots of water discharge (abscissa) and suspended-sediment discharge (ordinate) for the following stations:

| Map No. (pl. 3) | Stream-gaging station and drainage area | Type of sediment record and period collected |
|---|---|---|
| 910 | Brazos River near Glen Rose, Tex. (15,600 sq mi contributing). | Daily, June 1924 to December 1927, July to September 1928, January to August 1929. |
| 1005 | Leon River near Gatesville, Tex. (2,279 sq mi). | Daily, March 1953 to September 1964. |
| 948 | North Bosque River at Hico, Tex. (357 sq mi). | Daily, April 1962 to September 1964. |

| Map No. (pl. 3) | Stream-gaging station and drainage area | Type of sediment record and period collected |
|---|---|---|
| 540 | Denton Creek near Roanoke, Tex. (621 sq mi). | Intermittent (364 samples), November 1946 to July 1951. |
| 515 | Clear Creek near Sanger, Tex. (295 sq mi). | Periodic (5 samples), 1964 to 1966. |
| 535 | Denton Creek near Justin, Tex. (400 sq mi). | Periodic (3 samples), 1964 to 1966. |
| 428 | West Fork Trinity River near Jacksboro, Tex. (683 sq mi). | Reconnaissance, 1 sample in 1964. |
| 440 | Big Sandy Creek near Bridgeport, Tex. (333 sq mi). | Reconnaissance, 1 sample in 1964. |
| 445 | West Fork Trinity River near Boyd, Tex. (1,725 sq mi). | Reconnaissance, 1 sample in 1964. |

An average value of the exponent in the basic equation, $S_q=KQ^n$, was obtained by averaging the exponent found for station 910 (1.494), station 1005 (1.408), station 540 (1.577), and the exponent for a composite plot for stations 515, 535, 428, 440, and 445 (1.425). A value of 1.48 for the exponent $n$ was found and used for all computations involving monthly water-sediment discharge in the West Cross Timbers land-resource area.

Only stations 910, 1005, and 540 had sufficient record to provide reliable values of the coefficient $K$ in equation 5. As previously pointed out, this coefficient was found to vary with size of drainage area. Because of the need for values of $K$ covering a larger range of areas, results of reservoir-sedimentation surveys were used for information on the smaller drainage areas. Analyses showed that the average figures they provide could be used because for longer periods of record the average monthly value for sediment and water discharge was found to plot very near the log curve relating individual values of monthly water and sediment discharge. Therefore, the procedure followed in determining values of $K$ from sedimentation surveys was to (1) determine average monthly sediment inflow to reservoir (adjusted for trap efficiency); (2) determine average monthly water inflow to reservoir (gaged at some reservoirs and estimated at others on the basis of nearby runoff and rainfall); and, (3) using the previously defined value of 1.48 for $n$, substitute in the basic equation $S_q=KQ^{1.48}$ and solve for $K$.

Results of most sedimentation surveys for reservoirs draining the land-resource areas covered by this report have been compiled by Spraberry (1964). Those reservoir surveys used in this report for the West Cross Timbers land-resource area are given in the following tabulation. For the location of the reservoirs listed, see plate 3. Drainage areas given are for the net land area contributing to sedimentation.

| Map no. (pl. 3) | Reservoir name and drainage area | Period of sedimentation |
|---|---|---|
| 21 | Lake Eanes near Comanche, Tex. (13.57 sq mi). | May 1926 to September 1946. |
| 23 | T & P Reservoir near Weatherford, Tex. (6.18 sq mi). | May 1930 to November 1938. |
| 450 | Eagle Mountain Reservoir above Fort Worth, Tex. (809 sq mi contributing sediment). | March 1934 to March 1939. |
| 502 | Elm Fork Trinity River, site 6–O, near Muenster, Tex. (0.76 sq mi). | August 1956 to July 1964. |
| 940 | Green Creek, site 1, near Dublin, Tex. (3.18 sq mi). | April 1955 to June 1967. |

Even with the additional values of the coefficient $K$ obtained from the results of reservoir-sedimentation surveys, definition of the relationship between drainage area and $K$ in this or any of the individual land-resource areas was not attempted until the slope of the log regression was defined by considering all the data from all land-resource areas. This analysis is presented as the last subsection ("Sample Drainage-Basin Composite Sediment Discharge") under this section. The relationship between drainage area and the coefficient $K$ for the West Cross Timbers land-resource area was found to be $K=2.12\ D.A.^{-0.468}$, where $D.A.$ is the drainage area, in square miles.

The resulting equation expressing the relationship between monthly water and sediment discharge for any size drainage area in the West Cross Timbers land-resource area was found to be $S_q=2.12\text{D.A.}^{-0.468}\ Q^{1.48}$, with $S_q$ in tons, $D.A.$ in square miles, and $Q$ in acre-feet.

### BLACKLAND PRAIRIE WATER-SEDIMENT DISCHARGE RELATIONSHIP

Streamflow and sediment discharge records used in defining $n$ in the basic equation $S_q=KQ^n$ for the curve relating water and sediment discharge in the Blackland Prairie land-resource area are tabulated below. An average value of $n$ of 1.38 was computed from these records.

| Map No. (pl. 3) | Stream-gaging station and drainage area | Type of sediment record and period collected |
|---|---|---|
| 3425 | South Sulphur River near Cooper, Tex. (527 sq mi). | Daily, March 1962 to September 1964. |
| 632 | Pin Oak Creek near Hubbard, Tex. (17.6 sq mi). | Daily, October 1956 to September 1960. |
| 1070 | Big Elm Creek near Temple, Tex. (70.5 sq mi). | Daily, March 1934 to September 1936. |
| 1075 | Big Elm Creek near Buckholts, Tex. (167 sq mi). | Daily, March 1934 to September 1936. |
| 1080 | North Elm Creek near Ben Arnold, Tex. (33.6 sq mi). | Daily, October 1934 to September 1936. |
| 527 | Little Elm Creek near Aubrey, Tex. (75.5 sq mi). | Daily, July to September 1964. |

As in the sediment-discharge analyses in the West Cross Timbers, results of reservoir-sedimentation surveys were used to aid in definition of the coefficient $K$ in the basic equation. Reservoirs draining the Blackland Prairie land-resource area and for which sedimentation surveys were available are listed below:

| Map No. (pl. 3) | Reservoir name and drainage area | Period of sedimentation |
|---|---|---|
| 968 | Cow Bayou, site 4, near Bruceville, Tex. (5.20 sq mi). | July 1956 to April 1958. |
| 968A | Cow Bayou, site 3, near Bruceville, Tex. (1.32 sq mi). | November 1955 to August 1960. |
| 575 | Honey Creek, site 11, near McKinney, Tex. (2.08 sq mi). | February 1952 to July 1967. |
| 580 | Honey Creek, site 12, near McKinney, Tex. (1.24 sq mi). | January 1952 to April 1964. |

Using values of the coefficient $K$ computed from the above listed data as explained in the preceding section ("West Cross Timbers Water-Sediment Discharge Relationship") and those found in other land-resource areas, a relationship between $K$ and drainage area expressed by $K=1.58D.A.^{-0.468}$ was found for the Blackland Prairie land-resource area. The relationship between monthly water and sediment discharge for the Blackland Prairie land-resource area was then computed as $S_q=1.58D.A.^{-0.468}Q^{1.38}$, where $S_q$ is in tons, $D.A.$ in square miles, and $Q$ in acre-feet.

### GRAND PRAIRIE WATER-SEDIMENT DISCHARGE RELATIONSHIP

The relationship between monthly water and sediment discharge for the Grand Prairie land-resource area was defined in the same manner as previously described for the West Cross Timbers land-resource area. Records for the following streamflow and sediment-discharge stations were used in defining the slope of the log curve of the relationship:

| Map no. (pl. 3) | Stream-gaging station and drainage area | Type of sediment record and period collected |
|---|---|---|
| 1055 | San Gabriel River at Circleville, Tex. (602 sq mi). | Daily, June 1924 to October 1929. |
| 1025 | Leon River near Belton, Tex. (3,547 sq mi). | Daily, September 1945 to December 1949. |
| 1005 | Leon River near Gatesville, Tex. (2,279 sq mi). | Daily, March 1953 to September 1964. |
| 505 | Elm Fork Trinity River near Sanger, Tex. (381 sq mi). | Periodic (6 samples), 1964 to 1966. |

Not all the drainage area upstream from every station listed above is totally within the Grand Prairie land-resource area. (See plate 3.) In fact, data from station 1055 was also used to help define the slope of the curve relating water and sediment discharge to the West Cross Timbers land-resource area. Because the above stations also had drainage in the West Cross Timbers and the Blackland Prairie land-resource areas, a weighting procedure was used in defining the slope of the curve relating water and sediment discharge in the Grand Prairie land-resource area. Using the previously defined values of $n$ for the West Cross Timbers and Blackland Prairie land-resource areas and the effective area of each of the drainage areas for the above stations, a weighted value of the slope of the curve relating water and sediment discharge in the Grand Prairie land-resource area was computed. The resulting equation for the curve was $S_q = KQ^{1.35}$.

