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DIGITAL SIMULATION OF THE EFFECTS OF URBANIZATION ON RUNOFF IN THE UPPER SANTA ANA VALLEY CALIFORNIA

U.S. GEOLOGICAL SURVEY
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Prepared in cooperation with the
San Bernardino County Flood Control District

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UNITED STATES DEPARTMENT OF THE INTERIOR

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DIGITAL SIMULATION OF THE EFFECTS OF URBANIZATION ON RUNOFF IN THE UPPER SANTA ANA VALLEY, CALIFORNIA

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ABSTRACT

The Stanford Watershed Model was used to simulate the effects of urbanization on the discharge from five drainage basins in the upper Santa Ana Valley, an area with an average annual precipitation of 15 inches. The drainage basins ranged in size from 3.72 to 83.4 square miles. Using the model, synthetic records of streamflow for each basin were generated to represent various degrees of urban development. Examination of the synthetic records indicated that urbanization has the following effects on streamflow in the area:

1. Average annual runoff from a drainage basin with an effective impervious area of 10 percent of the drainage area is approximately 2 inches, and increases by 1 inch for each increase in effective impervious cover equal to 10 percent of the drainage area. About 30 percent of a fully urbanized area is effectively impervious.

2. Urbanization can increase the magnitude of peak discharge and daily mean discharge with a recurrence interval of 2 years by a factor of three to six.

3. Peak discharges and daily mean discharges that have recurrence intervals greater than a limiting value ranging from 50 to 200 years or more are little affected by urbanization.

INTRODUCTION

Purpose and Scope

The undeveloped lands in the upper Santa Ana Valley (fig. 1) are becoming more highly urbanized, and the demand for water by the growing number of residential, commercial, and industrial water users will eventually exceed the local supply. In an effort to deal with this problem, local water managers are planning to import additional water, are undertaking more intensive management of the local ground-water resources, and are developing programs for conserving the local surface-water resources. One of the most important conservation programs involves the storing of surface water in the ground-water reservoir underlying the valley. Streamflow is diverted into ponds along watercourses where it then percolates into the ground-water reservoir.

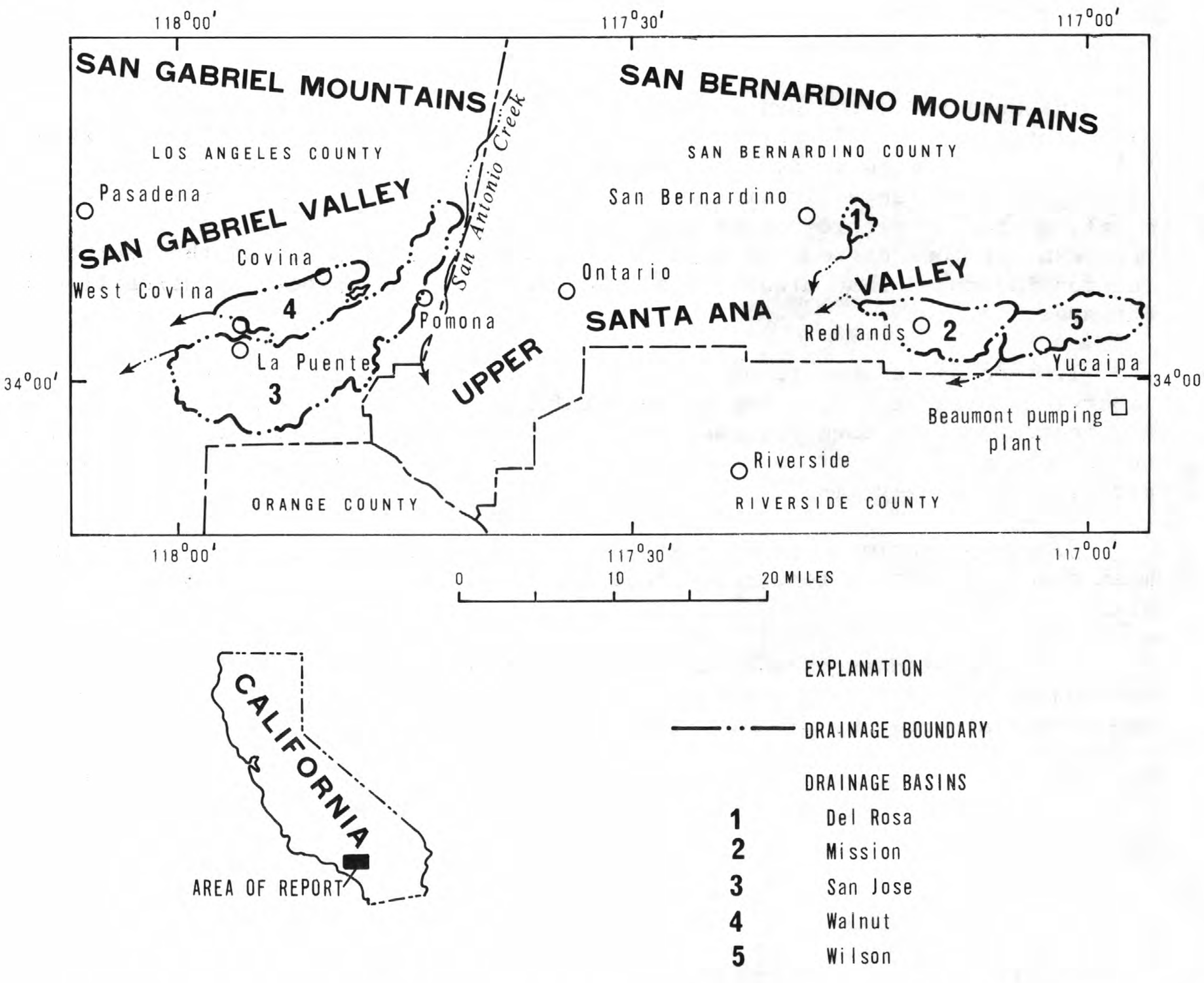

FIGURE 1.--Location of the report area and drainage basins studied.

The San Bernardino County Flood Control District plans to store surface runoff from urbanized areas of the upper Santa Ana Valley in the ground-water reservoir. As a planning aid to the flood control district, this report describes the effects of increased urbanization on the annual runoff, peak discharge, and daily mean discharge from drainage basins in the valley.

Five drainage basins, with areas ranging in size from 3.72 to 83.4 square miles, were studied. The hydrologic conditions in the basins that were selected for study are considered to be representative of the general hydrologic conditions in the upper Santa Ana Valley. The Stanford Watershed Model, a computer-oriented model, was used to simulate the effects of urbanization on the drainage basins studied. Using this model, synthetic records of streamflow for each basin were generated (for several degrees of urbanization). The synthetic records were then examined for the effects of urbanization. The report also includes a general discussion of drainage basins or watershed models and streamflow-simulation techniques.

The term "urbanization," as it is used in this report, refers to the addition of impervious area in a watershed accompanying the changes in land use from its natural state or from agricultural uses to residential, commercial, or industrial uses.

Acknowledgments

This report was prepared by the U.S. Geological Survey in cooperation with the San Bernardino County Flood Control District. Acknowledgment is made to the San Bernardino County Flood Control District and the Los Angeles County Flood Control District for hydrologic and meteorologic data made available for the study.

STREAMFLOW SIMULATION FOR URBANIZED DRAINAGE BASINS

Simulation of drainage-basin behavior using a computer-oriented model is an effective tool for quantitatively analyzing the impact of urbanization on streamflow (Linsley, 1971). The process by which an urbanized basin responds to precipitation and eventually yields runoff is easily described in qualitative terms. The principal components of the process and their major interactions are described in standard hydrology textbooks (such as Linsley, Kohler, and Paulhus, 1958, p. 162-167). A quantitative description, however, is much more difficult. For example, the instantaneous soil infiltration rate is not easy to predict without the aid of a computer-oriented model, because the rate varies continuously in time and space depending on the supply rate and on the interaction between the quantity of moisture stored and the physical characteristics of the soil profile.

Simulation of drainage-basin behavior using a computer-oriented model has not been used widely outside of research applications. In recognition of this fact, drainage-basin or watershed models are discussed briefly in this section. Crawford (1971) and Linsley (1971) give more detailed descriptions.

The subject of simulation and models is best introduced by using examples. An example outside of hydrology, yet familiar to many engineers, is the scale model of a hydraulic structure: a scale model of a canal can be used to simulate physically the operation of the prototype. Similarly, a mathematical model such as the Manning equation (Manning, 1895) might also be used to simulate the operation of a prototype structure. In each case, simulation is used to abstract the essence of a system without having to examine the actual system. In addition, the use of a mathematical model requires the selection of appropriate parameter values. For example, a value for the Manning roughness coefficient must be applied to the Manning equation before this model can be used.

Hydrologic Models

Although scale models have been used very little in urban hydrology, mathematical models have been used widely. A commonly used mathematical model of urban drainage-basin behavior is the rational method (Dooge, 1957) for computing peak discharge. As in the case of the canal model, a critical parameter value (the runoff coefficient) must be chosen before the model can be used.

Another commonly used mathematical model in hydrology is the unit-hydrograph method for relating runoff to precipitation excess (Linsley, Kohler, and Paulhus, 1958, p. 194-209). The ordinates of the unit hydrograph are parameters that must be adjusted in order to adapt the model to a specific drainage basin. The unit-hydrograph model is applicable to a drainage basin only for the conditions of urbanization that exist when the unit-hydrograph ordinates were obtained, and it can be difficult to adjust the ordinates to account for the effects of continuing urbanization.

Two distinct modeling approaches have been used in urban-hydrology investigations. These are the correlative models and the parametric models.

Correlative models (Anderson, 1970) replace the complex and interactive components of drainage-basin behavior with a single mathematical expression. Quantitative relations are developed between precipitation or another variable and some streamflow characteristic without regard to the actual physical process involved in the transformation. Regression models, the unit-hydrograph model, and the rational method are included in this general approach (Linsley, 1971). One shortcoming with correlation models is that the results provide little grounds for extrapolation to situations not covered in the data base. Such models do not explain drainage-basin behavior but can only project the historic performance of the basin.

If correlative models are considered as "black box" approaches to urban hydrology, then parametric models introduce varying degrees of transparency to the "box." Parametric models (James, 1965) divide the basin behavior into individual hydrologic components. Each component represents a known process, such as infiltration or overland flow, and is represented in the model by a mathematical formulation. This approach attempts to simulate the interactions between the components as they occur in the actual basin. A parametric model, the Stanford Watershed Model, was used in this investigation.

Stanford Watershed Model

Mathematical expressions can be used that represent each process that significantly affects moisture movement through a drainage basin. Crawford and Linsley (1966) have worked these expressions into a computer program that is known as the Stanford Watershed Model. This model simulates the major actions and interactions of interception, depression storage, infiltration, soil-moisture storage, evapotranspiration, overland flow, interflow, ground-water flow, channel conveyance, and channel storage. The model employs a fixed set of mathematical expressions, which are adapted to a specific drainage basin by selecting the proper set of numerical values for certain critical parameters (table 1) within the mathematical expressions.

TABLE 1.—*Stanford Watershed Model parameters and their application in the modeling process*

Parameter identifier	Application[1]
CB[2]	Infiltration index.
CC	Interflow index.
EPXM	Maximum interception storage, in inches.
IMPV[2]	Ratio of effective impervious area to drainage-basin (segment) area.
IRC	Interflow recession constant.
K1	Ratio of average drainage-basin (segment) precipitation to average gage precipitation.
K3	Evapotranspiration-loss index.
K24EL	Ratio of area subject to evapotranspiration from ground water to drainage (segment) area.
K24L	Part of ground-water recharge assigned to deep percolation.
KK24	Ground-water recession constant.
KS1[2]	Channel-storage recession constant.
L	Overland-flow length, in feet.
LZSN[2]	Nominal lower zone soil-moisture storage, in inches.
NN	Manning roughness coefficient for overland flow.
SS	Overland-flow slope, in feet per foot.
UZSN[2]	Nominal upper zone soil-moisture storage, in inches.

[1]For a detailed description see Crawford and Linsley (1966).

[2]Parameters for which values must be obtained from the trial-and-error calibration process.

Parameter values are selected by a calibration process that requires precipitation data from a recording rain gage, pan-evaporation data, and discharge data. Initial values of the model parameters are assigned by analysis of measured hydrographs and of drainage-basin characteristics and on the basis of prior experience with the model. The response of the model to the input of precipitation and evaporation data is then compared to the measured streamflow, and adjustments are made to the parameter values to better reproduce the observed streamflow. Adjustment is continued, by repeated trials, until the response of the model represents the physical system to an acceptable degree.

Once the model parameter values have been determined for a given condition of urbanization, a synthetic streamflow record can be generated for the period of available record of precipitation. In addition, parameter values can be adjusted for the effects of continuing urbanization, and synthetic streamflow records can be produced for various degrees of urbanization.

DETERMINATION OF EFFECTIVE IMPERVIOUS AREA

Values must be selected for 16 model parameters (table 1). Eleven of these values either can be estimated or can be determined directly from topographic maps, aerial photographs, or measured streamflow data. The five remaining parameters (CB, IMPV, KS1, LZSN, and UZSN) must be assigned values on the basis of the results of the trial-and-error calibration process. Of these latter parameters, simulation results are the most sensitive to the value selected for the impervious area parameter (IMPV).

The impervious area in a watershed can be determined from aerial photographs. However, not all of the impervious area in a drainage basin is necessarily hydrologically important, and the effective impervious area is generally smaller than the actual impervious area. The effect of a given area of impervious cover on the hydrology of a drainage basin depends on the spatial relation of the impervious cover to the drainage system. For example, as described by Rantz (1971), precipitation reaching a roof may leave the roof (a) through a downspout onto a lawn where infiltration may take place, (b) through a downspout and pipe drain directly into a street gutter or storm drain without infiltration, or (c) by evaporation from surface storage on a flat roof. Similar concepts apply to the disposition of precipitation reaching a street or paved parking area.

The above discussion provides a qualitative description of effective impervious area. A quantitative description, however, is more elusive. One plausible quantitative definition would relate the effective impervious area of a drainage basin to the minimum runoff coefficient—the minimum ratio of runoff to precipitation observed for small storms. On the basis of data obtained from Echo Park drainage basin (30 miles east of the study area in Los Angeles County), Crawford (1971) indicated that the parameter for impervious area of the Stanford Watershed Model (IMPV) conforms to this definition. The minimum runoff coefficient for Echo Park drainage basin was 19 percent, and the value determined for IMPV by calibration was 18 percent. The actual impervious area of the drainage basin, as determined from aerial photographs, was 22 percent.

When the necessary information is not available to determine the minimum runoff coefficient, the effective impervious area of a drainage basin can be estimated from figure 2. Figure 2 was developed from data derived by calibrating the Stanford Watershed Model to the drainage basins of this report. However, the data are consistent with minimum runoff coefficients for similar basins. For example, the effective impervious area for a completely developed watershed, as determined from figure 2, is 35 percent. The Los Angeles County Flood Control District (1971) published minimum runoff coefficients of 21 percent for single-family residential areas and 48 percent for multiple-dwelling or commercial areas. Using these coefficients, the minimum runoff coefficient for a completely developed watershed that is divided into 65 percent single-family residential areas and 35 percent multiple-dwelling and commercial areas (which is representative of the distribution of these types of development in the urbanized areas of the basins studied) would be approximately 30 percent.

For the calibration of the study basins, the effective impervious area was determined by adjusting the impervious area parameter (IMPV) so that the model would reproduce small runoff events. This procedure reasonably applies to the upper Santa Ana Valley because sandy, pervious soils are prevalent and thus runoff from small storms is produced almost entirely from the effective impervious area in the watersheds. For these small storms simulation results are independent of the values selected for the other four parameters that must be adjusted by calibration.

