NUMERICAL SIMULATION OF A WATERSHED AS A MEANS TO EVALUATE SOME EFFECTS OF FLOODWATER-RETARDING STRUCTURES ON RUNOFF

by

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PREFACE

This report is one of several to be prepared under Grant No. 14-01-0001-1051 sponsored under the program of the Office of Water Resources Research, U. S. Department of Interior.

New methods of relating runoff to rainfall are needed to provide input into the planning of water resources developments. Different methods using analogue and digital computers show promise of meeting this need. In this investigation the continuous numerical simulation of a watershed is used. Among others this method has the advantage of supplying information on both peak flow events due to individual storms and on yield for a weekly or monthly period. The current study is on the application of the numerical simulation process to a small watershed in Texas to evaluate some effects of floodwater-retarding structures on runoff.

The authors wish to express their gratitude to Professor B. J. Claborn of Texas Technological University, who made the translation of the model, for his valuable suggestions, to Mr. S. P. Sauer of the U. S. Geological Survey who made available the necessary data for the study, and to Professor C. W. Morgan of The University of Texas for his comments and review of the manuscript. The authors also are grateful for the assistance of Mrs. Karen Roberts of The University of Texas Bureau of Engineering Research who did the drafting, and Mrs. Linda Knight who typed the manuscript.

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ABSTRACT

This study was undertaken to investigate the application of a continuous accounting method for relating runoff to rainfall to a 70.4 square mile watershed in Texas and, in addition, to explore use of the method as a means for evaluating the effect of floodwater-retarding structures on the runoff characteristics of the watershed. During a period of five years, six floodwater-retarding structures were built in the watershed at locations which controlled the runoff from 39.3 percent of the watershed area.

The method of the study was to first apply the continuous accounting process for a period before the structures were built to fix the model parameters for the watershed. Then using these parameters simulation was done for a post-construction period. The results which represented the runoff to be expected had the structures not been built were compared with the recorded runoff for the same period. This gave an overall indication of the effects of the floodwater-retarding structures on the runoff characteristics. Results indicate that the digital simulation was satisfactorily applied to the watershed and that the floodwater-retarding structures reduced flood peaks, lengthened the recession parts of the hydrographs and slightly reduced the water yield.

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CHAPTER I

INTRODUCTION

Hydrologists have developed techniques for the collection of basic data, and for the analysis, correlation and extension of these data in order to accomplish the goals of hydrology. Adequate projections and correlations of data involve considerable numerical analysis, and many of the methods originally developed for manual solution can be profitably programmed for digital computers. Comprehensive digital simulation models of the hydrologic cycle that generate streamflow, actual evapotranspiration, and related data directly from meteorological inputs are products of the computer revolution and such have a short history. Linsley and Crawford have developed a computer program based on water balance methods for simulation of the hydrologic cycle which is known as the Stanford Watershed Model IV. A large scale digital computer is required to use the watershed model.

This program can be used to evaulate the effects of changes in hydrologic characteristics of a watershed on runoff. It has been used in this investigation to evaluate the effects of six floodwater-retarding structures on the runoff of Mukewater Creek at Trickham, Texas, whose area is 70.4 square miles. This objective was accomplished by simulating the runoff without the structures for a post-construction period and comparing this with the measured runoff for the same period which would give an overall indication of the effects of the floodwater-retarding structures on the runoff characteristics. This report contains the summary of this study.

A. Scope and Procedure of the Study

The digital model uses mathematical expressions to provide a running account of all moisture entering, stored within, and leaving the watershed by placing it into such hydrologic categories as precipitation, interception, evapotranspiration, groundwater, interflow, and surface runoff. All the water entering the basin is accounted for until it evaporates, infiltrates to groundwater, or enters a channel. The computer program then routes the runoff from the point it enters tributary channels to the downstream point for which a hydrograph is required. The input necessary for the computer program consists of hourly precipitation, daily streamflow (optional), average daily evaporation by 15-day periods, a translation histogram for channel routing, an array describing interflow characteristics of the basin, another array describing infiltration characteristics, 28 constants describing physical characteristics of the watershed, and 4 constants describing initial moisture conditions. Precipitation, streamflow and evaporation data are obtained from climatological and hydrologic records. Most of the values of the arrays and constants can be estimated from hydrologic and topographic data. The rest have to be selected by a trial-and-error process of attempting to match computer synthesized hydrographs with recorded hydrographs.

For this study precipitation, streamflow and evaporation data have been collected for three water-year periods, 1956-1957-1958, prior to the construction of the structures and prepared as input for the model with some of the parameters. The rest of the parameters were chosen by trial-and-error process of trying to match synthesized and recorded hydrographs and mean daily flows for preconstruction period. The same parameters were used to simulate runoff with the precipitation and evaporation data of water years 1965-1966 in the post-construction period. The simulation results and recorded runoff data have been compared for these water years and the effects of the reservoirs have been analyzed from the point of views of hydrograph shape and water yield. Finally an attempt has been made to simulate the runoff from the watershed with the structures by adjusting the parameters.

B. Selection of Study Area

Mukewater watershed was selected as the study area for the following reasons:

i) It has a dense rainfall recorder pattern (Fig. II. 2)

ii) It has a long period of rainfall and runoff data prior to the construction of the floodwater-retarding structures.

iii) A fairly large portion of the watershed (about 40%) is controlled by the structures, thus their influence on the runoff should be significant.

iv) There is a comprehensive report available containing data for the period of record prior to basin development, namely the 1954-60 water years. (Sauer, 1965)

C. A Short History of Small Watershed Projects in Texas

The U. S. Soil Conservation Service is actively engaged in the installation of flood and soil erosion reducing measures in Texas under the authority of "The Flood Control Acts of 1936 and 1944" and "Watershed Protection and Flood Prevention Act" (Public Law 566), as amended. The Soil Conservation Service has found a total of 3,438 floodwater-retarding structures to be physically and economically feasible in Texas. As of September 30, 1966, 1,081 of these structures had been built.

Investigation of small watersheds in Texas by the Geological Survey were started in 1951 and are now being made on 11 small watersheds (study areas) to provide needed data for analyses. Figure I.1 shows location of Mukewater Creek and the other study areas. The 11 study areas were chosen to sample watersheds having different rainfall, topography, geology and soils. On four of the study areas (Mukewater, North, Little Elm, and Pin Oak Creeks), streamflows and rainfall records were collected prior to construction of the floodwater-retarding structures, thus affording the opportunity for analyses of the conditions "before and after" development. Structures have now been built on three of these study areas.

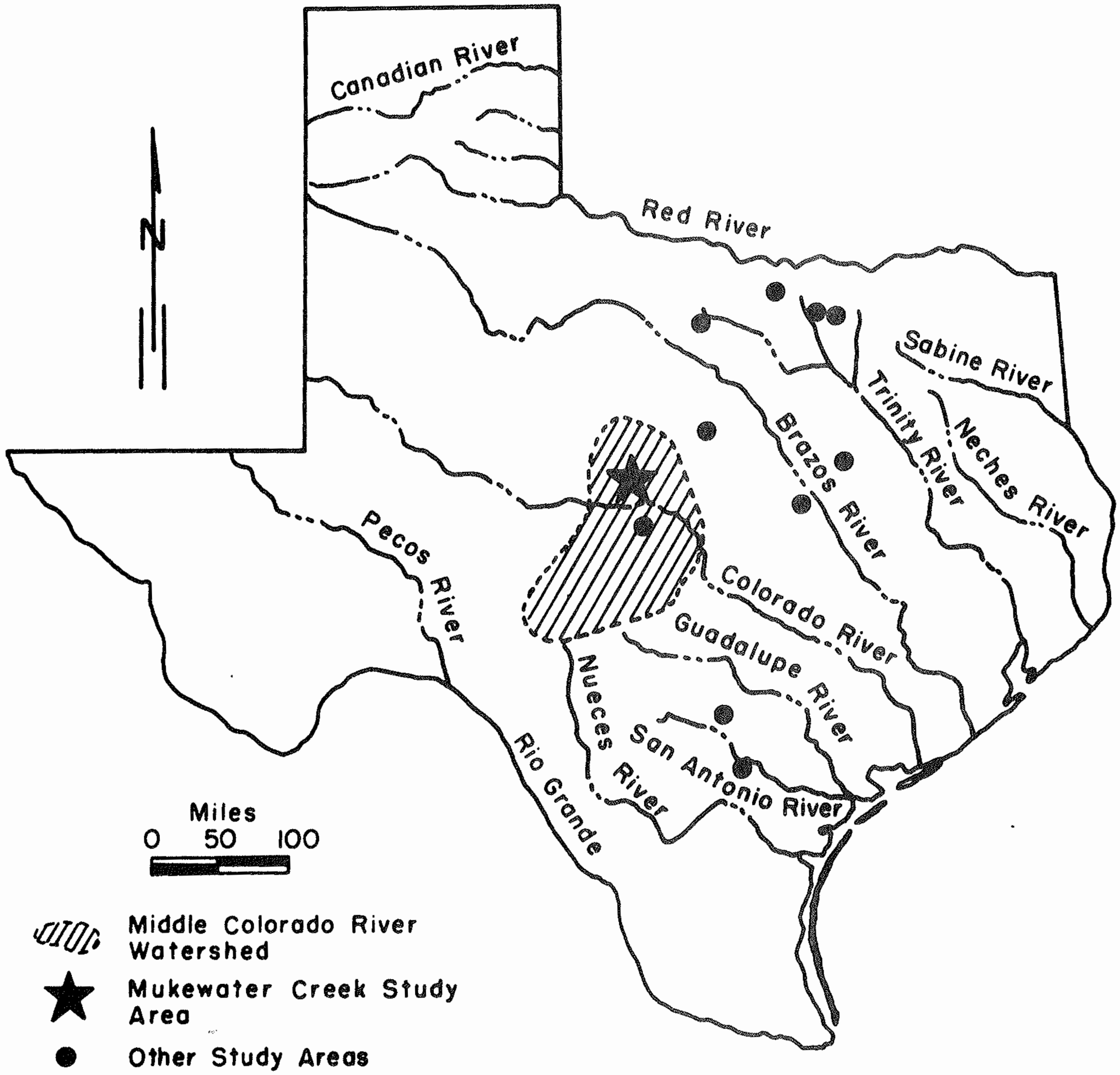

FIGURE I.1 MAP OF TEXAS SHOWING THE LOCATION OF MUKEWATER CREEK AND OTHER STUDY AREAS

CHAPTER II

MUKEWATER CREEK STUDY AREA

A. Location

The headwaters of Mukewater Creek are near the towns of Santa Anna in Coleman County and Bangs in Brown County. The creek flows in a southeasterly direction for approximately 30 miles before entering Home Creek, a tributary of the Colorado River. Figure I.1 shows the location of the watershed. Width of the watershed ranges from 4 to 10 miles. Total area of the watershed is 137 square miles, of which 70.4 square miles is in the study area above the stream gaging station, Mukewater Creek at Trickham, Texas (Fig. II.1)

B. Climate

The climate of the study area is temperate and subhumid. Moderate winters with sudden large changes in temperature are common, as are long summers and comparatively low humidity. The average minimum temperature for January is about 34°F, and the average maximum temperature for August is about 96°F. Maximum and minimum recorded are 114°F and -6°F. The average growing season is 232 days and extends from March 25 to November 12. Frost has occurred as late as April 13 and as early as October 19.

The 68-year (1893-1960) average rainfall at Brownwood (15 miles northeast of the study area) is 27.55 inches. The weighted mean rainfall on the study area during 9-year period, 1952-1960, was 22.05 inches. Annual rainfall ranges from about 13 inches to about 45 inches, a large

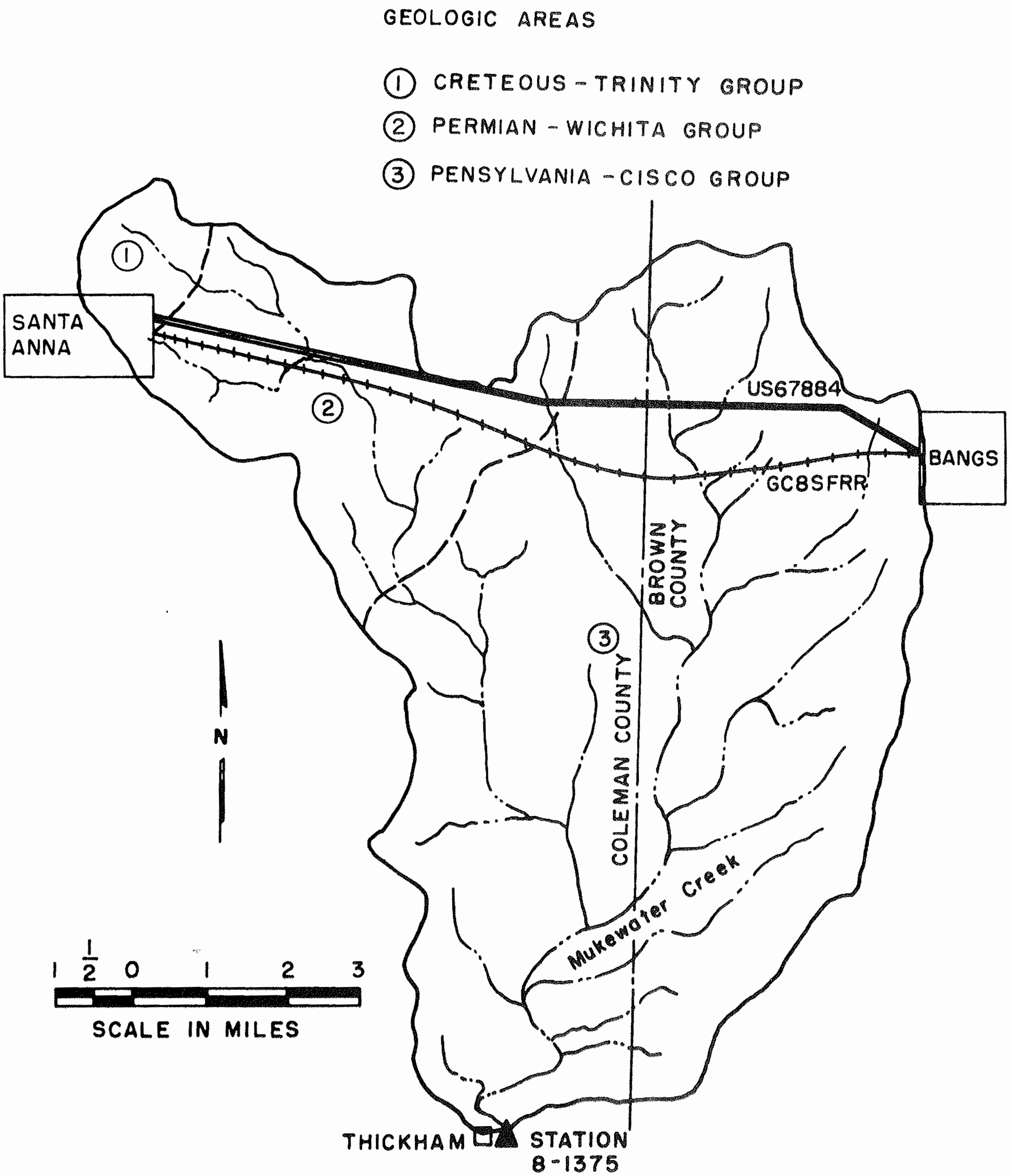

FIGURE II.1 MUKEWATER CREEK STUDY AREA AND ITS GEOLOGIC SUBAREAS percentage of which sometimes occurs in a single storm. In the storm of April 30 to May 1, 1956, 4.85 inches or 38 percent of the annual rainfall occurred in five hours.

C. Topography and Surface Cover

The topography is mildly rolling in the lower and eastern part to steeply rolling along the western edge and in the northwestern part. Divides within the watershed are well defined. The flood plain of the main channel is wide and relatively flat. The steepest part of the area is the northwest corner. In this area two flat-topped buttes, with very steep side slopes, rise approximately 300 feet above the rolling plains. These two buttes are known locally as the Santa Anna Mountains.