To aid in defining the relationship between the coefficient $K$ and drainage area in the Grand Prairie land-resource area, results of sedimentation surveys at the following reservoirs were used in the manner previously described:

| Map no. (pl. 3) | Reservoir name and drainage area | Period of sedimentation |
| --- | --- | --- |
| 955.5 | Lake Waco near Waco, Tex. (1,658 sq mi). | April 1930 to December 1947. |
| 525 | Lake Dallas near Lake Dallas, Tex. (1,157 sq mi). | February 1928 to September 1938. |
| 33 | Lake Merritt near Goldthwaite, Tex. (11.5 sq mi). | May 1917 to May 1940. |
| 34 | Lometa Reservoir at Lometa, Tex. (4.60 sq mi). | 1912 to February 1941. |
| 32 | Meridian Lake at Meridian, Tex. (3.20 sq mi). | May 1934 to April 1948. |
| 30 | Hamilton City Lake at Hamilton, Tex. (11.9 sq mi). | June 1923 to March 1941. |

After the composite analysis for slope of the curve relating the coefficient $K$ with drainage area, utilizing data from all four land-resource areas, the curve of relation for the Grand Prairie land-resource area was determined to be $K = 1.36 D.A.^{-0.468}$. The equation relating monthly water and sediment discharge was then computed as $S_q = 1.36 D.A.^{-0.468} Q^{1.35}$, where $S_q$ is in tons, $D.A.$ in square miles, and $Q$ in acre-feet.

### EAST CROSS TIMBERS WATER-SEDIMENT DISCHARGE RELATIONSHIP

Very few sediment data were available to define the relationship between monthly water and sediment discharge in the East Cross Timbers land-resource area. Only the following two stations provided data for definition of the exponent $n$ in the basic equation $S_q=KQ^n$:

| Map no. (pl. 3) | Stream-gaging station and drainage area | Type of sediment record and period collected |
|---|---|---|
| 935 | Aquilla Creek near Aquilla, Tex. (306 sq mi). | Daily, June 1963 to September 1964. |
| 510 | Isle du Bois Creek near Pilot Point, Tex. (266 sq mi). | Periodic (7 samples), 1964 to 1967. |

On the basis of the above record and data given in Texas Board of Water Engineers Bulletin 5912 (U.S. Soil Conservation Service, 1959), a value of 1.35 for the exponent $n$ was selected for the East Cross Timbers land-resource area.

Data on reservoir sedimentation in the East Cross Timbers land-resource area also were lacking. The results of only two sedimentation surveys of reservoirs draining the East Cross Timbers were available to aid in definition of the relationship between the coefficient $K$ and size of drainage area. These reservoirs are listed below:

| Map no. (pl. 3) | Reservoir name and drainage area | Period of sedimentation |
|---|---|---|
| 28 | Variety Club Lake near Bedford, Tex. (0.29 sq mi). | July 1942 to May 1950. |
| 27 | Lake Erie near Handley, Tex. (1.01 sq mi). | 1899 to April 1939. |

Because of the lack of data for defining the relationship between the coefficient $K$ and size of drainage area in the East Cross Timbers land-resource area, the average relationship indicated from data for all land-resource areas was used. This was computed to be $K=1.77D.A.^{-0.468}$ in the following subsection of this report. With this value for the coefficient $K$, the monthly water-sediment discharge relationship for the East Cross Timbers can be expressed as $S_q=1.77D.A.^{-0.468}Q^{1.35}$, where $S_q$ is in tons, $D.A.$ in square miles, and $Q$ in acre-feet.

### SAMPLE DRAINAGE-BASIN COMPOSITE SEDIMENT DISCHARGE

In the preceding subsections of this report giving the relationship between monthly water and sediment discharge for the individual land-resource areas it was explained that a composite analysis of data for all land-resource areas formed the basis for determining the values of $K$ in the basic equation of relation: $S_q=KQ^n$. This analysis consisted of plotting the value of $K$, determined for all suspended-sediment discharge stations and reservoir-sedimentation surveys, against the respective drainage area. This plot is shown in figure 18. A least-squares regression yields the equation $K=1.77D.A.^{-0.468}$. Owing to lack of other better definition, this relationship was also used for determining the value of $K$ for the East Cross Timbers land-resource area. The previously given relationships between $K$ and drainage area in the other land-resource areas were then determined by assuming the same exponent (−0.468) for each and by passing the resulting parallel log curve through the mean deviation of the points for each land-resource area. Although data for some land-resource areas trend toward a different slope than that defined by composite least-squares regression, the size of the sample would not statistically justify individual regressions.

For this study of the effects of floodwater-retarding structures on the water and sediment yield to Garza-Little Elm Reservoir, total suspended-sediment yield was taken to be the sum of the yields from each land-resource area. To facilitate progressive computation in the computer-programed response model, the water discharge–sediment discharge relationships were modified for the individual drainage area involved. The equations were modified to yield monthly sediment in acre-feet rather than in tons. Monthly runoff input also was modified to acre-feet per square mile rather than total acre-feet as derived. The following is a summary of the equations used in the sample basin model for the area and condition stated:

*West Cross Timbers, 135 square miles total drainage:*

1. 58 structures controlling 125.0 square miles or an average of 2.16 square miles each.
2. On the basis of an initial specific weight of 55 pounds per cubic foot and a drainage area of 2.16 square miles applied to 58 structures, monthly sediment inflow is $S_q=0.228Q^{1.48}$ for the system of reservoirs, where $S_q$ is sediment, in acre-feet, and $Q$ is runoff, in acre-feet per square mile.
3. On the basis of a trap efficiency of 98 percent and a sediment pickup of 10 percent by outflow, monthly sediment yield from flow through structures is $S_q=0.00501Q_o^{1.48}$, where $S_q$ is sediment, in acre-feet, and $Q_o$ is outflow, in acre-feet per square mile.
4. Monthly sediment yield for the 10.0 square miles below structures is $S_q=0.0181Q^{1.48}$, where units are same as in No. 2 above.
5. Monthly sediment yield for the entire 135 square miles without structures is $S_q=0.252Q^{1.48}$, where units are same as in No. 4 above.

*Grand Prairie, 749 square miles total drainage:*

1. 80 structures controlling 239.2 square miles or an average of 2.99 square miles each.

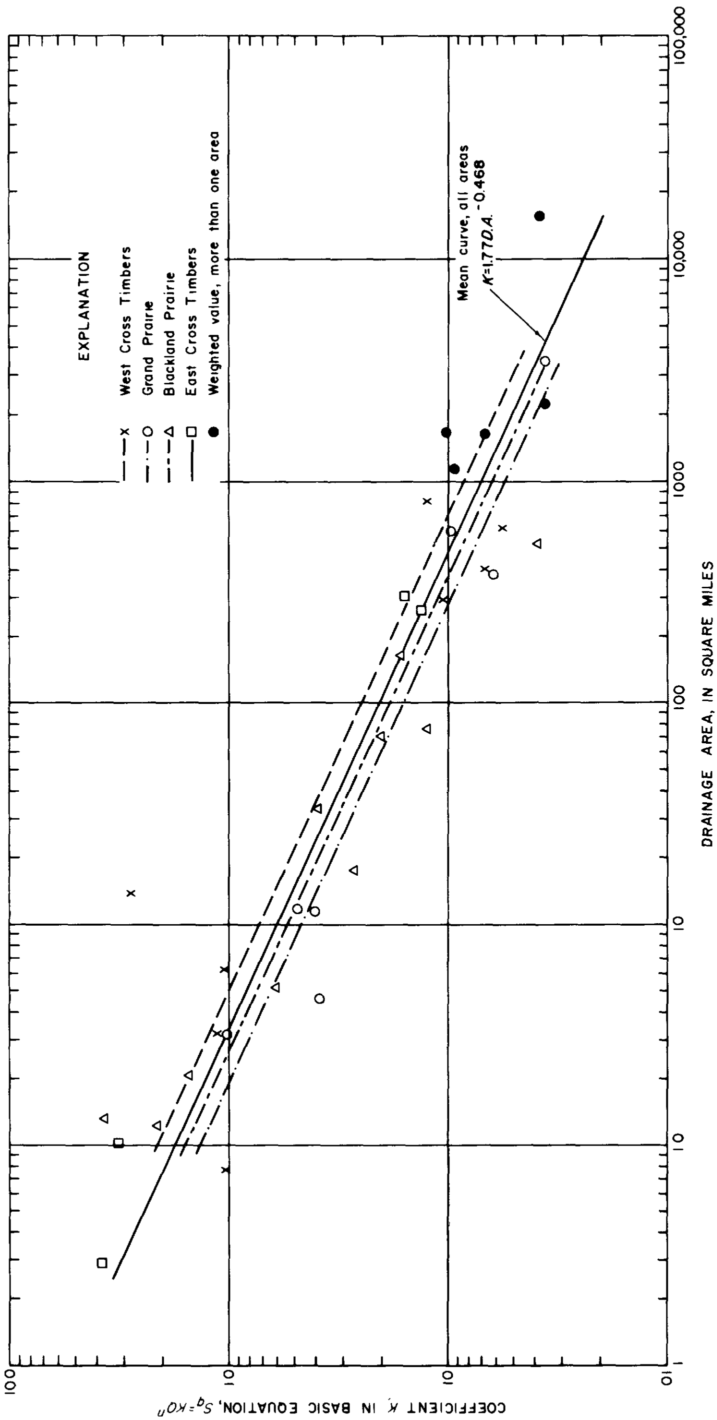



FIGURE 18.—Relationship between drainage area and coefficient $K$ in sediment-discharge equation, $S_a = KQ^n$.