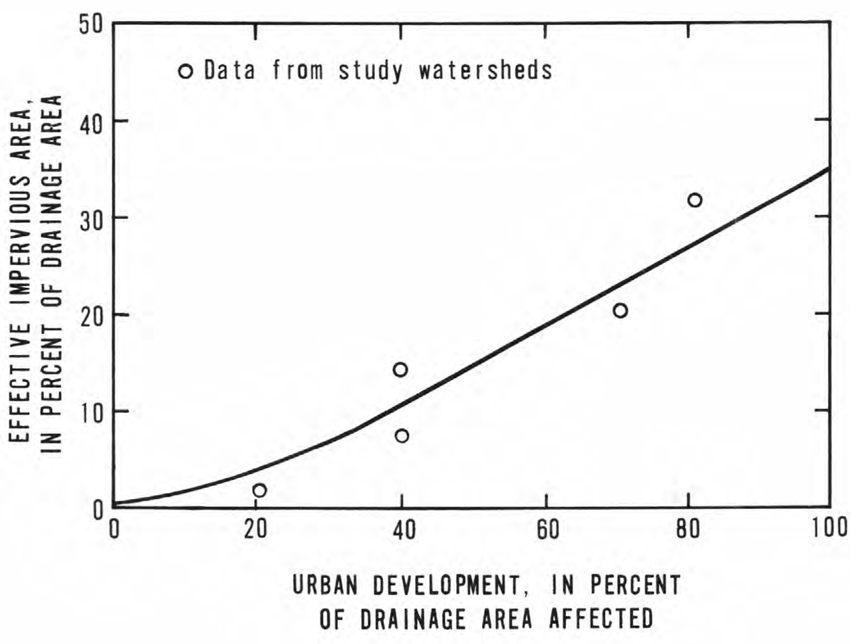

FIGURE 2.—Curve relating the effective impervious area in drainage basins in the upper Santa Ana Valley to the area affected by urban development. The curve represents an approximate division of the developed area into 65 percent single-family residential areas and 35 percent multiple-dwelling and commercial areas.

SELECTION OF DRAINAGE BASINS

Drainage-Basin Specifications

The streamflow records of the San Bernardino County Flood Control District, the Los Angeles County Flood Control District, and the Geological Survey were searched for drainage basins having data that would be compatible with the methodology proposed for the investigation. The original intent was to restrict the study to drainage basins having the following qualifying specifications:

1. An urbanized or partly urbanized drainage-basin.

2. Significant changes in land use during the period of streamflow record.

3. Drainage area less than 30 square miles.

4. One or more records of precipitation, of at least 20 years length, from recording rain gages located within or very near the drainage basin.

5. Quantitative documentation of any streamflow regulation or diversion.

However, in order to select five drainage basins to use in the investigation, it was necessary to relax some of the original constraints. Although various water agencies in the upper Santa Ana Valley currently (1972) collect streamflow data on more than 75 drainage basins, only a few met the original specifications. The basins that were finally selected (fig. 1) have the following ranges in specifications:

1. Drainage area 3.72 to 83.4 square miles.

2. Effective impervious area 1 to 31 percent.

3. Streamflow record length 23 to 49 years.

4. Precipitation record length 15 to 27 years.

Descriptions of Watersheds

Brief descriptions of the physical characteristics of each of the selected drainage basins are given in this section. In general, the basins that were selected are only partly urbanized, as is typical of many basins in the upper Santa Ana Valley. The headwater areas are hilly or mountainous (topographic relief from 500 to 2,000 feet) and are undeveloped. The downstream areas consist of broad alluvial surfaces (slopes from 60 to 140 feet per mile) which are urbanized. Soils are generally highly permeable, well drained, and range in texture from coarse gravel and sand at the valley borders to coarse loamy sand, sand, and sandy loam near the valley axis (Muckel and Aronovici, 1952). The primary drainage channel in each drainage basin has been modified in the downstream reaches from its natural condition. In the urbanized areas, a system of street drains, lined and unlined storm channels, and storm sewers provide secondary drainage. Except during storm periods, watercourses are dry.

Del Rosa Basin

Del Rosa basin, as studied, includes only the lower drainage area of a larger catchment. Two debris detention dams separate Del Rosa basin from the upper drainage area (fig. 3). The impoundments behind the dams usually trap and retain all inflow, so that streamflow at the outlet of Del Rosa basin primarily represents runoff from the drainage area below the detention dams.

The drainage area of Del Rosa basin is 3.72 square miles in size. This sloping area is underlain by alluvial fan deposits of gravel, sand, and silt, which have accumulated at the base of the San Bernardino Mountains. Eighty percent of the study area in the basin has been developed, and its effective impervious area is 31 percent of the drainage area.

Mission Basin

The drainage area of Mission basin (fig. 4) is 27.8 square miles in size. Three-quarters of this drainage basin is underlain by a broad alluvial plain, which slopes to the west at 120 feet per mile. The northern boundary of the basin is poorly defined; its exact location changes with the placement of temporary irrigation ditches in orchards. The southern boundary is defined by the crest of a range of hills that rise 500 to 2,000 feet above the level of the alluvial plain. Approximately 40 percent of Mission basin has been developed for residential and commercial uses. The effective impervious area is 7 percent of the drainage area. Three-quarters of the nonurbanized area is planted with orange groves.

San Jose Basin

The drainage area of San Jose basin (fig. 5) is 83.4 square miles in size. The lower area of this drainage basin is a narrow alluvium-filled valley, bordered on the north and on the south by hills that rise approximately 500 feet above the valley floor. The headwater area of San Jose basin contains part of an alluvial fan that was deposited by San Antonio Creek. Residential and commercial development covers approximately 40 percent of the watershed, and the effective impervious area equals 14 percent of the drainage area.

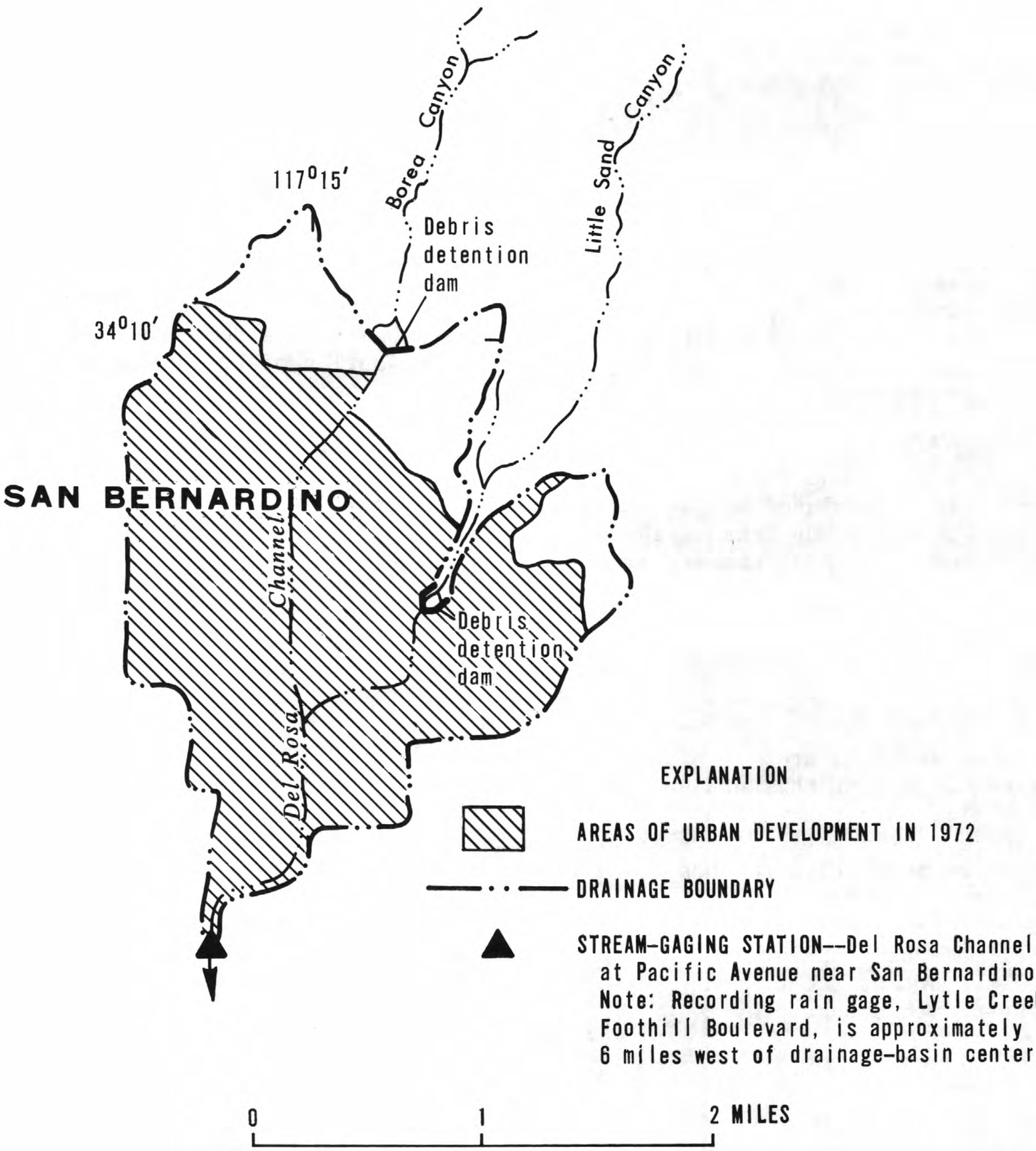

FIGURE 3.—Del Rosa basin.

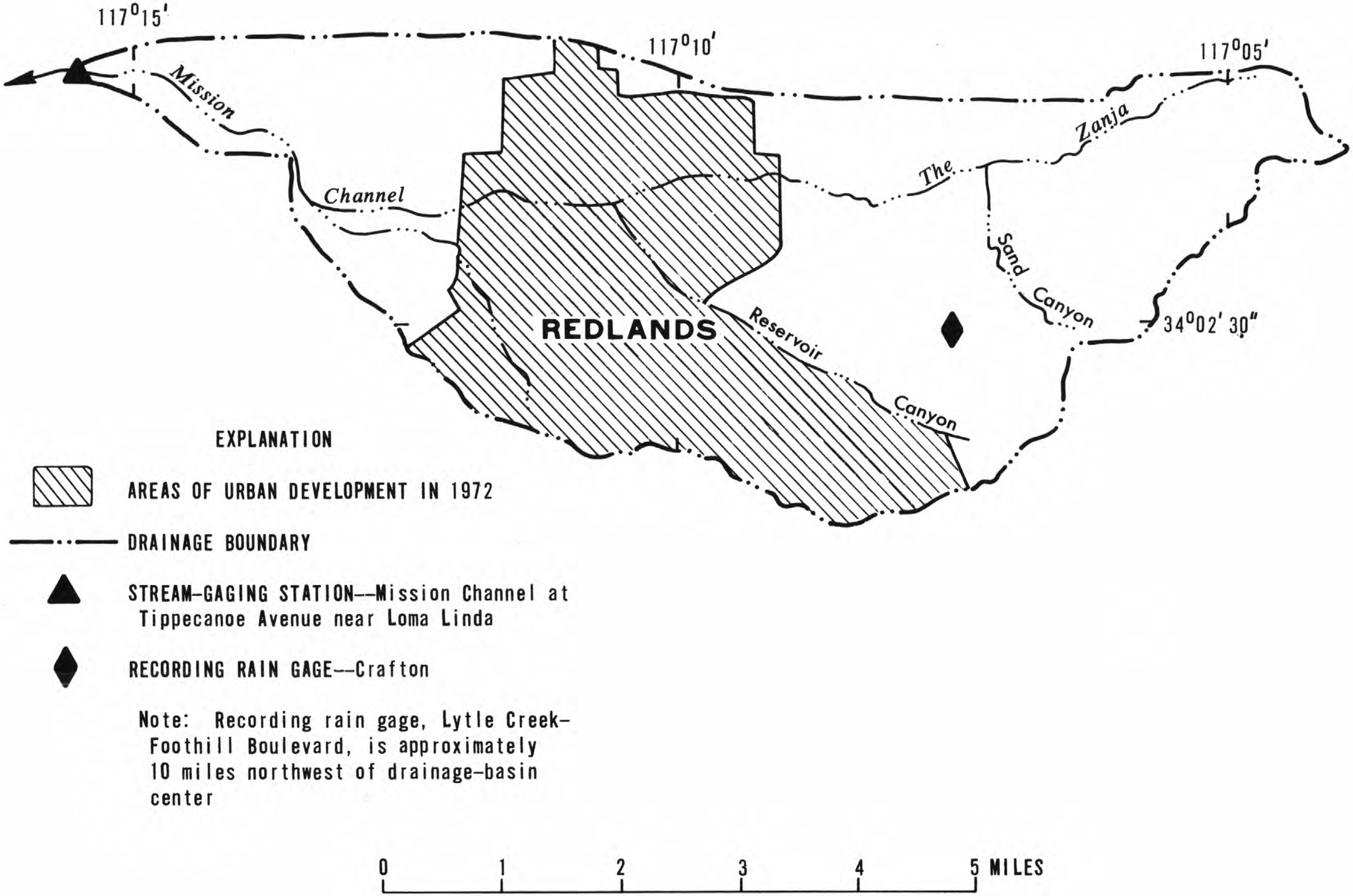

FIGURE 4.--Mission basin.

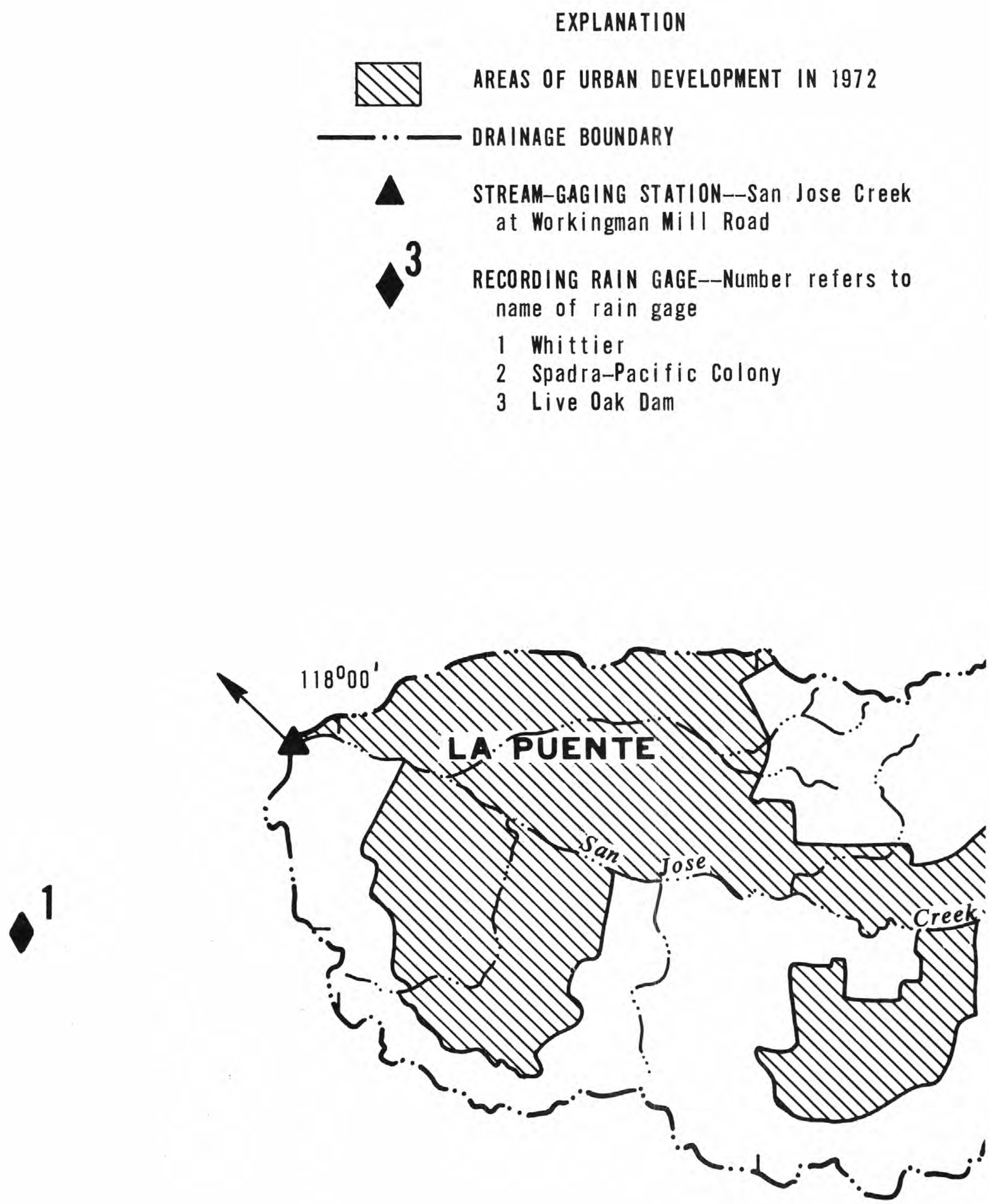

FIGURE 5.—San Jose basin.

