EFFECTS OF URBAN DEVELOPMENT ON THE FLOOD-FLOW CHARACTERISTICS OF THE WALNUT CREEK BASIN DES MOINES METROPOLITAN AREA, IOWA

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This report deals with the probable impact of urban development on the magnitude and frequency of flooding in the lower reach of the Walnut Creek Basin. Stream-modeling techniques, which include complete definition of unit hydrographs and precipitation loss-rate criteria, were utilized to evaluate the effects of urban development as measured by percentages of impervious area over the basin. A mathematical model, called HEC-1, was calibrated by using concurrent rainfall-runoff data collected at three gaging stations in the basin. The model parameters were regionalized to allow future users to estimate the model parameters for ungaged areas within the basin. Long-term rainfall data recorded at two nearby stations were employed as basic input to the calibrated model to generate annual peak discharges corresponding to selected degrees of urbanization. Results are presented in tables and graphs, which compare the pre-urban and urban flood flow characteristics of the lower reach of the Walnut Creek basin.

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EFFECTS OF URBAN DEVELOPMENT ON THE FLOOD-FLOW CHARACTERISTICS OF THE WALNUT CREEK BASIN DES MOINES METROPOLITAN AREA, IOWA

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Multiply English units	By	To obtain SI units
	LENGTH	
inch (in)	25.40	millimeter (mm)
foot (ft)	.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	AREA	
square feet (sq ft)	.093	square meters (m^2)
square miles (sq mi)	2.590	square kilometers (km^2)
	FLOW	
cubic feet per second (cfs)	.02832	cubic meters per second (m^3/s)

EFFECTS OF URBAN DEVELOPMENT

ON THE FLOOD-FLOW CHARACTERISTICS

OF THE WALNUT CREEK BASIN

DES MOINES METROPOLITAN AREA, IOWA

ABSTRACT

This report deals with the probable impact of urban development on the magnitude and frequency of flooding in the lower reach of the Walnut Creek Basin.

Stream-modeling techniques, which include complete definition of unit hydrographs and precipitation loss-rate criteria, were utilized to evaluate the effects of urban development as measured by percentages of impervious area over the basin. A mathematical model, called HEC-1, was calibrated by using concurrent rainfall-runoff data collected at three gaging stations in the basin. The model parameters were regionalized to allow future users to estimate the model parameters for ungaged areas within the basin.

Long-term rainfall data recorded at two nearby stations were employed as basic input to the calibrated model to generate annual peak discharges corresponding to selected degrees of urbanization. Results are presented in tables and graphs, which compare the pre-urban and urban flood flow characteristics of the lower reach of the Walnut Creek basin.

INTRODUCTION

Purpose and Scope

Walnut Creek basin, located within the Des Moines metropclitan area, is one of the more rapidly urbanizing areas in the State of Iowa. A particularly significant aspect of this trend is its effect upon the natural hydrologic system of the basin.

The specific objective of this study was to assess the impact of urban development on the magnitude and frequency of flocding in the lower reaches of the Walnut Creek basin.

Observed flood data of adequate period of record are, obviously, the most reliable source for directly evaluating the consequences of urban development. Lacking these data, as in the Walnut Creek basin, where only 5 years of flood records are available, planners must resort to other sources of usable information and alternate methods of analysis. A surrogate approach often employed in urban planning is known as deterministic modeling or system simulation. According to McGuinness and others (1970),"... deterministic oriented mathematical models of watershed systems appear to offer the most rational approach both for quantitatively describing hydrologic performance of watersheds and for delineating the effects of land use and management practices on stream flow".

Based on the preceding reasoning, a deterministic modeling method was utilized in this study. In general, the steps selected to implement this study can be summarized as follows:

1. Using a rainfall-runoff model, extend the short-term annual flood peaks at the gaging station by utilizing the long-term climatic data recorded at the nearby Des Moines airport and at Perry, Iowa.
2. Using watershed simulation techniques, generate concurrent long term annual peaks for selected degrees of urbanization.
3. Fit flood-frequency curves to the generated annual peak. arrays.

This report describes the simulation technique which was employed and summarizes the results of the investigation.

This report was prepared by the U.S. Geological Survey under the administrative direction of S. W. Wiitala, District Chief, and is the result of a 3-year cooperative agreement between the Geological Survey and the Iowa Natural Resources Council.

The author is grateful to Arlen D. Feldman of the Corps of Engineers Hydrologic Engineering Center, Davis, California, for his advice, assistance, and cooperation in supplying computer programs and documentation.

STUDY AREA

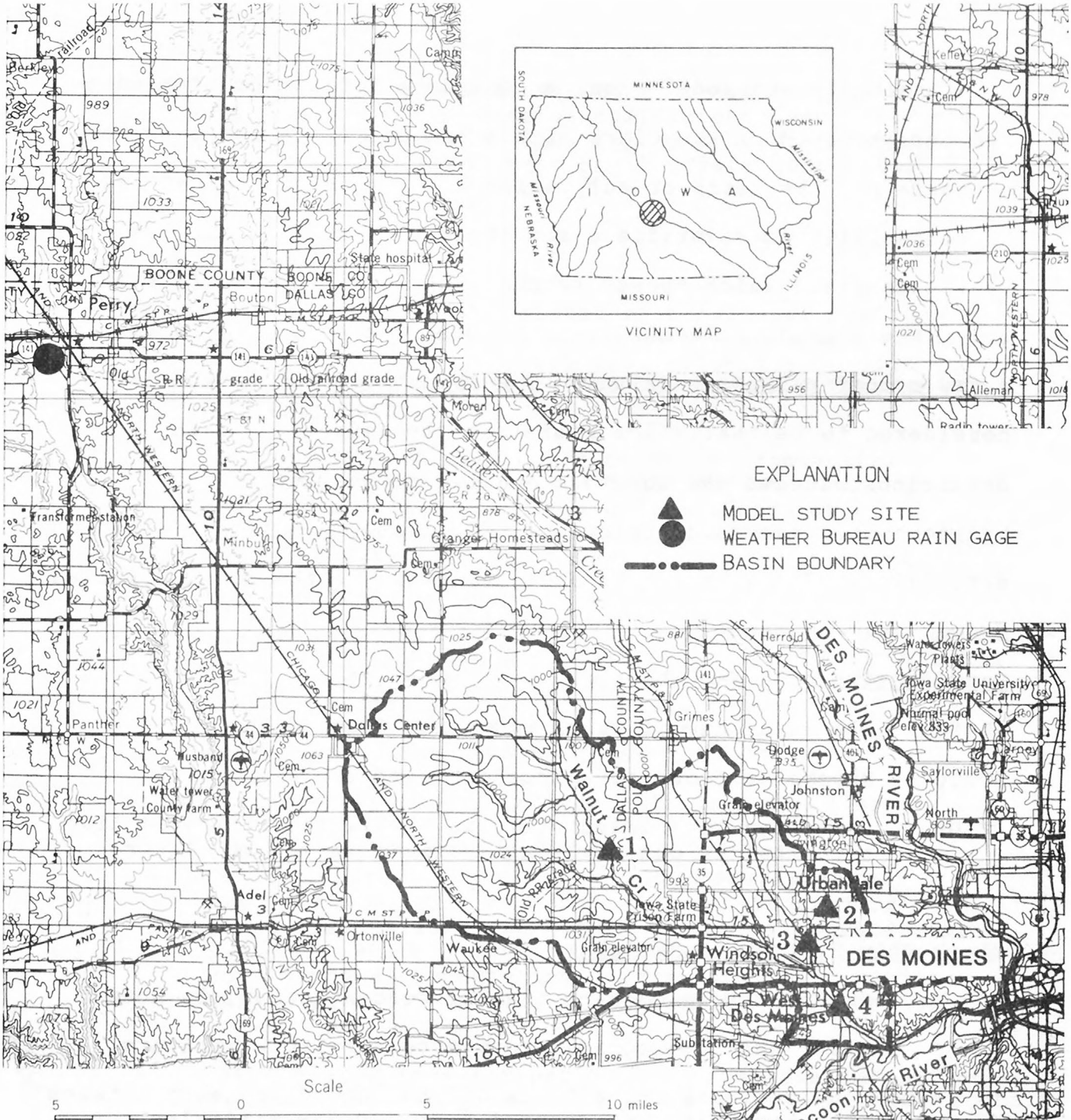
The Walnut Creek basin is in parts of Dallas and Polk Counties, as shown on the location map (fig. 1).

