SIMULATION OF QUANTITY AND QUALITY OF STORM RUNOFF FOR URBAN CATCHMENTS IN FRESNO, CALIFORNIA

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CONVERSION FACTORS

For readers who prefer to use the International System of Units (SI) rather than inch-pound unit, the conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
foot (ft)	0.3048	meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in)	2.54	centimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
pound (lb)	453.59	gram

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ABSTRACT

Rainfall-runoff models were developed for a multiple-dwelling residential catchment (two applications), a single-dwelling residential catchment, and a commercial catchment in Fresno, California, using the U.S. Geological Survey Distributed Routing Rainfall-Runoff model (DR3M-II). A runoff-quality model also was developed at the commercial catchment using the Survey's Multiple-Event Urban Runoff Quality model (DR3M-qual). Data from the U.S. Environmental Protection Agency's Fresno National Urban Runoff Program for the rain seasons 1981-82 and 1982-83 were used to calibrate and verify the two models. The purpose of this study was (1) to demonstrate the capabilities of the two models for use in designing storm drains, estimating the frequency of storm runoff loads, and evaluating the effectiveness of streetsweeping on an urban drainage catchment; and (2) to determine the simulation accuracies of these models.

Pipe capacities were exceeded at all three catchments when the 2-year design rainfall was input to DR3M-II. Two-year peak discharges also were estimated using the rational formula method for comparison with DR3M-II. The results of the two methods were similar only because the rainfall-runoff model cannot simulate flows greater than the calculated capacity of the pipes, and the runoff coefficients for the rational formula were too low. The runoff from the 2-year event probably would cause little or no pressurized flow or ponding at the multiple(1) catchment, but pressurized flows and ponding probably would occur at the single and commercial catchments. As a result, the 2-year peak discharge at the multiple(1) catchment probably is a reasonable estimate, but the estimated peaks at the single and commercial catchment probably are low. Simulation errors of the two models were summarized as the median absolute deviation, in percent, between measured and simulated values. Calibration and verification mad errors for runoff volumes and peak discharges ranged from 14 to 20 percent.

A long-term time series of annual storm-runoff loads at the commercial catchment was produced by entering historical rainfall data to DR3M-II and entering the simulated discharges to DR3M-qual. Return periods for annual storm-runoff loads were determined by fitting a log-Pearson type III distribution to the time series of annual storm-runoff loads. The estimated annual storm-runoff loads from effective impervious areas that could occur once every 100 years at the commercial catchment were determined as 95 pounds per acre for dissolved solids, 1.6 pounds per acre for dissolved nitrite plus nitrate, 0.31 pound per acre for total recoverable lead, and 120 pounds per acre for suspended sediment. Calibration and verification errors for the above constituents ranged from 11 to 54 percent. The effectiveness of streetsweeping at the commercial catchment was evaluated by entering the long-term time series of discharges into DR3M-qual with various estimates for the model streetsweeping criteria. The analysis showed that a daily cleaning of all parking areas of the catchment by a 50-percent efficient sweeper could decrease the annual storm-runoff loads for dissolved solids and total recoverable lead by 27 percent.

INTRODUCTION

Urbanization in the Fresno metropolitan area, California, has altered the runoff and runoff-quality characteristics. The construction of parking lots, streets, sidewalks, and houses has created impervious surfaces that have increased runoff volumes, peak discharges, and storm runoff loads.

The Fresno Metropolitan Flood Control District (FMFCD) is responsible for controlling urban runoff and runoff quality in the Fresno area. These responsibilities include designing storm drains and retention basins, and estimating quantity and quality of stormwater. The FMFCD currently uses the rational formula (Kibler, 1982) method to design storm drains. This study was done by the U.S. Geological Survey in cooperation with the Fresno Metropolitan Flood Control District.

Background

The rational formula method is used to design storm drains in 90 percent of the engineering offices in the United States (Ardis and others, 1969). The results of the rational formula method are limited because the method requires an empirically determined runoff coefficient, called the "C" factor, to determine peak discharges. This coefficient is normally assumed as constant and is used to determine runoff for a variety of storms. Because the rational formula cannot accurately simulate the complex runoff conditions that are found on an urban catchment, computer models that incorporate many of the fundamental physical processes that occur on urban catchments increasingly are being used. Although computer models often are more labor intensive than other methods, the improved simulations that are possible usually can justify their use. Also, if a well designed data-management system is available, the labor involved in using these models may be greatly reduced.