Although some upland parts of the study area are relatively flat, a reconnaissance of the area October 13-14, 1962, following a rainstorm, indicated that all areas contributed to the runoff. Some ponding was noted, particularly in fields which are terraced. Although these terraced areas drain rather slowly, they are considered as contributing to the runoff.

Stream gradients in the study area are moderate ranging from 0.0018 ft/ft in the lower part of the watershed to 0.0090 ft/ft near the headwaters. Sauer (1965) has divided the watershed into six subareas and calculated the weighed mean slope of the study area as 0.0029 ft/ft by using Carter's formula. Channel lengths and slopes were determined only for well-defined channels. Stream gradients were based on elevations determined by altimeter. An altimeter survey of stream channels in the watershed was made by Sauer on October 13-14, 1962. Stream gradients are low but in general increase rapidly near the rim of the watershed.

Trees in the study area are generally sparse, except along stream channels where shrubs, grass and trees are more dense. Constrictions in the channel often become clogged with logs and debris during flood periods. The area north of U.S. Highway 67 has a denser growth of trees than the remainder of the area. This area also has a smaller percentage of land in cultivation.

The study area is entirely rural. Small towns near the headwaters do not affect the runoff characteristics of the study area. Farmland treatment and stock ponds comprise the major man-made features that affect the runoff characteristics of the watershed. According to data furnished by the U.S. Soil Conservation Service, there were 211 stock ponds in the study area with a total capacity of 709 acre-feet and a total drainage area of 14.0 square miles in March 1962. Their number remained the same during the construction period for the floodwater structures.

Land use in the watershed is as follows:

Land Use	Percent
Cultivation	36
Pasture	62
Miscellaneous	2

Impervious area, roads and towns, is less than half of 1 percent. Cultivated land is predominant in the valleys near the stream channels, and the drainage divides are used primarily for pasture and range land. The above percentages are almost the same for the periods studied before and after building of the structures.

D. Geology

From the geological investigations for occurrence and quality of groundwater in Coleman and Brown Counties, Texas, the watershed can be divided into three geologic areas. These areas are shown on Figure II.1.

The Cisco Group, the youngest rocks of Pennsylvanian age, covers the greatest part of the watershed. This group is approximately 400 feet in thickness. The rocks assigned to the group include the shales, limestones, sandstones, siltstones and thin beds of coal. The Group also contains channel-fill deposits consisting of lenticular sandstone and conglomerate. Most of the groundwater is in these lenticular sand units. Some water occurs also in the fractured limestone beds at or near their outcrop area.

Rocks of Wichita Group cover the second area. Rocks assigned to the Wichita Group of Lower Permian age include the thick shales, thin to massive limestones, thin sandstones and channel sands. The thickness of the Group averages about 1,200 feet. These rocks were deposited in an extensive shallow sea, and thus were deposited under widely varying conditions. Water-bearing strata of the Wichita Group consist of channel sands, fractured limestones, and also thin sands that occur in massive shale beds.

A small part of the watershed is covered by the Trinity Group of Cretaceous age. The thickness of this group ranges from a few feet to approximately 150 feet. Water-bearing zones of the group consist of sandstone, clay, gravel and sandy to shaley limestone. Grain size of sand and gravel varies from a fine grained pack sand to a rather coarse gravel. Facies changes within the group apparently cause local variations in water availability.

E. Instrumentation

Instruments to collect rainfall, runoff, and storage data in the study area consist of a network of rain gages, staff gages, or water-stage recorders at each of the six floodwater-retarding structures, and a stream gaging station on Mukewater Creek downstream from the six structures. Location of the instruments in the 1966 water year is shown on Figure II.2.

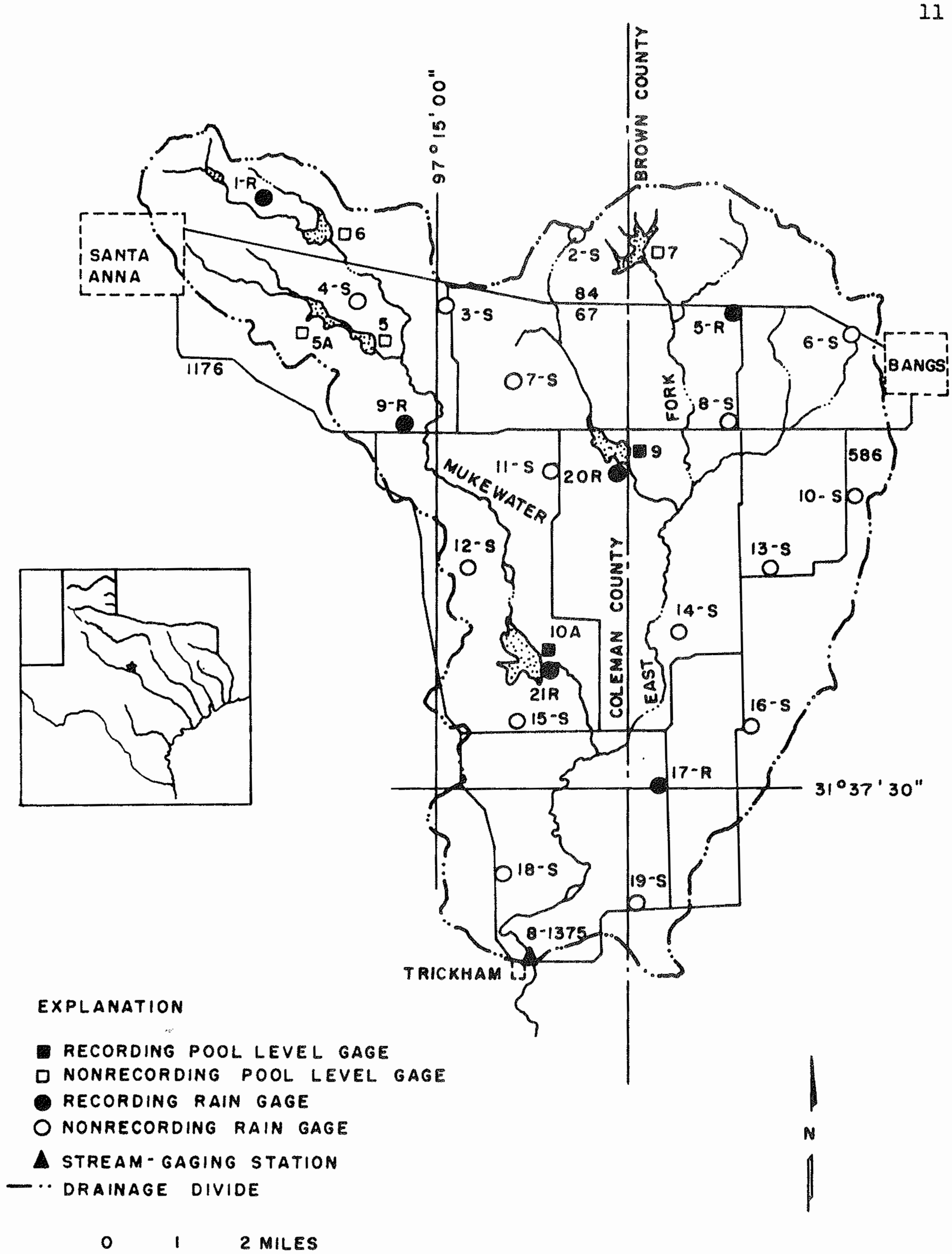

FIGURE II.2 MUKEWATER CREEK STUDY AREA SHOWING LOCATIONS OF FLOOD-WATER RETARDING STRUCTURES AND HYDROLOGIC INSTRUMENT INSTALLATIONS

1. Rainfall

Six recording and fifteen non-recording rain gages are located to provide the best geometric coverage of the study area to define the total rainfall and rainfall intensities. Two of the recording gages (20R and 21R) were installed in September 1965, and the rest were installed in September 1953. The locations of the gages were chosen in accordance with the United States Weather Bureau (USWB) procedures to provide the best geometric coverage of the study area. Gages were serviced and rainfall measured weekly by employees of the U.S. Soil Conservation Service.

Only the data from the recording gages have been used as input data for this study.

2. Runoff and Pool Contents

A continuous water-stage recorder at the stream-gaging station on Mukewater Creek at Trickham records the stage, which, together with measurements of streamflow, allows the computation of the total runoff from the study area. Streamflow records at this gage began August 28, 1951.

Two continuous water-stage recording gages are operated on two representative floodwater-retarding pools (sites 9 and 10-A), at which data are collected to compute the contents, surface area, inflow and outflow. Records at site 9 began January 19, 1961 and at site 10-A, records began April 2, 1965. Weekly readings of staff gages are made by Soil Conservation Service personnel at each of the remaining four floodwater-retarding pools. This provides data to determine the quantity of water retained or released from the structures in the study area.

F. Earlier Studies on the Watershed

Stanley P. Sauer (Sauer, 1965) investigated the effects of areal distribution of rainfall on the Mukewater study area by multiple correlation estimates. He estimated monthly and annual runoff both using areal distribution and neglecting it as a factor for the seven-year period, 1952-60. In accounting for areal distribution he divided the study area into six subareas. Estimated runoff by either procedure gave a degree of correlation on a monthly basis, good correlation on an annual basis and excellent correlation for the seven-year total runoff. For the seven-year period total runoff was estimated within one percent and three percent respectively, by the weighted mean rainfall and six subarea methods. However, no significant improvement in results was noted when areal distribution was accounted for, indicating that this factor was not as significant for the study area as it was thought to be.

G. Watershed Development

Six floodwater-retarding structures which control 27.6 square miles (39.3%) of the watershed were built by U.S. Soil Conservation Service in the period 1960-1965. Location of the structures is shown on Figure II.2. A typical cross section of the structures with outlet works is shown on Figure II.3. They have a combined storage capacity of 6184 acre-feet at emergency spillway crest, and 621 acre-feet (sediment pool capacity) at principle spillway crest. Their combined surface area is 853.5 acres at emergency spillway crest and 173.5 acres at principle spillway crest. Each structure has controlled openings also. Structure 10-A has a 42 inch, structure 9 has a 19 inch and the rest have 17 inch diameter outlet pipes. Data about the structures is given on Table II.1.

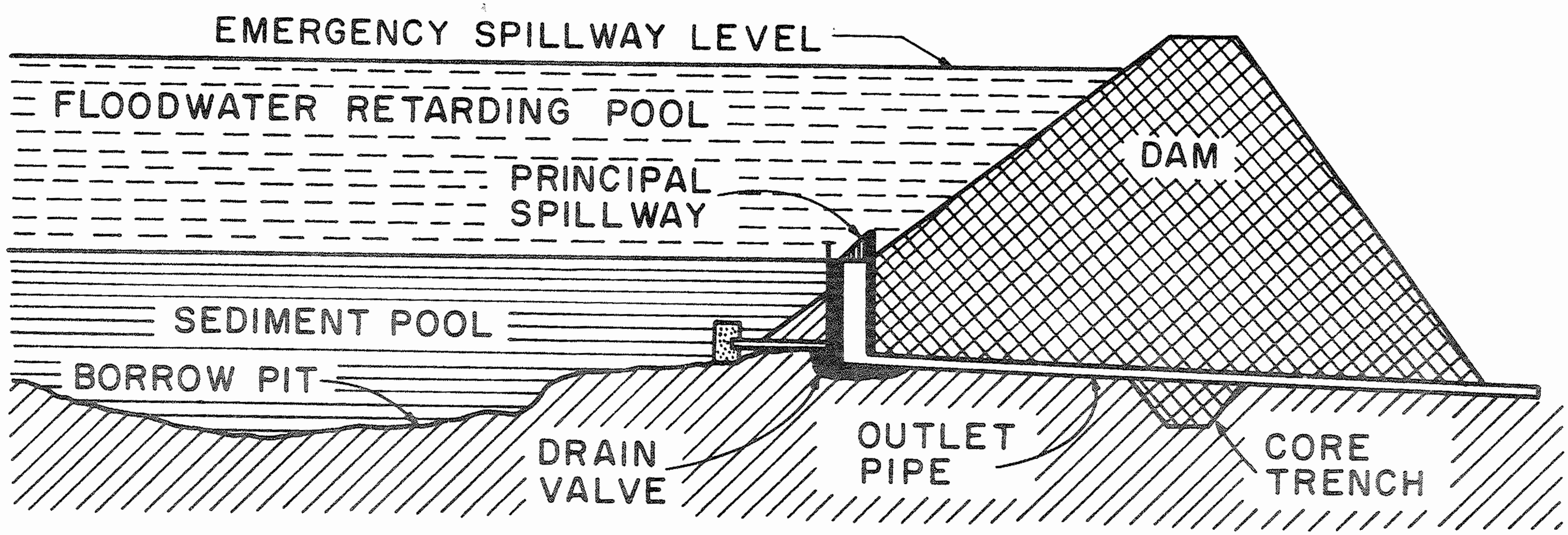

FIGURE II.3 SECTION OF TYPICAL FLOODWATER-RETARDING STRUCTURE WITH OUTLET WORKS

TABLE II.1 - FLOODWATER-RETARDING STRUCTURE DATA, MUKEWATER CREEK STUDY AREA

Site Number	Date Dam Completed	Drainage Area (Sq.Mile)	Storage Capacity (Acre-ft.)		Surface Area (Acre)		Staff Gage	
			Principal Spillway	Emergency Spillway c/	Principal Spillway	Emergency Spillway	Date Gage Established	Datum of The Gage Above Mean Sea Level
5	3-10-61	a/ 3.33	d/ 159	d/ 761	d/ 31	d/ 94.9	5-25-62	1,560.00
5-A	3-10-61	2.95					5-25-62	1,590.00
6	3-10-61	3.19	87	754	20.5	93.6	5-25-62	1,600.00
7	11-21-60	1.78	56	396	15	70	5-25-62	1,560.00
9	11-21-60	4.03	119	893	44	149	12-12-60	1,500.01
10-A	1-15-65	b/ 21.8	200	3380	63	446	4-2-65	1,462.00
	Total	27.6	621	6184	173.5	853.5		

a/ The 2.95 square mile above site 5-A is included in this total.
b/ The 6.50 square mile above sites 5, 5-A, and 6 is included in this.
c/ Included principal spillway storage capacity.
d/ Combined capacities and areas of 5 and 5-A.

Structures 5 and 5A are designed to operate as a unit and are classified as one structure by the U.S. Soil Conservation Service. The emergency spillway of site 5A drains into site 5. Site 5A has a small amount of floodwater-retarding storage which will drain past site 5, and therefore, is classified as a separate structure for this report.

Sauer (1965) states (written communication with M.L. Millgate, geologist, USGS, 1961) that there is little seepage and ground water recharge from the sites, because rocks in the vicinity of the study area are mostly shales and dense limestones through which water can not readily move.

CHAPTER III

THE WATERSHED MODEL

The availability of the high-speed digital computer has increased the importance of numerical analysis in hydrology, and it has become feasible to construct mathematical models of the entire runoff process for a watershed. Probably the best known model is the Stanford Watershed Model. Model IV was used for this study at the time Model V was under development. This model was conceived by Professor Linsley at Stanford in 1957 and evolved over the next few years with the aid of many people, notably Dr. Norman H. Crawford.

Another model, which might be classified basically as a statistical model, has been used by the Portland River Forecast Center. This model had its inception (prior to 1961) (Rockwood, 1958) and development is continuing (Kuehl, Schermerhorn, 1967). This model is used to predict stream hydrographs for flood forecasting. Statistical models have been used by other investigators to predict the location of water within a system on a monthly or annual basis. Such models lack the detail which characterize the continuous accounting models. The Stanford Model has been modified by Boughton (Boughton, 1966) for use in Australia in regions where only daily rainfall records are available. The Stanford Model was programmed for the computer in a compiler language peculiar to the Stanford University computer. Model II was translated into Fortran by Dr. James of the University of Kentucky, and Model IV has been translated by B. J. Claborn at The University of Texas at Austin.