Walnut Creek is a left-bank tributary of the Raccoon River and flows in a southeast direction entering the Raccoon River within the city limits of Des Moines. The lower portions of the basin consisting of about 8 to 10 percent of the total area is highly urbanized. Nearly all the remaining area is agricultural with approximately 75 percent in cropland. The predominant soil type is a combination of Clarion and Nicollet (Stevenson and Brown, 1922), which are classified in the hydrologic group B (U.S. Soil Conservation Service, 1972). Soils in this group are characterized by moderate infiltration rates.

Elevation in the basin ranges from 850 to 1,050 feet above mean sea level. The topography varies from nearly level to rolling terrain. The average annual precipitation is about 32 inches, most of it falling during freeze-free periods.

RAINFALL-RUNOFF MODEL

A model called HEC-1 which was developed by the Hydrologic Engineering Center, U.S. Army Corps of Engineers, (1973), was selected for use because it satifies the project requirements, is relatively simple to use, and it requires less data than alternate models.



1 Walnut Creek near Grimes (30.0 mi^2)
2 North Walnut Creek tributary at Clive (1.95 mi^2)
3 North Walnut Creek at Clive (13.14 mi^2)
4 Walnut Creek at Des Moines (78.4 mi^2)

Figure 1. Map of Walnut Creek basin, Iowa.

Basically the model requires complete definition of a unit hydrograph based on the Clark method and precipitation loss-rate criteria for the basin or sub-basins to be modeled. HEC-1 has the capability to determine a set of unit hydrograph and loss-rate parameters which "best" reconstitute observed runoff events, given the average rainfall over the basin, the drainage area, and a few runoff parameter values. The "best" reconstitution is considered to be that which minimizes the weighted square deviations between the observed and the reconstituted hydrographs. For ready reference, following is a list of definitions of the variables and parameters of the model compiled from the Users Manual.

Runoff Hydrograph Variables

QRCSN - The discharge at which recession flow begins.

STRTQ - Recession flow for antecedent runoff.

RTIOR - Recession coefficient that is the ratio of flow at time t to that 10 computational periods (t + 10 t) later during recession.

Clark Unit Hydrograph Variables

TC Clark unit hydrograph time of concentration, in hours.

R Clark unit hydrograph storage coefficient, in hours.

To reduce the compensating effects of the interdependency between TC and R, the variables are grouped into two new variables for use in the automatic derivation routine.

TC+R Sum of time of concentration and storage coefficient, variable used in HEC-1 for optimizing unit hydrograph parameters.

R/(TC+R) - Ratio of storage coefficient to sum of time of concentration and storage coefficient; variable used in HEC-1 for optimizing unit hydrograph parameters. For a graphical representation of the Clark unit graph coefficient, see figure 2.

Loss Rate Parameters

DLTKR Amount of initial accumulated rainfall loss during which the loss rate coefficient is increased. This parameter is considered to be a function primarily of antecedent soil moisture deficiency and is usually different for different storms.

STRKR Starting value of loss coefficient on exponential recession curve for rainfall losses (snow-free ground). The starting value is considered a function of infiltration capacity and thus depends on such basin characteristics as soil type, land use, and vegetal cover.

RTIOL Ratio of rain loss coefficient on exponential loss curve to that corresponding to 10 inches more of accumulated loss. This variable may be considered a function of the ability of the surface of a basin to absorb precipitation and should be reasonably constant for large rather homogeneous areas.

ERAIN Exponent of precipitation for rain loss function

$$ALOSS = (AK + DLTK)\ PRCP^{ERAIN}$$

that reflects the influence of precipitation rate on basin-average loss characteristics. It reflects the manner in which storms occur within an area and may be considered a characteristic of a particular region. Varies from 0.0 to 1.0. The terms in the equation are defined as:

ALOSS = loss rate for particular time interval in inches per hour.

AK = loss rate coefficient at beginning of time interval.

PRCP = rainfall intensity in inches per hour

DITK = incremental increase in loss rate coefficient. DLTK is assumed to be a parabolic function of