The U.S. Geological Survey has been involved in urban studies since the late 1950's. For use in early studies that emphasized flood and sediment problems, the Survey began developing simulation models in the late 1960's. This research produced a lumped-parameter rainfall-runoff model described by Dawdy and others (1972) that was based on the unit-hydrograph method. In 1978, a Distributed Routing Rainfall-Runoff Model (DR3M) was completed that incorporated a hydraulic approach to routing runoff adapted from the Massachusetts Institute of Technology catchment model (Leclerc and Schaake, 1973). This model is described in Dawdy and others (1978) and Alley and others (1980). Later research produced an improved version of the DR3M model (DR3M-II) (Smith and Alley, 1982; Alley and Smith, 1982a), and a new urban-runoff-quality model (DR3M-qual) (Smith and Alley, 1982; Alley and Smith, 1982b).

The DR3M and DR3M-II models have been applied to catchments in or near Rochester, New York (Kappel and others, 1986); Middleton, Wisconsin (Krug and Goddard, 1986); Bellevue, Washington (Prych and Ebbert, 1986); Denver, Colorado (Lindner-Lunsford and Ellis, 1984); Oahu, Hawaii (Shade, 1984); Atlanta, Georgia (Inman, 1983); Chester County, Pennsylvania (Sloto, 1982); and Miami, Florida (Doyle and Miller, 1980). Of these, only the Rochester and Denver studies included the DR3M-qual model. The calibration and verification results of DR3M and DR3M-II at 37 catchments, including many unpublished reports, are summarized by Alley (1986).

The goals of the Survey's urban studies program are, in part, to continue to develop improved methods for analyzing urban hydrologic data. This includes determining characteristics of urban runoff, developing methods to transfer information to ungaged drainage basins, and evaluating the effectiveness of stormwater management practices on urban runoff loads.

Objectives and Scope

The objectives of this study were (1) to demonstrate the capabilities of the Survey's Distributed Routing Rainfall-Runoff Model (DR3M-II) and Multi-Event Urban Runoff Quality Model (DR3M-qual) for use in designing storm drains, estimating the frequency of storm-runoff loads, and evaluating the effectiveness of streetsweeping on an urban drainage basin; and (2) to determine the simulation accuracies of these models. Rainfall-runoff models were applied to a multiple-dwelling residential catchment (two applications), a single-dwelling residential catchment, and a commercial catchment in Fresno, California. A runoff-quality model was applied to the commercial catchment only.

Approach

Data from the U.S. Environmental Protection Agency's (EPA) Fresno National Urban Runoff Program (NURP) were used to calibrate and verify the rainfall-runoff and runoff-quality models. Simulation errors for runoff volumes, peak discharges, and storm-runoff loads were summarized using the median absolute deviation in percent (mad) between measured and simulated values. The storm-drain design capabilities of the rainfall-runoff model were evaluated by entering a 2-year design storm to DR3M-II to simulate the 2-year runoff and estimate the 2-year peak discharge. A 2-year peak discharge also was determined using the rational-formula method to compare with DR3M-II.

DR3M-qual was used to simulate the storm-runoff loads for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended sediment. A long-term time series of annual storm-runoff loads was developed for the four constituents using DR3M-II, DR3M-qual, and historical rainfall. The return periods of the annual loads were estimated by fitting the time series to a log-Pearson type-III distribution. The effectiveness of streetsweeping was evaluated by adjusting the streetsweeping criteria in the runoff-quality model.

Location and Description of Study Area

The city of Fresno is in the San Joaquin Valley about 160 miles southeast of San Francisco, California (fig. 1). The valley is bordered by the Coast Ranges on the west and the Sierra Nevada on the east. Rainfall for the Fresno area averages about 10 inches annually, nearly all of which falls between October and April. The city currently uses ground water for its domestic water supply. Ground-water supplies are replenished through percolation by a system of stormwater retention/recharge basins. The retention/recharge basins throughout the Fresno area are designed to hold runoff from the 100-year storm. The storm-drain pipes that feed these basins are designed to carry the runoff from the 2-year storm. A typical catchment is about 1 square mile in size and drains