The watershed model was used by Clarke (1968), Miller (1968), James (1965), and Dempsey (1968) for different purposes.

In this chapter Stanford Watershed Model will be discussed mostly based on the report given by Linsley and Crawford (Linsley, Crawford, 1966).

A. Model Structure

Mathematical expressions, which are mostly empirical, have been used for the diversion of the precipitation coming to the watershed. During any storm an assigned amount of the precipitation is taken by interception storage. The rest of the water infiltrates or flows as overland and interflow. Some of the infiltrated water reaches the groundwater and later flows into the channel as groundwater base flow. Evaporation takes place during and after the storm. The channel inflows which consist of overland flows, interflow and groundwater flows, are routed from the point they enter tributary channels to the downstream point for which a hydrograph is required.

Precipitation and potential evapotranspiration are the major data inputs. Additional meteorological data are used if snow fall is significant. Calculations begin from known or assumed moisture conditions, and are continued until the input data is exhausted. Precipitation is stored in the snowpack and in three soil-moisture storage zones.

The upper and lower zone storages, together with the groundwater storage, combine to represent variable soil-moisture profiles and groundwater conditions. The upper- and lower-zone storages control overland flow, infiltration, interflow and inflow to the groundwater storage. The upper-zone controls the initial watershed response to rainfall and is of major importance for smaller storms, and for the first few hours of larger storms. The lower zone controls watershed response to major storms by controlling longer term infiltration rates. Groundwater supplies the base flow to stream channels. Evaporation and transpiration may occur from all of these storages.

The total channel inflow from overland flow, interflow, and groundwater flow enters channel system simulation and emerges as synthesized streamflow, a continuous hydrograph of outflow from the watershed.

B. Input

The general model is a detailed simulation program that monitors watershed conditions and produces a wide variety of output. Included in the general model is a data tape section that reads data cards and stores precipitation data on magnetic tape for use in simulation. This conserves both computer time and core storage since the magnetic tapes of rainfall records can be stored and used many times. The tapes are read in small sections during simulation runs.

The general model input can be divided into fixed categories: Input used to create magnetic tapes of precipitation data and the additional input needed for streamflow simulation. The runs that prepare precipitation data tapes and the actual simulation runs are not usually made at the same time. The first card that the watershed model reads for any run contains two Boolean, or true-false variables, TAPE and RUN. If TAPES is non-zero the input for the precipitation tape option is read. In this portion hourly or quarter hourly rainfall data can be read and thus tapes can be prepared for the simulation. If RUN is non-zero the simulation input is read, and simulation output is to be obtained, the input required is of four types:

i) Control cards that key the program to input and output only what is required for the run.

ii) Physical data for each flow point in the run. This includes evapotranspiration data, streamflow and diversion data, and the initial soil-moisture and groundwater storages.

iii) Physical parameters for each watershed segment. Each segment has a channel time-delay histogram and data cards that contain general physical parameters, land surface parameters, and channel system parameters.

iv) Magnetic tape precipitation input previously prepared under the TAPES option.

The model will consecutively run any number of water years for any number of flow-points with any number of watershed segments or recording rain gages per flow point. All watershed conditions including flow in transit in the stream channels are carried over from one calculation period or water year to the next. The model will also read actual stream-gage data on an upstream gage, augment this through simulation of additional flows, and produce the continuous hydrograph that would occur downstream at some ungaged site. Figure III.1 shows the input sequence used for a typical simulation run.

On this figure tape files will have the precipitation data. Control card will have 0 or 1 for 11 options. 1 will indicate that the option is to be done, 0 will omit the option.

STANFORD WATERSHED MODEL IV

Simulation Input Sequence

Number of Water Years in Run
Number of Flowpoints per Water Year
Tape Files Space Forward

Repeats for each flowpoint.

Control Card
Station Name
Starting Moisture Condition (1st year only)
Evaporation Array
Streamflow (Optional)
Diversions (Optional)

Repeats for each Segment

Segment Name
Time-Delay Histogram
Physical Data
Land Surface Parameters
Channel System and Groundwater Parameters

FIGURE III - 1

These options are

DCS (1)	Detailed storm analysis
DCS (2)	and parameters optimization output
DCS (3)	Input bimonthly evaporation data
DCS (4)	Input stream flow
DCS (5)	Input diversions
DCS (6)	Output flow duration error table
DCS (7)	Output maximum rainfall runoff
DCS (8)	Plot mean daily flows
DCS (9)	Input daily max & min temperature
DCS (10)	Input daily radiation
DCS (11)	Input 15-min. rainfall

The other important parameters are:

1. Routing Parameters

RINT — Routing interval in hours (time base of histogram), approximately the time for a particle of water originating in the most remote subarea of the basin to reach the measuring station.

Z — the number of time increments into which the histogram is divided; also number of subareas considered in arriving at the histogram.

C_i — subscripted variable representing the fraction of the total histogram contributed during each increment of time

$$\sum_{i=1}^{Z} C_i = 1$$

2. Land Surface Parameters

EPXM — Maximum value of interception storage in inches. No provision is made to vary this with season of year.

UZSN — Upper Zone Storage Nominal; a reference volume (in inches) for determining the response of the upper zone storage, i.e., "depression storage and storage in highly permeable surface soils." No provision is made for changing this reference volume during a storm as seems desirable for expansive soils which crack open.

LZSN	Lower Zone Storage Nominal; a reference volume (in inches) for determining the response of the lower zone storage, i.e., "the storage level at which fifty percent of all incoming moisture moves to groundwater storage."
K3	actual evaporation loss index, ratio of simulated evaporation to potential evapotranspiration
K24L	portion of groundwater recharge assigned to deep percolation, i.e., not contributory to streamflow.
K24EL	that fraction of the area from which evapotranspiration takes place directly from the groundwater, i.e., the fraction of the area where the root zone penetrates the groundwater table.
CB	an infiltration index; should be related to soil type, no correlation to soil type given
CC	an interflow index, no physical significance
L	Length of overland flow
SS	slope of overland flow
NN	Manning's rougness for overland flow segment

3. Channel System and Groundwater

KS1	hourly stream channel storage recession constant
IRC	daily Interflow Recession Constant
KV	groundwater recession constant for variable component of flow
KK24	daily groundwater recession constant for fixed component of groundwater flow

Most of the parameters can be found from hydrologic or meteorologic records and topographic maps. Values of the rest of the parameters are selected by a trial-and-error process of attempting to match computed synthesized hydrographs with recorded hydrographs. Selection and optimization of the parameters will be discussed in Chapter IV.

C. Output

The watershed model will produce basic output and a variety of optional output on demand. This output consists of:

i) A summary table of the end of the month values such as soil moisture conditions for each segment.

ii) Monthly summaries of processes such as total interflow discharge and actual evapotranspiration

iii) Complete hydrographs for all storms that produced flows greater than some preselected base flows

iv) Summary tables of mean daily flows for each flowpoint

Optional output includes:

i) Maximum clock hour rainfall and channel inflow values.

ii) Statistical comparisons of mean daily simulated and recorded streamflow

iii) Graphical plots of simulated and recorded mean daily flows at the flowpoints

iv) Daily snowpack water equivalent, depth, density and liquid water storage

v) Detailed storm analysis with 15-minute rainfall, interception, infiltration, and overland flows

vi) Storm period summaries with indicated or assigned parameter or variable changes and data consistency output

Many other items of output data can be printed where necessary by adding output statements to the general program

D. Model Operation

A schematic representation of the model and its operation is shown on Figure III.2. The operation of the model during a storm can be described as follows:

Precipitation falling over impervious area, which is defined as a fraction of total area, is directly diverted to the stream. Over the pervious area, all incoming moisture enters interception storage until the preassigned volume (EPXM) is filled. Evaporation from interception storage is assumed to occur at a rate that corresponds to the current rate of potential evapotranspiration. Thus, interception will continue during a storm due to evaporation losses. The remaining water from interception infiltrates or becomes surface water. This division depends on the values of infiltration index (CB), interflow index (CC), and the ratio of the lower zone storage at that time to the nominal lower zone storage (LZS/LZSN). Dashed line at lower zone storage on Figure III.2 represents the value of nominal lower zone storage. Some of the surface water goes to valve 2 (Figure III.2) depending on the ratio of upper zone storage at that time to the nominal upper zone storage (UZS/UZSN). The division between overland flow storage and interflow storage is a function of lower zone storage, interflow index and the volume of surface water. All water not released through valve 2 is released through valve 3 to upper zone storage. (All these steps occur at 15-minute intervals unless another interval is specified). Potential evapotranspiration tries to satisfy itself from upper zone storage through valve 6. The rest of water at upper zone storage is removed as percolation only when ratio UZS/UZSN is greater than LZS/LZSN. Division at valve 7 is a

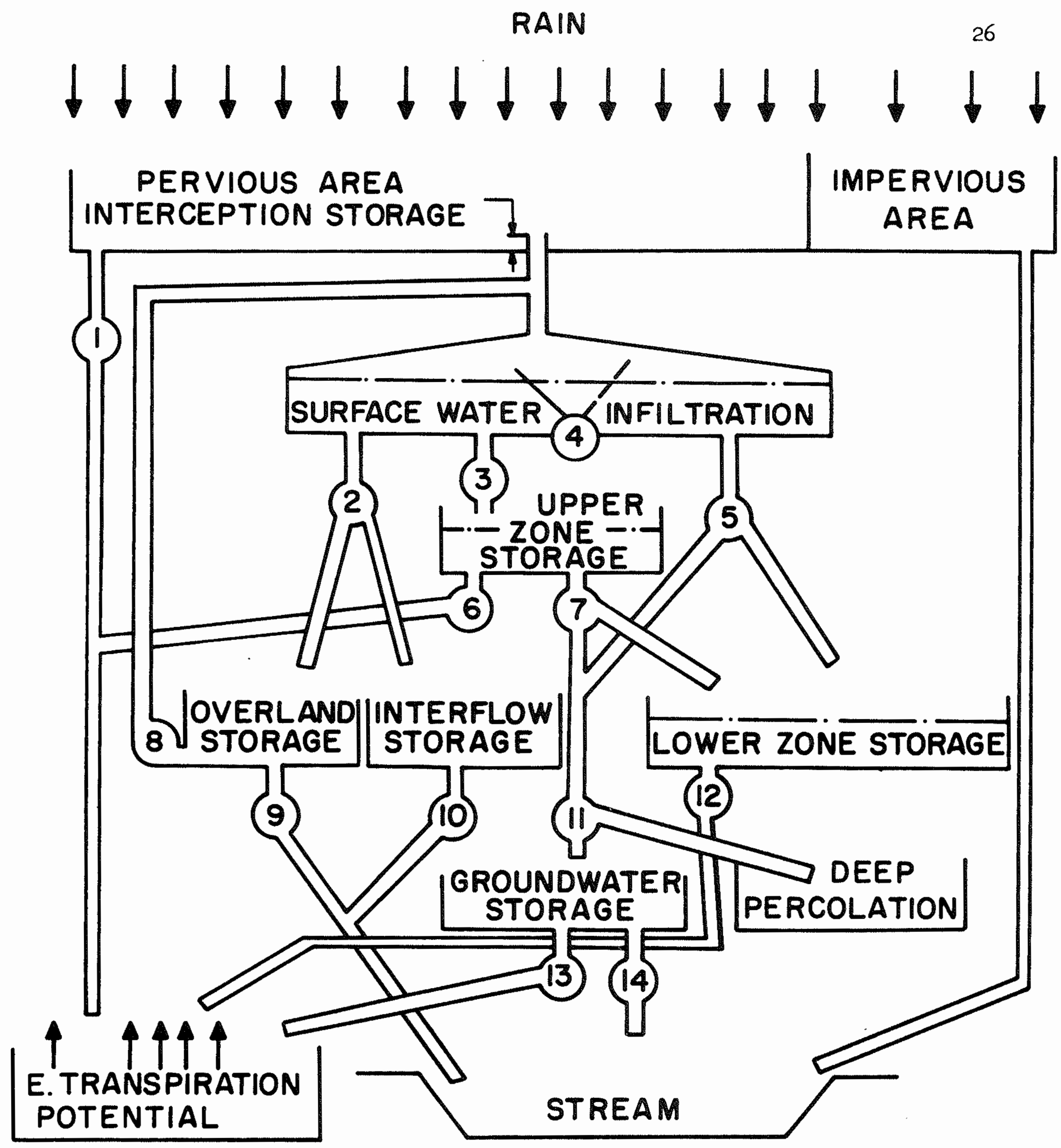

FIGURE III.2 STANFORD WATERSHED MODEL IV function of lower zone storage volume. Water at overland flow storage is subjected to removal by valve 9. The amount of water passing through this valve, overland flow, is determined by the volume in the storage and overland hydraulic characteristics: overland flow length (L), overland flow slope (SS), Manning's roughness coefficient for overland flow. This is calculated by some semi-laminar formulas which are described in Report No. 39 (Linsley, Crawford, 1966). Water remaining in overland flow storage at the end of 15-minute period is returned to the system at a point where it adds to the water applied to the pervious area during the next 15-minute period. Another component of stream inflow is interflow which comes through valve 10 depending upon the amount of interflow storage and daily interflow recession parameter (IRC). Division of the infiltrated water at valve 5 is determined by the amount currently in the lower zone storage. Lower zone storage is filled by water coming from valves 7 and 5, and is emptied by valve 12 which is mainly operated by the volume in the storage and actual evaporation loss index (K3). Water is divided at valve 11 by a preassigned parameter, the fractional portion of groundwater recharge assigned to deep percolation (K24L). Groundwater storage is emptied by two ways: First through valve 14 as groundwater flow which is governed by the amount of water at the storage, groundwater recession variable component (KV) and daily groundwater recession rate (KK24); second through valve 13 which is a function of selected fraction of area of evapotranspiration from groundwater (K24EL).

Channel inflow consists of overland flow, interflow, groundwater flow and water coming from the impervious area. The channel inflow hydrograph is, therefore, a function of land surface and rainfall characteristics and has the advantage, compared to the ordinary streamflow hydrographs, of being independent of the channel system. The influence of the channel system comes after this point. The volume of channel inflow in any time interval is multiplied by successive elements (C_i) of the time-delay histogram to give an outflow hydrograph that neglects storage attenuation. For each time interval, the discharge neglecting storage attenuation is calculated as

$$I_t = \sum_{X=0}^{X=Z-1} R_{t-x} \; C_{x+1}$$

Where I_t is the inflow in the current time interval to a hypothetical reservoir storage used to represent storage attenuation, R_{t-x} is the channel inflow x time intervals ago, and C_{x+1} is an ordinate of the normalized time delay histogram. The outflow hydrograph produced by channel translation calculations in above equation is routed through a storage system to simulate attenuation in the channel system by using the equation:

$$O_2 = \overline{I} - KSI\,(\overline{I} - O_1)$$

Where $\overline{I}$ is the average inflow during the time interval (1 hour), O_1 is the outlfow at the beginning of the interval, and O_2 is the outflow at the end of the time interval and an ordinate of final outflow hydrograph KSI is hourly stream channel storage recession parameter. Evaporation takes place from the stream surfaces which is defined as a fraction of total area (ETL).