2. On the basis of an initial specific weight of 45 pounds per cubic foot and a drainage area of 2.99 square miles applied to 80 structures, monthly sediment inflow is $S_q=0.283Q^{1.35}$ for the system of reservoirs, where $S_q$ is sediment, in acre-feet and $Q$ is runoff, in acre-feet per square mile.
3. On the basis of a trap efficiency of 97 percent and a sediment pickup of 15 percent by outflow, monthly sediment yield from flow through structures is $S_q=0.0101Q_o^{1.35}$, where $S_q$ is sediment, in acre-feet, and $Q_o$ is outflow, in acre-feet per square mile.
4. Monthly sediment yield for the 509.8 square miles below structures is $S_q=0.341Q^{1.35}$, where units are same as in No. 2 above.
5. Monthly sediment yield for the entire 749 square miles without structures is $S_q=0.474Q^{1.35}$, where units are same as in No. 4 above.

*East Cross Timbers, 433 square miles total drainage:*

1. No structures. On the basis of an initial specific weight of 50 pounds per cubic foot, monthly sediment yield from total area is $S_q=0.349Q^{1.35}$, where $S_q$ is sediment, in acre-feet, and $Q$ is runoff, in acre-feet per square mile.

*Blackland Prairie, 307 square miles total drainage:*

1. 24 structures controlling 62.6 square miles or an average of 2.61 square miles each.
2. On the basis of an initial specific weight of 45 pounds per cubic foot and a drainage area of 2.61 square miles applied to 24 structures, monthly sediment inflow is $S_q=0.0892Q^{1.38}$ for the system of reservoirs, where $S_q$ is sediment, in acre-feet, and $Q$ is runoff, in acre-feet per square mile.
3. On the basis of a trap efficiency of 97 percent and sediment pickup of 25 percent by outflow, monthly sediment yield from flow through structures is $S_q=0.00334Q_o^{1.38}$, where $S_q$ is sediment, in acre-feet, and $Q_o$ is outflow, in acre-feet per square mile.
4. Monthly sediment yield for the 244.4 square miles below structures is $S_q=0.245Q^{1.38}$, where units are same as in No. 2 above.
5. Monthly sediment yield for the entire 307 square miles without structures is $S_q=0.296Q^{1.38}$, where units are same as in No. 4 above.

The values for initial specific weight of sediment in each land-resource area are based on particle-size analyses and results of reservoir-sedimentation surveys. The variability of the initial specific weight of sediment should be recognized, even when acceptable methods are used in its computation. The method used in this report is that given by Lara and Pemberton (1965) for a type II reservoir. For the values of initial specific weight used in this report, an error of 1 pound gives about a 2-percent error in sediment yield in acre-feet.

## SEDIMENT DEPOSITION IN FLOODWATER-RETARDING RESERVOIRS

For input to the response model for the Garza–Little Elm Reservoir drainage basin, it was necessary to distribute the sediment deposited in the upstream system of reservoirs to afford periodic adjustments in the area-capacity relationships. The method used to distribute sediment deposited is that given by Borland and Miller (1960) and described as the empirical area-reduction method.

Results obtained from use of the method are graphically illustrated in figure 19. Also shown in the plot are results of sedimentation surveys of individual floodwater-retarding reservoirs furnished by the U.S. Soil Conservation Service. Good agreement between the actual and computed data at the lower end of the curves is apparent. The curves diverge at the upper end because of criteria used in application of the method. These criteria pertain to the proportion of sediment distributed in the permanent and detention pools. In the West Cross Timbers land-resource area, because of more sand, it was assumed that when the permanent pool was full of sediment, 30 percent of the sediment inflow would have dropped out in the detention pool; for the Grand Prairie and Blackland Prairie, numerical values for this assumption were 15 and 10 percent, respectively.

Although it is well known that considerable compaction of the deposited sediments occurs in floodwater-retarding reservoirs, this factor was not considered in either the sediment-yield or the surface-area-reduction computer programs. This report is concerned with how much sediment the structures prevent from occupying usable storage in a downstream water-supply reservoir. Had the sediment been allowed to reach the larger downstream reservoir, most of it would not have been aerated and thus compacted because of differences in draw-down in the two types of reservoirs. Therefore, a more logical procedure is to use the volume of sediment computed using values of initial specific weight as that volume of storage savings in a downstream reservoir. Although this procedure tends to deplete storage in the floodwater-retarding reservoirs faster than actually occurs, it is not the intent of this report to check the sedimentation design for floodwater-retarding structures.

From the relationships shown in figure 19, area-capacity relationships were revised and used in the computer model after each sediment deposition of an amount equal to 10 percent of the original capacity of the permanent pools.

## CLIMATOLOGICAL DATA

Computation of pool consumption in the model requires average monthly values of rainfall, temperature, and relative humidity. The nearest first-order weather station having records of temperature and relative humidity dating back to 1928 was Dallas. The Dallas record was used in the model with the following adjustments, which were

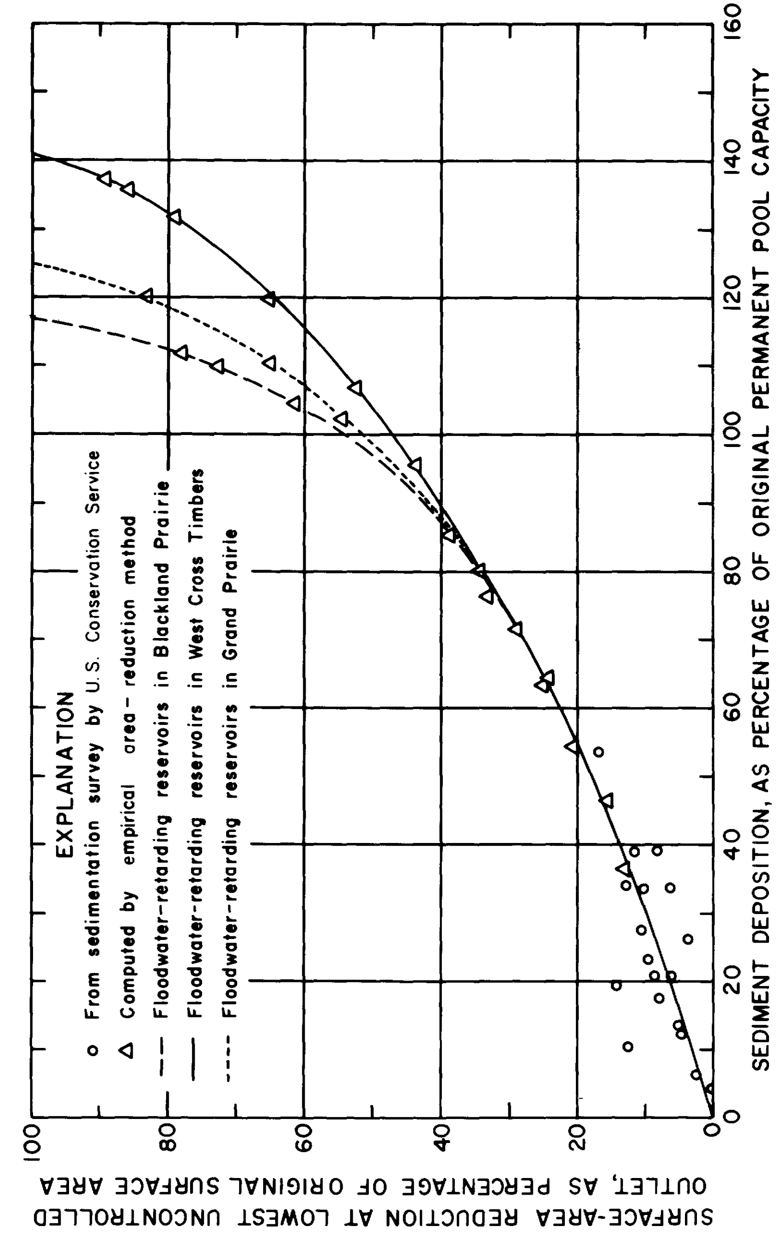



FIGURE 19.—Surface-area reduction due to sedimentation of floodwater-retarding reservoirs.

based on a comparison of Dallas and Wichita Falls record for the period 1953–66:

| Climatic parameter | Conversion factor for Dallas observations | | |
|---|---|---|---|
| | West Cross Timbers | Grand Prairie | Blackland Prairie |
| Temperature | 0.98 | 0.99 | 1.00 |
| Relative humidity | .97 | .98 | 1.00 |

A number of long-term rainfall stations are in and adjacent to the Garza–Little Elm Reservoir drainage basin. Available record includes that for Bridgeport, Denton, Gainesville, McKinney, and Sherman. A study was made of rainfall records for these five stations for the period 1931–60. On the basis of this study, it was found that an average of the Denton and Gainesville records would serve as an adequate base for monthly rainfall on the sample basin, with the following correction factors:

| *Land-resource area* | *Rainfall correction factor, base = average of Denton and Gainesville* |
|---|---|
| West Cross Timbers | 0.94 |
| Grand Prairie | 1.00 |
| Blackland Prairie | 1.11 |

Although some values for individual months may be in error by using this procedure, errors would be compensating on a long-term basis.