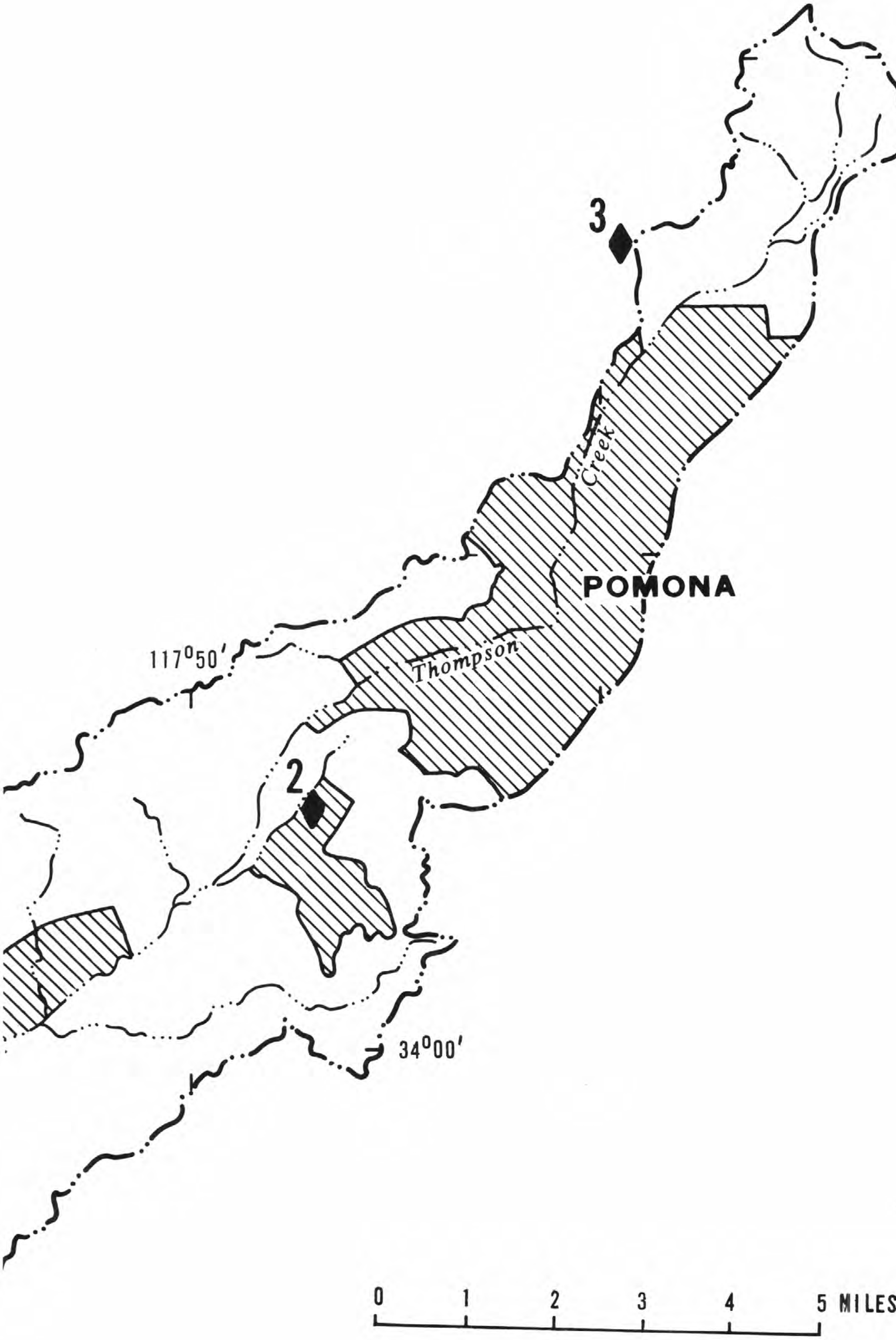

FIGURE 5.--Continued.

Walnut Basin

The drainage area of Walnut basin (fig. 6) is 25.3 square miles in size. As in the case of Del Rosa basin, this area includes only the lower part of the drainage of a larger catchment area. Puddingstone Dam separates Walnut basin from the upstream area (fig. 6). An alluvial plain, sloping to the southeast at about 80 feet per mile, underlies most of the basin, and a low range of hills rises along its southern boundary. Seventy percent of the basin has been developed, and the effective impervious area covers 20 percent of the basin.

Wilson Basin

The drainage area of Wilson basin (fig. 7) is 25.6 square miles in size. A large part of this watershed is a moderately dissected alluvial surface, which slopes southwest at about 140 feet per mile. The watershed is bordered on the north and on the east by highlands that rise 1,500 to 2,000 feet above the level of the surface. Approximately 20 percent of the watershed is urbanized; most of this area is in residential development. However, the size of individual residential lots is generally an acre or more, so that the effective impervious area equals only about 1 percent of the drainage basin.

CALIBRATION OF THE MODEL TO THE DRAINAGE BASINS

Data Requirements

The first step in applying the Stanford Watershed Model to the basins studied was to gather the necessary precipitation, evaporation, and streamflow data. The Stanford Watershed Model simulates the time variance of soil-moisture storage in a drainage basin during and between storms. Accurate representation of soil-moisture storage accretion requires the input of data to the model from small precipitation events as well as from major storms. Records of precipitation, measured on an hourly or shorter interval, are essential to the operation of the model. Pan-evaporation data are required to simulate the withdrawal of moisture by evapotranspiration from soil storage.

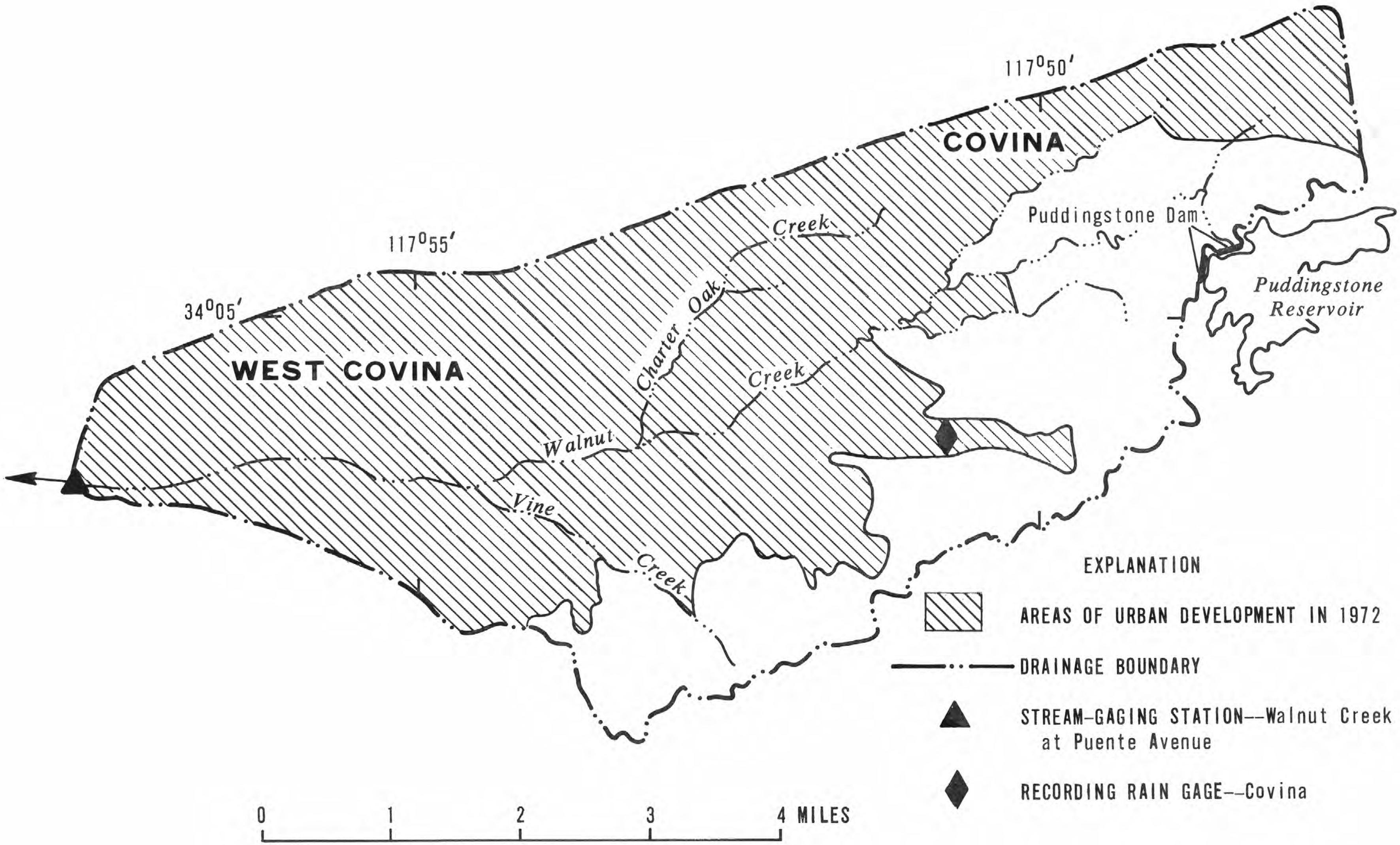

FIGURE 6.--Walnut basin.

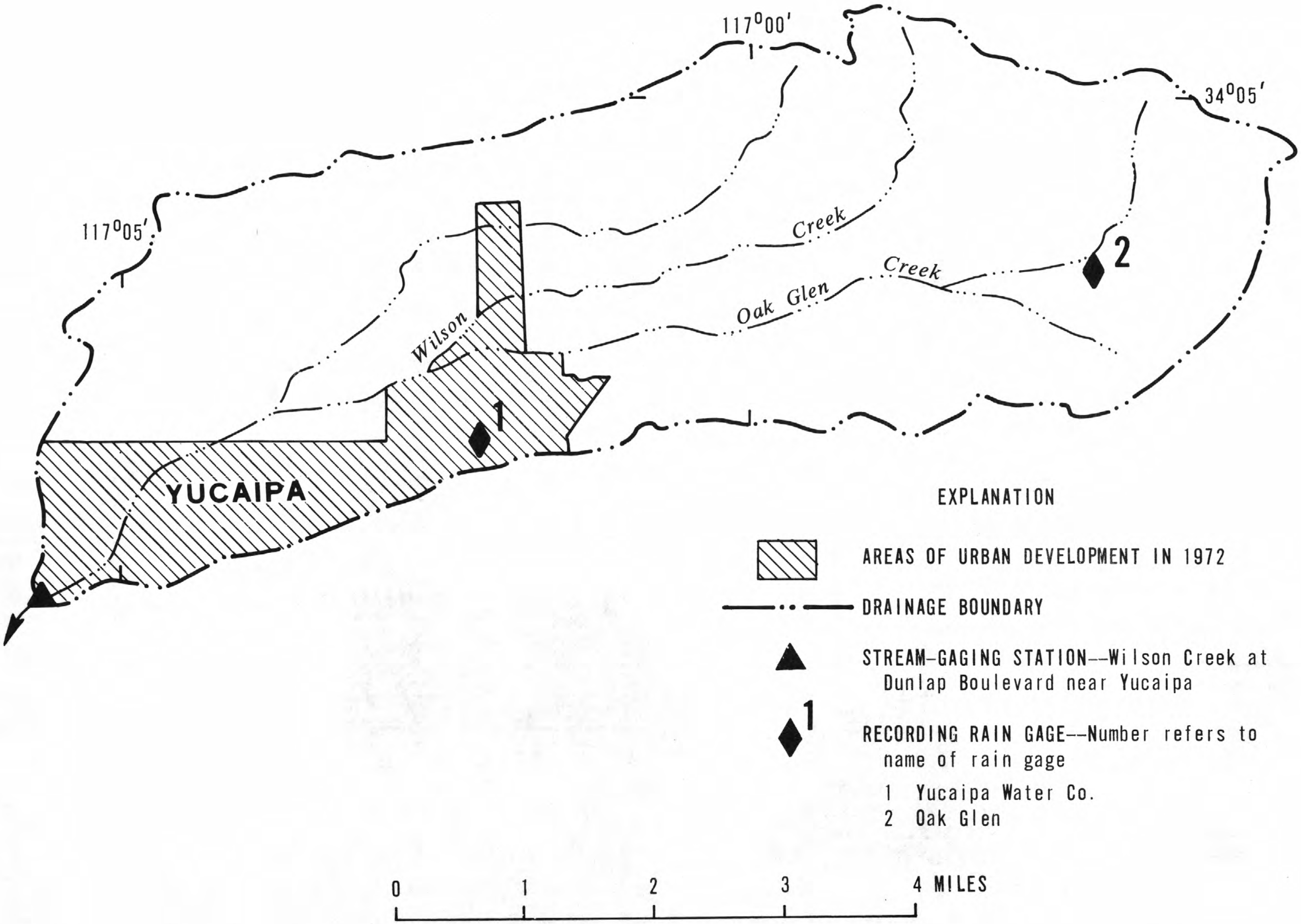

FIGURE 7.--Wilson basin.

The model simulates continuous streamflow hydrographs, and continuous streamflow records are required for the trial-and-error calibration process. The proper simulation of annual runoff volume depends on the selection of values for one group of model parameters, and the proper simulation of peak discharge and hydrograph shape depends on the selection of values for another group of parameters. Daily discharge records, uninterrupted during the calibration period, are required for the adjustment of the parameters that determine runoff volume. The adjustment of the parameters that affect simulated peak discharge and hydrograph shape require data from selected instantaneous discharge hydrographs.

Although it is difficult to assess theoretically the optimal length of streamflow record required for calibration, various investigators have found that, in most instances, 3 years of record will provide acceptable results and that using more than 10 years of record does not improve simulation results (oral commun., R. K. Linsley, 1970; Liou, 1970). Inasmuch as hydrologic conditions in many urbanized basins are typically nonstationary, a short calibration period was used. Two separate periods of streamflow record, each 3 years long and identified as periods A and B in table 2, were used to calibrate the model to each of the drainage basins. The two separate calibration periods were used to test the effects of changes in the degree of urbanization on the model parameter values. After determining the value of each parameter for the model, 3 years of additional streamflow record were used to verify the calibration for each drainage basin (table 2).