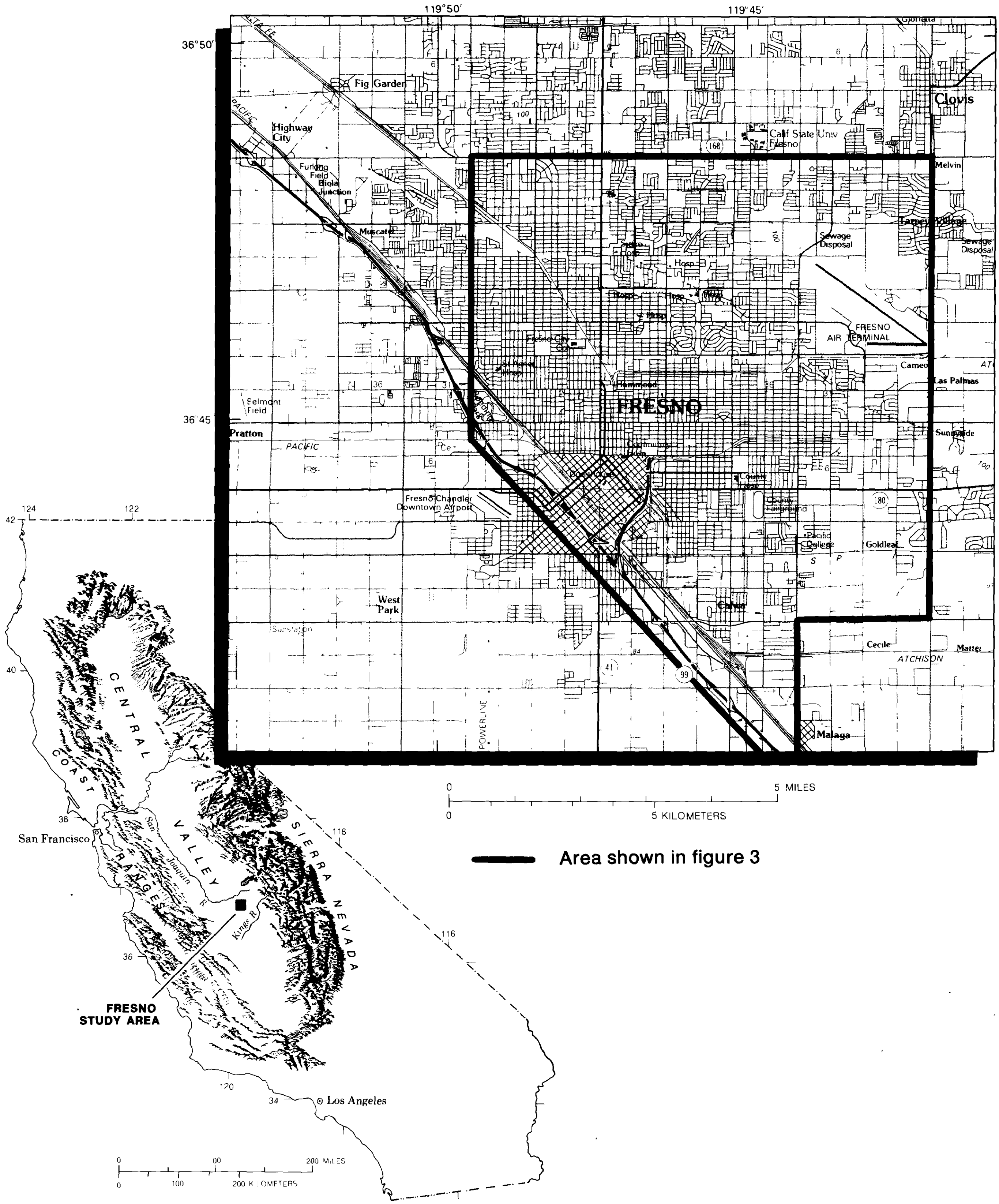


FIGURE 1. Index map of California showing Fresno study area.

into a 10- to 15-acre retention/recharge basin about 15 feet deep. During the dry season, most of the basins are used as recreational facilities such as soccer and baseball fields (fig. 2). The three catchments are in the city of Fresno a few miles northwest of the Fresno Air Terminal (fig. 3). The characteristics of the catchments are summarized in table 1.

The multiple-dwelling residential catchment includes 45.1 acres that is 87 percent high-density residential, and 13 percent vacant land. Soils are classified as Hydrologic Soil Group A using the U.S. Soil Conservation Service (SCS) designation (U.S. Soil Conservation Service, 1975). The catchment is 57-percent impervious. Runoff is carried by gutters to the southwest section of the catchment. Drop inlets convey the water to storm-drain pipes that run south, then west to a large connecter pipe under Maple Avenue (fig. 4). Runoff characteristics were altered during the second year of the NURP study (1982-83) by new construction and additional catchment area. New housing was constructed in the area south of East Alamos Avenue, and about 3.9 acres were added to the northeast corner of the catchment. These changes caused the effective impervious area of the catchment to increase by 5 percent. The DR3M-II model defines effective impervious surfaces as areas that drain directly into channel drainage systems; noneffective impervious surfaces are areas that drain to pervious areas. Because of the changes, a separate application of the model was made for each year of the NURP study. These two models are called multiple(1) and multiple(2), referring to the first and second year of data collection. Each application used the same number of model segments, but the multiple(2) model had a higher effective impervious area and one larger segment to account for its additional area.