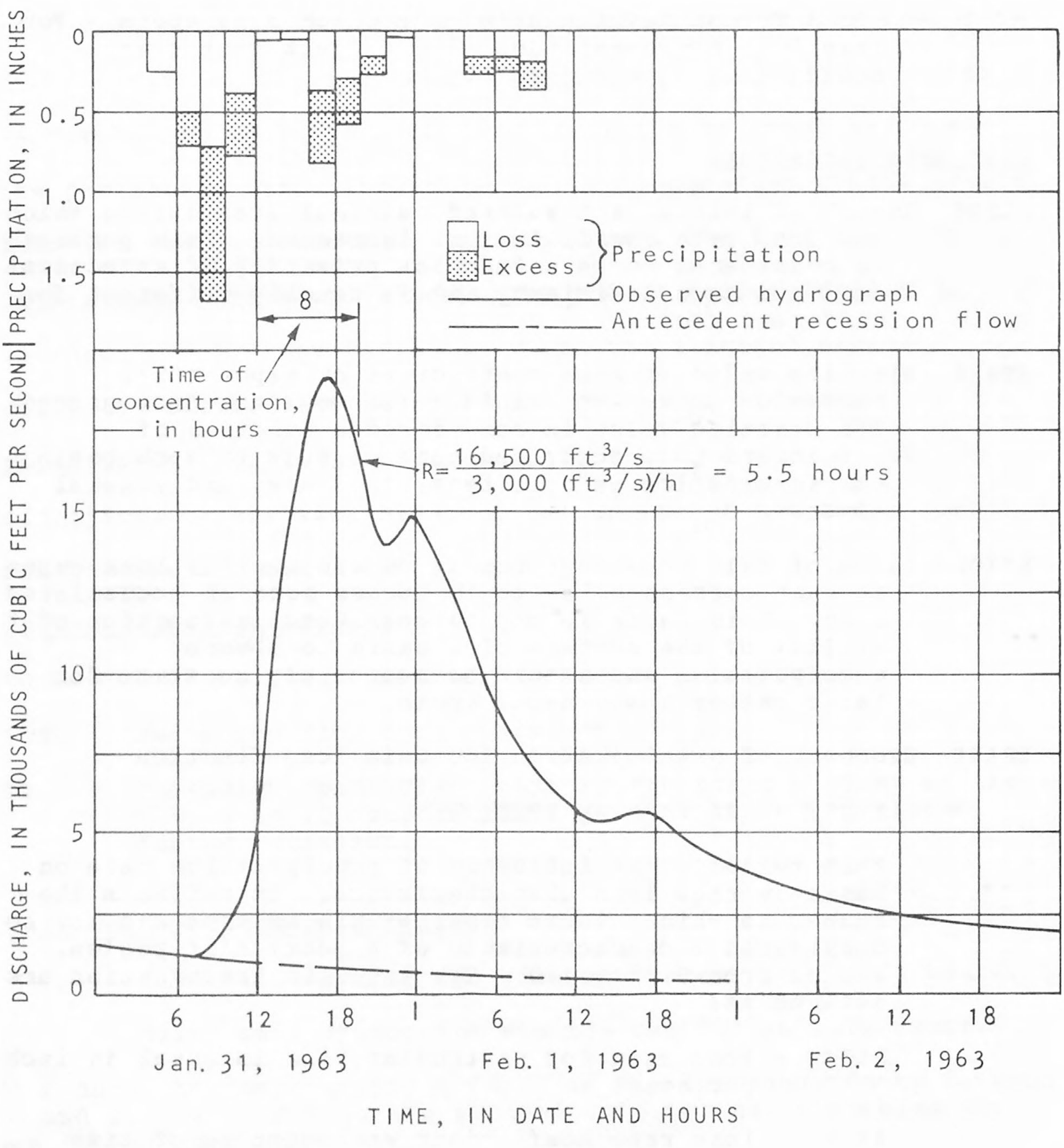


Figure 2. Clark unit graph coefficients.

the accumulated loss for DLTKR amount of accumulated loss. DLTK is a maximum of 0.2 DLTKR initially reducing to zero when the accumulated loss equals DLTKR. A graphical representation of the loss rate parameters is illustrated in figure 3.

BASIC DATA

During the first year (1975) of this three-year project, a data-collection network was established to obtain concurrent streamflow and rainfall data. The gaging stations in the basin were installed in accordance with the following criteria:

1. Update the instrumentation at the recording station near the mouth of Walnut Creek which has been in operation since 1971.
2. Select a site in the basin to collect data for an essentially rural area.
3. Select a site in the basin to collect data for a partially urbanized area.
4. Select a site in the basin to collect data for a completely urbanized area.
5. Assure that stations in the network represent a significant range of drainage-area sizes.

Budget constraints limited the number of gaging stations to four including the existing gaging station. Each gaging site was equipped with a Stevens A-35 water-stage recorder with a rainfall recording attachment. Figure 1 shows their locations.

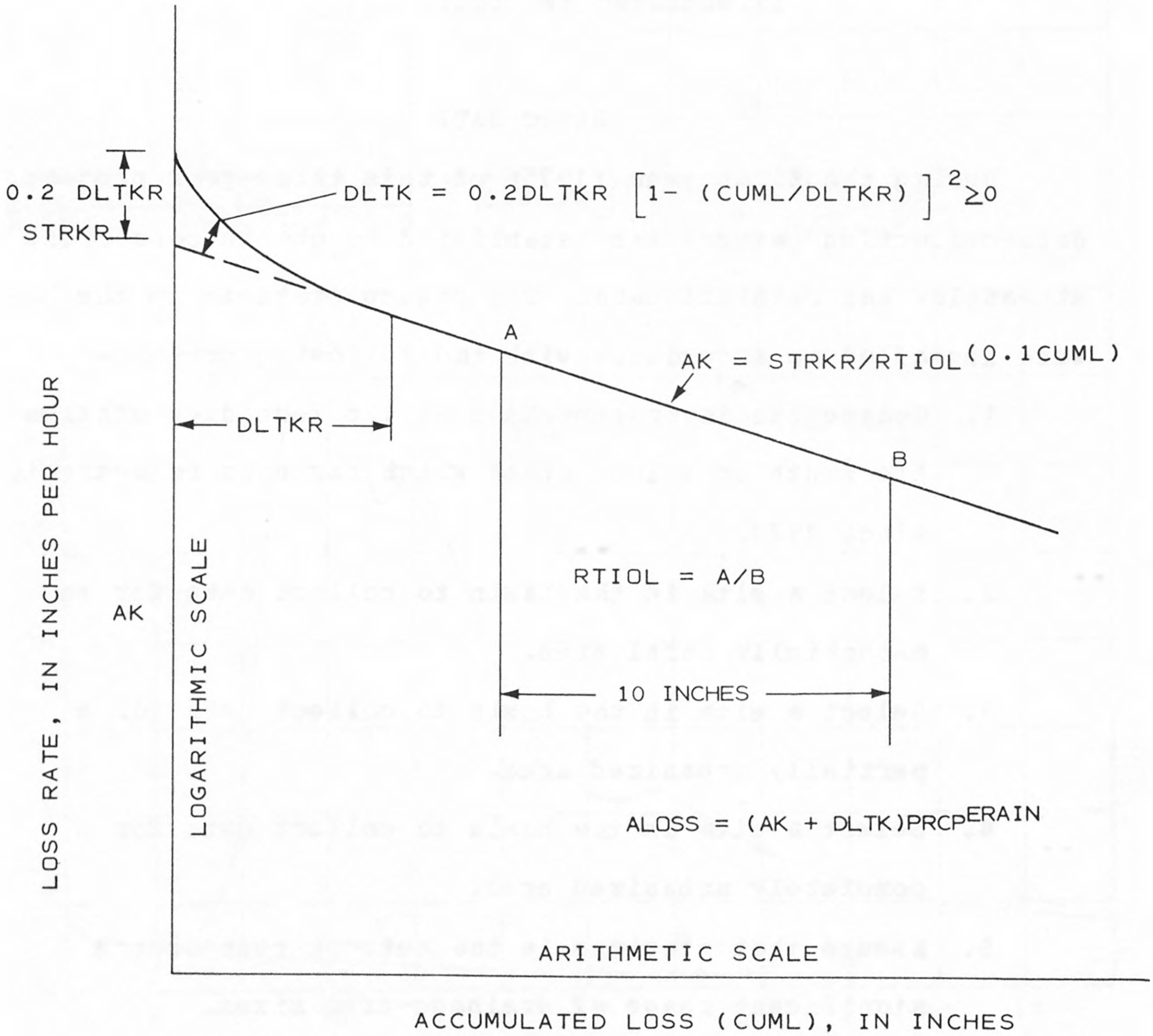


Figure 3. Schematic diagram of loss rate parameters.

Data-collection expectations were not fully realized because the study area, experienced severe drought conditions with very little storm activity. This situation persisted throughout the time of the project limiting the collection of data to no more than two or three significant storms at each gaging station. Furthermore, the location of the gage installed to collect data for a fully urbanized area proved to be unsatisfactory and had to be moved. Hence, data from only three stations were available at the time of this study (1977).

Other data used in this study were long-term records of hourly rainfalls at the Des Moines airport and concurrent 24-hour total rainfall amounts recorded at Perry, Iowa. The locations of these rainfall stations are shown in figure 1.