## REGRESSION EQUATION FOR MONTHLY RESERVOIR CONSUMPTION

The previously derived multiple-linear-regression equation (eq 4) of the form

$$C=a_o+a_1[e_o-e_a][A+K_1(P/S)]+a_2[T_a-40][S.F.]+a_3[(K_3\overline{D}P+A)/\nu],$$

was used in the response model for computation of monthly consumption. Regression coefficients $a_o$, $a_1$, and $a_2$ were previously given as 0, 0.026, and 0.010, respectively. Values for the seepage-regression coefficient $a_3$ were selected on the basis of the relationship between hydrologic soil group and $a_3$ given in figure 16 and values found in the Elm Fork Trinity River and Honey Creek study areas. The following coefficients were selected for the three land-resource areas that are developed with systems of floodwater-retarding structures:

| *Land-resource area* | $a_3$ |
|---|---|
| Blackland Prairie | 0.35 |
| Grand Prairie | .45 |
| West Cross Timbers | .55 |

The physical parameters necessary to the above equation for the system of reservoirs in each land-resource area were computed as described in the section giving the derivation of the basic equation. On the basis of values found in the seven study areas, a side slope of 0.075 foot per foot was used in the model.

Monthly climatological data were derived as indicated in the preceding section.

## COMPUTER PROGRAM FOR RESPONSE MODEL

A computer program was written for monthly water and sediment yield from the response model (Garza–Little Elm Reservoir drainage basin) utilizing the previously derived relationships. The program was applied separately to the four land-resource areas, with and without the 162 structures in place, and the results were summed for yield to Garza–Little Elm Reservoir.

The primary component of the response-model computer program is that simulating the hydrologic response of the system of floodwater-retarding reservoirs in each land-resource area. Input for this component of the computer 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. Side slope,
   d. Surface-area–storage relation,
   e. Surface-area–perimeter relation,
   f. Design outflow rate from principal spillway,
   g. Regression coefficients for consumption equation,
   h. Total storage at lowest uncontrolled outlet.

A simplified block diagram of the floodwater-retarding reservoir component of the computer program is shown in figure 20. Essentially, the program is an iterative procedure to determine the mean monthly surface area because all computations of depletion hinge on this parameter. The procedure is to assume a value for average monthly surface area and compute net pool consumption from the regression equations. Average monthly contents is then computed on the basis of storage at the beginning of the month, inflow during the month, time required for pool to drain to lowest uncontrolled spillway, and net depletion. A value of average surface area is then computed on the basis of the average contents. This value of surface area is compared with the

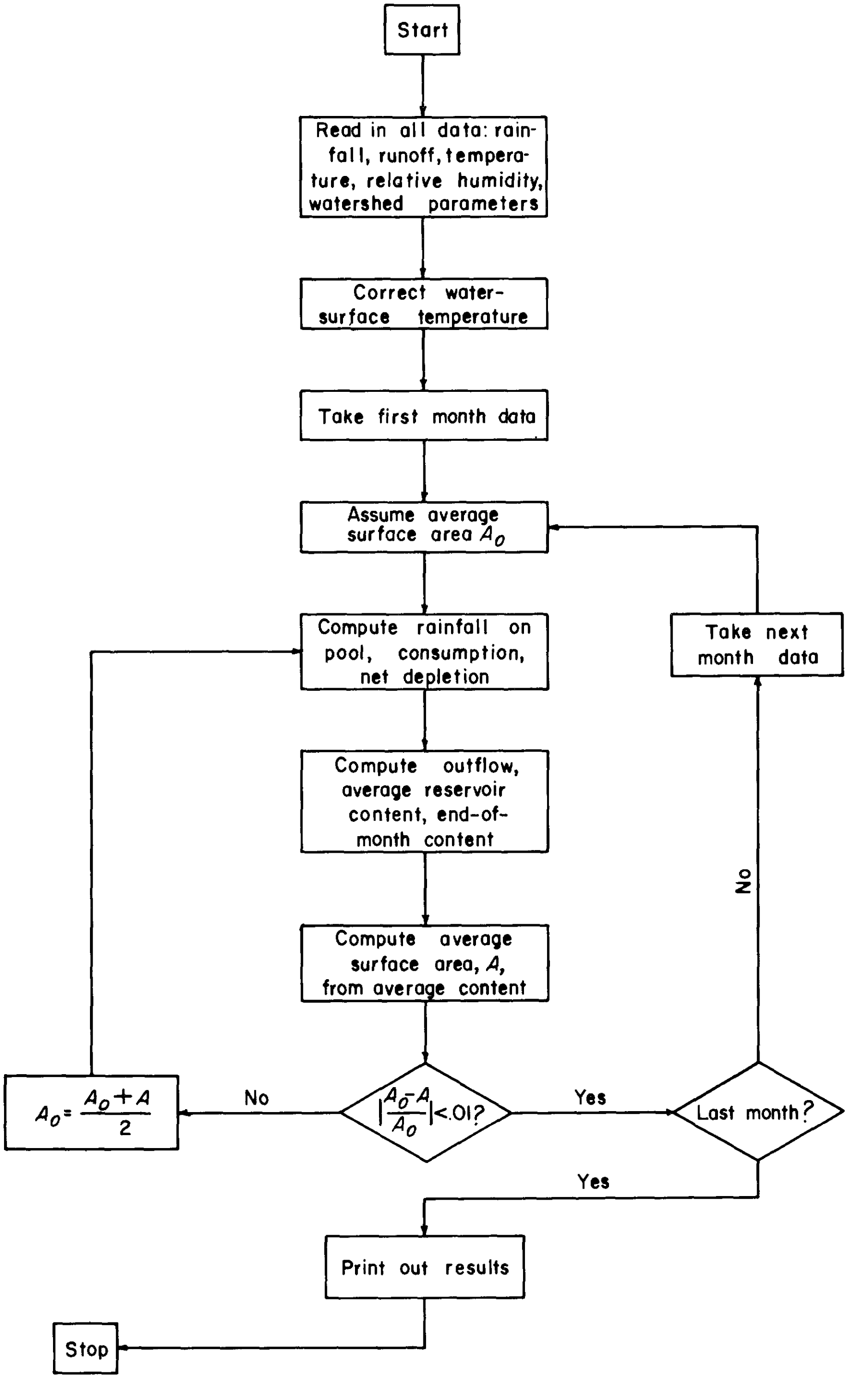



FIGURE 20.—Simplified flow chart of the computer program for a mathematical model of the hydrologic response of a system of floodwater-retarding reservoirs.

assumed value, and if the difference is greater than 1 percent, the assumed value of surface area is incremented by one-half the difference. This procedure is continued until the surface areas agree within 1-percent tolerance limits. The procedure converges rapidly, generally within four or five 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 the average surface area for the month in computing rainfall on pool.
4. Reservoir surface area is exponentially related to capacity, and is adjusted for sedimentation.

The first assumption was made for ease of computation; the time distribution of inflow is not critical for a monthly water budget. The remaining three assumptions were based on a study of existing study-area data. Additional details, verification, and documentation of the computer program simulating the hydrologic response of a system of floodwater-retarding structures were given by Sauer and Masch (1969).

## RESULTS FROM RESPONSE MODEL

In applying the model, the total planned development of 162 structures was assumed to have been done before the beginning of the period. Any combination of chronological development could be used. The permanent pools were assumed to be full at the beginning of the period. The historical runoff and climatic data, adjusted as previously explained, were run through the model for the period 1928–66. Sediment inflows, depositions, and outflows were computed, and pool-surface-area–capacity relations were adjusted as previously outlined.

Output for the program was monthly, annual, and cumulative totals of water and sediment runoff into structures, rainfall on pool surface, pool consumption of runoff at structures, net depletion, water and sediment outflow from structures, and water and sediment runoff below the structures. This information was printed out by land-resource area and was a summary for the watershed, including inflow into Garza–Little Elm Reservoir with and without the system of floodwater-retarding reservoirs. In this way, the effects of sedimentation of the reservoirs was taken into account.

## DEPLETION OF RUNOFF INTO GARZA–LITTLE ELM RESERVOIR

Results of the response model were an annual water budget for the system of 162 floodwater-retarding reservoirs and net inflow to Garza–Little Elm Reservoir, as given in table 19.