The single-dwelling residential catchment includes 94.2 acres that is 87.3 percent medium-density residential, 9.0 percent low-density residential, and 3.7 percent vacant land. The soils have a moderate infiltration rate and are classified as Hydrologic Soil Group B (SCS method, U.S. Soil Conservation Service, 1975). The catchment is 43.4 percent impervious. Drainage in the area north of Gettysburg Avenue flows south and east, by means of gutters, to a siphon at

FIGURE 2. Multiple-use stormwater retention basin with inundated baseball diamond.

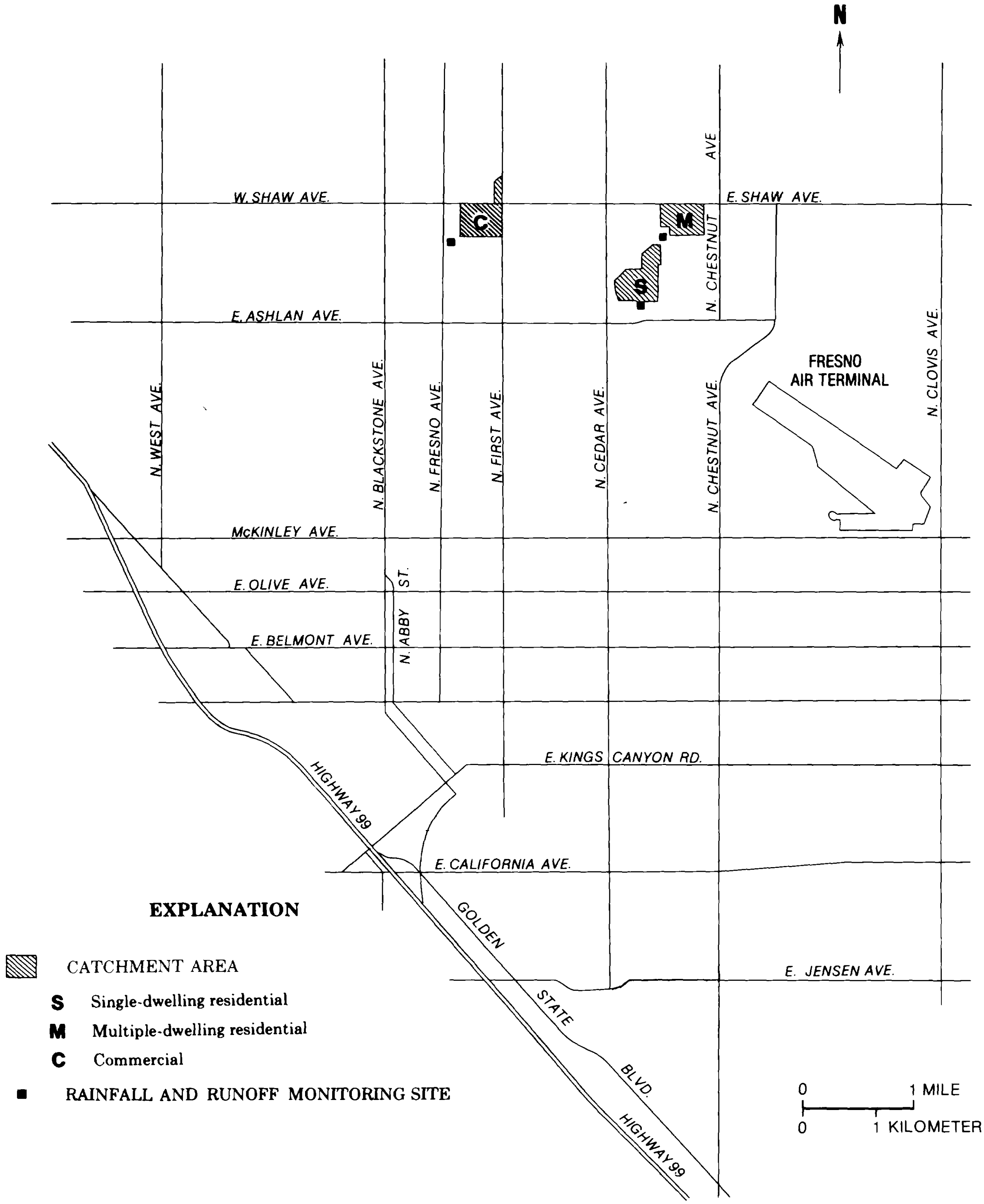


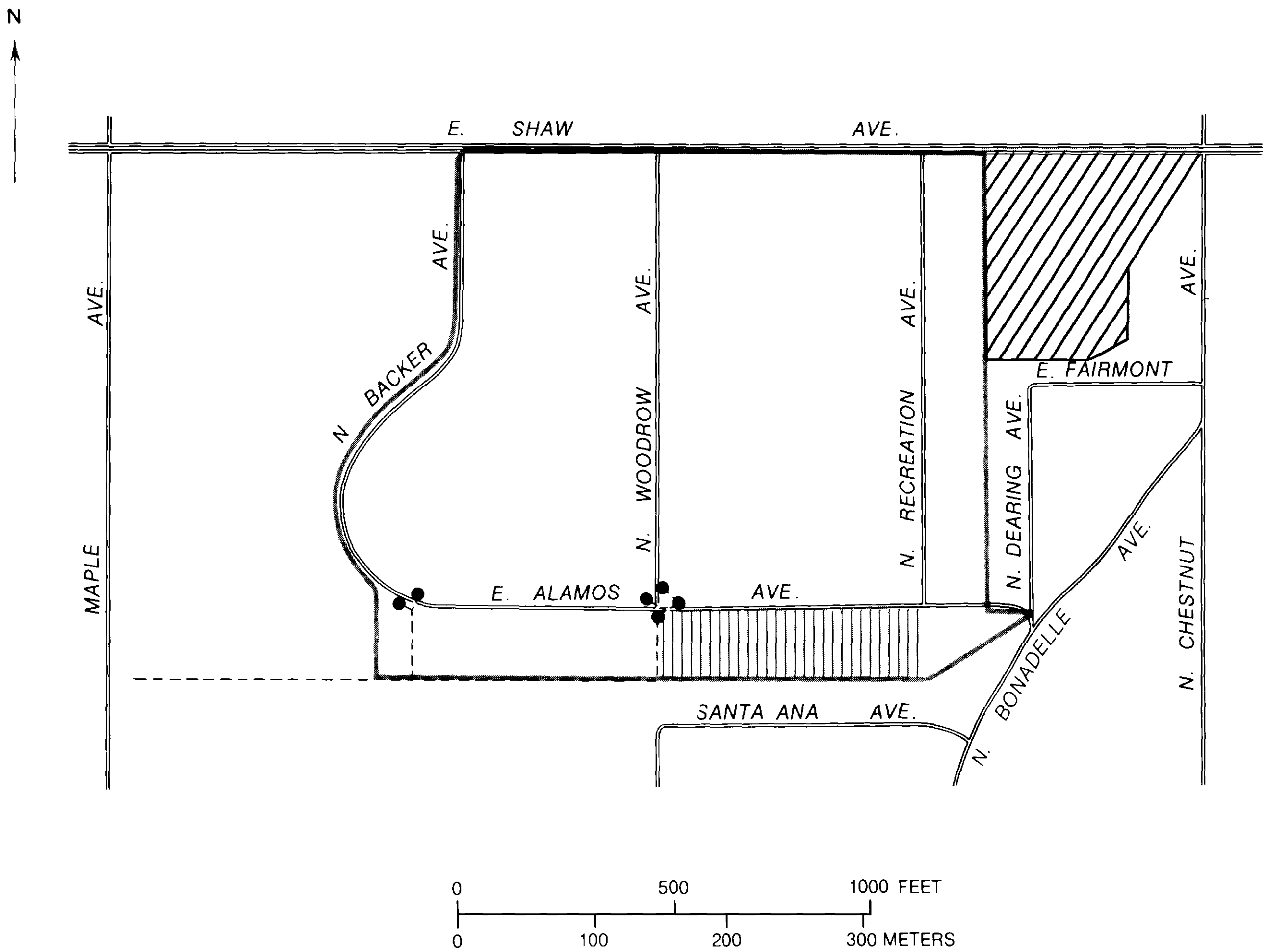
FIGURE 3. Location of catchment areas.