MODEL CALIBRATION

Regional Analysis of Model Parameters

The usefulness of a calibrated model, such as the one described above, is considerably expanded by providing future investigators with the ability to estimate the model parameters for ungaged areas within the basin. This was accomplished by regionalization techniques in which model parameters were related to physiographic, land-use, and climatic characteristics of the basin. Regionalization of model parameters is not one of the primary objectives of the present study. However, efforts have been made at this time to develop a set of criteria for estimating model parameters for ungaged watersheds within the Walnut Creek basin.

The modeling sequence and the results of the regionalization studies are summarized below.

Modeling Sequence

The calibration of the model and definition of regional relations were accomplished generally in the following sequence.

1. Compile precipitation and runoff data for all of the storms at the gage.
2. Determine STRTQ for each storm at the gage.
3. Determine QRCSN for the recorded flood by plotting the flow recession on semilogarithmic paper and selecting the discharge above which the recession significantly departs from a linear relation.
4. Determine RTIOR. This value is equal to the slope of the linear function discussed in Step 3.
5. Compute TC, R, STRKR, DLTKR, RTIOL, and ERAIN for all storms at the gage using the optimizing routine of the model.
6. Repeat steps 1 through 5 for all gages in the basin. Based on the results, select an average regional value for ERAIN.

7. Repeat Step 5 for all gages and selected storms with ERAIN fixed to equal the regional value. Select a regional value for RTIOL based on previous computations.

8. Compute TC, R, STRKR, DLTKR, using the optimizing routine of the model for all storms at all gages with the regional values of ERAIN and RTIOL fixed.

9. From the results of Step 8, select a representative value of STRKR for each gage, and recompute TC, R, and DLTKR for all gages and storms with ERAIN, RTIOL, and STRKR fixed.

10. Select an appropriate value for DLTKR and an average value for R/TC+R for each subbasin and optimize TC and R, with R/TC+R, STRKR, ERAIN, DLTKR, and RTIOL fixed for the selected storms at each gage.

11. Select an average representative value of TC and R for each stream, check the goodness of fit of selected storms. Adjust TC+R and rerun if needed.

12. Regionalize the model parameters.

13. To judge the quality of the regional approach compute the model parameters by using the regional relations and reconstitute known runoff events at each site and compare. Examples of such comparisons are shown in figures 4, 5, and 6. In addition, the final rainfall-runoff values were compared to the relations developed by the Soil Conservation Service (1972) where loss rates

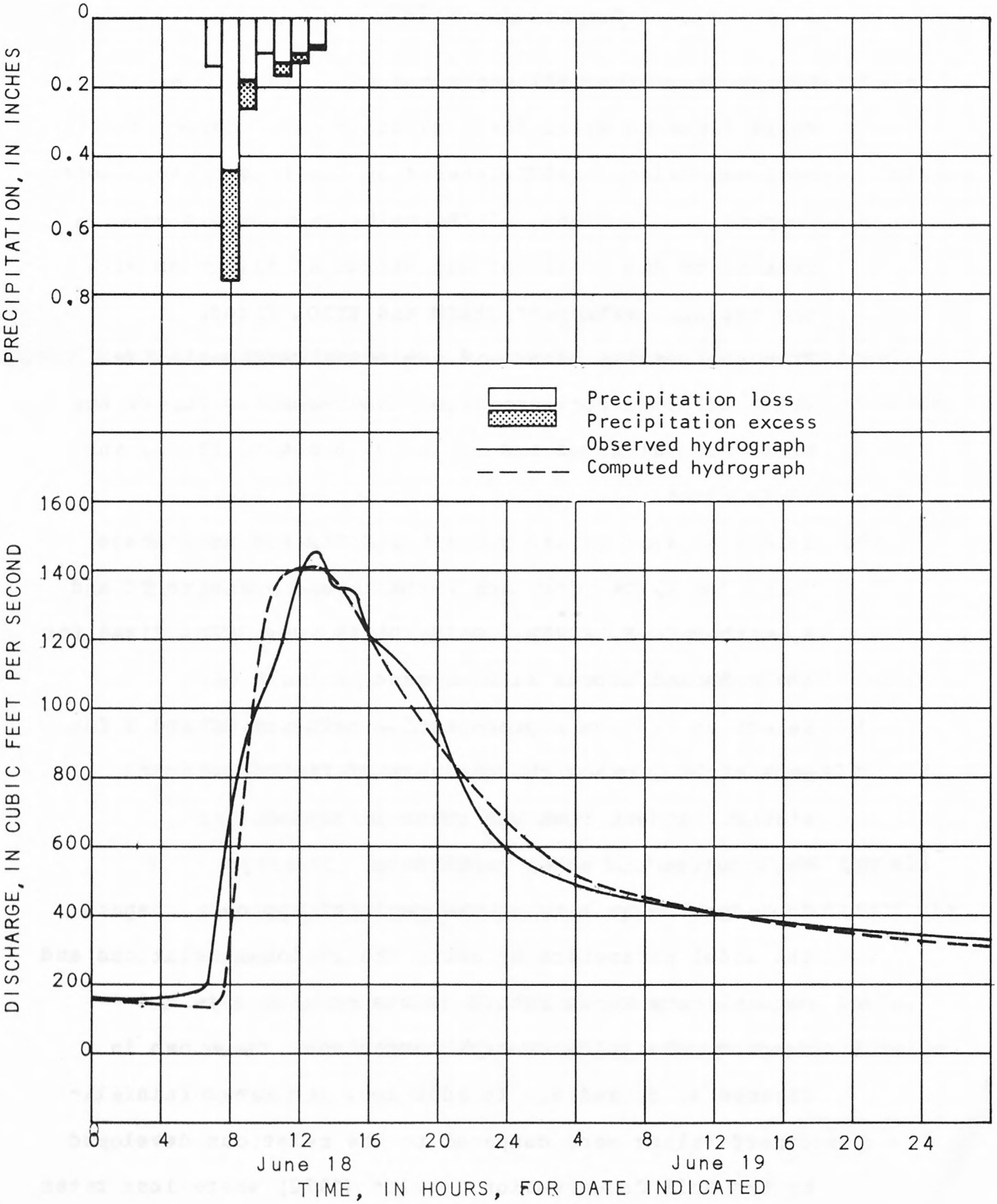


Figure 4. Observed and computed hydrographs for Walnut Creek at Des Moines, Iowa (drainage area, 78.4 mi^2) for flood of June 18, 1975.