TABLE 2.--*Calibration and verification periods*

Drainage basin	Effective impervious area (percent)	Calibration		Verification	
		Period identifier	Period (water years[1])	Period identifier	Period (water years[1])
Del Rosa	31	A	1966-67, 1969	A	1965, 1970-71
	6	B	1950-52	B	--
Mission	7	A	1967-69	A	1965-66, 1970
	3	B	1950-52	B	1948-49, 1953
San Jose	14	A	1967-69	A	1964-66
	2	B	1953-55	B	1956-58
Walnut	20	A	1967-69	A	1964-66
	11	B	1956-58	B	1955, 1959-60
Wilson	1	A	1967-69	A	1965-66, 1970
	1	B	1950-52	B	1948-49, 1963

[1]The water year is the 12-month period ending September 30 and is designated by the calendar year in which it ends.

Input Data

Precipitation Data

Hourly precipitation data, obtained from the San Bernardino County Flood Control District, the Los Angeles County Flood Control District, and the National Weather Service, were prepared in a computer-compatible form for the study watersheds. Tabulated hourly data were available for several of the records. For the other records, hourly precipitation data had to be extracted from rain-gage recorder charts.

Each of the watersheds, except for Del Rosa basin, was represented in the model as two or more segments, each segment generally using a separate precipitation record (table 3). Modeling of the basin in segments was used to approximate the areal variations in land use and precipitation. Mission basin was modeled as two segments, one segment representing undeveloped and agricultural areas of the watershed and the other segment representing urbanized areas. San Jose basin was divided into three segments; each segment contained both undeveloped and urbanized areas. However, the divisions of this basin represented areal variation in the intensity of development. For similar reasons, the Walnut basin was divided into two segments, each containing both undeveloped and urbanized areas. The Wilson basin was also divided into two segments; in this instance, the division was based on areal variation in precipitation.

TABLE 3.--*Precipitation data used as input to the model*

Drainage basin	Model segment	Precipitation gage		Responsible agency	Average annual precipitation 1950-70 (inches)
		No.	Name		
Del Rosa	1	5212	Lytle Creek Foothill Blvd.	NWS[1]	14.8
Mission	1	5212	Lytle Creek Foothill Blvd.	NWS[1]	14.8
	2	24	Crafton	SBCFCD[2]	15.3
San Jose	1	1035	Whittier	LACFCD[3]	14.4
	2	356	Spadra-Pacific Colony	LACFCD[3] LACFCD[3]	15.1
	3	445	Live Oak Dam	LACFCD[3]	18.9
Walnut	1 and 2	1078	Covina	LACFCD[3]	15.5
Wilson	1	132	Yucaipa Water Co.	SBCFCD[2]	16.7
	2	174	Oak Glen	SBCFCD[2]	27.8

[1]National Weather Service.
[2]San Bernardino County Flood Control District.
[3]Los Angeles County Flood Control District.

Pan-Evaporation Data

Daily pan-evaporation data were obtained from a National Weather Service station at the Beaumont pumping plant. Even though this station is near the eastern boundary of the study area (fig. 1), the data are considered to be representative of pan evaporation throughout the upper Santa Ana Valley. The average annual pan evaporation at Beaumont pumping plant is 72.6 inches.

Streamflow Data

Records of daily mean discharge and peak discharge for the drainage basins studied were obtained from the San Bernardino County Flood Control District and the Los Angeles County Flood Control District. Table 4 identifies the records used for each basin and lists some of the characteristics of discharge.

TABLE 4.--*Streamflow data used to calibrate and verify the model*

Drainage basin	Stream-gaging station		Respon-sible agency	Average annual runoff for 1965-70 (inches)	Maximum peak runoff rate 1965-70 (cubic feet per second)
	Number	Name			
Del Rosa	S-2507B	Del Rosa Channel at Pacific Ave. near San Bernardino	SBCFCD[1]	5.0	[2]600
Mission	S-3501B	Mission Channel at Tippecanoe Ave. near Loma Linda	SBCFCD[1]	.4	980
San Jose	F48-R	San Jose Creek at Workingman Mill Road	LACFCD[3]	3.9	10,200
Walnut	F304-R	Walnut Creek at Puente Ave.	LACFCD[3]	5.9	[2]4,000
Wilson	S-3601A	Wilson Creek at Dunlap Blvd. near Yucaipa	SBCFCD[1]	.5	1,400

[1]San Bernardino County Flood Control District.
[2]Estimated.
[3]Los Angeles County Flood Control District.

The records of streamflow for all of the drainage basins except for Wilson basin include extraneous discharge (discharge other than that resulting from precipitation within the basin). Overflow from two debris-detention basins occasionally contributes to the outflow from Del Rosa basin. Excess water from irrigation passes the stream-gaging site for Mission basin. At times, the discharge from Walnut basin includes large releases from Puddingstone Reservoir. The discharge from San Jose basin includes effluent from a sewage-treatment plant.

Extraneous discharge for each of the affected streamflow records was either measured directly or estimated by inspection of concurrent streamflow and precipitation records. Using this information, streamflow records were then adjusted according to the following relations so as to represent only runoff generated within the drainage basin:

$$Q_r = Q_m - Q_e$$

and

$$q_{r,t} = q_{m,t} - q_{e,t-\Delta t}$$

or, if instantaneous discharge hydrographs were not available for extraneous discharge,

$$q_{r,t} = q_{m,t}\, Q_r/Q_m$$

where, for the appropriate relation,

- Q is daily mean discharge
- q is instantaneous discharge
- r indicates runoff
- m indicates measured outflow (from all sources) from the study drainage area
- e indicates extraneous discharge
- t is time
- Δt is the travel time through the study drainage area for extraneous discharge.

Effect of Data Errors

The utility of the Stanford Watershed Model depends on the selection of parameter values that best represent the physical system. Ideally, the calibration process should yield such parameter values. However, errors in streamflow and precipitation data are transferred to model parameters in the calibration process, precluding the elimination of deviations between measured and simulated streamflow. Model parameter errors then combine with precipitation data errors in subsequent model runs to produce even greater deviations between measured and simulated streamflow (Dawdy, 1969).

Gaging of discharge from drainage basins in the upper Santa Ana Valley is difficult, owing to high sediment loads, the generally short duration of significant flow, and high velocities. Error in measured streamflow data is a major source of deviations between measured and simulated streamflow. Errors in gaging are introduced primarily in the computation of a theoretical stage-discharge relation. The various sources of error in the relation are as follows:

1. Stage-discharge relations are based on uniform-flow conditions.

2. High velocities, especially when flow is supercritical, may reduce the reliability of current-meter measurements used to verify the stage-discharge relation.

3. Undefined shifts in the stage-discharge relation caused by changing bed characteristics.

4. Instability of the control due to scour and fill.

Precipitation in the upper Santa Ana Valley has a high degree of spatial variability, and the necessary use of precipitation data obtained at a point is a second major source of deviations between measured and simulated streamflow. The use of such data as input to the model causes errors in simulated streamflow because of the following factors:

1. A point measurement of precipitation for a particular storm is seldom the mean precipitation for the drainage basin (or basin segment) for that storm.

2. The distribution of precipitation in time as measured at a point does not represent the spatial variations in the distribution of precipitation in time.

Calibration Results

Streamflow Simulation

Two general criteria were used to determine that parameter values for the model were acceptable:

1. Volume criterion--the model approximated the record of annual, monthly, and daily runoff.

2. Shape criterion--the model approximated the record of peak discharge and hydrograph shape.

Parameter values for the model were selected primarily to achieve agreement between the measured and simulated long-term runoff volume. Table 5 lists the measured and simulated discharge for each of the calibration periods and for each of the corresponding verification periods. For the calibration periods, the absolute values of the deviations between measured and simulated runoff ranged from 1 to 22 percent. For the verification periods, the deviations ranged from 4 to 69 percent.

TABLE 5.--*Measured and simulated runoff volumes for calibration and verification periods--not including runoff for days when either streamflow or precipitation data are missing*

Drainage basin	Calibration				Verification			
	Period identifier[1]	Measured runoff (acre-feet)	Simulated runoff (acre-feet)	Error (percent)	Period identifier[1]	Measured runoff (acre-feet)	Simulated runoff (acre-feet)	Error (percent)
Del Rosa	A	3,520	3,720	6	A	592	466	-21
	B	564	532	-6	B	—	—	—
Mission	A	3,600	3,970	2	A	1,370	1,140	-16
	B	1,820	1,570	-13	B	612	686	12
San Jose	A	73,400	72,600	-1	A	21,900	26,900	24
	B	4,930	5,790	17	B	22,300	17,800	-20
Walnut	A	23,900	23,500	-2	A	9,350	11,500	23
	B	12,300	11,300	-8	B	3,120	3,040	-4
Wilson	A	2,810	3,430	22	A	1,120	506	-55
	B	490	504	3	B	1,730	534	-69

[1]See table 2 for period definitions.

The deviations between measured and simulated daily mean discharge were larger than the deviations between measured and simulated long-term runoff volume. For the calibration periods, the standard error of estimate of the residuals between the logarithms of measured and simulated daily mean discharge—the logarithmic transformation is meant to make the error of estimation commensurable for large and small daily mean discharges (Dawdy, Lichty, and Bergmann, 1972)—ranged from 0.28 to 0.58 log units (table 6). For the verification periods, the standard error of prediction ranged from 0.15 to 0.63 log units. These errors can be attributed primarily to large deviations between measured and simulated runoff from minor storms. The deviations among individual days appear to be random in distribution with respect to time, magnitude, and sign. As a result, simulation errors tend to nullify each other over a long period of time, and the gross characteristics of the response of the watershed to precipitation are contained in the model output.

TABLE 6.--*Standard error of residuals between logarithms of measured and simulated daily mean discharge--not including days when either measured or simulated discharge is zero*

Drainage basin	Calibration				Verification			
	Period identi-fier[1]	Standard error of estimate			Period identi-fier[1]	Standard error of prediction		
		(log units)	(percent)			(log units)	(percent)	
Del Rosa	A	0.28	+90 to	-47	A	0.15	+41 to	-29
	B	.46	+187	-65	B	--		--
Mission	A	.37	+135	-57	A	.40	+151	-60
	B	.40	+151	-60	B	.43	+117	-63
San Jose	A	.38	+140	-58	A	.36	+130	-56
	B	.56	+267	-73	B	.41	+155	-61
Walnut	A	.40	+151	-60	A	.33	+110	-54
	B	.39	+146	-59	B	.31	+105	-51
Wilson	A	.58	+278	-73	A	.42	+162	-62
	B	.58	+278	-73	B	.63	+327	-77

[1]See table 2 for period definitions.

The details of the hydrographs of instantaneous discharge were not simulated correctly by the model. However, the general characteristics of the hydrographs were reproduced (figs. 8-12). In addition, the frequency relations for annual peak discharge that are applicable to the measured streamflow appear to be preserved in the model output (figs. 13-17). Deviations between the hydrographs of measured and simulated instantaneous discharge are primarily related to the deviations between measured and simulated daily mean discharge and to the failure of point precipitation data to represent the effective time distribution of precipitation over the basin.

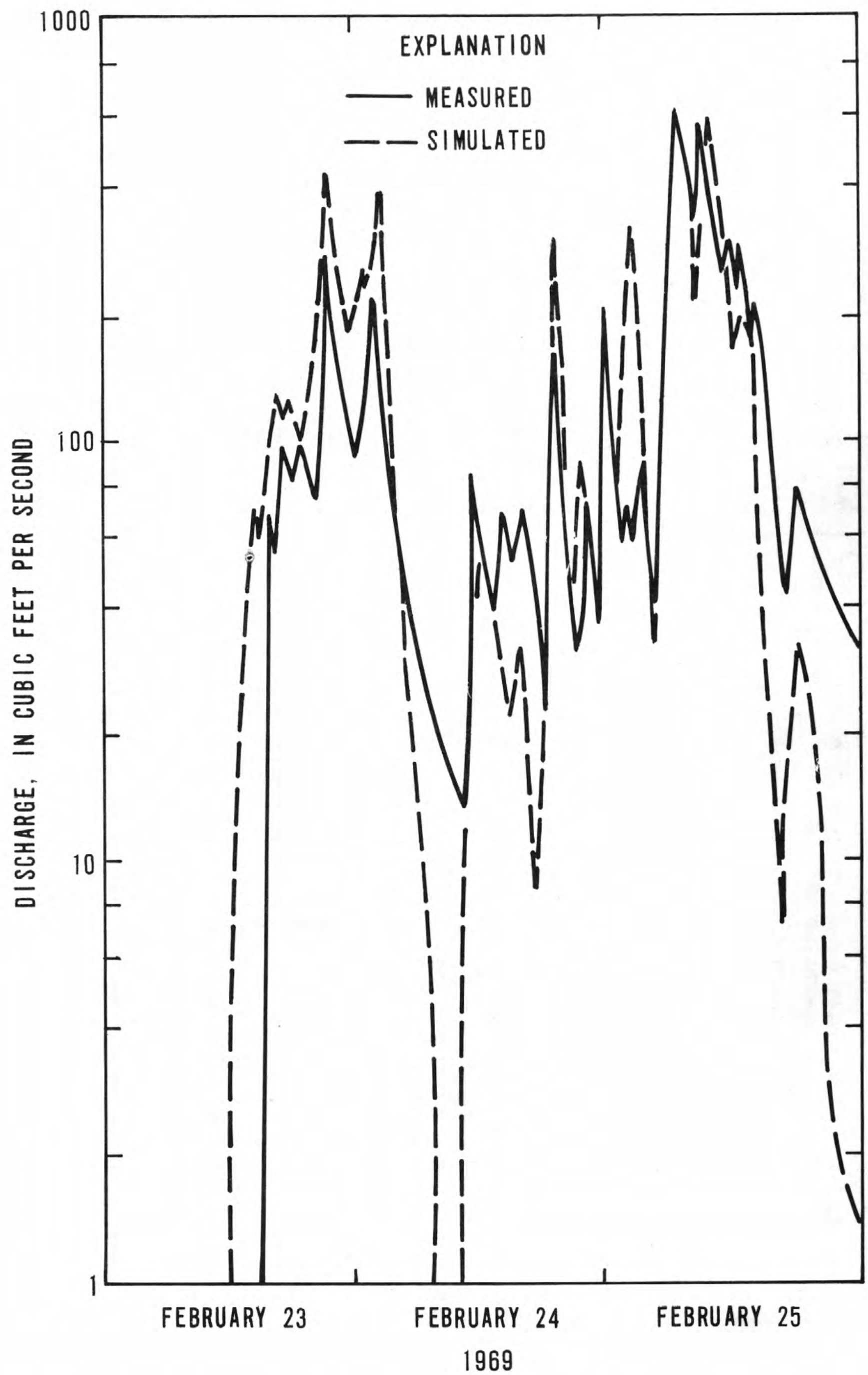

FIGURE 8.—Hydrographs of measured and simulated discharge from Del Rosa basin.