Valve No.	Operation and function of valves in Figure III.2
1	Water removed from Interception Storage once each hour 0900 through 2000 hrs. Volume removed is minimum of hourly evapotranspiration or interception storage.
2	Water released from Surface Water every 15 minutes. The amount released is a function of the amount of water in Upper Zone Storage. The division between Overland Flow Storage and Interflow Storage is a function of Lower Zone Storage and the volume of Surface Water.
3	All water not released through valve 2 is released at 15-minute intervals to Upper Zone Storage.
4	The division between immediate infiltration and water subject to surface storage is determined by an input parameter and by the amount in Lower Zone Storage. This valve is reset each 15 minutes.
5	Operation is on 15-minute cycle. All water is removed from infiltration and division is based on the amount currently in Lower Zone Storage.
6	Water removed from Upper Zone Storage once each hour 0900 through 2000 hrs. Volume removed is minimum of hourly evaportranspiration volume remaining (after valve 1) or Upper Zone Storage.
7	Water removed from Upper Zone Storage only when the volume stored in Upper Zone Storage is large compared to volume stored in Lower Zone Storage. Division is a function of these two storage volumes.
8	At the end of each 15-minute period the pump empties Overland Flow Storage, returning the water to the system at a point where it adds to the water applied to the Pervious Area during the next 15 minutes.
9	Water is removed from Overland Flow Storage each 15 minutes. The amount is determined by the volume in storage and the overland hydraulic characteristics. (Slope, Manning n, and length).
10	An input parameter describing the interflow recession is applied to the volume in Interflow Storage on 15-minute intervals.
11	Water coming from both Upper Zone Storage and Infiltration are divided in accordance with an input parameter. Operation is on a 15-minute cycle.

Valve No.	Operation and function of valves in Figure III.2 (continued)
12	At 2100 hours, if the day's potential evapotranspiration has not been satisfied by valves 1 and 2, an amount depending on the volume present in Lower Zone Storage and an input parameter is removed.
13	Any remaining potential evapotranspiration is supplied from Groundwater Storage in accordance with an input parameter.
14	Flow from Groundwater Storage is a function of the volume in storage, a slope index, and a recession input parameter. Releases are on 15-minute intervals.

E. Revisions to the Model at The University of Texas, Austin

Revisions to the model have been made by Moore and Claborn (Moore, Claborn, 1969) at The University of Texas at Austin to make the simulation of infiltration and soil-moisture movement correspond more closely to physical parameters. In the modified model the parameters representing the watershed are related to physical quantities and it is hoped that they can be related to measurable characteristics of the watershed. A detailed analysis was made of infiltration and soil-moisture movement in a vertical soil column using the basic differential equations for movement of moisture in the saturated and unsaturated conditions.

The revised model incorporates a feature which will make it more adaptable for use with small watersheds. As discussed before the Stanford Watershed Model IV operates on a fifteen-minute cycle in the computer, but the stream routing period is in units of whole hours and effectively removes the quarter-hour variations. On small watersheds this is a serious limitation. In the revised model the basic accounting cycle has a maximum length of fifteen minutes but may be chosen as short as one minute.

CHAPTER IV

APPLICATION OF THE MODEL TO THE WATERSHED

The digital model has been applied to the Mukewater Creek study area using the data of the three year period, 1955-56, 1956-57, 1957-58, prior to the construction of the floodwater-retarding structures for selection of program parameters. For this purpose precipitation, evaporation and streamflow data were collected and punched for computer runs. Watershed parameters for the preconstruction period were estimated either from hydrologic and topographic data or by the trial-and-error process of attempting to match synthesized and recorded streamflow data.

Simulating one year of streamflow record on the Contral Data 6600 computer at The University of Texas at Austin used about 10 seconds of central processing time and required 107,000 storage space.

In this chapter how the data were prepared and how the parameters were selected will be described and some results will be presented.

A. Collection and Preparation of Data

The watershed has widely varying temporal patterns of rainfall in different years. Therefore, the preconstruction years chosen as a basis for developing the watershed model parameters were selected to include a variety of rainfall patterns. If parameters could be selected so the watershed model would well represent the output from these widely varying rainfall patterns, it should also well represent the output from expected future rainfall patterns.

The water year 1955-56 was a dry year with a total annual rainfall of 12.3 inches which produced 2.3 inches total annual runoff. In the storm of April 30 to May 1, 4.85 inches or 38 percent of the annual rainfall occurred in 5 hours. This caused 15,000 cfs peak flow and 4040 cfs mean daily flow on May 1. This was the highest recorded flow in the history of the watershed.

The year 1956-57 had 27.7 inches of annual rainfall which made 5.15 inches of annual runoff. Fifty-two percent of annual rainfall occurred in April and May. In this water year the following values were measured.

	Peak Flow (cfs)	Mean Daily Discharge (cfs)
April 26	--	1180
April 27	6760	1560
May 11	2580	1040
May 13	--	921
May 18	3430	1730

Rainfall pattern in the 1957-58 water year was entirely different. Its annual rainfall was 28.5 inches, but it had only 0.8 inches of annual runoff causing 0.028 yearly runoff-rainfall ratio which was about 1/6 of ratios 0.187, 0.185 of water years 1955-56, 1956-57 respectively. Rainfall in 1957-58 was almost uniformly distributed in the months of the year and occurred in storms of long duration. Maximum mean daily flow was 239 cfs on February 23 with a peak of 515 cfs. Plot of monthly rainfall and runoff values is shown on Figure IV.1. It is evident

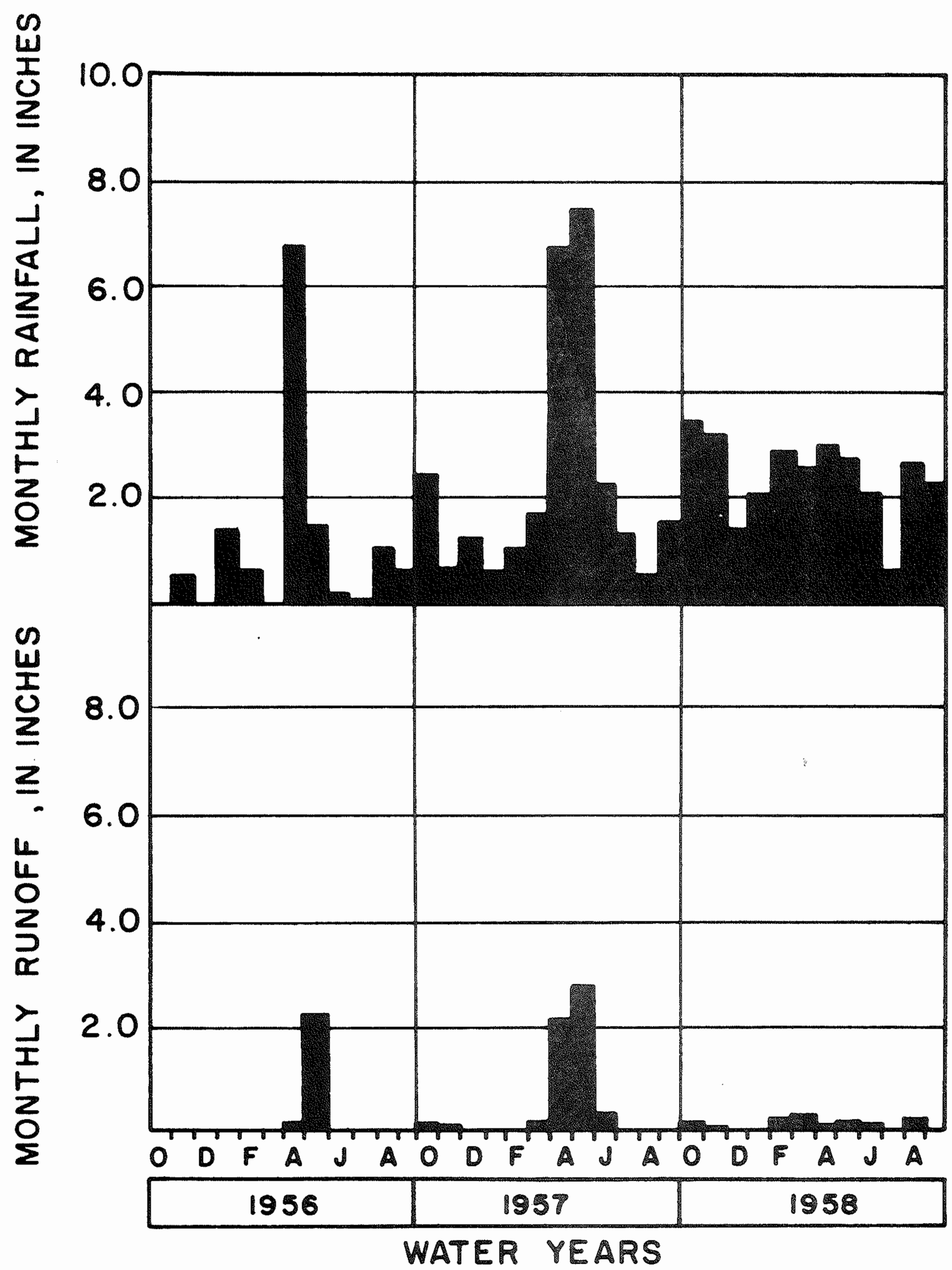

FIGURE IV.1 RECORDED MONTHLY RAINFALL AND RUNOFF that the years have different rainfall patterns. Optimization of some parameters depends on the rainfall distribution for the watershed, whether it is seasonal or reasonably uniform throughout the year. If a watershed has a constant rainfall pattern, from year to year it is easier to fix the parameters and a very good match can be obtained between simulation and recorded runoffs. Mukewater study area does not have a constant rainfall pattern in the selected three-year period. For that reason it was difficult to optimize the parameters and better matches would be obtained by using optimized parameters for each year or for each pattern of rainfall. This matter will be explained more in the discussion of optimization of the parameters.

1. Rainfall

Only the data from the four recording gages for the period prior to the construction of the structures and five after the construction were used as rainfall input for the program. Sauer (Sauer,1965) shows that using the arithmetic average of 4 gages, for 67 percent confidence limits (67 percent of the storms), storm rainfall may be determined within +10 percent and -9 percent of the weighted-mean rainfall as determined from 19 rain gages. He also calculated that 7-year totals of storm rainfall computed by weighted-mean rainfall (19 gages) and average of 4, 7, and 10 rain gages for all storms with weighted mean rainfall exceeding 0.40 inch are practically identical. For these reasons, it can be concluded that 4 (5 after construction period) recording gages are good enough to delineate the pattern and amount of rainfall for this watershed.

Rainfall data were directly taken from original graphs of recording gages, weighted according to the gage and then punched on computer cards.

Hourly or 15-minute rainfall data can be used as program input. Type of rainfall data required depends on the size of the watershed and distribution of the storm rainfall in any hour.

Hourly rainfall data have been used for this study. 15-minute rainfall data were used for the first six months in 1955-56 water year to see the difference between its outcoming hydrograph for the storm on April 30 - May 1 and the hydrograph from hourly rainfall data for the same storm.

The outcoming hydrographs from hourly and 15-minute rainfall data are shown on Figure IV.2. 15-minute rainfall data caused runoff slightly more than the hourly data did. It produced peak 5.6% and mean daily flow 6.6% more than the other. This difference is small although the storm is severe and the rainfall is very badly distributed in quarter hours. For that reason using two types of rainfall data would not make more difference than the figures shown above for other storms. Nevertheless, this difference between two hydrographs would not be significant in our investigations since hourly rainfall data were used for both periods before and after the construction.

2. Streamflow

Mean daily flow values were taken from U.S.G.S. Water Supply papers for Mukewater Creek Study Area and punched on cards. This input was optional for the program and used for statistical comparison between the recorded and simulated mean daily flows.

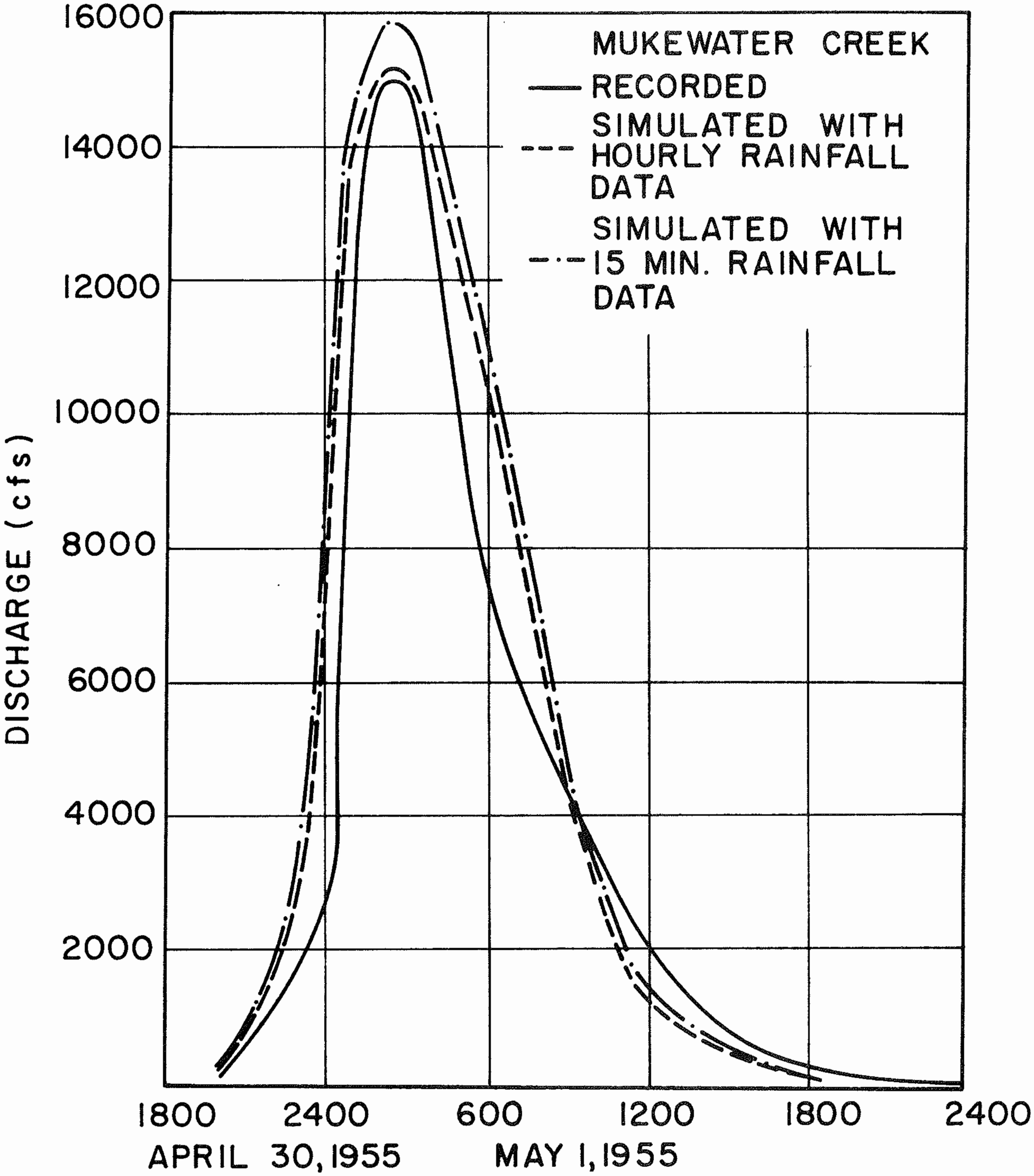

FIGURE IV.2 COMPARISON OF RECORDED AND SIMULATED HYDROGRAPHS

Detailed hydrographs of large storms were obtained from yearly reports of U.S.G.S. Water Resources Division about the study area and used for matching with synthesized hydrographs.

B. Selection and Optimization of the Parameters

Selection of paramters is the most difficult task in applying the digital model to a particular watershed. Ranges of parameters and sketches or tables of expected values are given in the report by Linsley and Crawford (Linsley, Crawford, 1966). Some of the parameters can be estimated from hydrologic and topographic data with the help of these tables and sketches. The rest have to be determined by trial-and-error. The final test as to whether a given set of values is adequate is whether it produces a synthetic hydrograph that matches the corresponding record hydrograph for the same spot. After each trial it is necessary to compare the synthetic hydrograph with the recorded hydrograph and decide which constants should be altered to get a better fit. The difficulty at this point comes from the facts that the physical significance of the parameters is obscure and some of them are strongly dependent upon each other. Thus it is difficult to know which parameters should be changed for a better fit and what will be the effects of this alteration on simulated flows. For that reason experience will speed the trial-and-error process.