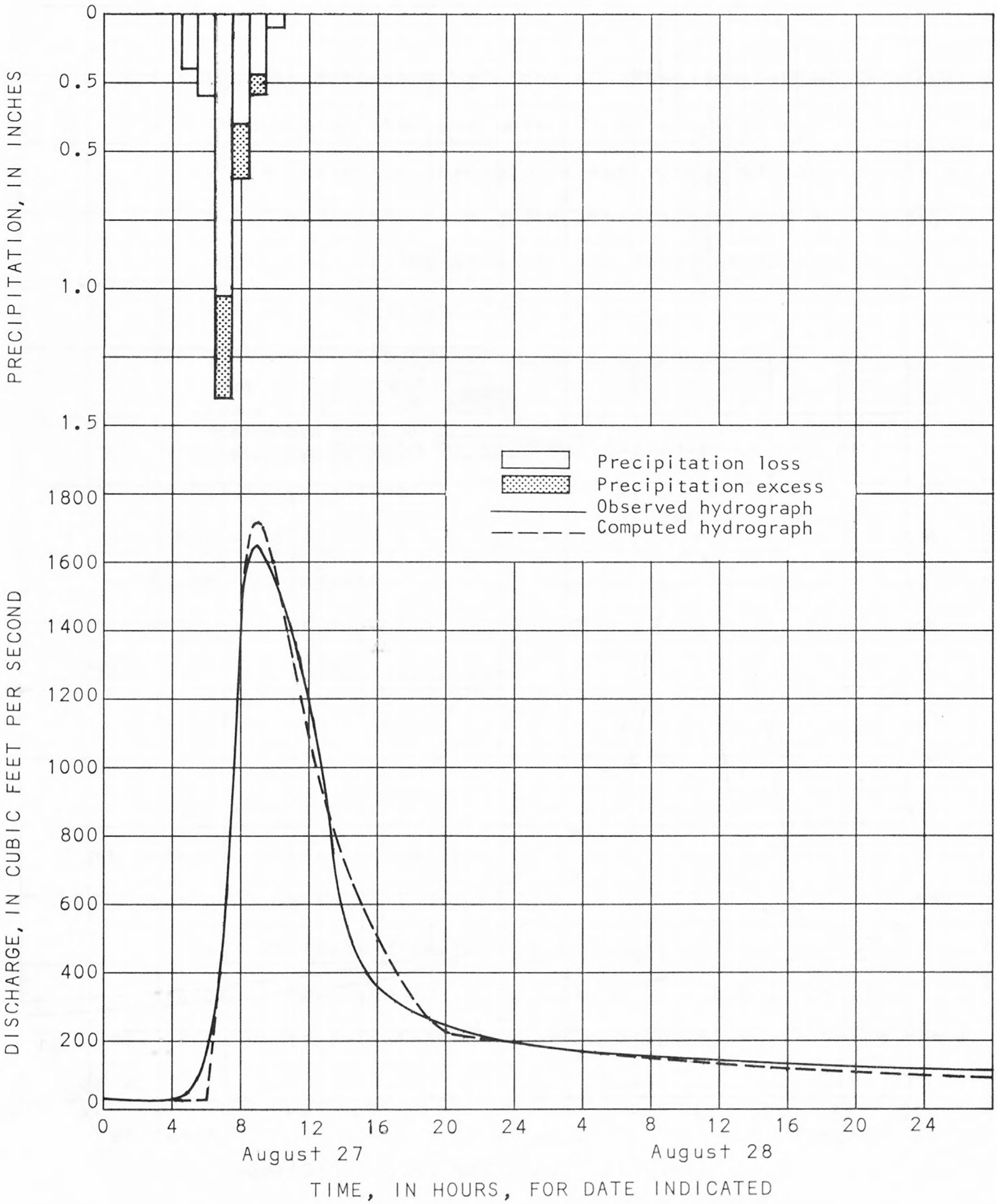


Figure 5. Observed and computed hydrographs for Walnut Creek near Grimes, Iowa (drainage area, 30.0 mi^2) for flood of June 18, 1975.

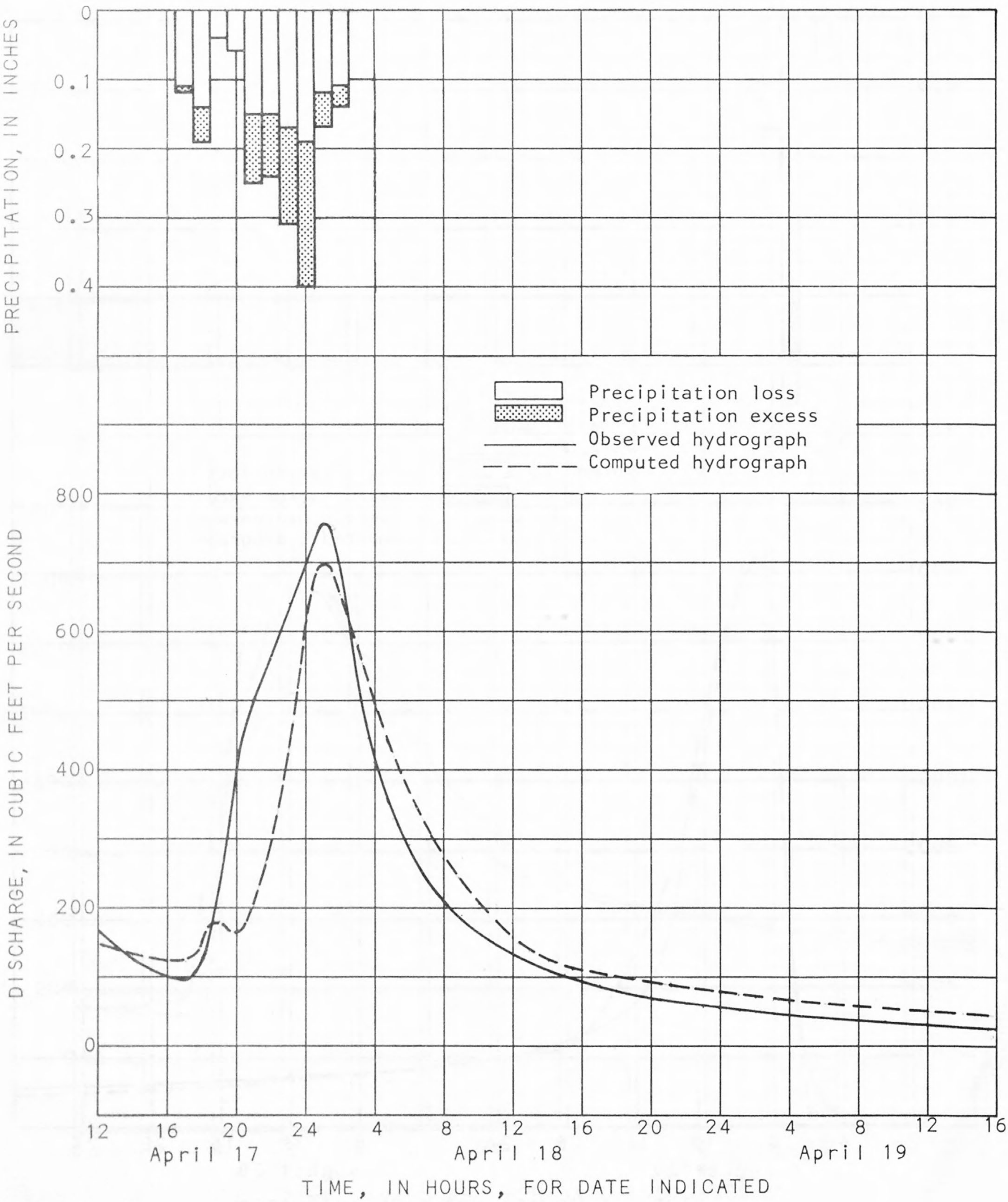


Figure 6. Observed and computed hydrographs for North Walnut Creek at College Drive (drainage area, 13.14 mi^2) for flood of April 18, 1976.

are characterized by a curve number (CN) which is a function of the land cover (land use) and soil characteristics (hydrologic soil group). The results of this comparison were quite satisfactory and well within acceptable limits of departure from the curves that apply to the Walnut Creek basin.

The results of the regional study are summarized below.