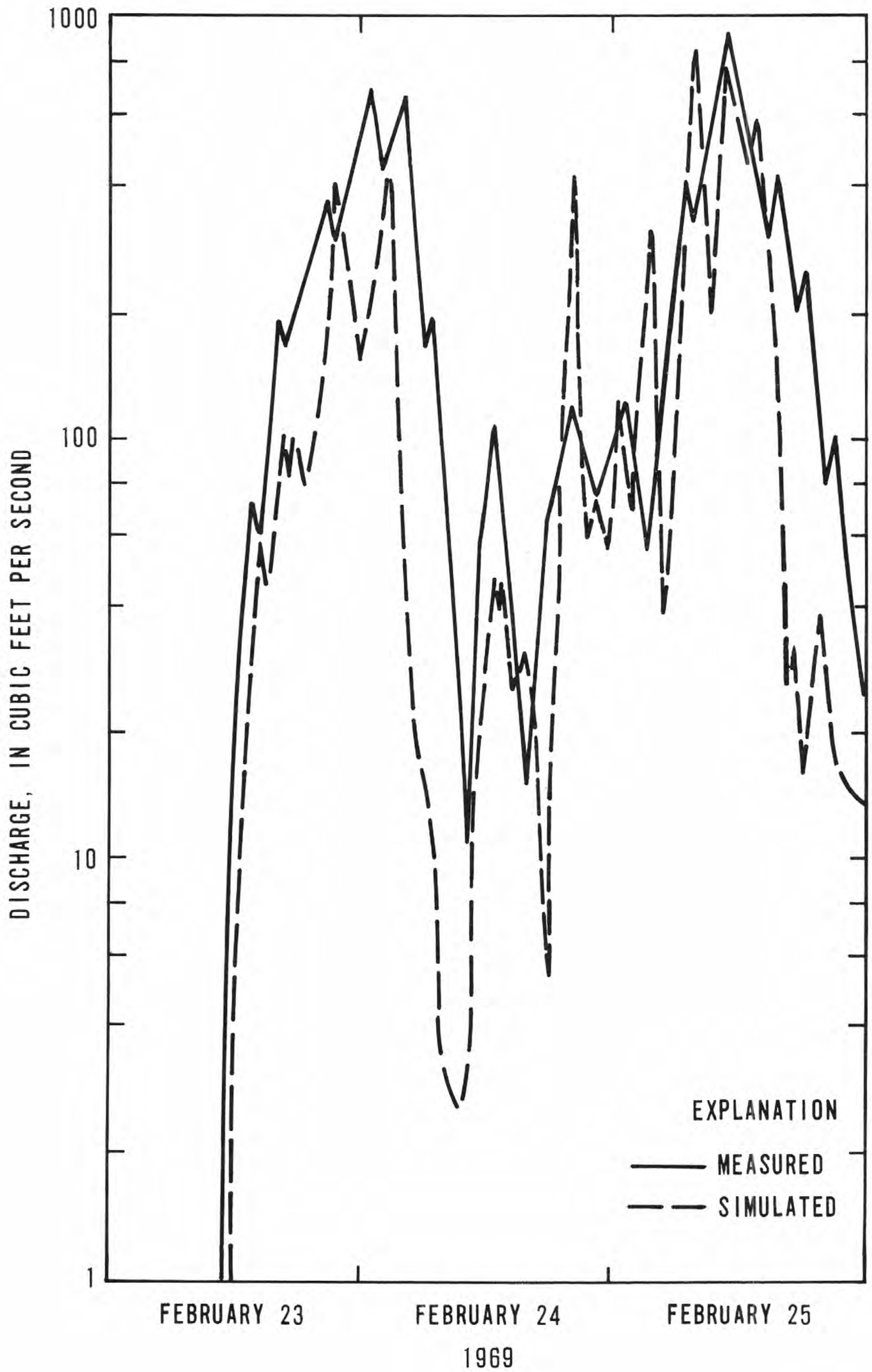

FIGURE 9.--Hydrographs of measured and simulated discharge from Mission basin.

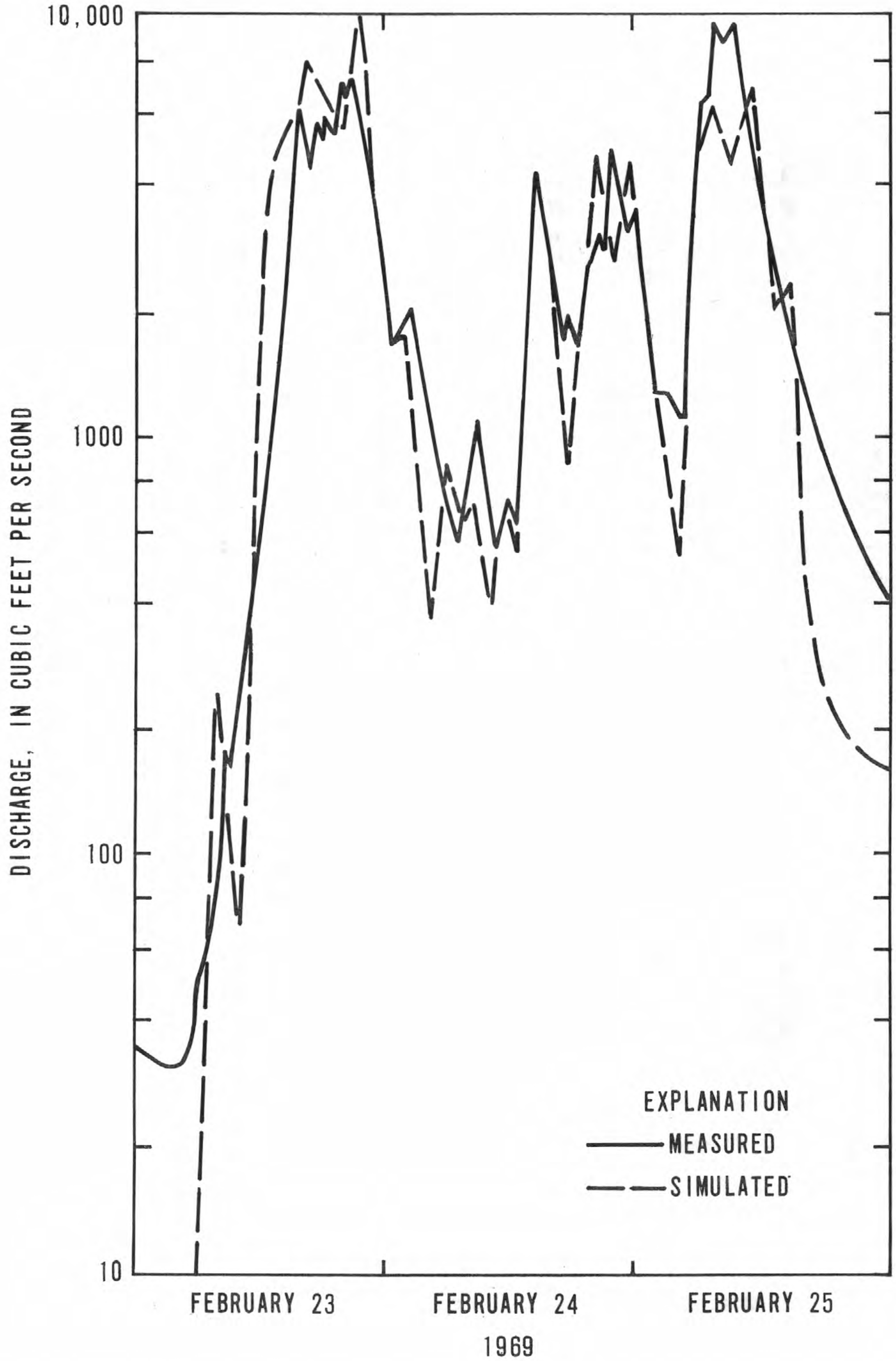

FIGURE 10.--Hydrographs of measured and simulated discharge from San Jose basin.

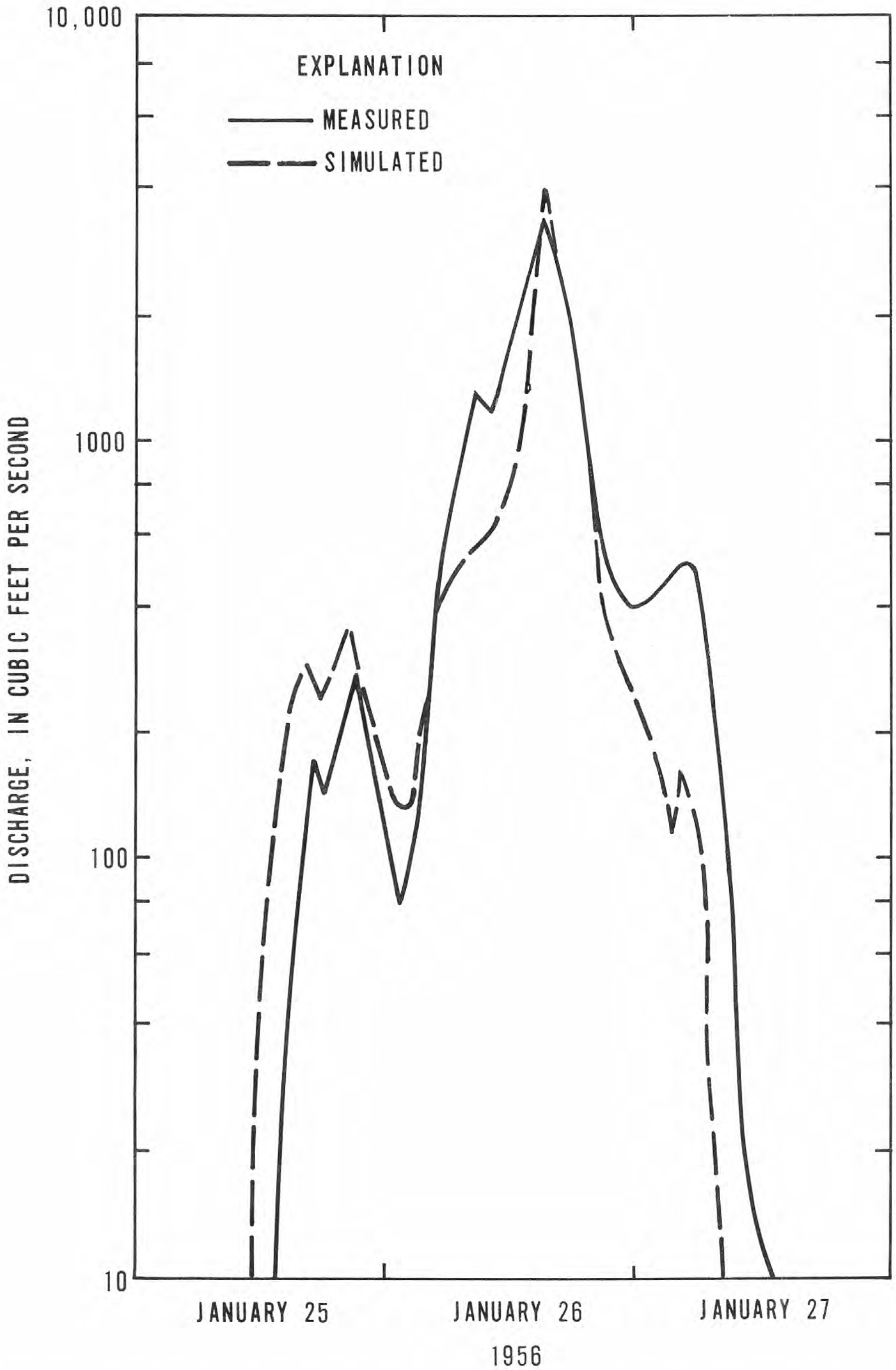

FIGURE 11.—Hydrographs of measured and simulated discharge from Walnut basin.

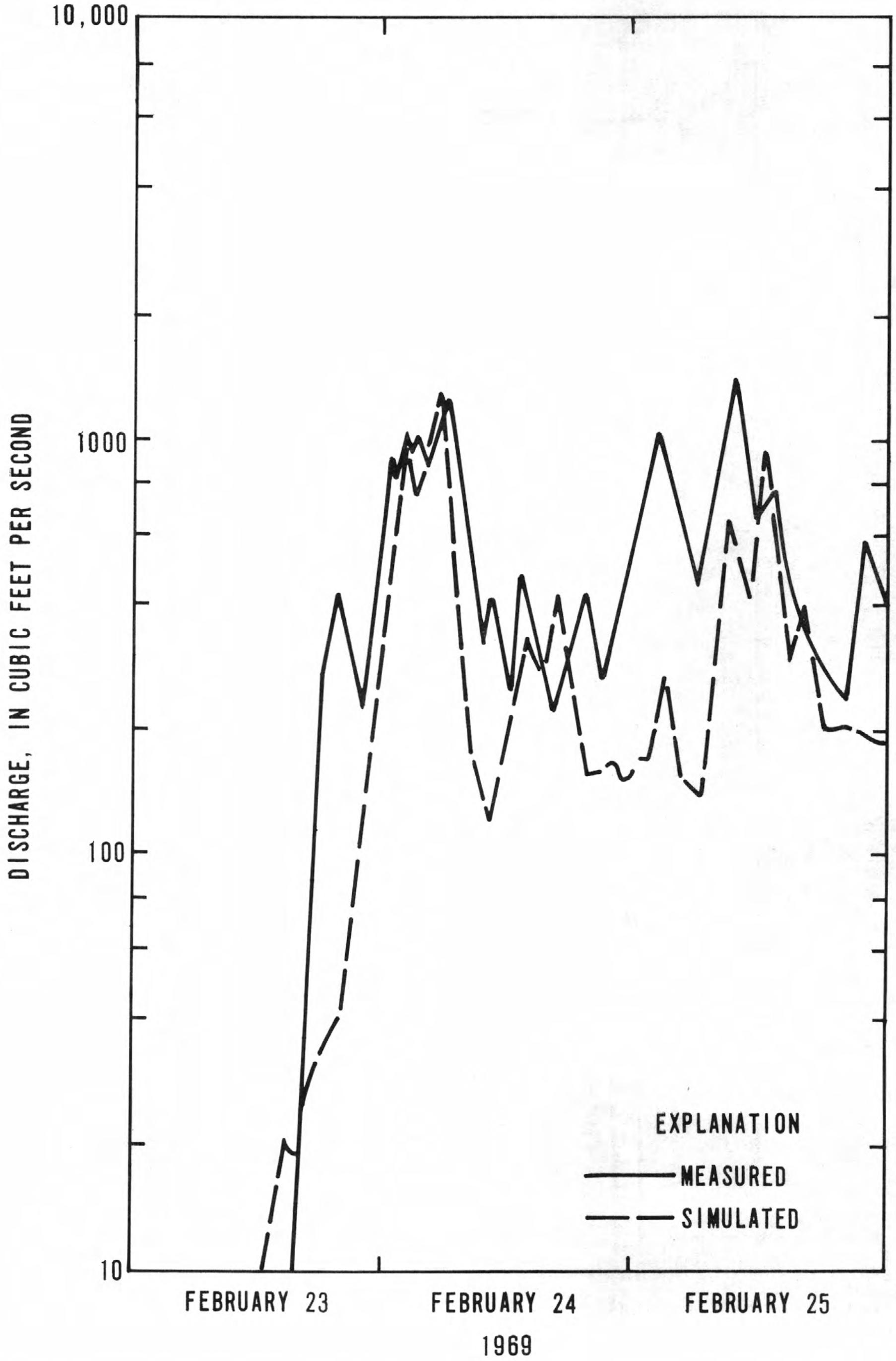

FIGURE 12.—Hydrographs of measured and simulated discharge from Wilson basin.