TABLE 1.--*Characteristics of the urban-runoff catchments*

[Multiple(1)-dwelling residential catchment: Data available for first year (1981-82) NURP study only. Abbreviations: ft/mi, feet per mile; in/h, inches per hour; mi^2, square miles; acre-ft, acre-feet]

Catchment characteristic	Catchment: Multiple(1)-dwelling residential	Single-dwelling residential	Commercial
Contributing drainage area (acres)	45.1	94.2	61.9
Impervious area (percentage of drainage area)	57.0	43.4	98.9
Average basin slope (ft/mi)	7.03	7.90	13.8
Main conveyance slope (ft/mi)	9.96	28.6	5.70
Permeability of A horizon of soil profile (in/h)	7.50	3.75	--
Soil-water capacity (inch of water/inch of soil)	0.07	0.12	--
Soil water pH of A horizon	6.7	6.7	--
Hydrologic soil group, SCS methodology[1]	A	B	--
Population density (person/mi^2)	16,400	7,700	0
Street density (lanes/mi^2)	39	47	11
Land use, percentage of drainage area:			
Low-density residential	0	9.0	0
Medium-density residential	0	87.3	0
High-density residential	87.0	0	0
Commercial	0	0	100.0
Industrial	0	0	0
Idle or vacant	13.0	3.7	0
Detention storage, within catchment associated with storage facilities (acre-ft of storage)	0	0	0
Percentage of area drained by storm-sewer system	100.0	100.0	100.0
Percentage of streets with curb and gutter drainage	96.3	100.0	100.0
Percentage of streets with ditch and swale drainage	3.7	0	0

[1]Soil Conservation Service (SCS) designations: A, soils having a high infiltration rate; B, soils having a moderate infiltration rate.



EXPLANATION

AREA ADDED TO CATCHMENT, 1982-83

NEW CONSTRUCTION, 1982-83

CATCHMENT BOUNDARY, 1981-82

STORM DRAIN PIPE

STORM DRAIN DROP INLET

FIGURE 4. Location of multiple-dwelling residential catchment.

the corner of Gettysburg and Barton Avenues, then south along Barton Avenue by means of street gutters (fig. 5). The areas to the east and west of Barton Avenue drain toward Barton Avenue, by a series of gutters to two drop inlets near the corner of Ashcroft and Barton Avenues. Storm-drain pipes then carry the runoff south to a retention/recharge basin near the corner of Richert and Barton Avenues.

The commercial catchment is a 61.9-acre shopping center and parking lot. The catchment is 98.9-percent impervious. The commercial catchment includes the Fashion Fair Mall, and a small parcel of land north of the mall (fig. 6). Runoff north of Shaw Avenue is routed by gutters to a siphon at the corner of East Shaw Avenue and First Street. A gutter along First Street then carries the water to a drop inlet at the east end of the mall. Runoff in the north and south parking lots flows into a system of drop inlets and pipes that carry the water to the southwest corner of the catchment. Runoff then flows west to a large connecter pipe that carries the water south along North Fresno Street.

RAINFALL-RUNOFF MODEL

Description of Model

The rainfall-runoff model (DR3M-II) continuously simulates stormwater hydrographs from rainfall input and a physical description of the drainage basin. The model attempts to describe the actual physical processes that occur in the drainage basin so that the need for calibration is minimized. A drainage basin is represented as a set of overland-flow and channel segments, which are combined to describe the drainage features of the basin. Unsteady flow-routing methods are used to simulate the movement of runoff over contributing overland-flow areas and through the channel network. Infiltration is modeled on the basis of a variation of the Green-Ampt equation (Green and Ampt, 1911). DR3M-II was developed principally for application to urban drainage basins. Additional documentation of the model is given by Alley and Smith (1982a).

The DR3M-II model simulates on two different time intervals. A short time interval (1-minute to hourly) is used for infiltration and routing calculations during days for which short-time-interval storm rainfall are entered into the program. Flows are routed by the model only during these short-time interval days, referred to as unit days. Between unit days, DR3M-II simulates on a daily time interval using daily precipitation and evaporation data to perform an accounting of soil moisture. This daily soil moisture accounting design has the advantage of allowing antecedent conditions to be determined for storms without incurring the excessive computer costs of continuous short-time-interval calculations made during long periods.