Results of Regional Analysis

Runoff-Hydrograph Variables

$$QRCSN = 35\ A^{0.50} \tag{1}$$

$$RTIOR = 2.10/A^{0.10} \tag{2}$$

$$STRTQ = 0.5A \tag{3}$$

Clark Unit Hydrograph Variables

$$TC + R = 1.65\ A^{0.51} \tag{4}$$

and

$$R/(TC + R) = 0.50 \tag{5}$$

Substituting between 4 and 5

$$R = 0.83\ A^{0.51} \tag{6}$$

A = Drainage area in square miles.

Figure 7 shows the relation between TC + R and drainage area. Each point represents the average optimized value at the gage.

Loss Rate Parameters

ERAIN = 0.54

RTIOL = 2.94

STRKR = 0.32

DLTKR (function of antecedent conditions).

It should be noted that the results obtained from the regional relations are applicable only to the Walnut Creek basin.

SYNTHESIS OF FLOOD PEAKS

Processing of rainfall data

The rainfall-runoff model, calibrated as explained previously, was used to synthesize flood peaks using long-term rainfall records for Walnut Creek at Des Moines (drainage area 78.4 mi^2). Rainfall storms were selected from data recorded at the Des Moines airport and at Perry, Iowa.

The Des Moines rainfall-recording station has been in operation since 1879. However the time response of the basin is such that the model requires hourly rainfall distribution data. Therefore, only the 36-year record for 1941-76 water years is usable.

HEC-1 performs "lumped" parameter modeling. This means that the computed parameters and the input data, such as rainfall, are considered to be average values and, in the case of rainfall, uniformly distributed over the watershed. In order to meet this

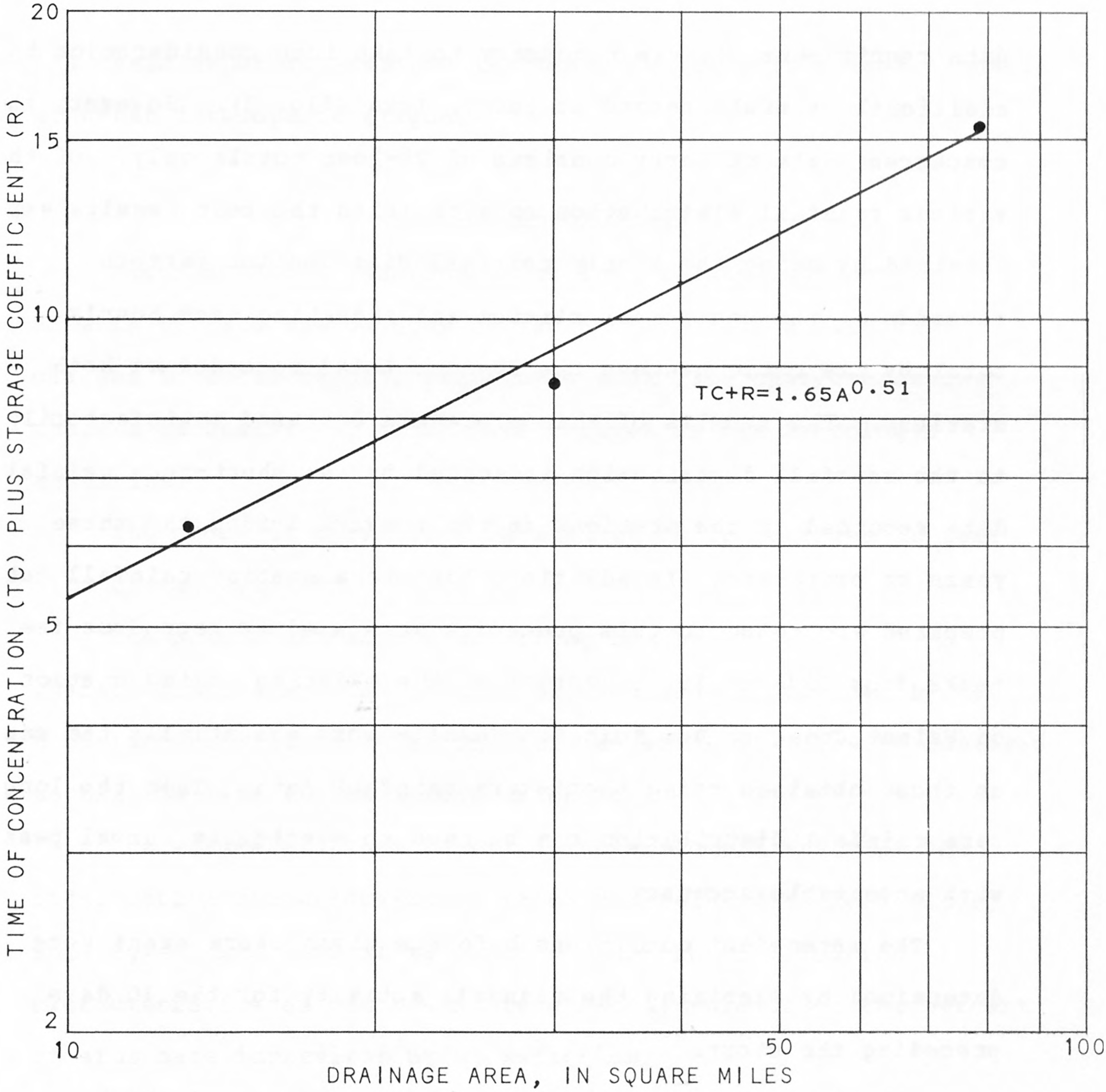


Figure 7. Relation between Clark unit hydrograph parameters and the drainage area for Walnut Creek basin.

data requirement, it was necessary to take into consideration the additional rainfall record at Perry, Iowa (fig. 1). However, the concurrent data at Perry consists of 24-hour totals only. Of the various rainfall distribution schemes tried the best results were obtained by using the hourly rainfall distribution pattern recorded at the Des Moines station and adjusting each hourly total by the ratio between the 24-hour total recorded at both stations. The results of this procedure compared satisfactorily to the rainfall distribution indicated by the short-term rainfall data recorded at the stations in the network during the three years of operation. In addition, long-term station rainfall data prepared according to this procedure were used to reproduce the peaks from 1972 to 1976 recorded at the existing gaging station on Walnut Creek at Des Moines. Results were essentially the same as those obtained using short-term rainfall data. Thus the long-term rainfall distribution can be used to synthesize annual peaks with acceptable accuracy.

The antecedent conditions before a given storm event were determined by examining the rainfall activity for the 10 days preceding the storm.

All of the storm events in the long-term record which appeared likely to produce a high peak were simulated with the model. From these runs, the storm event which resulted in the highest peak discharge within a water year was selected and included in an array of 36 annual storms. These data constitute the basic input to simulate the basin response to selected levels of urban development stages.

Simulation of Peaks

Leopold (1968) describes four interrelated but separable effects of land use changes on the hydrology of a watershed: changes in total runoff, changes in peak flow characteristics, changes in quality of water, and changes in the hydrologic amenities.

The scope of this study is limited to the changes in peak flow characteristics.

The principal factors governing the peak flow characteristics are the portion of area made impervious by the urbanization processes and the rate at which the flow is conveyed across the land to the stream channels.

The volume of storm runoff is governed primarily by the infiltration characteristics, which are related to land slope, soil types, and vegetative cover. Thus the infiltration characteristics of the basin are directly related to the percent of area made impervious by urbanization.