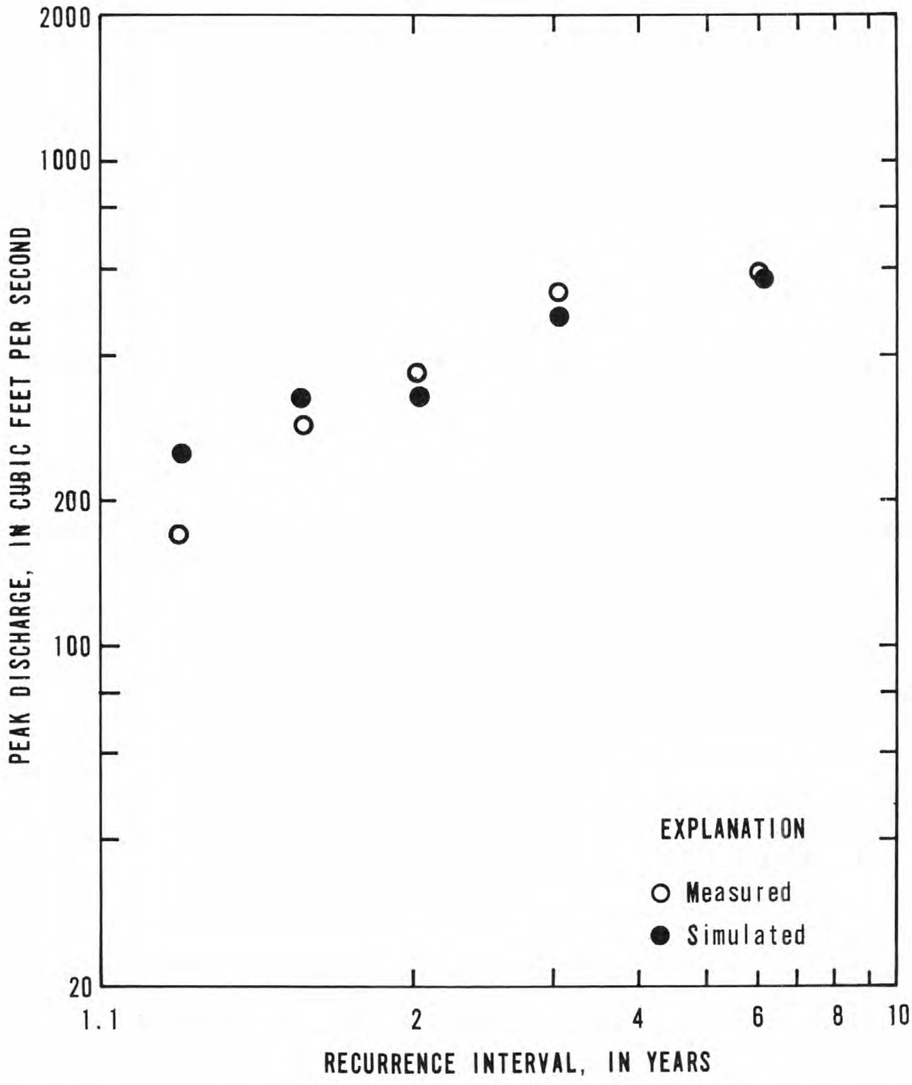

FIGURE 13.--Frequency plot of measured and simulated annual peak discharge from Del Rosa basin--based on data from water years 1965-67 and 1969-70.

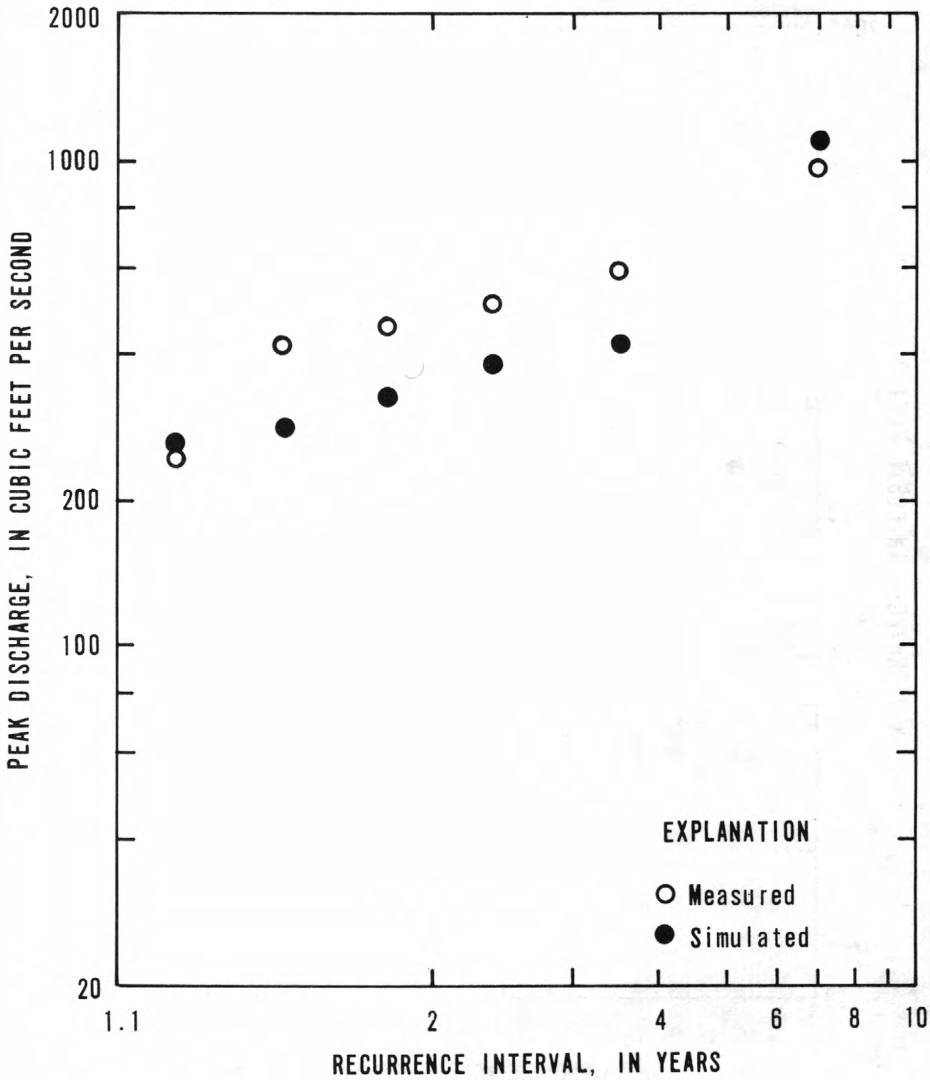

FIGURE 14.--Frequency plot of measured and simulated annual peak discharge from Mission basin--based on data from water years 1965-70.

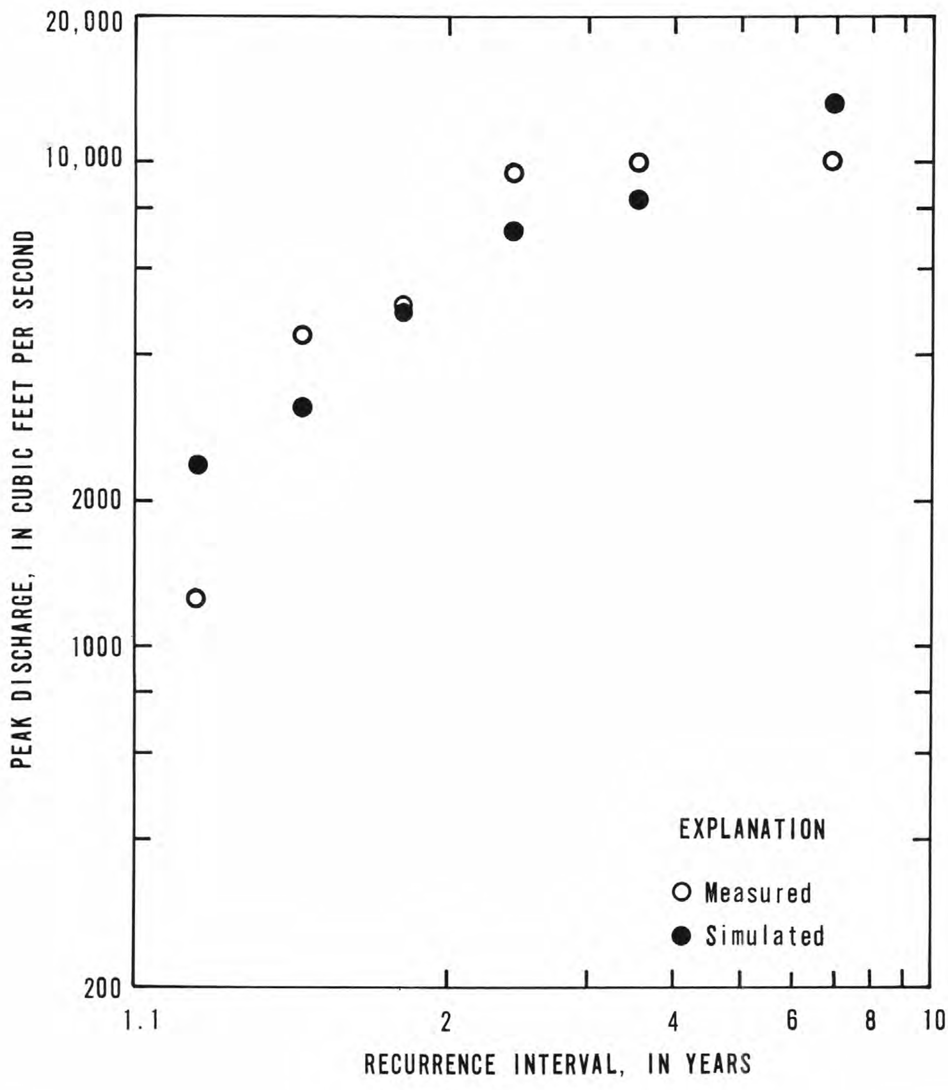

FIGURE 15.—Frequency plot of measured and simulated annual peak discharge from San Jose basin--based on data from water years 1964-69.

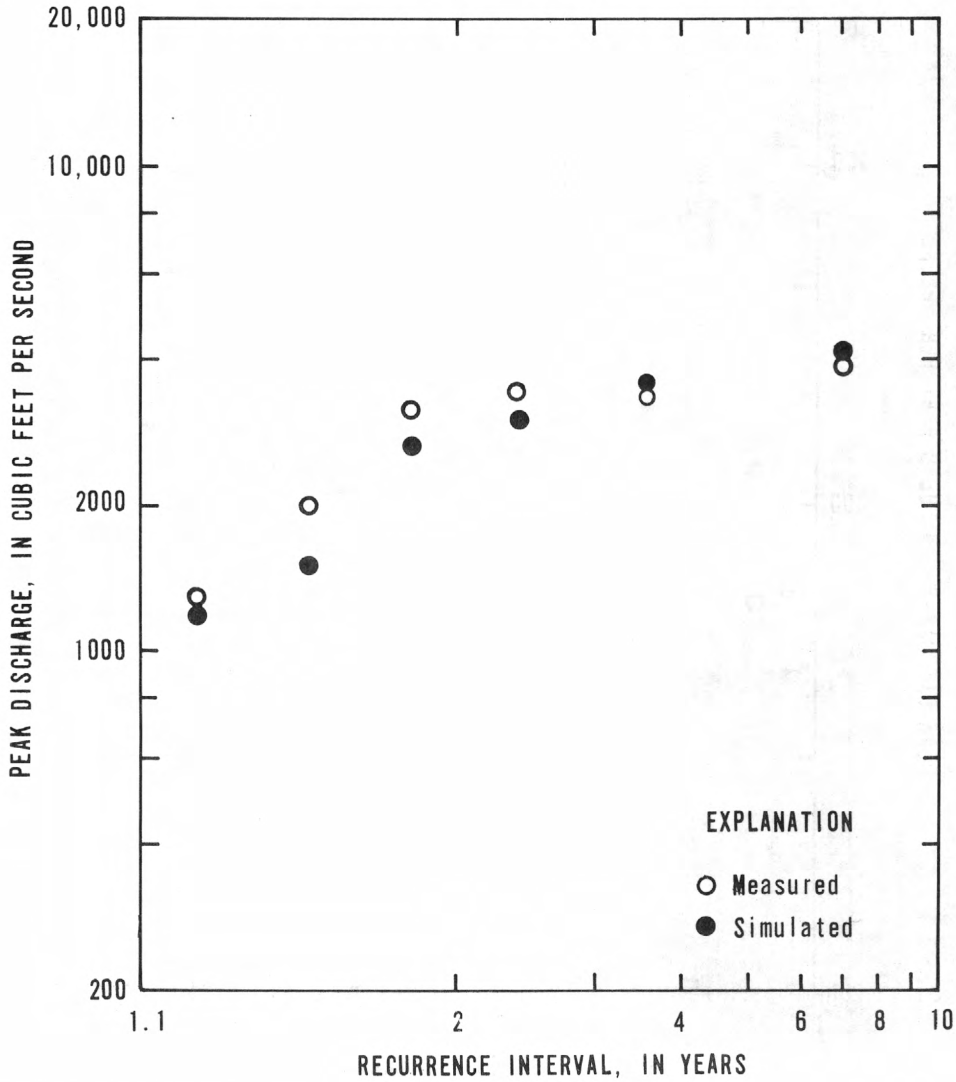

FIGURE 16.--Frequency plot of measured and simulated annual peak discharge from Walnut basin--based on data from water years 1964-69.

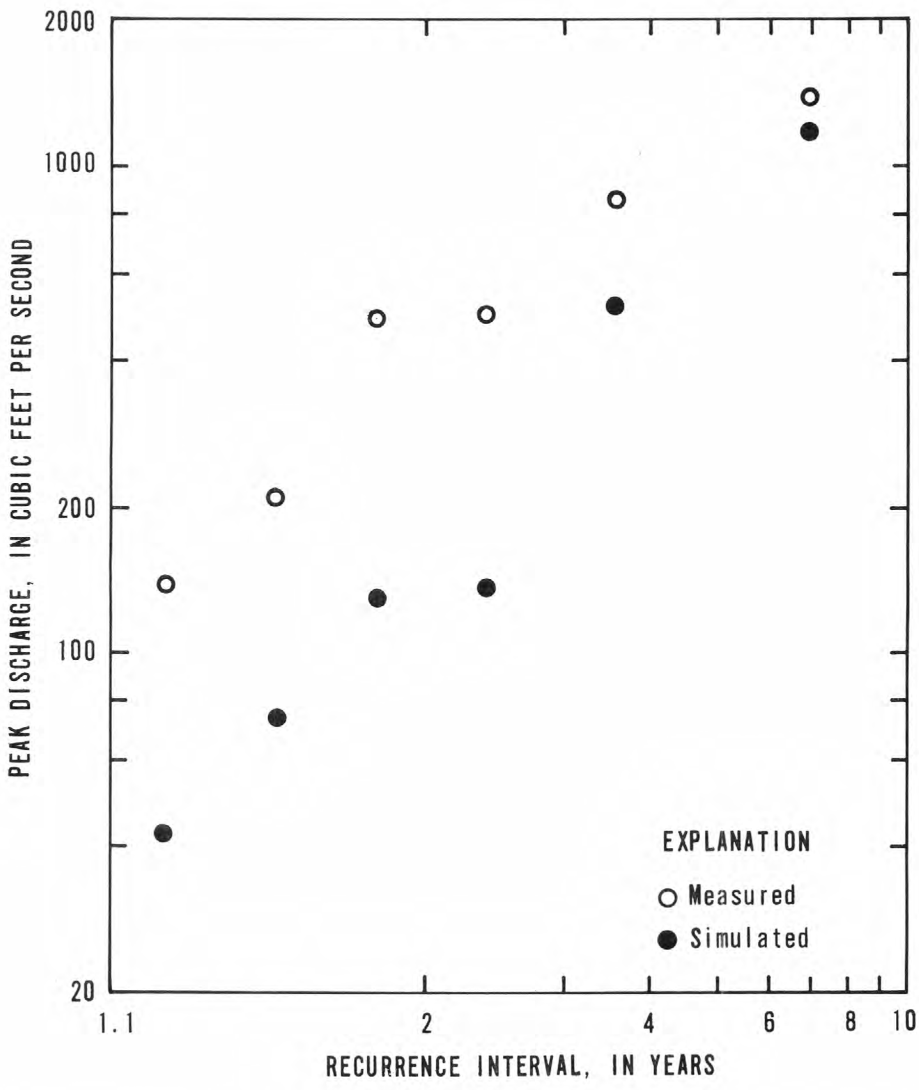

FIGURE 17.--Frequency plot of measured and simulated annual peak discharge from Wilson basin--based on data from water years 1965-70.