TABLE 19.—*Annual results computed from response model for Garza–Little Elm Reservoir drainage basin at full development, 1928–66*

[Totals rounded]

| Water year | Net inflow to structures (acre-ft) | Rainfall on pools (acre-ft) | Pool consumption (acre-ft) | Net depletion (acre-ft) | Outflow from structures (acre-ft) | Net inflow to Garza–Little Elm Reservoir (acre-ft) | Yield depletion[1] (percentage) |
|---|---|---|---|---|---|---|---|
| 1928 | 39,230 | 9,090 | 27,140 | 18,050 | 26,860 | 158,600 | 10.5 |
| 1929 | 89,150 | 8,950 | 25,520 | 16,570 | 70,690 | 370,200 | 4.3 |
| 1930 | 50,150 | 7,020 | 24,330 | 17,300 | 38,580 | 207,000 | 7.9 |
| 1931 | 65,680 | 9,180 | 25,210 | 16,030 | 48,380 | 269,000 | 5.6 |
| 1932 | 174,400 | 10,880 | 26,260 | 15,370 | 156,600 | 742,200 | 2.0 |
| 1933 | 87,440 | 9,220 | 24,770 | 15,550 | 73,860 | 367,600 | 4.1 |
| 1934 | 51,300 | 5,140 | 22,180 | 17,040 | 39,360 | 211,700 | 7.6 |
| 1935 | 168,200 | 11,060 | 20,420 | 9,360 | 154,000 | 719,200 | 1.3 |
| 1936 | 102,900 | 9,250 | 24,270 | 15,020 | 84,080 | 429,600 | 3.4 |
| 1937 | 61,510 | 6,710 | 23,770 | 17,060 | 48,970 | 255,600 | 6.4 |
| 1938 | 163,400 | 8,580 | 22,080 | 13,500 | 154,100 | 703,100 | 1.9 |
| 1939 | 41,020 | 4,390 | 18,890 | 14,500 | 27,100 | 164,900 | 8.1 |
| 1940 | 91,870 | 7,320 | 16,800 | 9,480 | 80,100 | 388,700 | 2.4 |
| 1941 | 211,000 | 10,830 | 21,040 | 10,220 | 199,800 | 908,700 | 1.1 |
| 1942 | 233,600 | 10,180 | 19,570 | 9,380 | 227,400 | 1,012,000 | .9 |
| 1943 | 71,160 | 4,750 | 17,060 | 12,310 | 61,050 | 300,100 | 4.0 |
| 1944 | 89,380 | 5,140 | 15,720 | 10,570 | 76,870 | 377,100 | 2.7 |
| 1945 | 266,700 | 8,430 | 16,160 | 7,730 | 258,200 | 1,154,000 | .7 |
| 1946 | 171,100 | 4,850 | 13,580 | 8,730 | 164,700 | 739,400 | 1.2 |
| 1947 | 120,200 | 4,200 | 11,260 | 7,060 | 113,900 | 517,500 | 1.4 |
| 1948 | 114,800 | 3,100 | 8,330 | 5,220 | 109,700 | 495,300 | 1.0 |
| 1949 | 69,300 | 2,430 | 5,820 | 3,390 | 65,380 | 298,100 | 1.1 |
| 1950 | 211,200 | 4,120 | 9,010 | 4,890 | 206,300 | 915,800 | .5 |
| 1951 | 39,380 | 610 | 3,510 | 2,900 | 37,520 | 169,800 | 1.7 |
| 1952 | 21,870 | 620 | 2,850 | 2,230 | 19,810 | 93,270 | 2.3 |
| 1953 | 36,510 | 820 | 3,170 | 2,340 | 34,300 | 156,900 | 1.5 |
| 1954 | 24,890 | 780 | 2,830 | 2,050 | 23,070 | 106,700 | 1.9 |
| 1955 | 30,330 | 480 | 2,450 | 1,980 | 28,970 | 130,800 | 1.5 |
| 1956 | 4,770 | 120 | 850 | 730 | 4,300 | 20,320 | 3.5 |
| 1957 | 329,200 | 3,460 | 2,470 | −990 | 330,800 | 1,436,000 | −.1 |
| 1958 | 197,900 | 64 | 1,350 | 1,290 | 197,900 | 862,800 | .1 |
| 1959 | 24,370 | 11 | 1,300 | 1,290 | 24,160 | 106,000 | 1.2 |
| 1960 | 84,420 | 16 | 1,310 | 1,300 | 84,390 | 368,000 | .4 |
| 1961 | 47,170 | 14 | 1,230 | 1,210 | 47,060 | 205,500 | .6 |
| 1962 | 120,400 | 19 | 1,360 | 1,340 | 120,400 | 525,000 | .3 |
| 1963 | 52,120 | 10 | 1,150 | 1,140 | 52,030 | 227,100 | .5 |
| 1964 | 86,660 | 16 | 1,040 | 1,030 | 86,530 | 337,600 | .3 |
| 1965 | 162,800 | 18 | 1,350 | 1,340 | 162,600 | 709,600 | .2 |
| 1966 | 173,900 | 18 | 1,360 | 1,340 | 173,800 | 757,800 | .2 |
| Totals | 4,181,400 | 171,900 | 468,800 | 296,800 | 3,914,000 | 17,959,000 | 1.6 |

[1] Net depletion at structures divided by inflow to Garza–Little Elm Reservoir without structures in place.

Figure 21 illustrates the effects of reservoir sedimentation on annual depletion of runoff at the floodwater-retarding structures. Note that estimated annual depletion decreases steadily to a somewhat uniform rate of 1,300 acre-feet per year after the permanent pools are filled with sediment. The runoff depletion effects of the structures diminish as sedimentation of the reservoirs progresses because the primary factors affecting depletion are surface area and storage at the lowest uncontrolled outlet and outflow rate.

## REDUCTION OF SEDIMENT YIELD TO GARZA–LITTLE ELM RESERVOIR

For the 39-year period 1928–66, the response-model results for sediment inflow to Garza–Little Elm Reservoir were 60,400 acre-feet with the 162 floodwater-retarding structures in place throughout the period,

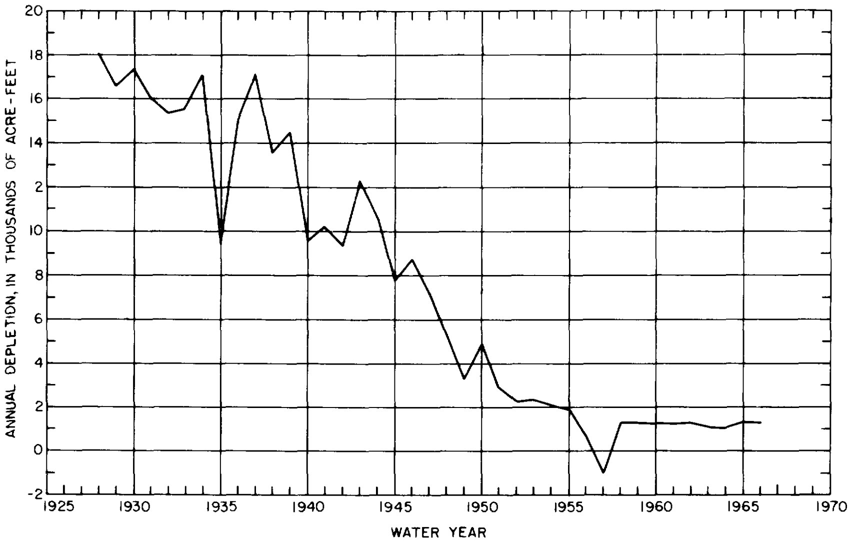



FIGURE 21.—Estimated depletion of runoff into Garza–Little Elm Reservoir with full development of floodwater-retarding structures.

and 80,100 acre-feet without the structures in place. A total savings in sediment storage of 19,700 acre-feet in Garza–Little Elm Reservoir is indicated.

The results of two reservoir-sedimentation surveys were available as checks on the results from water-sediment discharge relations derived and used on a monthly basis in the response model. These surveys were: (1) Lake Dallas survey of September 1938, covering the storage period since February 1928, in which the average annual sediment yield was 1.13 acre-feet per square mile, and (2) Garza–Little Elm Reservoir survey of September 1960, covering the storage period since November 1954, in which the average annual sediment yield was 1.40 acre-feet per square mile. For the period covered by the Lake Dallas survey, the response-model results showed an average annual sediment yield to Garza–Little Elm Reservoir of 1.09 acre-feet per square mile. This 4-percent difference between the two results is well within the accuracy limits for either determination. Before comparing the results of the Garza–Little Elm Reservoir sedimentation survey of 1960 with results from the response model, it was necessary to adjust the sediment survey data for sediment trapped by upstream floodwater-retarding structures in place during the period November 1954 to September 1960. After this adjustment was made, an average annual sediment yield of 1.49 acre-feet per square mile was obtained for the survey. This value compares with 1.62 acre-feet per square mile from the response model—a difference of 9 percent.

Because sediment yield varies exponentially with runoff, the use of average annual values, although widely accepted, is to be avoided where possible. To illustrate this point, the response model showed the sediment yield to Garza–Little Elm Reservoir during April and May 1957 to be 60 percent of the total sediment yield during the period November 1954 to September 1960. Moreover, sediment yield for May 1957 was greater than the annual yield for all but 3 of the 39 years in the model.

## CRITICAL RUNOFF STUDIES

From the preceding section, it is obvious that the critical condition (maximum depletion) occurs immediately after the floodwater-retarding structures are put into operation. Depletion of surface flow diminishes as the permanent pools are filled with sediment. Hence, the rate at which effects diminish depends on the sediment yield of the watershed. The problem for planning and operating agencies is, then, threefold:

1. Immediate effects on watershed yield.
2. Immediate effects on firm yield of existing reservoirs.
3. Long-term effects on watershed yield.