The parameters for which no estimates or estimating procedures have been given are four in number. Three of these, the storage parameters UZSN, LZSN, and the net infiltration parameter CB, determine runoff volumes. The fourth parameter CC governs the proportion of interflow and is a time distribution parameter. Optimization of these parameters will be explained after description of how the other parameters were selected.

1. Routing Parameters

Time-delay curve represents the flow time in channels neglecting storage attenuation and may be found by planimetering contributing areas, estimating channel flows at successive points in the stream channel system, and calculating the time of flow to the outlet of the watershed. Manning equation is used to calculate the flow time.

$$t = \frac{n^{3/5}\ L\ W^{2/5}}{4560\ s^{3/10}\ Q^{2/5}}$$

where t is time in hours, L is channel length, W is channel width, S is slope, Q is discharge, and n is Manning's n.

For this purpose the watershed was divided into small subareas, discharge values were allocated to each subarea according to their sizes, approximate values were given for channel roughness and width, and then flow time from each segment to the stream flow station was estimated using the above equation. Discharges were added up and thus the discharge vs. channel flow time to outlet, time-delay histogram, was drawn. Width of this histogram, routing interval (RINT), was divided into Z number of increments, and the histogram was normalized so that

$$\sum_{i=1}^{Z} C_i = 1$$

where C_i is an ordinate of normalized time-delay histogram. During the trials these values of time delay elements were altered by trying to match widths and peak times of simulated and recorded hydrographs. Finally the following figures were obtained:

RINT = 2 hours

$$\overset{7}{\underset{i=1}{C}} = 0.08,\ 0.13,\ 0.20,\ 0.25,\ 0.20,\ 0.10,\ 0.04$$

2. Physical Parameters

AREA = 70.4 square miles

A = 0.0

A is impervious area (fraction) and assumed to be zero since the watershed is undeveloped. For developed watersheds a curve is given by Linsley and Crawford (Linsley, Crawford, 1966) to approximate relative effective impervious area (A) for the model, to the total impervious area estimated or measured from aerial photographs.

3. Land Surface Parameters

Interception storage parameter (EPXM) was estimated as 0.10 from Table 5.5 of Stanford Report. 0.23 was chosen from Table 5.6 for actual evaporation loss index (K3). Fraction of area from which groundwater evaporation (K24EL) was estimated to be zero.

L is the mean overland flow length in feet and SS is the average slope is feet per foot of the overland flow surfaces perpendicular to the channel they were estimated as 1300 feet and 0.05 respectively from the topographic map of the watershed. 0.075 were chosen for Manning's roughness coefficient for overland flows (NN) from roughness tables.

4. Channel System and Groundwater Parameters

The parameters KSI for the surface runoff recession and the parameters IRC and KK24 for the interflow and groundwater recessions respectively were estimated from hydrographs using graphical techniques suggested by Barnes (Barnes, 1940) and described in the book of Linsley, Kohler, Paulhus (Linsley, Kohler, Paulhus, 1958). The recession part of May 1, 1956 hydrograph was drawn on semilogorithmic paper. It does not give a straight line but a curve with gradually decreasing slope. The reason for this is that the water is coming from three different types of storage--stream channels, surface soil, and the groundwater--each having different lag characteristics. The slope of the last portion of the recession should represent groundwater recession parameter (KK24) since, presumably, both interflow and surface runoff have ceased. By projecting this slope backward in time and replotting the difference between the projected line and the total hydrograph, a recession which for a time consists largely of interflow is obtained. With the slope applicable to interflow thus determined the process is repeated to establish the recession characteristics of surface runoff.

KK24 = 0.51

IRC = 0.0028

KSI = 0.62

The above values were calculated from the graph.

ETL was estimated as 0.001 which is the stream area as a fraction of total watershed area, from which evaporation should occur at the potential rate.

5. CC, UZSN, LZSN, CB

These are the parameters which have to be estimated by trial-and-error process. In this process attempts should be made to match recorded and simulated hydrographs daily, monthly and annual flows.

After each trial, simulated hydrographs were drawn to see how well they matched with the recorded hydrographs so that appropriate parameter or parameters could be altered. Additionally, the change of the parameters should result in a high daily correlation coefficient and better fit between simulated and recorded annual and monthly flows.

Among these four parameters, CC has very little effect on the amount of outflow. It governs the proportion of interflow and is a time distribution parameter. It has a range 0.5 to 3.0 and is difficult to anticipate, but is fairly easy to adjust so that simulation will reproduce observed hydrographs. Increased values of CC reduce flood peaks and more moisture enters into interflow. This interflow parameter can be kept constant until the last few trials. When the other parameters have been fixed, CC can be used to adjust the peaks and shape of hydrographs, since it does not change yield.

The other three runoff volume parameters were more difficult to derive. The parameters UZSN, LZSN and CB are not independent. Logically in nature and by definition in the watershed model, temporary storage at or near the surface in the upper zone, storage in the remainder of the soil profile or lower zone, and the rate of infiltration into the soil profile from the surface, will all interact in hydrologic response.

The upper zone parameter UZSN is effective on runoff volumes from the study area, particularly in the water year 1957-58. UZSN governs depression storage and storage in the soil profile near the land surface. These are temporary storages and act to retain or delay water from later infiltration, thus they dominate showers and small storms and are important in the early stages of larger storms. Since the 1957-58 water year has uniform precipitation pattern throughout the year with low intensity showers, the upper zone storage is filled at the beginning of each storm and then most of it is emptied by high potential evapotranspiration over the area, the rest infiltrates to groundwater and lower zone storages. For that reason UZSN played a great role on the yield and hydrograph shape in the 1957-58 water year. The precipitation pattern of this year helped materially in choosing the value for UZSN. As a rule UZSN is an effective parameter for low annual rainfall reasonably uniform throughout the year. Increased value of UZSN decreases hydrograph peaks and volumes, particularly small hydrographs.

Interaction occurs between UZSN and CB (infiltration index). Increased value of CB decreases peaks of both small and large hydrographs. CB is a useful tool for adjusting the shapes of large hydrographs, but its effects depend on the value of LZSN. When the value of CB is increased the peak is decreased and most of the moisture appears as groundwater flow at the recession part of the hydrograph, thus no significant change can be seen in annual runoff. Increased value of LZSN decreases groundwater flow and annual runoff because soil profile becomes more capable to retain water for eventual evapotranspiration. For these reasons CB and LZSN are dependent to each other. They can be separable when soil profile is saturated frequently. In this case UZSN governs the annual yield, and CB can be used to produce better hydrograph adjusting surface and groundwater flows. In April and May of 1956-56 water year (52% of annual rainfall, and 91% of total runoff occurred in these two months) soil profile was almost saturated, so LZSN was used to produce observed annual yield, and CB was adjusted to obtain the best fit with the observed hydrographs. Clarke (Clarke, 1968) shows the sensitivity of Model Response to the parameters on some hydrographs.

At the end parameters were found to be:

CB = 0.65

UZSN = 0.45

LZSN = 4.70

CC = 1.50

Table IV.1 gives a list of model parameters for Mukewater Creek prior to the construction of the floodwater retarding structures.

Figures IV.3, 4 show some of the actual and generated hydrographs. Figure IV.5 is a plot of mean daily recorded and simulated flows for 1956-56 water year. Table IV.2 gives monthly and annual recorded and simulated runoff values and daily correlation coefficients.

C. Further Simulation for Justification of the Parameters

After fixing the parameters for the 1956, 1957, 1958 water years, simulation was done for another three years before the construction using the same parameters (Parameter Set I) to check the validity of the parameters chosen for the watershed. Table IV.3 gives the recorded values and the simulation results for the water years 1954, 1955, 1959. As it can be seen from the monthly and annual simulation results using Parameter Set I, agreement for two years, 1954 and 1955, is even better than that for the years which were used to fix the parameters. The

TABLE IV.1

STANFORD WATERSHED MODEL PARAMETERS

FOR MUKEWATER CREEK PRIOR TO CONSTRUCTION OF THE STRUCTURES

Model Parameter	Parameter Value	Model Parameter	Parameter Value
RINT	2	K3	0.23
Z	7	K24L	0.00
C_1	0.08	K24EL	0.0
C_2	0.13	CB	0.65
C_3	0.20	CC	1.50
C_4	0.25	SS	0.05
C_5	0.20	L	1300.
C_6	0.10	NN	0.075
C_7	0.04		
		KSI	0.62
K1	1.0	IRC	0.0028
AREA	70.4	KV	0.90
A	0.0	KK24	0.51
		ETL	0.001
EPXM	0.10		
UZSN	0.45		
LZSN	4.70		