Parameter Values

Within the limits of accuracy of the simulation results, changes in the degree of urbanization had little effect on the values determined by calibration for infiltration and channel parameters. Calibration results indicate that these values, derived for one degree of urbanization, can be applied to the same drainage basin for a different degree of urbanization. Consequently, changes in streamflow due to urbanization can be studied by varying only the values for the impervious area parameter (IMPV). Except for Wilson basin, calibration results also indicate that infiltration and channel parameter values are generally consistent among basins. Anomalously high values for the infiltration parameters were derived for Wilson basin, possibly owing to the failure of the model to account for seepage losses from channels. However, the following ranges of values were found for the other basins:

1. Nominal upper zone storage (UZSN) 0.4 to 1.0 inch.

2. Nominal lower zone storage (LZSN) 10 to 14 inches.

3. Infiltration index (CB) 0.10 to 0.35.

4. Channel storage recession constant (KS1) 0.3 to 0.4.

INTERROGATION OF THE MODEL

The reason for using a model to investigate the effects of urbanization on streamflow is to snythesize needed data that otherwise would not be available. For example, the determination of the effects of urbanization on average annual runoff or on the frequency relation for some streamflow characteristic requires discharge records obtained for a long period of time under static conditions of urban development. Urbanization typically is a dynamic process involving continuous changes in the drainage basin, which precludes obtaining such measured streamflow data. However, parameter values can be determined for a model from only a small amount of data, and the model can then be used in conjunction with available precipitation data to synthesize a long streamflow record representing a desired static condition.

Employing this strategy, the Stanford Watershed Model was used to synthesize discharge records with an average length of 20 years for each of four levels of effective impervious area (5, 10, 20, and 30 percent) for each of the drainage basins studied. These data were then used to compute average annual runoff and to construct frequency relations for peak discharge and daily mean discharge for each basin and for each degree of urbanization.

EFFECTS OF URBANIZATION ON ANNUAL RUNOFF

The water-balance equation for a drainage basin, applied over any time interval, is

$$Q = P - E - R - \Delta S$$

where Q is runoff, P is precipitation, E is evapotranspiration, R is deep percolation of soil moisture, and ΔS is the change in moisture stored in the watershed over the time interval being considered. Studies in the upper Santa Ana Valley by Young and Blaney (1942) show that deep percolation is small compared to the other terms in the equation. In addition, if a sufficiently long period of time is considered, the change in moisture stored in the watershed is also small. Therefore, for drainage basins in the upper Santa Ana Valley, the water-balance equation can be approximated by

$$Q = P - E.$$

If the precipitation regime remains unchanged, the water-balance equation for a drainage basin indicates that significant changes in average annual runoff can be achieved only by changes in average annual basin evapotranspiration. As indicated by figure 18, average annual runoff increases as the amount of effective impervious area in a basin increases—a result of lower average annual evapotranspiration losses from impervious surfaces than from pervious surfaces. Results of simulation indicate that approximately 3 inches of water evaporates annually from impervious surfaces, and 14 inches or more of water, when available, evaporates annually from pervious surfaces. Average annual precipitation in the upper Santa Ana Valley is 15 inches. In accordance with the water-balance equation, an average of 12 inches of runoff occurs annually from impervious surfaces, while 1 inch or less occurs from pervious areas. Thus, average annual runoff from a drainage basin with 10-percent effective impervious area is about 2 inches, and average annual runoff from a fully urbanized basin with 30-percent effective impervious area is about 4 inches.

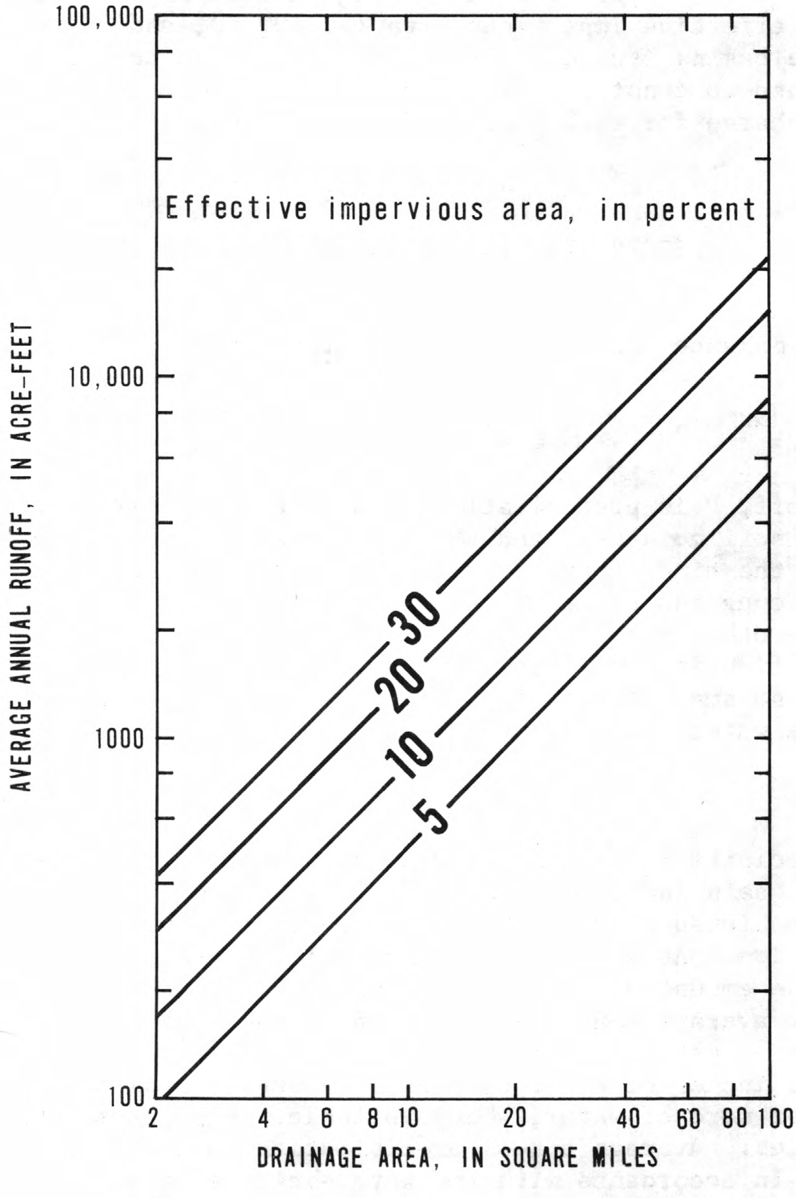

FIGURE 18.—Average annual runoff from drainage basins in the upper Santa Ana Valley for effective impervious areas of 5, 10, 20, and 30 percent.

EFFECTS OF URBANIZATION ON PEAK DISCHARGE AND DAILY MEAN DISCHARGE

Two factors influence the maximum discharge produced by a given period and pattern of precipitation. The first factor is the volume of runoff generated; the second is the modifying influence of the channel system on the distribution of runoff in time. In general, the changes in the magnitude and frequency of flood peaks due to urbanization of a drainage basin can be attributed to the effects on these two factors. Because the channels are nearly uniform and slopes are steep in the basins that were studied, flood waves in the channels move vertically as kinematic waves (Lighthill and Whitham, 1955). Kinematic waves do not disperse in a prismatic channel (Henderson, 1966, p. 370), and the magnitude of discharge at the crest of the wave is affected mostly by changes in lateral inflow to the channel (Harley and others, 1970). As a consequence, past practices in primary drainage channel modification that have accompanied urbanization should have had little impact on peak discharge. This last statement was tentatively verified by the calibration of the model to the basins studied.

The increase in volume of runoff due to urbanization does increase peak discharge. The effect of urbanization is greatest for storms that occur when antecedent soil conditions are dry. Figure 19 shows simulated hydrographs of instantaneous discharge for Walnut basin for selected days in January and February 1969 for two degrees of urbanization. The differences between the ordinates of the two hydrographs decrease with time as soil moisture is accumulated. On February 25, soil moisture levels are near saturation, and urbanization has very little effect on the hydrograph ordinates.

The frequency relation is similarly affected by urbanization. Storms occurring with dry antecedent conditions produce peak discharges with generally short recurrence intervals. Urbanization increases the peak discharge with a recurrence interval of 2 years by a factor of three to six (fig. 20). However, urbanization in a drainage basin has a decreasing effect on annual peak discharge with increasingly longer recurrence intervals. At a recurrence interval greater than a limiting value ranging from 50 to 200 years or more, urbanization has little effect on peak discharge (fig. 20). The value of the limiting recurrence interval is greatest for basins with the largest potential soil moisture, depression, and channel storages. However, soil-moisture storage is probably the most important factor affecting the value. Figure 20 shows frequency curves for two drainage basins representing the probable range in the value for the limiting recurrence interval.

Daily mean discharge and instantaneous peak discharge are affected similarly by urbanization. Urbanization greatly increases the daily mean discharges of short recurrence intervals (fig. 21), but causes a much smaller increase in the daily mean discharges of longer recurrence intervals.

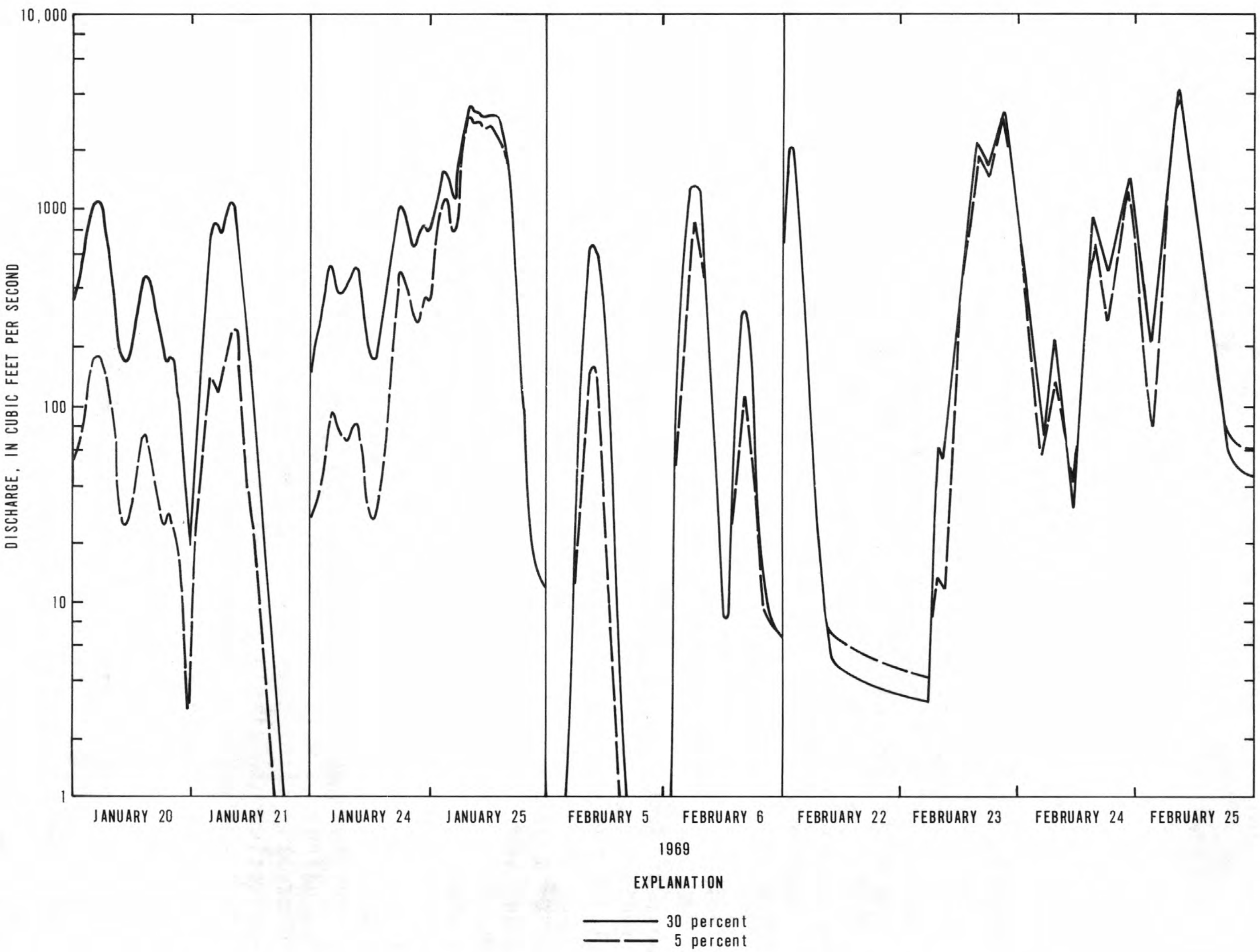

FIGURE 19.--Hydrographs simulated for Walnut basin representing effective impervious areas of 5 and 30 percent and showing the effects of changes in the degree of urbanization on hydrograph ordinates.

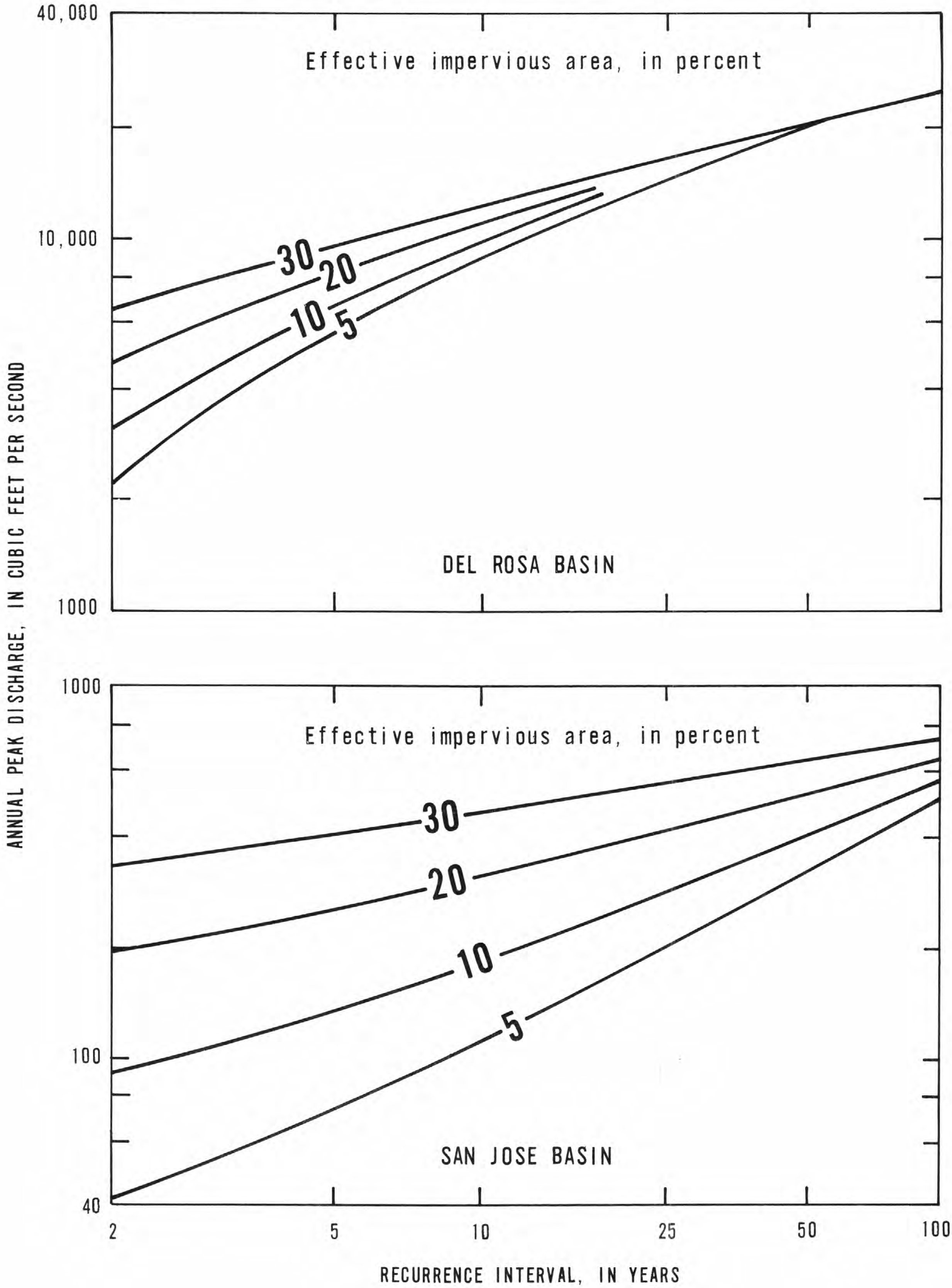

FIGURE 20.--Frequency curves of simulated annual peak discharge from Del Rosa basin and from San Jose basin--representing effective impervious areas of 5, 10, 20, and 30 percent.