Data Description and Management

Since 1978, the Survey has participated in 40 urban studies to determine the quantity and quality of urban runoff. Ten of these projects were in cooperation with the U.S. Environmental Protection Agency's (EPA) National Urban Runoff Program (NURP). A Fresno NURP study collected data on quantity and quality of rainfall and runoff for the rain seasons 1981-82 and 1982-83 (Oltmann and others, 1987). The data were collected from four catchments, each of which had a homogeneous land use. The four land uses were industrial, multiple-dwelling residential, single-dwelling residential, and

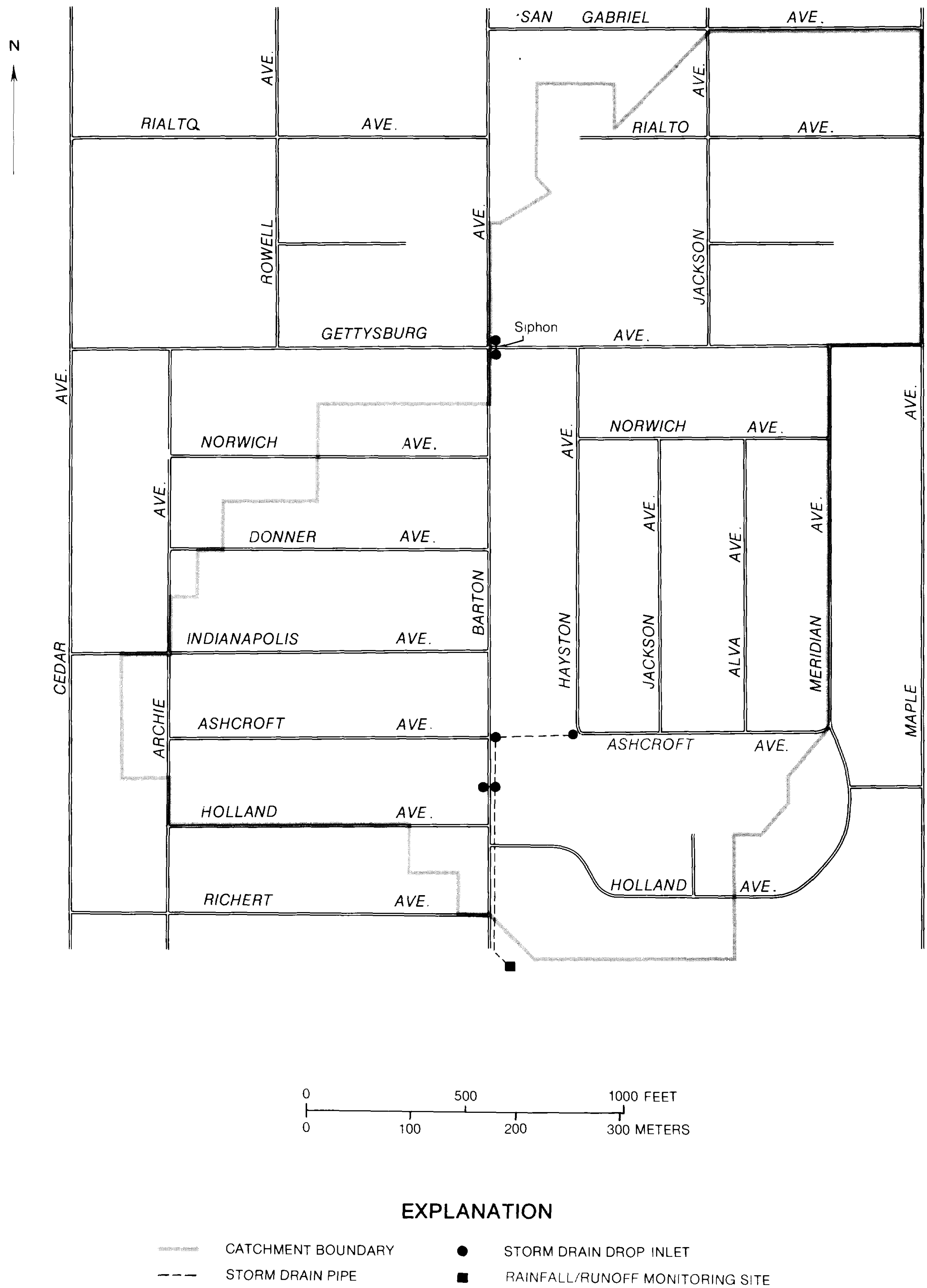


FIGURE 5. Location of single-dwelling residential catchment.