The rate at which water is conveyed across the basin is related to the density, size, and hydraulic characteristic of the tributary channels. Therefore it is also related to the provision of storm sewerage systems, which alter the natural conditions of the basin. Observed data to develop relations describing the effect of channel modification on the unit hydrograph parameters are not available at this time. For the purpose of this study, factors for adjusting these parameters have been obtained from experimental data compiled by the Soil Conservation Service (1975).

Results

To compare the effects of urbanization on the flood flow characteristics of Walnut Creek, five simulation runs were made. The first run was for the basin in its present stage of urbanization (abcut 5 percent of the area impervious). The remaining runs were made by changing the pertinent model parameters to reflect 20, 30, 50, and 100 percent of the basin impervious. Taking into account the size of the drainage area and the type of urban development expected to take place, the upper limit is likely to be less than 50 percent impervious.

The synthetic annual peaks for each year of rainfall record are listed in Table 1.

Frequency curves for each of the annual peak series listed in Table 1, were computed by fitting the Pearson Type III distribution function to the logarithms of the annual peaks. The computed log-Pearson distribution parameters are listed at the bottom of Table 1. The resulting frequency curves are shown in figure 8.

The variation of the log-Pearson type III distribution parameters with percent of impervious area is shown in figure 9. If desired, this figure could be used to calculate frequency curves between those shown in figure 8.

Included in figure 8 and for the purpose of comparison, is a "regional frequency curve" which was estimated by using an entirely different approach from the one discussed in this report. Methods for estimating regional flood-frequency curves for the state of Iowa are explained by Lara (1973, 1974). Theoretically, the regional curve describes the flood-frequency characteristics of Walnut Creek in its natural condition.

The impact of urbanization on the flood-frequency characteristics of Walnut Creek, as measured by increasing percentages of impervious area over the basin, can be evaluated from the data summarized in table 1 and figure 8.

Table 1. Synthetic annual peak discharges, in cubic feet per second, compiled from model responses to present conditons and to selected degrees of urbanization.

Water year	Impervious area over the basin in percent				
	5 present	20	30	50	100
1941	4080	4870	5230	5800	6930
1942	4140	5430	6030	6850	9390
1943	1890	2510	2820	3350	4670
1944	2870	3720	4140	4930	6500
1945	2230	3180	3660	4530	6320
1946	2000	2820	3240	3970	5430
1947	5310	6600	7190	8390	10400
1948	3280	4200	4730	5650	7400
1949	1970	3020	3560	4570	6480
1950	2820	3570	4040	4870	6300
1951	2640	3630	4120	5080	6880
1952	3380	4090	4430	5040	6340
1953	790	1420	1770	2430	3810
1954	4790	5980	6550	7680	9480
1955	2200	2860	3210	3830	5200
1956	345	818	1070	1550	2660
1957	775	1180	1400	1780	2740
1958	6890	8570	9360	10800	12700
1959	2350	3320	3790	5150	7210
1960	4010	5130	5700	6740	8600
1961	3600	4910	5550	6840	8850
1962	2830	3600	3970	4570	5690
1963	6030	7370	7990	9170	10800
1964	2260	2980	3380	4110	5440
1965	1730	2400	2740	3370	4670
1966	1630	2180	2470	2940	4020
1967	3080	3750	4090	4580	5700
1968	3810	4810	5390	6320	7990
1969	1170	1990	2390	3170	4830
1970	3220	4120	4560	5460	6770
1971	1630	2610	3130	4100	5970
1972	672	1360	1700	2370	3850
1973	8990	10800	11600	13400	15400
1974	8120	10000	10900	12800	14800
1975	5840	7290	8000	9340	11400
1976	2450	3310	3750	4540	6140
Mean	3.417	3.555	3.609	3.694	3.819
S.D.	0.307	0.251	0.235	0.215	0.180
Skew	-0.45*	-0.38	-0.30	-0.15	-0.03

* The skew for this array was adjusted according to U.S. Water Resources Council Guidelines Bulletin 17 (1976). It was assumed that these peaks represents closely the natural conditions of the basin. No other adjustments were made.

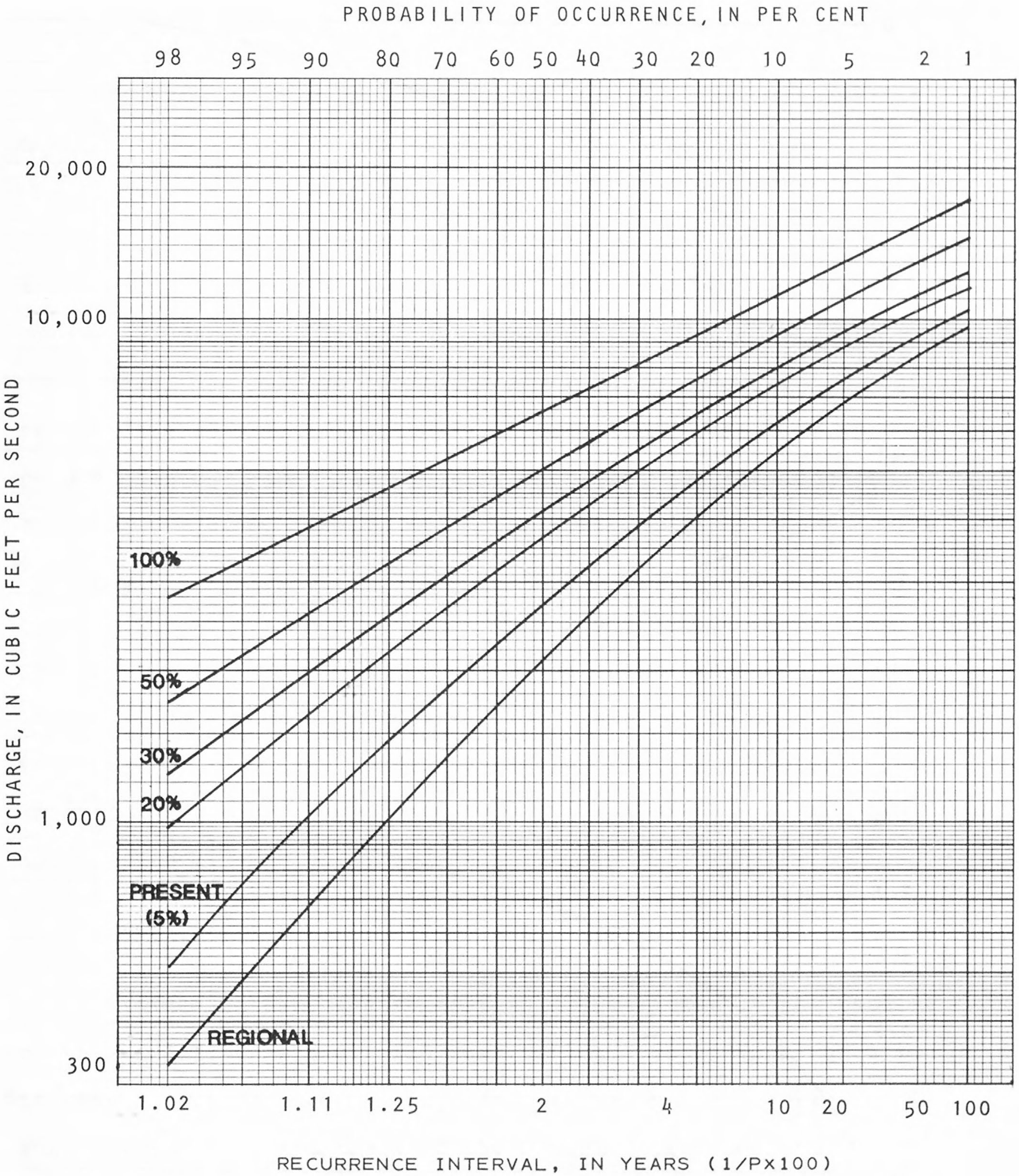


Figure 8. Flood frequency curves showing the effect of urbanization as measured by increased percentage of impervious area for Walnut Creek at Des Moines.