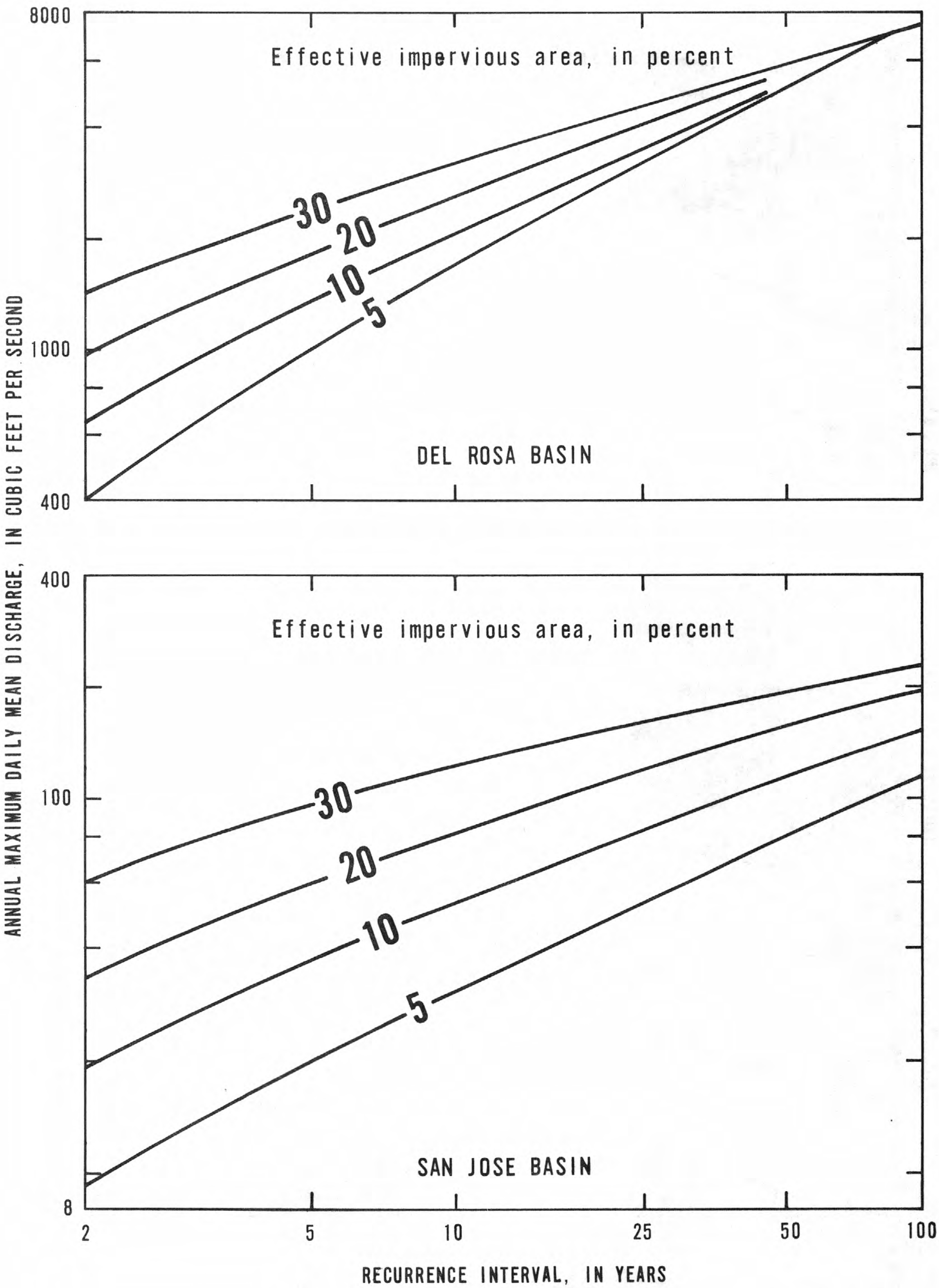

FIGURE 21.—Frequency curves of simulated annual maximum daily mean discharge from Del Rosa basin and from San Jose basin--representing effective impervious areas of 5, 10, 20, and 30 percent.

Figure 22 is a generalization of the results from the basins studied showing the magnitude and frequency of peak discharge from urbanized basins in the upper Santa Ana Valley. Figure 23 is a similar generalization for the magnitude and frequency of daily mean discharge. The relations apply to drainage basins that are on the valley floor or on the alluvial slopes bordering the valley. The relations have standard errors of estimate of 40 percent (determined graphically) on the basis of the simulated data used to construct the relations. However, the standard errors of the relations, with

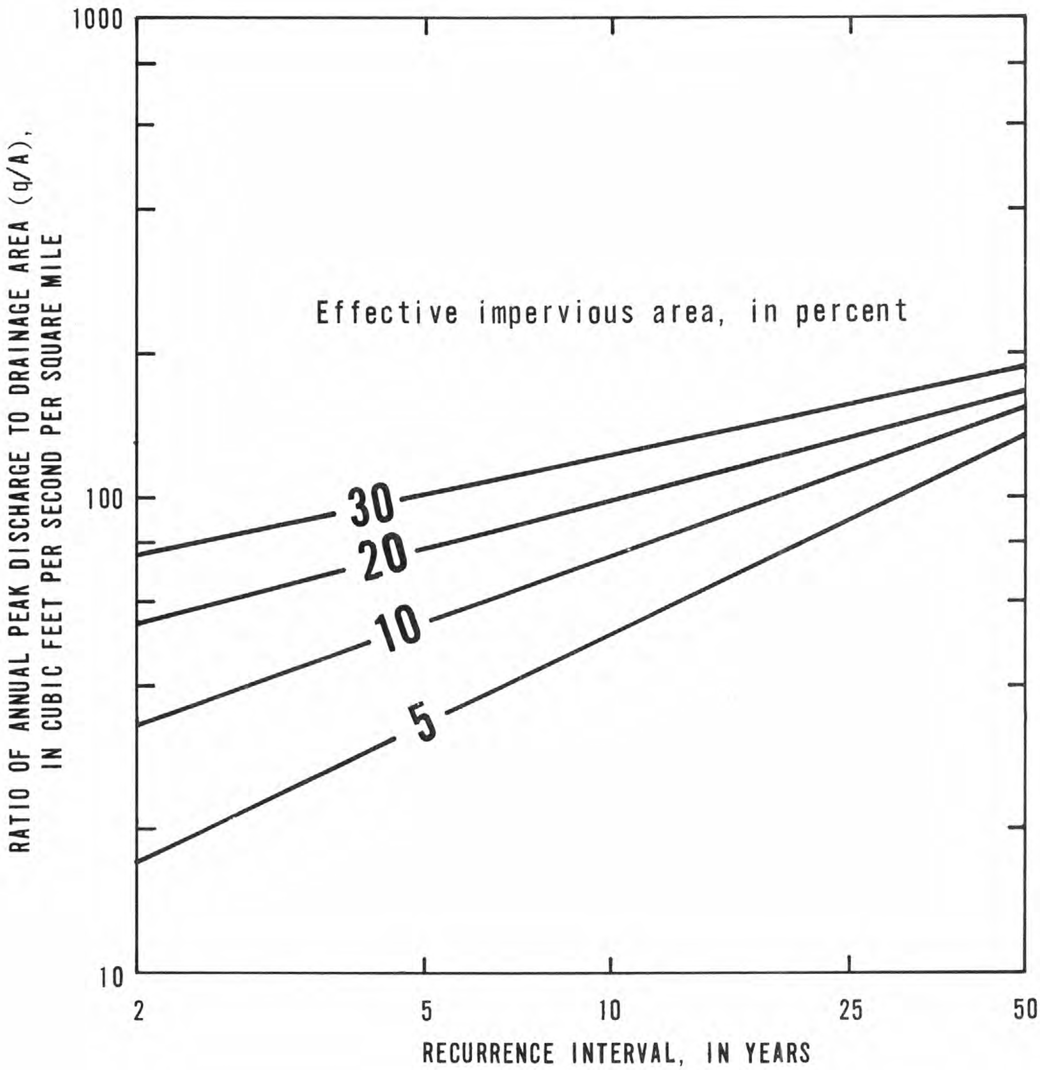

FIGURE 22.--Frequency curves of the ratio of simulated annual peak discharge (q) to drainage area (A) for effective impervious areas of 5, 10, 20, and 30 percent. The curves are based on simulated streamflow records with an average length of 20 years.

reference to the real world, are actually larger by an unknown amount, because of error in the simulated base data. Although the accuracy of the relations cannot be quantitatively assessed, the relative reliability of the relations is best for drainage basins with large amounts of impervious cover. Modeling of soil-moisture storage of a drainage basin is difficult, and the improved accuracy of the relations for more highly developed drainage basins is the result of a decrease in base data error, because of the reduced role of soil-moisture storage in the hydrology of an urbanized basin.

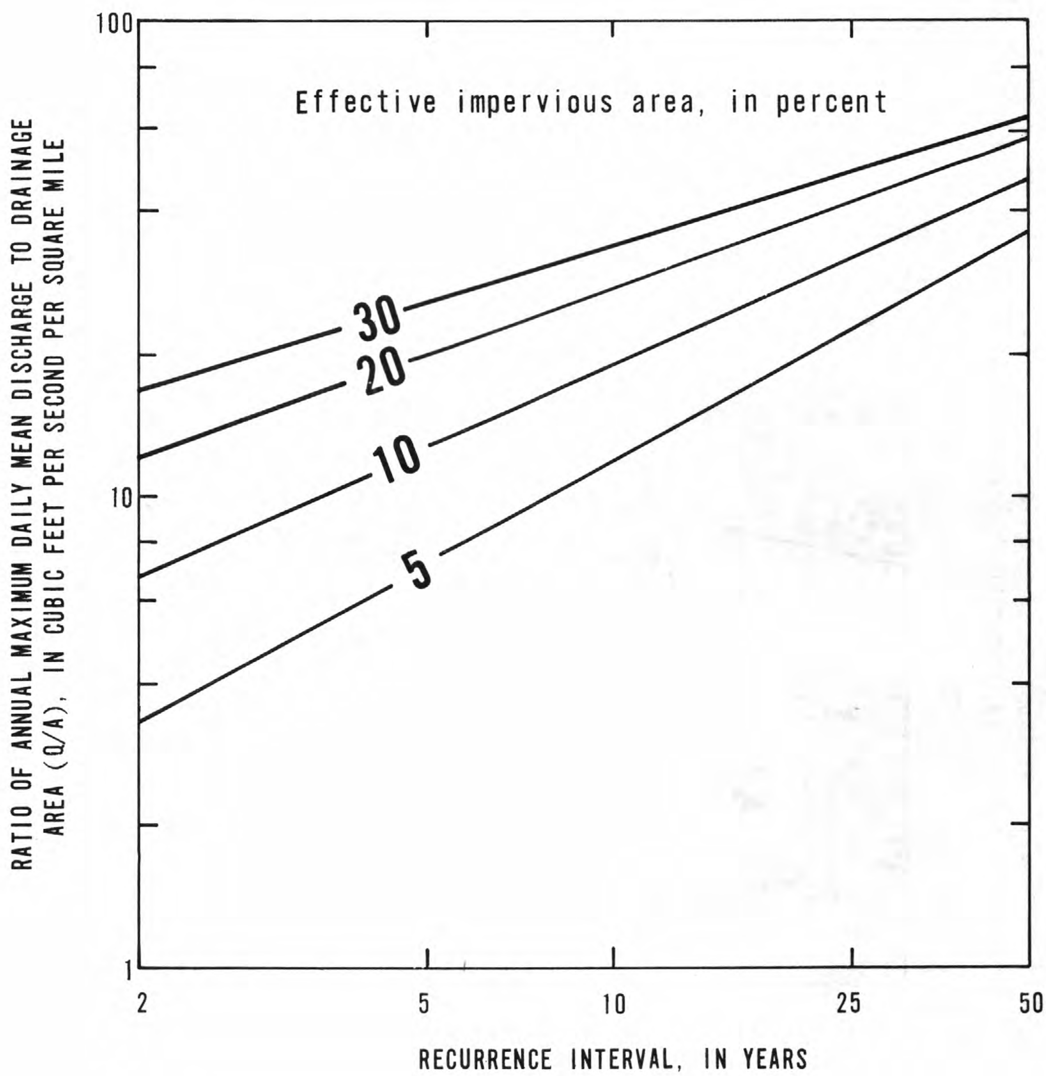

FIGURE 23.--Frequency curves of the ratio of simulated annual maximum daily mean discharge (Q) to drainage area (A) for effective impervious areas of 5, 10, 20, and 30 percent. The curves are based on simulated streamflow records with an average length of 20 years.

CONCLUSIONS

A graphical relation has been presented for estimating the average annual runoff from drainage basins having various degrees of urban development (fig. 18). Average annual runoff from pervious areas of urbanized basins in the upper Santa Ana Valley is 1 inch or less. Average annual runoff from impervious areas is about 12 inches. Average annual runoff increases by approximately 1 inch for each increase in effective impervious cover equal to 10 percent of the area. About 30 percent of a fully urbanized area is effectively impervious.

Graphical relations have also been presented for estimating the magnitude and frequency of peak discharges and daily mean discharges having recurrence intervals from 2 to 50 years for basins with various degrees of urban development (figs. 22 and 23). Urbanization can increase the 2-year peak discharge by a factor of three to six (fig. 20). However, peak discharges with recurrence intervals greater than a limiting value ranging from 50 to 200 years or more are affected very little by urbanization. Urbanization produces similar effects on both daily mean discharge and peak discharge.

The ratio of the effective impervious area to the total area of a drainage basin is approximately equal to the minimum runoff coefficient for the basin. Where data are not available to determine the minimum runoff coefficient, the effective impervious area can be estimated from figure 2.

Selected streamflow characteristics can be approximated for an ungaged urbanized drainage basin by first determining the effective impervious area of the basin from figure 2 and then by entering either figure 18 for average annual runoff, figure 22 for the magnitude and frequency of peak discharge, or figure 23 for the magnitude and frequency of daily mean discharge. The relations shown in figures 2, 18, 22, and 23 apply to urbanized basins that are located on the floor of the upper Santa Ana Valley or on the alluvial slopes bordering the valley.

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Durbin--DIGITAL SIMULATION OF EFFECTS OF URBANIZATION ON RUNOFF, UPPER SANTA ANA VALLEY, CALIFORNIA