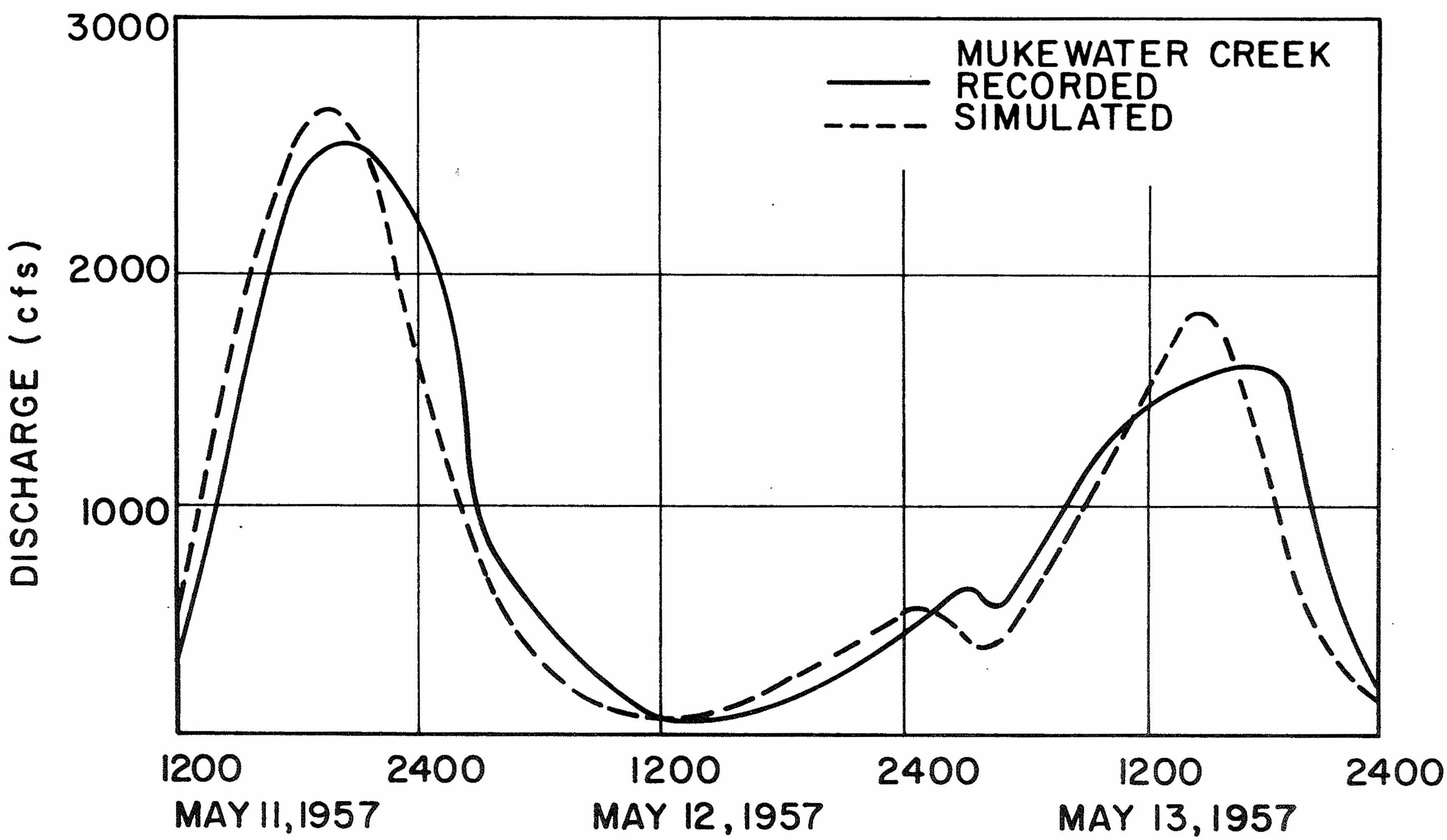

FIGURE IV.3 COMPARISON OF RECORDED AND SIMULATED HYDROGRAPHS

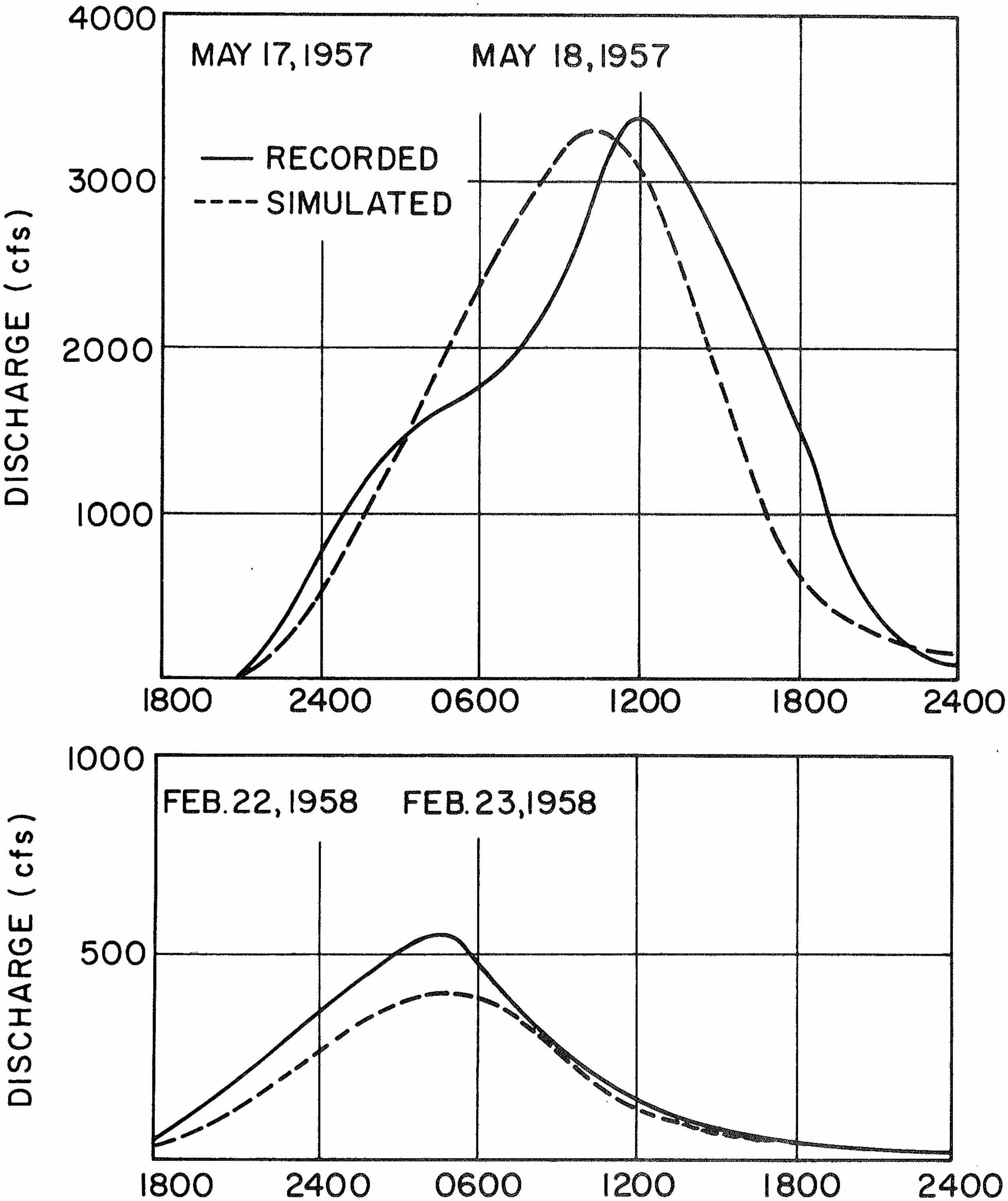

FIGURE IV.4 COMPARISON OF RECORDED AND SIMULATED HYDROGRAPHS

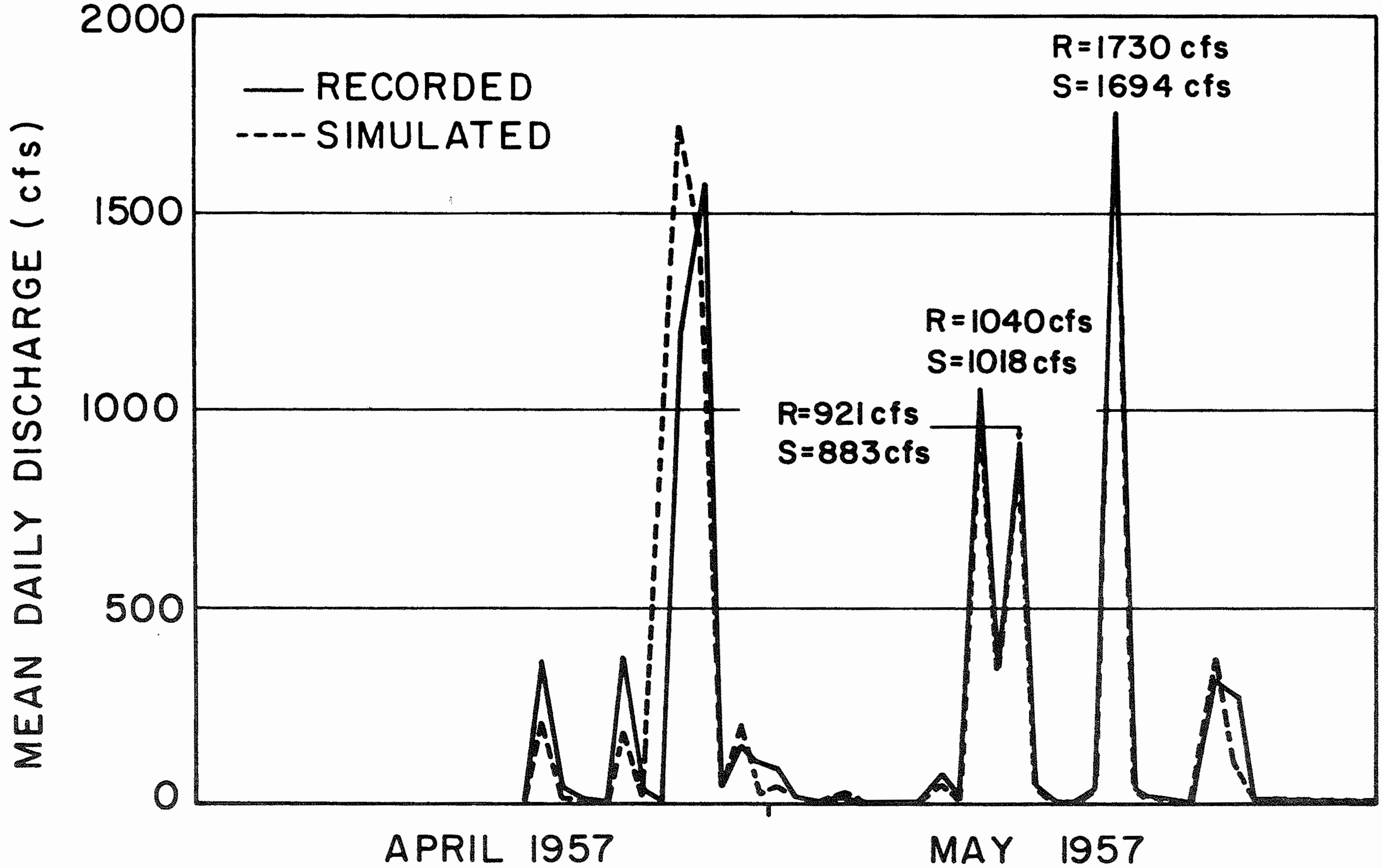

FIGURE IV.5 COMPARISON OF RECORDED AND SIMULATED MEAN DAILY FLOWS

TABLE IV.2 - COMPARISON OF RECORDED AND SIMULATED RUNOFF VALUES IN INCHES

Water Year		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual	Correlation Coefficient (m.d.d.)
1956	Rec.	0.0	0.0	0.0	0.0	0.0	0.0	0.10	2.15	0.0	0.0	0.0	0.0	2.25	0.9970
	Sim.	0.0	0.0	0.0	0.01	0.0	0.0	0.25	2.31	0.0	0.0	0.0	0.0	2.57	
1957	Rec.	0.07	0.05	0.0	0.0	0.0	0.08	2.03	2.75	0.20	0.0	0.0	0.01	5.19	0.9550
	Sim.	0.05	0.02	0.02	0.0	0.01	0.07	2.03	2.58	0.14	0.01	0.01	0.02	4.96	
1958	Rec.	0.12	0.04	0.0	0.01	0.17	0.17	0.04	0.11	0.07	0.0	0.10	0.0	0.83	0.9284
	Sim.	0.18	0.07	0.03	0.04	0.13	0.14	0.09	0.08	0.11	0.0	0.16	0.03	1.06	

TABLE IV.3 - COMPARISON OF SIMULATED AND RECORDED RUNOFF VALUES FOR TWO SETS OF PARAMETERS (IN INCHES)

Year	Parameters	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual	Correlation Coefficient
1954	Set I	0.60	0.0	0.0	0.0	0.0	0.01	0.18	0.14	0.02	0.0	0.01	0.00	0.97	0.9500
	Set II	0.66	0.0	0.0	0.0	0.0	0.01	0.14	0.15	0.02	0.0	0.01	0.0	1.02	0.9452
	Recorded	0.50	0.0	0.0	0.0	0.0	0.17	0.25	0.18	0.0	0.0	0.0	0.0	1.10	Recorded
1955	Set I	0.02	0.02	0.01	0.0	0.01	0.0	0.0	1.80	0.42	1.27	0.01	0.53	4.10	0.9318
	Set II	0.02	0.03	0.01	0.0	0.01	0.00	0.0	1.84	0.37	1.19	0.01	0.46	3.92	0.9248
	Recorded	0.0	0.05	0.0	0.0	0.03	0.03	0.0	2.03	0.95	0.91	0.06	0.49	4.55	Recorded
1959	Set I	0.01	0.01	0.0	0.0	0.0	0.0	0.01	0.04	3.18	2.62	0.03	0.02	5.92	0.9766
	Set II	0.02	0.01	0.0	0.0	0.0	0.0	0.01	0.04	3.17	2.60	0.02	0 02	5.89	0.9789
	Recorded	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	2.24	2.00	0.0	0.0	4.25	Recorded

correlation is not as good for 1959 water year. The difference in preparing the rainfall data for these two periods was one of the suspected reasons for the disagreement between simulated and recorded values of 1959 water year. The difference was in the preparation of the minor storms' data. In 1956, 1957, 1958 water years rainfall data for small storms was prepared as if the rainfall is uniformly distributed during the storm, thus the hourly rainfall was calculated dividing the amount of rainfall for any storm by its duration. Whereas, in 1954, 1955 and 1959 water years rainfall data for both major and minor storms was taken as their actual distribution during the storm. For this reason the data for 1956-1957-1958 water years was reprepared taking the actual distribution of the minor storms, and a new set of parameters (Parameter Set II) was fixed for the new data in the same manner as for the other set. The parameters for the two sets are:

	Set I	Set II
CB	0.65	0.65
LZSN	4.70	3.50
UZSN	0.45	0.50
CC	1.50	1.25

Table IV.4 gives the recorded monthly and annual values and simulation results using both sets of parameters.

Simulation was done for 1954-1955 and 1959 water years using Parameter Set II. The results are also shown on Table IV.3. No significant difference can be seen between the simulation results obtained using two different sets of parameters. Thus the cause of the disagreement in

TABLE IV.4 - COMPARISON OF RECORDED AND SIMULATED RUNOFF VALUES FOR TWO SETS OF PARAMETERS (IN INCHES)

Year	Parameters	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual	Correlation Coefficient
1956	Set I	0.0	0.0	0.0	0.01	0.0	0.0	0.25	2.31	0.0	0.0	0.0	0.0	2.57	0.9970
	Set II	0.0	0.0	0.0	0.01	0.0	0.0	0.18	2.48	0.01	0.0	0.0	0.0	2.68	0.9997
	Recorded	0.0	0.0	0.0	0.0	0.0	0.0	0.10	2.15	0.0	0.0	0.0	0.0	2.25	Recorded
1957	Set I	0.05	0.02	0.02	0.0	0.01	0.07	2.03	2.58	0.14	0.01	0.01	0.02	4.96	0.9550
	Set II	0.02	0.03	0.02	0.0	0.01	0.03	2.05	2.73	0.09	0.02	0.01	0.00	5.00	0.9740
	Recorded	0.07	0.05	0.0	0.0	0.0	0.08	2.03	2.75	0.20	0.0	0.0	0.01	5.19	Recorded
1958	Set I	0.18	0.07	0.03	0.04	0.13	0.14	0.09	0.08	0.11	0.0	0.16	0.03	1.06	0.9184
	Set II	0.09	0.10	0.03	0.04	0.17	0.15	0.08	0.08	0.06	0.01	0.08	0.04	0.94	0.9075
	Recorded	0.12	0.04	0.0	0.01	0.17	0.17	0.04	0.11	0.07	0.0	0.10	0.00	0.83	Recorded

1959 water year is believed to be the 9 month dry period including September from the 1958 water year, with insignificant runoff until June.

From this investigation two important conclusions can be drawn.

1) No assurance can be made about the validity of the parameters for any year other than the years used for fixing them, because the year may have different rainfall distribution or different types of storms. Thus longer periods for fixing the parameters will include more variations of the storms and their distributions, and result in more reliable parameters for the watershed.

2) It is possible to have more than one set of parameters for any watershed.

CHAPTER V

SOME EFFECTS OF FLOODWATER-RETARDING STRUCTURES ON RUNOFF

As explained in Chapter II six floodwater-retarding structures, which control 39.3% of the study area and have a total storage capacity of 6184 acre-feet, had been built in the period from 11-21-1960 to 1-15-1965. The next stage in the investigation was to apply preconstruction model parameters to estimate the runoff that would have occurred in the post-construction period if the actual post-construction rainfall had occurred on the watershed in its preconstruction condition. Comparison of this simulated runoff with the measured runoff would give an overall indication of the effect of the changes in the watershed during the intervening period.

In this chapter application of the model to 1964-65 and 1965-66 water years with preconstruction period parameters will be compared with recorded values. In the last part of the chapter the attempt to simulate the runoff from the modified watershed with the flood-retarding structures by changing the model parameters will be discussed.

A. Application of the Model to 1964-65 and 1965-66 Water Years

The model was used to simulate runoff with preconstruction period model parameters during the two-year period after the structures were built. In these water years the annual rainfall and runoff was as follows:

Water Year	Rainfall (inches)	Runoff (inches)	Runoff/Rainfall
1964-65	22.7	3.8	0.167
1965-66	24.1	0.7	0.029

B. Effects of the Structures on Runoff

Continuous simulation of runoff during these two years was done using the preconstruction model parameters. Thus by comparing recorded flows with the simulated flows without the structures, effects of the structures on peaks and shapes of hydrographs, mean daily flows, and runoff yeields were analyzed.

1. Effects on Peak Discharges and Time Distribution of Runoff

Effects of the structures on peak discharges are related to the contents of the reservoirs before the storm. If they are empty before the storm, they can store their full capacity, releasing it gradually. In this case, they are very effective in decreasing the peak discharges. If they are full, only the routing through the reservoirs will be effective in decreasing the peaks. In both cases flood peaks will be reduced and the recession parts of the hydrographs will be lengthened.

Continuous simulated and recorded hydrograph from May 12 to May 20, 1965, is shown in Figure V.1. Solid lines show the recorded hydrograph with the structures and dashed lines show the simulated hydrograph without the structures. They very well reflect the effects of the structures.

On May 13 the peak was reduced 63%. The main reason for this is that the reservoirs were almost empty before the storms. There was a very dry period of two months prior to the storms and the largest

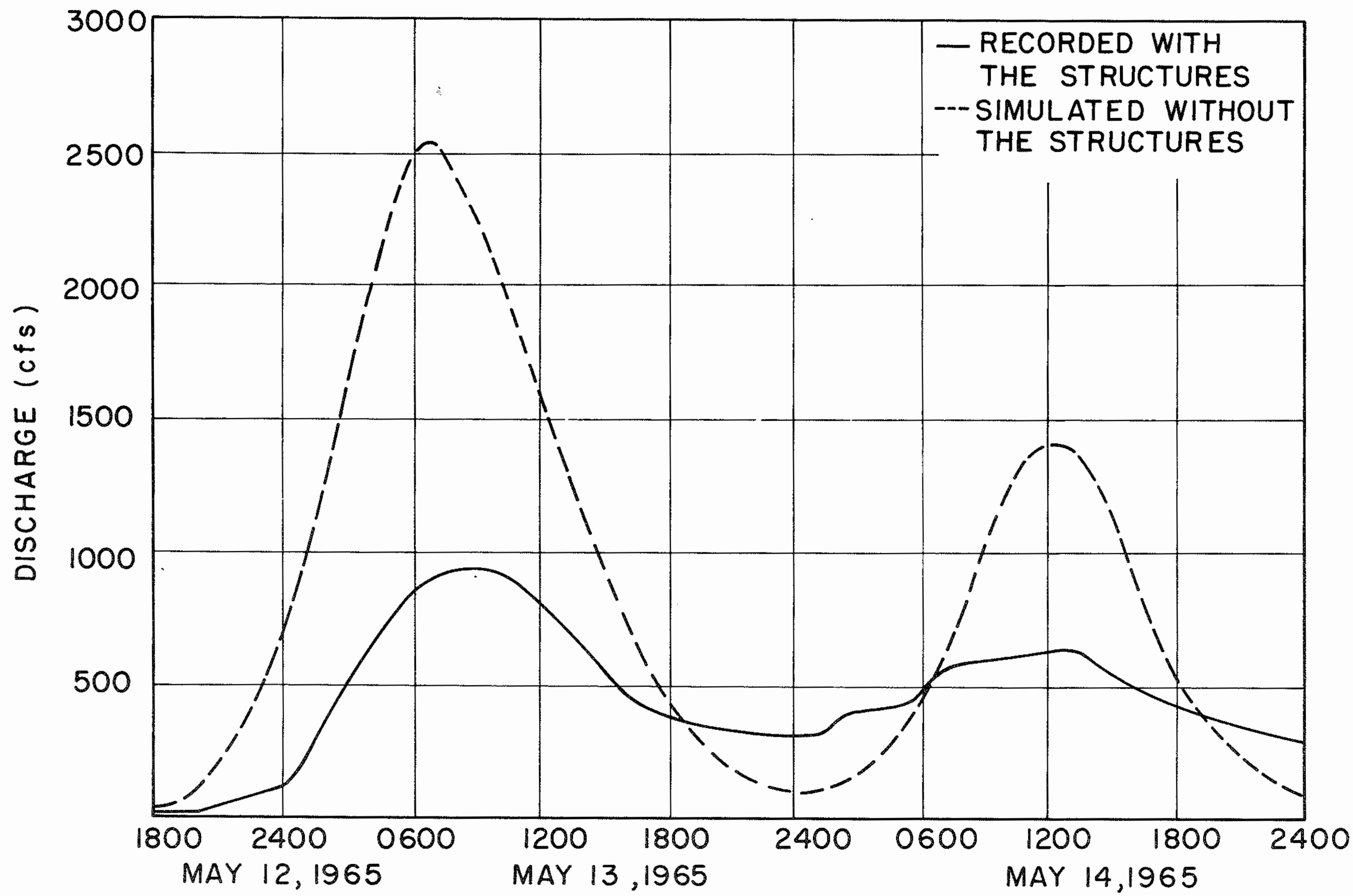

FIGURE V.1 RECORDED AND SIMULATED HYDROGRAPHS MAY 12-14, 1965
MUKEWATER CREEK, TEXAS 70.4 sq. mi.