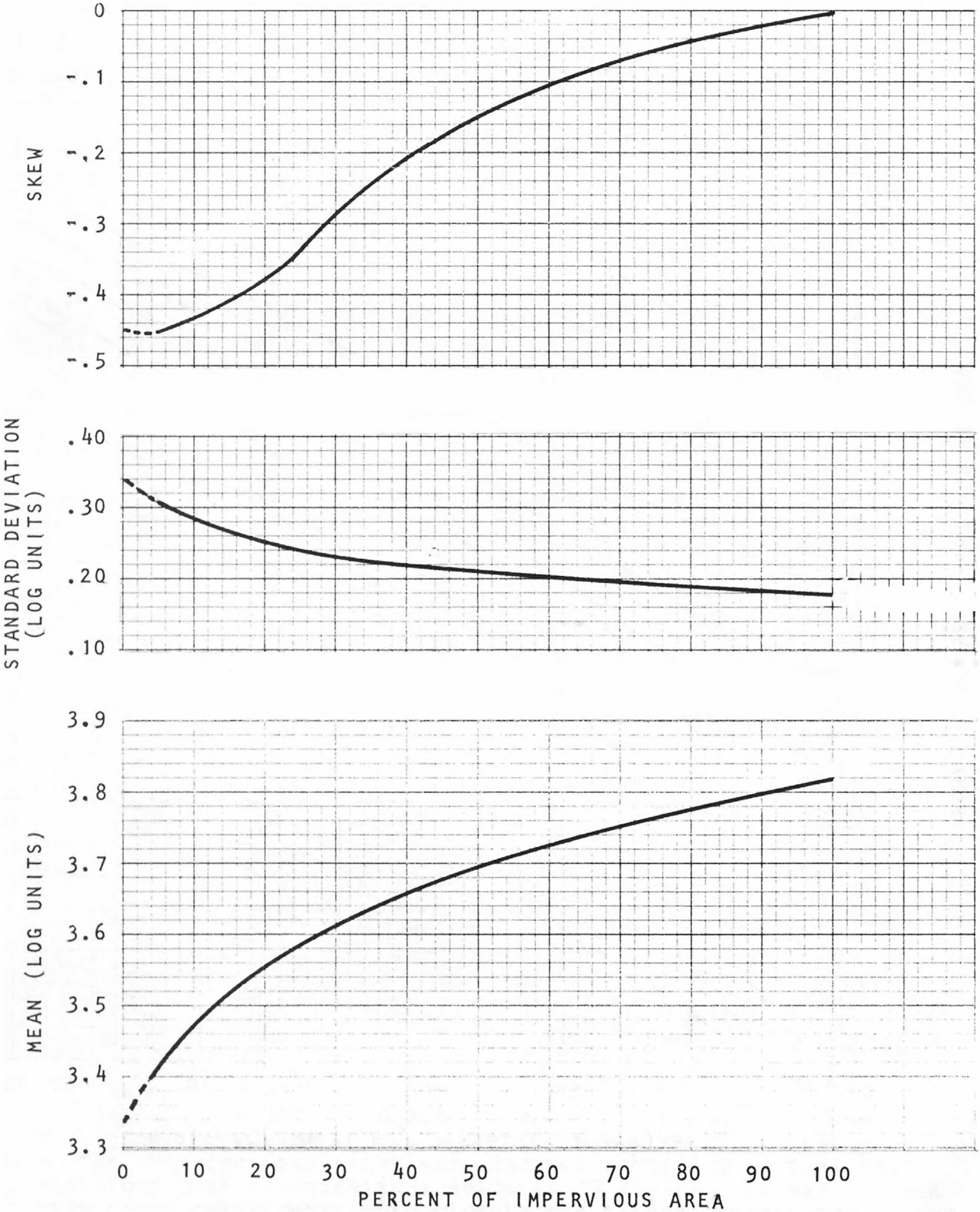


Figure 9. Relations between the log-Pearson type III distribution parameters and percent of impervious area for Walnut Creek at Des Moines.

For example, the flood discharge which has a 1 percent chance of occurring within any given year (100-year flood) for the basin in its present stage of urbanization (about 5 percent impervious) is 10,600 cubic feet per second (cfs). It could increase to 14,700 cfs when the impervious area in the basin reaches a 50 percent level. In terms of the probability of occurrence, the present 1 percent flood could have a future probability of 6 percent (17-year flood). Likewise, the 50 percent flood (2-year flood) could increase from the present 2,760 cfs to 5,000 cfs, or the present 2-year flood could have a future probability of 90 percent. Note that, in the preceding example the magnitude of the 100-year flood increases by 39 percent, while that of the 2-year flood increases by 81 percent. These trends are consistent with those reported by other investigators who have conducted similar studies elsewhere, such as Anderson (1968), Leopold (1968), Rantz (1971), and Waananen and Crippen (1977).

CONCLUSIONS

It could be anticipated that an appreciation of the results of this modeling project will vary with the level from which it is viewed. To the user basing his conclusions on the tabulated results, and the appearance of the computed and observed hydrographs, it may suggest that the complexities of the rainfall-runoff relations in the Walnut Creek basin have been satisfactorily explained. To the modeler who has had to struggle with data which may be inadequate and assumptions which may not be entirely satisfactory, it may appear that the results are tentative and in need of further refinement. Because this report has been prepared for the benefit of the user as well as the modeler, it is appropriate to point out briefly its strong points, identify its weaknesses, and suggest possible future studies.

Among its strengths are the conclusions derived from this study, which appear to be consistent and in close agreement with the results reported by investigators who have conducted similar studies elsewhere in the nation.

The reader also is referred to figure 8 to observe the close agreement between the synthetic frequency curve corresponding to the basin in its present state and the regional frequency curve, which theoretically represents the flood flow characteristic of the basin in its natural state. Considering that the basin is presently about 5 percent impervious, the agreement is indeed remarkable. Hence, another element of strength is the fact that the results from a simulation approach have been verified by the results of a widely used and accepted technique, which uses a statistical approach.

The obvious shortcoming and most probable source of criticism are the limited runoff data available to conduct this study. In addition there is a lack of recorded data concerning the effect of sewered or improved channels on the time of concentration and storage characteristics of the watershed and subbasins.

The above remarks are not intended in any way to demean the information presented in this report. By describing the strengths and deficiencies, the intention is to underline the confidence with which the information may be placed to practical use.

In reference to further studies in this basin, there is a need to develop a set of flood-routing criteria, similar to the unit hydrograph and loss-rate criteria developed in this study. A set of routing criteria would give the users of this model the capacity, for example, to evaluate the impact of a project in a distant tributary of the basin on the flood-flow characteristics at a downstream location, or to conduct comprehensive flood-plain management studies, such as the one outlined by Davis (1976) for the Oconee River basin in Georgia and Farnham (1977) for the Crow Creek basin in Iowa.

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