To determine some of these effects, the data for the Garza–Little Elm watershed for the period 1928–66 were run through the model with no diminution of sediment-pool storage capacity. This is, of course, a condition which would not exist but is useful in determining the critical condition which might occur.

The net results computed using the assumption of no sediment-pool diminution and other factors as previously defined are shown in table 20. The figures in this table are markedly different from those in table 19, illustrating the effects of diminution of permanent storage. The results of this study relative to net annual depletion are graphically shown in figure 22. The years having smallest values of net depletion are years of above average rainfall in which rainfall on pools largely offset consumptive losses—for example, in 1957.

## ANNUAL INFLOW-OUTFLOW RELATION

In a previous section of this report, a simple linear-regression equation for annual outflow from floodwater-retarding structures as a function of inflow was developed (eq 2). This relation was based on records for the seven study areas for period 1959–66. This relation is representative of the condition of little or no sediment trapped in the pools—that is, the critical condition insofar as flow depletion is concerned. A comparison of the outflow computed by the mathe-

TABLE 20.—*Annual water budget for floodwater-retarding reservoirs upstream from Garza–Little Elm Reservoir, assuming no sedimentation, 1928–66*

[Totals rounded]

| Water year | Net inflow (acre-ft) | Rainfall on pools (acre-ft) | Pool consumption (acre-ft) | Net depletion (acre-ft) | Outflow from structures (acre-ft) |
|---|---|---|---|---|---|
| 1928 | 39,230 | 9,090 | 27,140 | 18,050 | 26,860 |
| 1929 | 89,150 | 8,950 | 25,520 | 16,570 | 70,690 |
| 1930 | 50,150 | 7,020 | 24,330 | 17,300 | 38,580 |
| 1931 | 65,680 | 9,180 | 25,210 | 16,030 | 48,380 |
| 1932 | 174,400 | 11,150 | 27,040 | 15,890 | 154,800 |
| 1933 | 87,440 | 9,600 | 25,760 | 16,160 | 73,370 |
| 1934 | 51,300 | 5,440 | 23,550 | 18,110 | 38,010 |
| 1935 | 168,200 | 12,120 | 22,290 | 10,160 | 151,600 |
| 1936 | 102,900 | 10,350 | 27,180 | 16,830 | 80,920 |
| 1937 | 61,510 | 7,620 | 26,880 | 19,260 | 47,320 |
| 1938 | 163,400 | 10,100 | 26,320 | 16,220 | 150,800 |
| 1939 | 41,020 | 5,660 | 23,890 | 18,220 | 24,060 |
| 1940 | 91,870 | 9,080 | 21,400 | 12,320 | 75,730 |
| 1941 | 211,000 | 14,260 | 27,260 | 13,010 | 195,600 |
| 1942 | 233,600 | 13,910 | 27,050 | 13,140 | 223,400 |
| 1943 | 71,160 | 7,310 | 26,140 | 18,830 | 54,980 |
| 1944 | 89,380 | 7,970 | 24,040 | 16,070 | 70,770 |
| 1945 | 266,700 | 14,350 | 26,680 | 12,330 | 249,300 |
| 1946 | 171,100 | 10,160 | 27,430 | 17,270 | 159,000 |
| 1947 | 120,200 | 9,580 | 26,190 | 16,620 | 105,300 |
| 1948 | 114,800 | 9,200 | 26,420 | 17,220 | 97,160 |
| 1949 | 69,300 | 8,220 | 23,210 | 15,000 | 50,690 |
| 1950 | 211,200 | 14,320 | 27,410 | 13,040 | 194,700 |
| 1951 | 39,380 | 5,770 | 26,470 | 20,700 | 23,830 |
| 1952 | 21,870 | 5,180 | 22,460 | 17,280 | 9,420 |
| 1953 | 36,510 | 5,660 | 20,560 | 14,900 | 19,800 |
| 1954 | 24,890 | 6,510 | 24,790 | 18,290 | 8,200 |
| 1955 | 30,330 | 7,250 | 21,500 | 14,250 | 12,270 |
| 1956 | 4,770 | 2,000 | 15,380 | 13,380 | 0 |
| 1957 | 329,200 | 14,720 | 20,470 | 5,750 | 314,000 |
| 1958 | 197,900 | 12,120 | 26,500 | 14,380 | 182,900 |
| 1959 | 24,370 | 5,680 | 20,940 | 15,260 | 9,290 |
| 1960 | 84,420 | 9,650 | 26,700 | 17,040 | 64,360 |
| 1961 | 47,170 | 7,610 | 24,620 | 17,020 | 33,380 |
| 1962 | 120,400 | 12,150 | 26,270 | 14,120 | 100,200 |
| 1963 | 52,120 | 5,710 | 26,660 | 20,950 | 41,570 |
| 1964 | 86,660 | 9,080 | 22,670 | 13,580 | 62,940 |
| 1965 | 162,800 | 11,500 | 27,150 | 15,650 | 148,100 |
| 1966 | 173,900 | 11,490 | 26,300 | 14,810 | 159,300 |
| Totals | 4,181,400 | 356,800 | 967,800 | 611,000 | 3,571,600 |

matical model on a monthly basis, assuming no sedimentation of pools, with outflow computed using equation 2 on an annual basis is shown in figure 23. These results indicate that the simple linear equation is quite accurate on an annual basis for determining effects of floodwater-retarding structures on outflow before sedimentation occurs.

## FIRM-YIELD STUDY

The agency depending on water supply from a conservation reservoir downstream from a system of floodwater-retarding reservoirs is seeking answers to the following questions: (1) What are the effects of the system on dependable yield now? (2) What will be the effects in future years? Obviously, there is an immediate reduction in dependable yield as inflow is reduced. This reduction will diminish as the permanent pools of the floodwater-retarding structures are

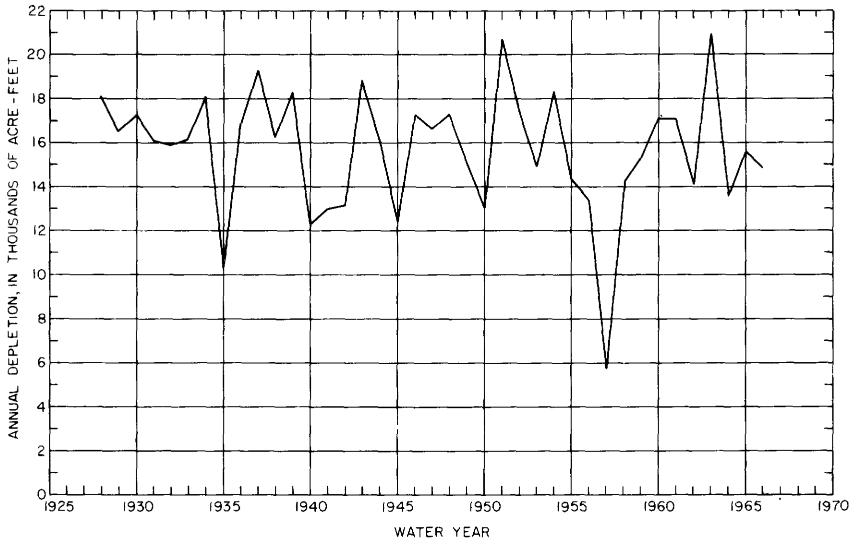



**FIGURE 22.**—Estimated depletion of runoff into Garza–Little Elm Reservoir with full development of floodwater-retarding structures, assuming no sedimentation of pools.

filled with sediment. The decrease in sediment inflow into the downstream conservation storage reservoir is beneficial because more water will be available for use during periods of low inflow at some future date.

Many methods are used in determining the dependable or "firm" yield of an existing water-supply reservoir. Probably the most common method used by municipalities is to use the "drouth of record" approach. In this approach, the worst drouth recorded in historical streamflow records is considered to be the critical period. The reservoir is assumed to be full at the beginning of the critical period. Using historical runoff and estimated evaporation rates, a reservoir-operation study is made wherein various draft rates are imposed until the reservoir is drawn down to a preselected level at the end of the critical period.