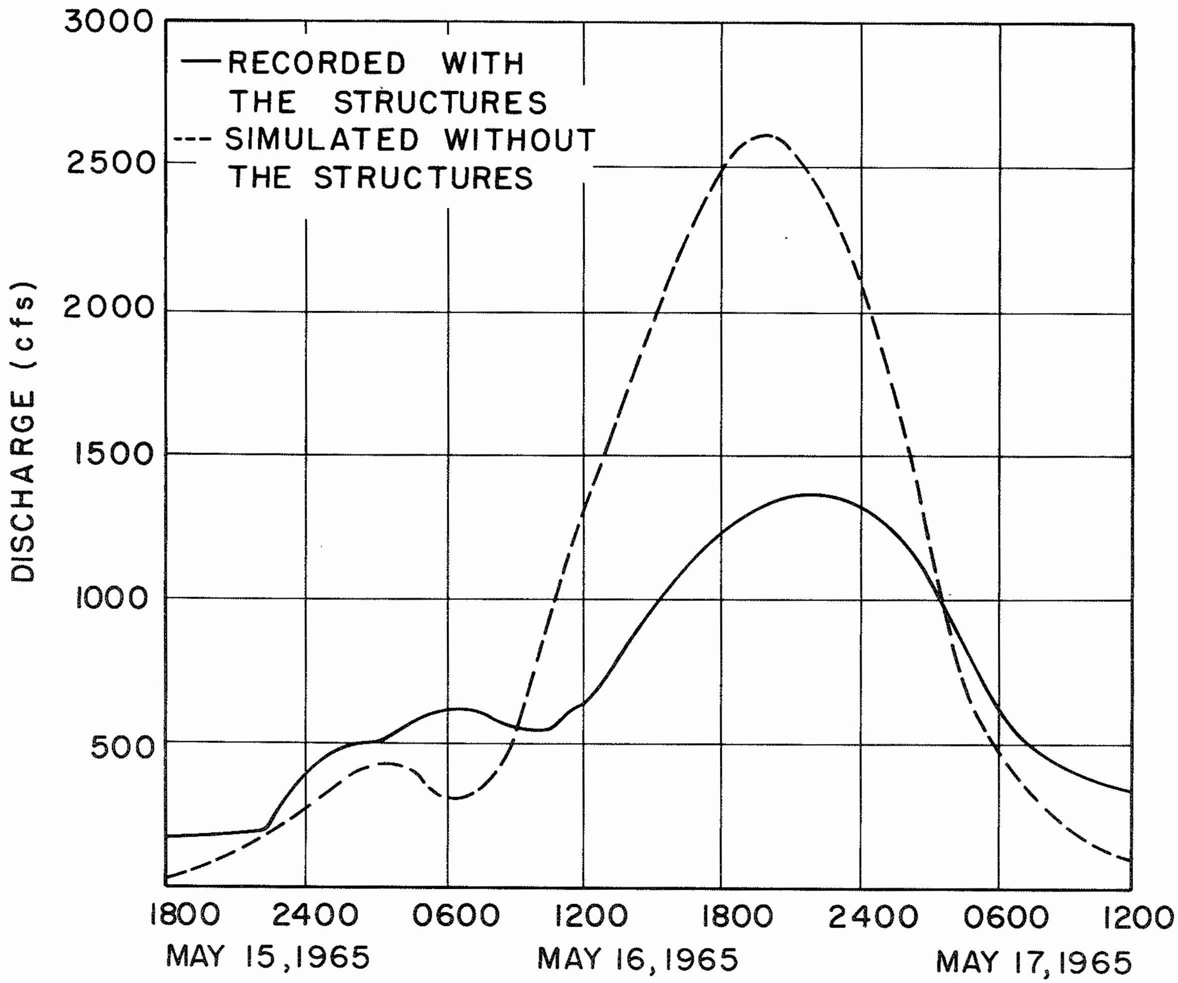

FIGURE V.1a RECORDED AND SIMULATED HYDROGRAPHS
MAY 15-17, 1965 MUKEWATER CREEK, TEXAS
70.4 sq. mi.

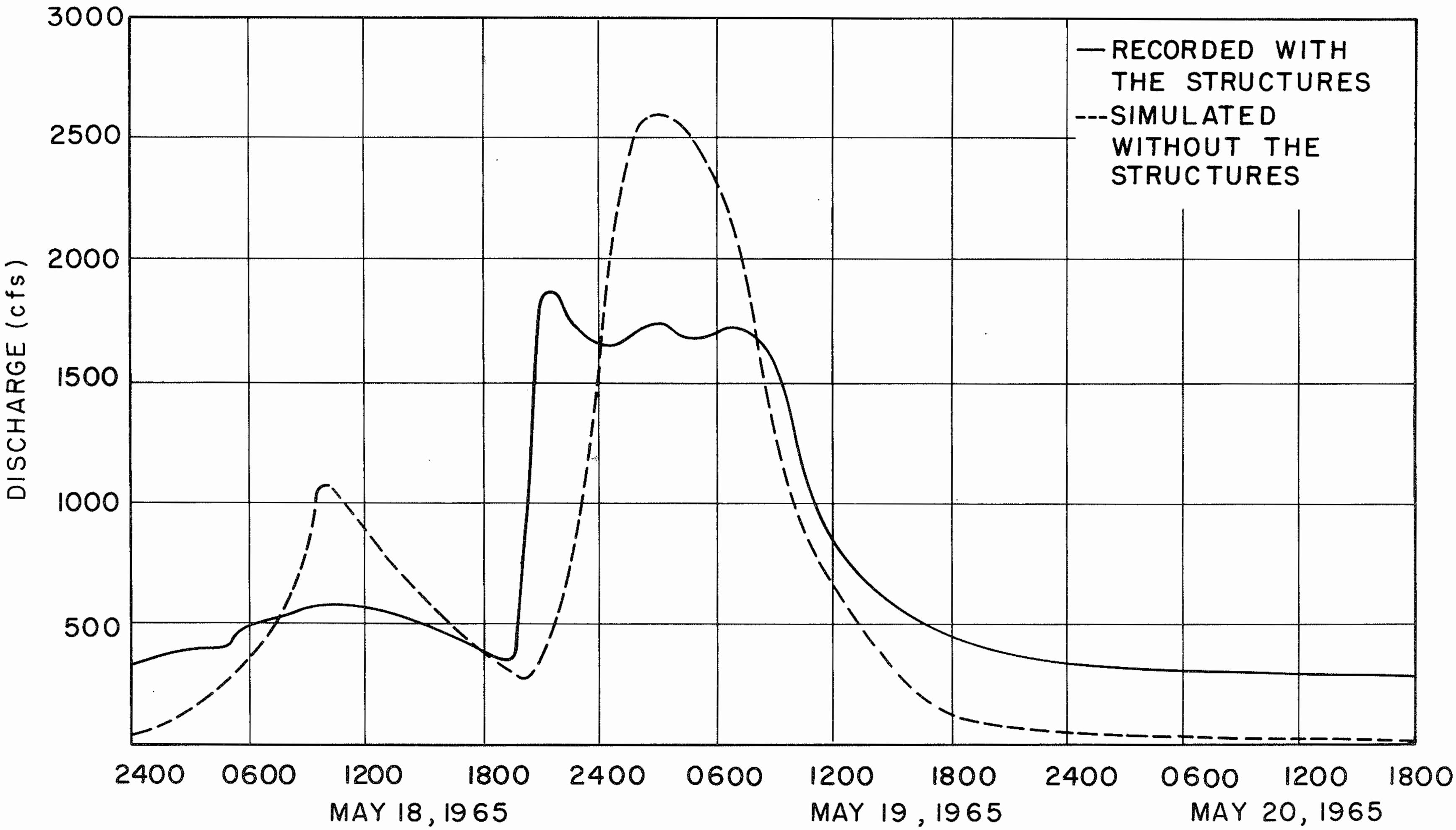

FIGURE V. 1 b RECORDED AND SIMULATED HYDROGRAPHS MAY 18-20, 1965 MUKEWATER CREEK, TEXAS 70.4 sq.mi.

reservoir 10A of 3380 acre-feet of storage capacity was put into operation in April. For that reason, almost all the water coming from the drainage area controlled by the structures was stored in the reservoirs. The recorded hydrograph consists essentially of the flood coming from the 60% of the total watershed which is not controlled by structures.

Reduction in the peak discharges becomes smaller in the succeeding floods, particularly on the last (May 18-19) hydrograph, because the reservoirs were almost full before the last storm so they did not store the water, but routed the flood and lagged the peak.

It is not obvious that the peaks of hydrographs are lagged, but it is very clear that crests are smoothened and lengthened. This is because of the fact that the total watershed is not controlled by the retarding structures. These hydrographs may be considered as the superposition of two hydrographs, one from the uncontrolled segment and the other from the controlled segment which is routed through the reservoirs.

The second hydrograph starts contributing near the end of the first hydrograph's rising limb, sustains the peak of the sumperimposed hydrograph, and the recession curve. For that reason recession curves of the hydrographs are lengthened and water is transferred to the succeeding day. Figure V.2 shows how the mean daily flows were smoothed in May(1965).

2. Effects of Runoff Yields

The main source of loss from this kind of flood protection program is evaporation from the reservoirs which depends on the mean surface area of the reservoirs and the amount of potential evapotranspiration. Infiltration at the reservoir sites is another source of

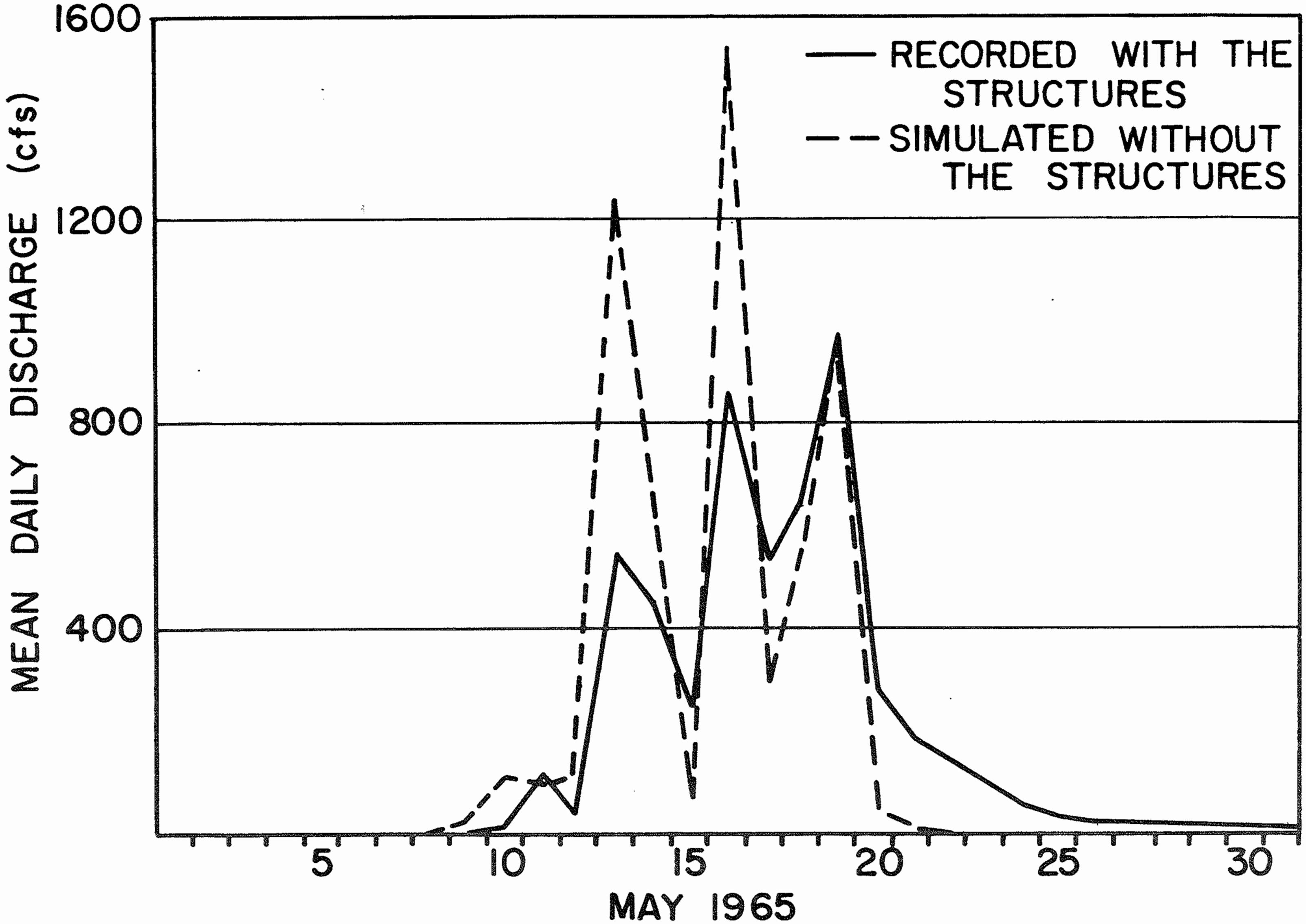

FIGURE V.2 COMPARISON OF RECORDED AND SIMULATED MEAN DAILY FLOWS water loss although some of the infiltrated water may return to the stream, depending on the opportunity for evapotranspiration and groundwater recharge. On the other hand the reduction of flood peaks reduces the area of infiltration from the stream channel. Without the flood control structures, the flood waters spread over the flood plain providing an opportunity for additional infiltration. This infiltration can be a significant factor in flood reduction in areas like Sugar Creek (Hartman, 1967) where infiltration has been found to be 1.25 feet per day over areas flooded. For the water years of interest the recorded and simulated runoff was as follows:

	Recorded Runoff With the Structures		Simulated Runoff Without the Structures	
Water Year	Inches	Acre-Feet	Inches	Acre-Feet
1964-65	3.82	14340	4.03	15134
1965-66	0.70	2704	0.96	3714

Table V.1 was prepared for May 1965 from water budgets of the individual pools and the corresponding evaporation data. Total loss from the reservoirs was found to be 122.7 acre-feet in May 1965. Evaporation loss was about 2/3 of the total. The rest occurred by seepage, bank storage, land surface evapotranspiration, etc.