A firm-yield study was made for the Garza–Little Elm watershed using computed inflows with and without full development at proposed floodwater-retarding structures in place and accounting for sediment inflows into floodwater-retarding structures and into Garza–Little Elm Reservoir. For the firm-yield study, a standard computer program developed by the city of Dallas Water Works Department for their use was utilized. The reservoir-yield program is designed to determine the draft rate which will draw a reservoir down to a selected

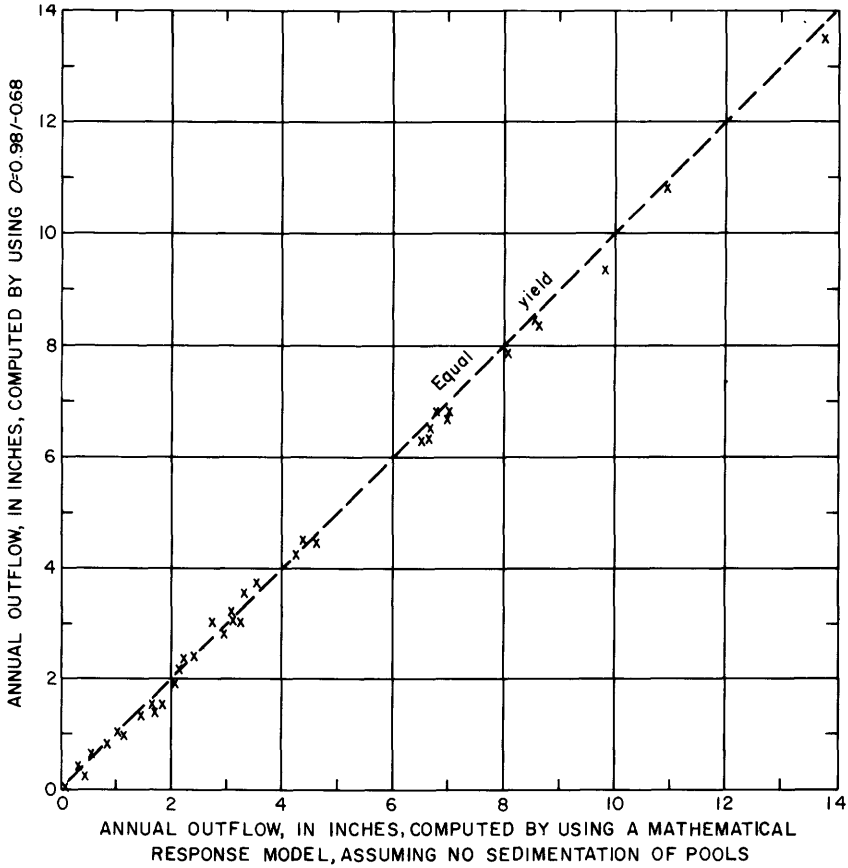



FIGURE 23.—Comparison of annual outflows from a system of floodwater-retarding structures, computed from linear regression and from a mathematical model (assuming no sedimentation of pools), water years 1928–66.

level during a period of drouth. Some features of the program are as follows:

1. The selected lower level may be at zero capacity or higher.
2. Reservoir capacity may be adjusted for sediment accretion by an area-increment method.
3. A varying monthly draft may be used.
4. Input is monthly inflow, net evaporation, draft rate, surface area at 10-foot intervals, and upper and lower limits of usable storage.
5. Computation of dependable yield is by an iterative procedure. Initial draft is set large so that the reservoir is emptied before the end of the drouth; draft rate is then reduced incrementally until storage remains at the end of the drouth period.

6. Output includes monthly and annual totals of inflow, draft, evaporation, net change in storage, storage at the beginning of each period, monthly mean surface area, calculated dependable yield, and surface-area and capacity tables.

Available for the study were monthly inflows for water years 1928–66, computed as previously explained. Net evaporation rates as shown by Kane (1967) were used. For the period 1928–66, the critical drouth was from July 1951 through January 1957. Lowry (1959) cited the period as the most severe drought period the State of Texas had experienced in 70 years of rainfall record. The period is a good example of the effects of the floodwater-retarding program.

A total of 12 different runs were made using the firm-yield program assuming the reservoir could be drawn down to 448.0 feet above mean sea level—essentially zero capacity. The monthly draft pattern used, shown in figure 24, was furnished by the city of Dallas Water Works Department. Two basic conditions were considered in the firm-yield study, one assuming full-watershed development, the other assuming no upstream development. No adjustments were made for changes in land-management practices. The basic capacity table for Garza–Little Elm Reservoir was developed by the U.S. Army Corps of Engineers in 1963 and based on the 1960 resurvey.

For the condition of no upstream development, firm yield was computed for six different sedimentation conditions in Garza–Little Elm Reservoir. The six conditions used data from the 1963 capacity table adjusted for estimated accumulated sediment at 0, 10, 20, 30, 40, and 50 years. Rates of sediment accumulation were based on the assumption that sediment inflow computed for the 39-year period, 1928–66, was representative of the average condition. Sediment was assumed to be deposited 25 percent in the flood pool—above 515.0 msl (mean sea level) elevation—and 75 percent in the conservation pool. Surface-area tables for the reservoir were adjusted by a linear area-proportion method. The results indicate that dependable yield during the 67-month drouth period would have been 120,300 acre-feet per year at the start, decreasing to 114,700 acre-feet per year at the end of 50 years.

For the condition of full upstream development (162 structures), six runs were made, all with the assumption that the reservoir could be drawn down to 448.0 feet elevation. Estimated sediment inflow into Garza–Little Elm Reservoir was reduced by 24.6 percent, as found in the previous computations. Inflow into the reservoir after 0, 10, 20, 30, 40, and 50 years was estimated as follows:

1. For 0 year after upstream development, inflow was assumed to be that computed by the mathematical model under the critical

condition—that is, no reduction in capacity of floodwater-retarding sediment pools. Original total capacity of the 162 sediment pools used was 16,409 acre-feet.

2. For 30 years after development, inflow was assumed to be that computed by the mathematical model allowing for diminution of sediment pools. At the beginning of this period in the mathematical model, only 300 acre-feet of storage in the sediment pools remained; therefore, the computations are representative of the condition of full sediment pools.
3. For 10 years and 20 years after development, inflow was linearly interpolated between the 0-year and 30-year condition.
4. For 40 years and 50 years after development, inflow was assumed to be the same as for the 30-year condition.

For these assumptions, the following firm yields were found:

1. Firm yield was initially decreased from 120,300 to 108,300 acre-feet per year.
2. Firm yield increased to 116,500 acre-feet per year for the 30-year condition.
3. Firm yield then decreased to 114,800 acre-feet per year for the 50-year condition.

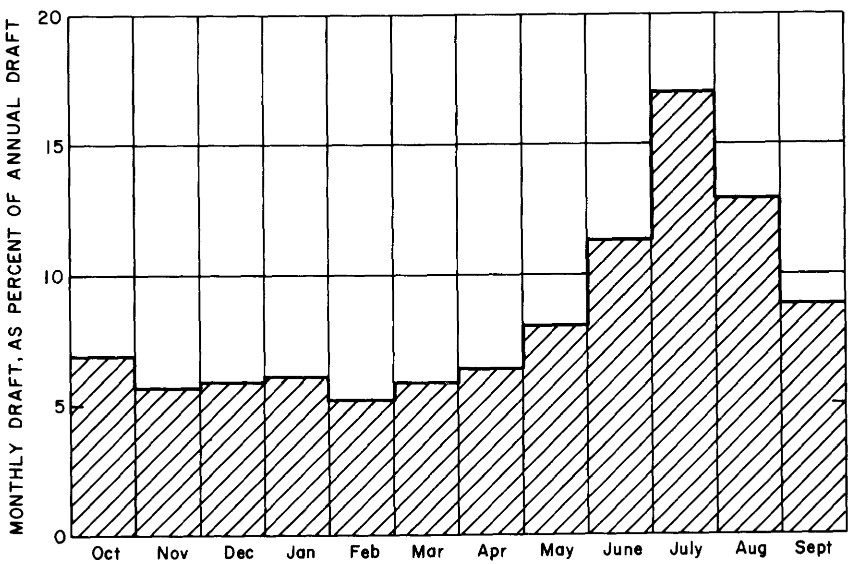



FIGURE 24.—Draft pattern used for firm-yield study of Garza–Little Elm Reservoir.

A summary of the results is shown in table 21 and figure 25. The results indicate that the firm yield would be initially reduced by 10 percent under the full-development condition. The results also indicate that after 50 years, the firm yield of Garza–Little Elm Reservoir would have been increased by almost 0.1 percent had the structures been effective throughout. However, it cannot be inferred from this study that the same applies to all watersheds. The distribution of inflow, draft, evaporation, and sediment in the reservoir all influence the computed firm yield, and a different set of assumptions could yield a different set of answers. However, because a uniform criterion was applied for all computations, the results are indicative of what may be expected from upstream development. In a watershed having a larger sediment yield, the increased storage available in the conservation reservoir owing to sediment trapped in the floodwater-retarding structures may more than offset the consumptive effects at a later date.