Similar monthly data representing the total for all pools together with corresponding runoff values are given in Tables V.2 and V.3 for 1965-1966. The months of June-September 1965 are omitted because the runoff was negligible during those months. Comparison of row 7 with row 8 is of particular interest. Row 7 is the sum of the recorded runoff (row 6), the change in contents (row 5), and the total

TABLE V.1 - MAY 1965 WATER BUDGET OF THE RESERVOIRS

Structure No.	5	5A	6	7	9	10A	Total
Mean Surface Area (Acre)	12.4	26.7	21.5	19.5	34.3	66.3	180.7
Total Loss (Acre-ft.)	8.1	17.4	14.0	12.7	27.4	43.1	122.7
Evaporation Loss (Acre-ft.)	5.7	12.2	9.9	8.9	15.7	30.4	82.9
Other Losses (Acre-ft.)	2.4	5.2	4.1	3.8	11.7	12.7	39.9
Change in Contents	8.1	24.9	24.0	10.4	24.2	167.2	258.8

TABLE V.2 - 1965 WATER BUDGET OF RESERVOIRS SIMULATED AND RECORDED MONTHLY RUNOFF VALUES

		May	Oct.	Nov.	Dec.
1	Total Mean Surface Area (Acre)	180.7	55.1	97.9	102.3
2	Total Evaporation Loss (Acre-ft.)	82.9	19.1	17.9	15.4
3	Other Losses (Acre-ft.)	39.9	15.8	28.1	23.4
4	Total Loss (Acre-ft.)	122.7	35.2	46.0	38.8
5	Change in Contents (Acre-ft.)	258.8	-15.3	172.9	-4.2
6	Recorded Runoff With Structures (Acre-ft.)	5264.0	0.0	265.0	0.0
7	Sum 4 + 5 + 6	5645.5	19.9	483.9	34.6
8	Simulated Runoff Without Structures (Acre-ft.)	5822.0	121.0	513.0	89.0

TABLE V.3 - 1966 WATER BUDGET OF RESERVOIRS SIMULATED AND RECORDED MONTHLY RUNOFF VALUES

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1	Total Mean Surface Acre (Acre)	98.0	94.5	97.5	83.8	131.8	111.5	99.8	88.9	140.0	100.0
2	Total Evaporation Loss (Acre-ft.)	15.5	17.3	35.0	34.2	74.5	63.0	73.0	44.5	56.4	466.1
3	Other Losses (Acre-ft.)	18.0	16.7	15.2	21.4	30.5	34.1	22.8	25.5	37.0	288.4
4	Total Loss (Acre-ft.)	33.5	34.0	50.2	55.6	105.0	97.1	95.8	70.0	93.4	754.5
5	Change in Contents (Acre-ft.)	-18.3	-14.0	-45.6	159.2	-89.4	11.0	-96.7	-38.1	191.5	213.0
6	Recorded Runoff With Structures (Acre-ft.)	0.0	0.0	0.0	55.0	463.0	6.0	0.0	129.0	1786.0	2704.0
7	Sum 4 + 5 + 6	15.2	20.0	4.6	269.8	478.6	114.1	-0.9	160.9	2070.9	3671.5
8	Simulated Runoff Without Structures (Acre-ft.)	14.0	32.0	8.0	299.0	337.0	209.0	6.0	91.0	1880.0	3599.0

measured losses at the reservoirs (row 4). Row 7 is thus an estimate of the flow without the structures based on the measurements at the reservoirs. Assuming there are losses in the channels below the reservoirs in addition to those measured at the reservoirs and that the simulated flows (row 8) are the best available estimate of the flow without the structures, the difference between row 8 and row 7 is a measure of additional losses in the channels attributable to the presence of the reservoirs.

For the 13 months of available record channel losses attributable to the structures were positive for 9 months amounting to 506 acre-feet or 7% of the flow during these months. During the other 4 months the losses with the structures were less, amounting to a total of 404 acre-feet or 17% of the flow during those months. Based on this limited data it would appear that the additional losses due to increased evapotranspiration resulting from prolonged flow in the channels were approximately balanced by the reduced losses due to less flood bank infiltration.

The results are not conclusive due to the limited data. The 1965 water year was very dry and the results may have been unrepresentative. Analysis of the data for the 1967 and 1968 water years in which there was more rainfall is being carried out to provide further information.

For the location and period of this study the watershed simulation method gave estimates of losses due to the presence of small structures which were in close agreement with those estimated from measurements of inflow, outflow, and change of storage at the reservoirs. The method should be applied in a similar manner for different conditions to explore the effect of small structures on channel losses. A watershed with a greater length of channel downstream from the structure may be desirable. Since the watershed simulation method evaluates the total change in response of the watershed, it appears to be the most reliable method for evaluating the effect of watershed changes and can provide a basis for comparison with simpler and more approximate methods.

C. Simulation of Runoff From the Watershed With the Floodwater-Retarding Structures

An attempt was made to simulate the runoff from the study area with the structures only by changing the model parameters.

Upper zone storage nominal, UZSN, was the first parameter to be altered, since it is a reference volume for determining the response of the upper zone storage. It was increased in order to take into account the reservoirs. This increase of UZSN reduced the peaks of small hydrographs, but did not have any significant effect on large hydrographs. Further increase of UZSN reduced the peaks of small hydrographs too much, even made some of them disappear and thus caused very small runoff yields compared to the recorded values particularly in 1965-66 water year since this year had mostly small storms.

UZSN was not a powerful parameter on the large hydrographs. For reduction of their peaks, infiltration index, CB, was increased. This means that more water will infiltrate, and go to lower zone storage and groundwater. Then it will gradually appear as groundwater flow. This is not the situation with the structures, but they have a similar effect. Because on the watershed some of the runoff is held by the reservoirs and then gradually released to base flow. This analogy is not perfectly true for the case when the reservoirs are full before the storm, and it also depends on the similarity between groundwater flow recession parameter and outflow from the reservoirs.

Increased infiltration caused more water entering the lower zone storage and more loss from the storage by evapotranspiration. This reduced the runoff yields significantly. In order to avoid this lower zone storage nominal, LZSN, was reduced. Thus this allowed more water going to groundwater.

After several trials UZSN was increased from 0.45 to 0.55, and CB from 0.65 to 1.30. LZSN was decreased from 4.70 to 4.00. These changes increased daily correlation coefficients from 0.8968 to 0.9548 for 1964-65 and from 0.9092 to 0.9353 for 1965-66 water years. Figures V.3-4 show recorded and simulated hydrographs with the structures. Table V.4 gives monthly recorded and simulated flows with and without the structures.

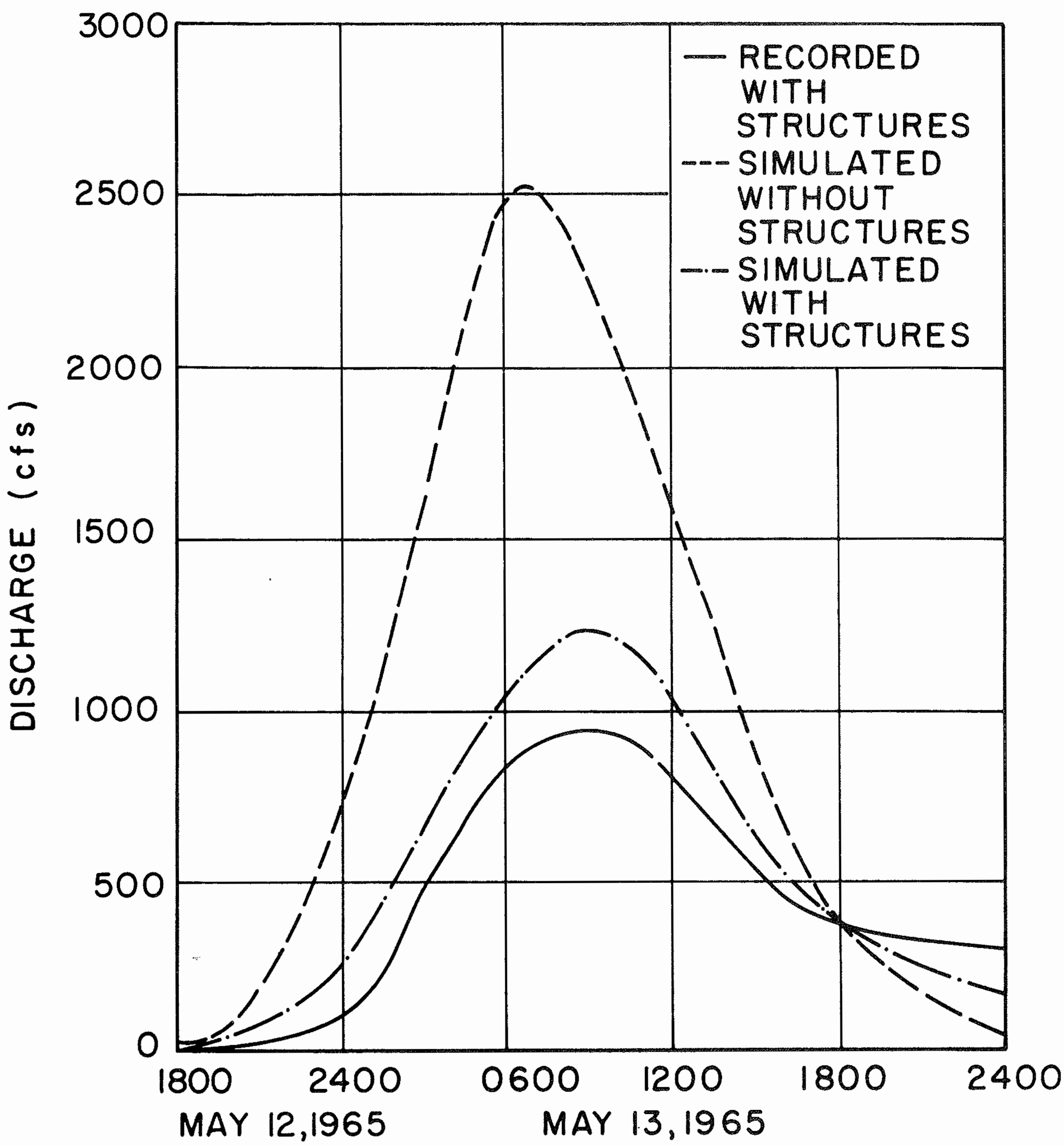

FIGURE V.3 COMPARISON OF RECORDED AND SIMULATED HYDROGRAPHS

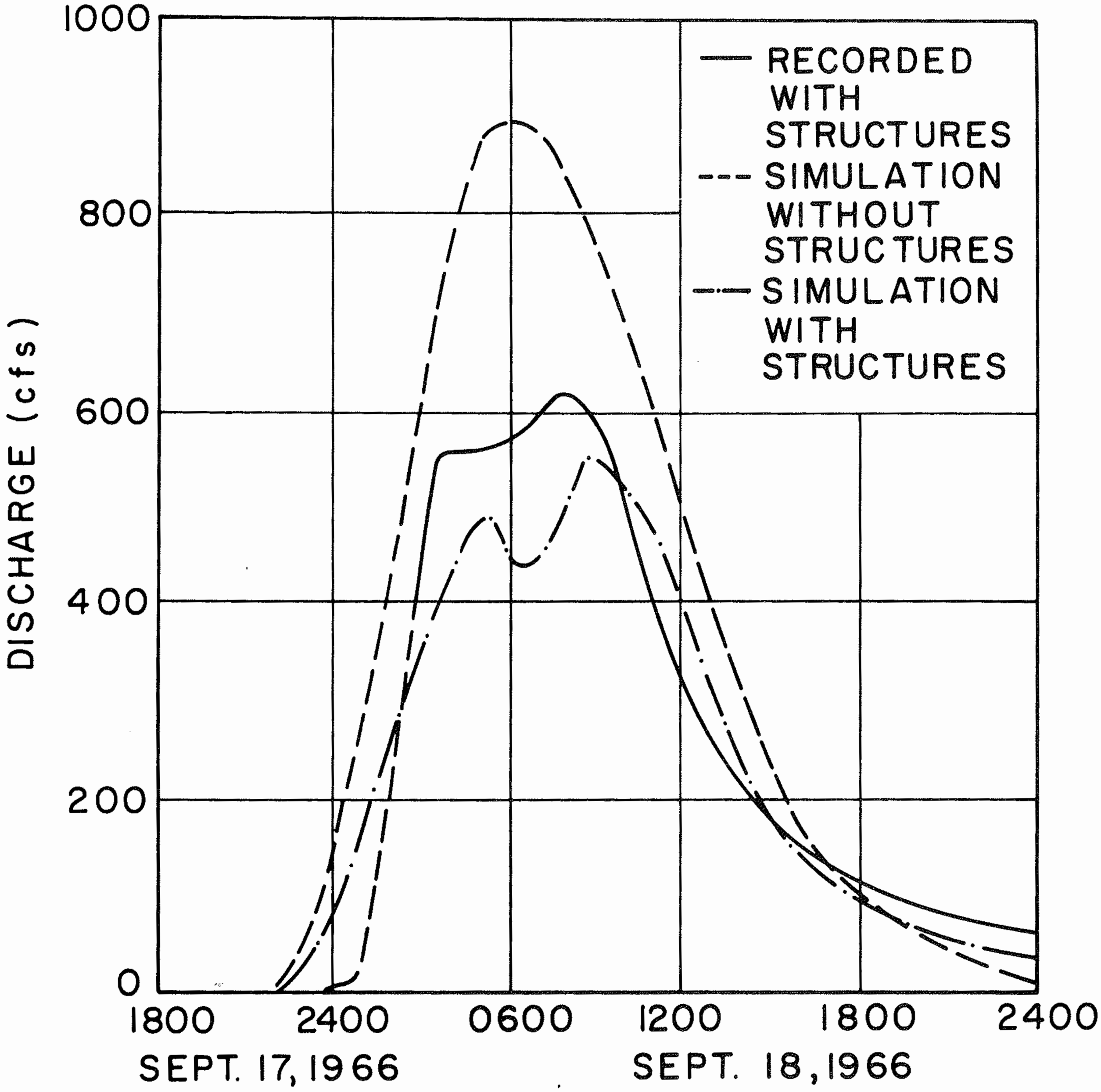

FIGURE V. 4 COMPARISON OF RECORDED AND SIMULATED HYDROGRAPHS

TABLE V.4 - COMPARISON OF RECORDED AND SIMULATED (WITH AND WITHOUT THE STRUCTURES) RUNOFF VALUES IN INCHES

Water Year		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual	Correlation Coefficient
1965	Recorded	0.02	0.79	0.02	0.01	0.10	0.01	0.0	2.78	0.09	0.0	0.0	0.0	3.82	
	Sim.Without Str.	0.01	0.74	0.01	0.03	0.09	0.0	0.0	3.05	0.10	0.0	0.0	0.0	4.03	0.8968
	Sim.With Str.	0.01	0.51	0.01	0.04	0.13	0.0	0.0	2.69	0.09	0.0	0.0	0.0	3.48	0.9548
1966	Recorded	0.0	0.07	0.0	0.0	0.0	0.0	0.02	0.12	0.0	0.0	0.03	0.47	0.71	
	Sim.Without Str.	0.03	0.14	0.02	0.0	0.01	0.0	0.09	0.09	0.06	0.0	0.02	0.50	0.96	0.9092
	Sim.With Str.	0.02	0.11	0.03	0.0	0.01	0.0	0.05	0.08	0.03	0.0	0.03	0.45	0.81	0.9353

CHAPTER VI

CONCLUSIONS

The following conclusions about the Stanford Watershed Model, and the effects of floodwater-retarding structures on runoff may be drawn from the report.

1. The Stanford Watershed Model is a useful and accurate method in simulation of runoff. It is useful, because it does continuous simulation of runoff from which one can obtain information about water yields, characterisitcs of hydrographs and allocation and processing of water at every step of the hydrologic cycle.

2. The Stanford Watershed Model tries to simulate every step of the hydrologic cycle which makes it, as some people complain, complicated and long. However, this brings the advantage that any change in watershed characteristics may be entered to the hydrologic cycle and its effects on runoff can be investigated, such as effects of urbanization. On the other hand simulating a year of streamflow record on the Control Data 6600 computer at The University of Texas at Austin uses less than 10 seconds of central processing time.

3. Simulation with the model requires a trial and error process to fix some parameters which are not clearly related to measurable physical quantities in the watershed. Besides, they are dependent upon each other. Therefore selection of these parameters causes difficulty in applying the digital model to a particular watershed.

4. Longer periods of record used for fixing the parameters will make them more reliable and representative of the watershed.

5. It is possible to get more than one set of parameters for any particular watershed.

6. The floodwater-retarding structures on Mukewater Watershed caused an average one-half reduction of flood peaks and lengthened the recession parts of the hydrographs.

7. Water yield was very slightly reduced by the retarding structures. Based on the limited data obtained it would appear that the additional losses due to increased evapotranspiration resulting from prolonged flow in the channels were approximately balanced by the reduced losses due to less flood bank infiltration. A more detailed study should be carried on to investigate the sources of losses.

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