TABLE 21.—*Summary of results of firm-yield study for Garza–Little Elm Reservoir, with and without upstream development, drought of July 1951 to January 1957*

[Conservation pool top 515.0 ft above msl; bottom, 448.0 ft above msl]

| Sedimentation condition | Conservation pool, capacity (acre-ft) | Period totals: Inflow (acre-ft) | Period totals: Draft (acre-ft) | Period totals: Evaporation (acre-ft) | Dependable yield (acre-ft per yr) |
|---|---|---|---|---|---|
| **Inflow without upstream development** | | | | | |
| 1963 capacity table unadjusted: | | | | | |
| Sediment pool used | 464,700 | 535,300 | 677,800 | 322,200 | 120,300 |
| 1963 capacity table adjusted for given number of years accumulated sediment: | | | | | |
| 10 years | 449,300 | 535,300 | 671,500 | 313,000 | 119,200 |
| 20 years | 433,900 | 535,300 | 665,200 | 303,900 | 118,100 |
| 30 years | 418,500 | 535,300 | 659,000 | 294,800 | 117,000 |
| 40 years | 403,100 | 535,300 | 652,600 | 285,800 | 115,800 |
| 50 years | 387,700 | 535,300 | 646,400 | 276,600 | 114,700 |
| **Estimated inflow with upstream development** [Based on the assumption that all floodwater-retarding reservoir consumption would have reached Garza–Little Elm Reservoir] | | | | | |
| 1963 capacity table unadjusted: | | | | | |
| Sediment pool used | 464,700 | 462,200 | 610,400 | 316,500 | 108,300 |
| Inflow and reservoir capacity adjusted for given number of years accumulated sediment: | | | | | |
| 10 years | 453,100 | 483,800 | 625,700 | 311,200 | 111,100 |
| 20 years | 441,500 | 505,400 | 641,100 | 305,800 | 113,800 |
| 30 years | 429,900 | 527,000 | 656,300 | 300,600 | 116,500 |
| 40 years | 418,300 | 527,000 | 651,400 | 293,800 | 115,600 |
| 50 years | 406,600 | 527,000 | 646,700 | 286,900 | 114,800 |

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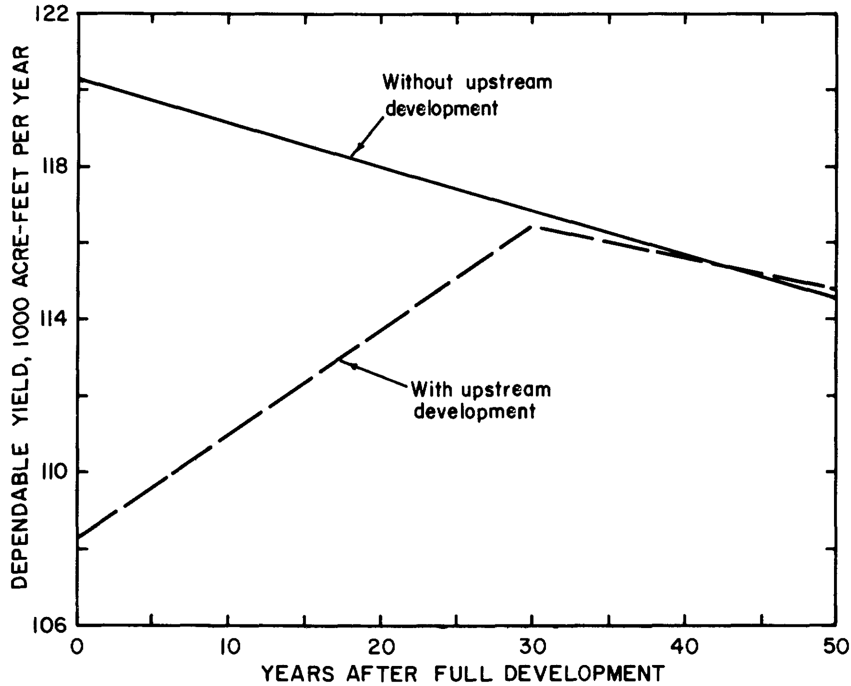


FIGURE 25.—Firm yield of Garza–Little Elm Reservoir, with and without upstream development, drought of July 1951 to January 1957.

## SUMMARY AND CONCLUSIONS

Hydrologic data collected since 1953 from the 11 study areas composing the Texas District small-watersheds project have afforded definition of the maximum probable effects of small upstream floodwater-retarding reservoirs on downstream water and sediment yield. The physiographic and climatic scope of the project further afforded development of techniques for making reliable areal extrapolation of pool consumption.

Inflow to and outflow from the system of floodwater-retarding reservoirs in the seven study areas with the longest record were found to be related on an annual basis by the equation: $O=0.98I-0.68$, where $O$ is annual outflow, in inches, and $I$ is annual net inflow, in inches. Because of the effects of carryover storage, a monthly relationship between inflow and outflow could not be adequately defined. The derived average relationship between annual net inflow to and outflow from these systems of floodwater-retarding reservoirs shows that when annual net inflow to the reservoirs is less than 0.7 inch, no outflow will generally occur. Whereas, when annual inflow is as much as 8 inches, 90 percent of the inflow will occur as outflow. Because the study period in the seven developed study areas spanned only the early years of the floodwater-retarding reservoir systems and thus the effects brought about by sedimentation and increased vegetal growth were of minimal influence, the inflow-outflow relationship should be qualified when used. As the permanent pools of the floodwater-retarding structures are filled with sediment, outflow will approach inflow. Therefore, the derived relationship should be used only to represent maximum consumptive effect of the reservoir system in preliminary hydrologic analyses subsequent to design and only in areas similar to the areas studied.

Analyses were made of the change in streamflow regimen resulting from the impoundment of tributary flood runoff and subsequent release at a much reduced rate but much longer duration. The analyses showed that although the maximum channel transmission losses of controlled flood discharge in these naturally ephemeral tributary streams are relatively high, maximum channel losses of storm runoff under uncontrolled conditions (based on 25 storm events) are of about the same order of magnitude. Therefore, the change in streamflow regimen imposed by systems of floodwater-retarding reservoirs was assumed to result in channel transmission losses not significantly different from those occurring in the passage of natural flood waves.

Suspended-sediment data collected by the U.S. Geological Survey and reservoir-sedimentation surveys made by the U.S. Soil Conservation Service provided the basis for definition of changes in the fluvial-sediment regimen brought about by systems of floodwater-retarding reservoirs. Trap efficiency of those reservoirs draining areas with approximately 15 percent sand in the suspended-sediment load was found to be about 98 percent; whereas, the trap efficiency of those reservoirs draining areas with mostly silt and clay in the suspended-sediment load was found to be about 97 percent. Analyses for suspended-sediment pickup by the outflow from structures were made in two study areas. These analyses showed that owing to the low magnitude of the outflow (5–10 cubic feet per second per square mile controlled) the sediment pickup is small. Although the increase in suspended-sediment concentration of the outflow was found to range from about 5 percent in the Pin Oak Creek study area to about 96 percent in the Little Elm Creek study area, the quantitative increase in fluvial-sediment load was minor. Degradation of stream channels downstream from the system of reservoirs has been observed and is expected to continue until the physical forces governing fluvial-sediment transport are in balance.

Average annual reservoir consumption from the actions of evaporation, evapotranspiration, and seepage in the seven study areas analyzed ranged from 1.57 inches of equivalent runoff in the easternmost study area, where the annual runoff averaged 6.96 inches, to 0.77 inch of equivalent runoff in the westernmost study area, where the average annual runoff was 2.35 inches. The effect of consumption on downstream flow is partially offset by rainfall on pool surface. Groundwater studies in two study areas did not show positive evidence that the impounded water was recharging the underlying ground water. Studies of streamflow at stream-gaging stations which gage outflow from the study areas indicated no change in base flow.

Multiple-linear-regression techniques (computer programed) were used in developing methodology to determine reservoir consumption in seven study areas and to estimate time-equating physical changes that take place in the reservoir systems. The physical and climatic factors causing consumption were grouped as variables in regard to their relative effect on the actions of evaporation, evapotranspiration, and seepage. Data from seven study areas with the common period of record October 1958 to September 1966 were used in the analysis. The resulting generalized regression equation is usable in determining monthly consumption in similar areas developed with floodwater-retarding structures. This equation was used in a response model to determine effects of structures on yield to a water-supply reservoir.

To demonstrate the effects of systems of floodwater-retarding reservoirs on the water and sediment yield to a downstream major reservoir, the results and methodology developed from all the studies were applied to the Garza–Little Elm Reservoir drainage basin in a computer-programed response model. This drainage basin of 1,660 square miles is to be developed with 162 floodwater-retarding structures controlling runoff and trapping sediment from 427 square miles, or 26 percent of the total drainage area. Reliable estimates of total monthly inflow to Garza–Little Elm Reservoir for the period October 1927 to September 1966 were available from the U.S. Army Corps of Engineers and the U.S. Study Commission—Texas as input data to the response model. Water-sediment discharge relations were derived for the areas controlled by the structures, as well as for the runoff through and below the structures, and used in the response model. Results of the response model showed that with full development, depletion of yield to Garza–Little Elm Reservoir would be as much as 10 percent annually in the early years, but after the permanent pools of the floodwater-retarding structures are essentially filled with sediment, depletion of yield would be generally less than 1 percent annually. Assuming full development in 1927, the total depletion of yield to Garza–Little Elm Reservoir during the 39-year period of study was found to be 296,800 acre-feet out of 18,256,000 acre-feet total inflow. During this period, the floodwater-retarding structures were estimated to have kept 19,700 acre-feet of sediment from being deposited in Garza–Little Elm Reservoir.

A firm- or critical-yield study was made for Garza–Little Elm Reservoir on the basis of two sets of conditions: with floodwater-retarding structures in the drainage basin, and without these structures. The 67-month period July 1951 to January 1957 was found to be the critical runoff period in the 39-year period of study. The monthly draft pattern and firm-yield computer program developed by the city of Dallas Water Works Department were used in the study. Results showed that with full development, assuming all water consumed at the floodwater-retarding structures would have naturally reached the reservoir, firm yield (annual) would have been initially reduced by 10 percent. After 30 or more years, when the permanent pools of floodwater-retarding reservoirs would have been mostly filled with sediment, the firm yield was found to be about the same with or without the upstream development.

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