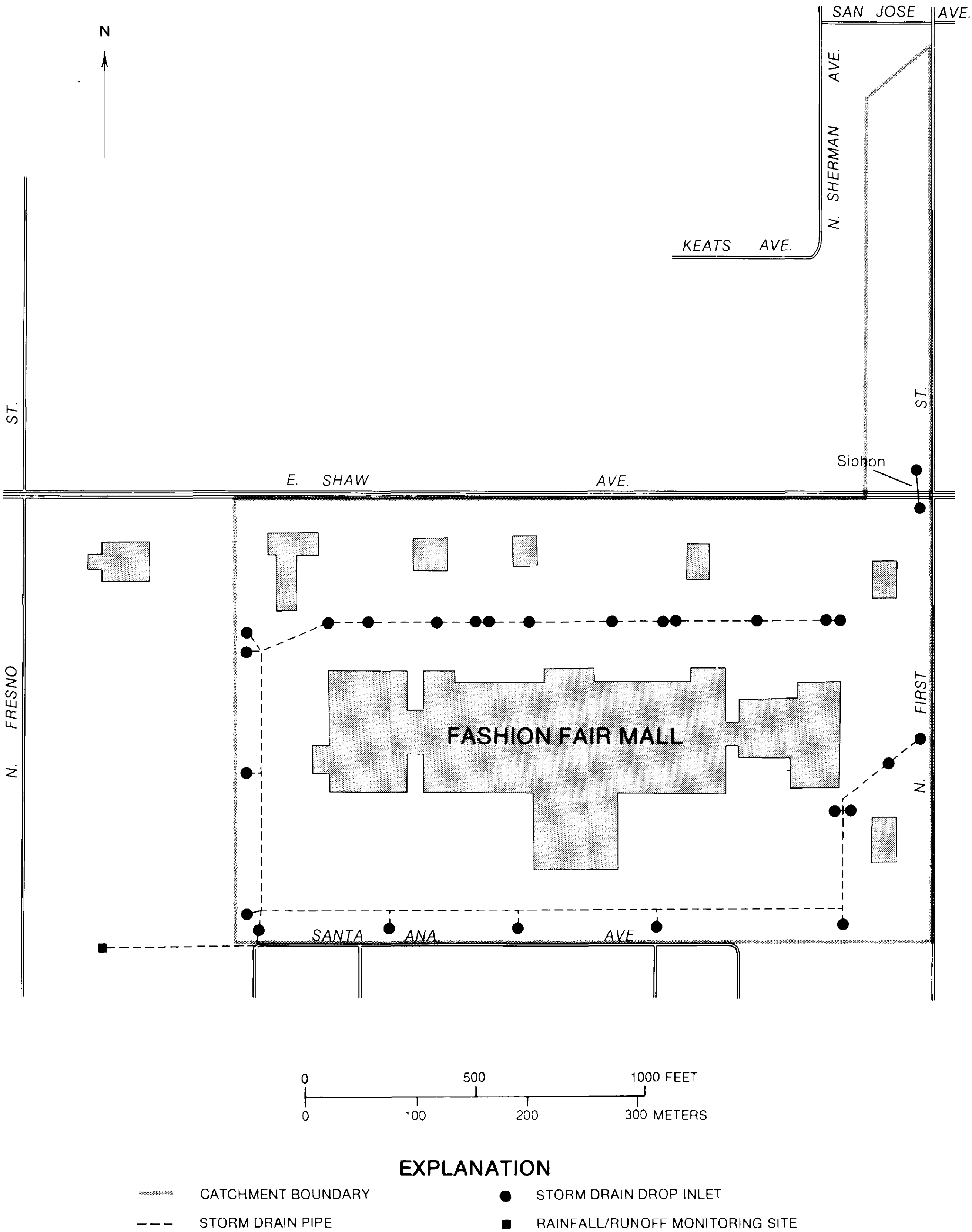


FIGURE 6. Location of commercial catchment.

commercial. Rainfall and runoff data were recorded in 4- or 5-minute intervals from October 28, 1981, to November 30, 1981, and in 2-minute intervals from December 1, 1981, to March 23, 1983. Rainfall was recorded in 0.01-inch increments, using a single rain gage at each catchment. Discharges at the multiple-dwelling residential and commercial catchments were calculated using measured stage data and a stage-discharge relation. The higher discharges were estimated by extending the stage-discharge curve. For the single-dwelling residential catchment, velocities from an electromagnetic flowmeter and measured stage data were used to determine discharge. Five to 35 runoff-quality samples were collected for most storms during the rain seasons 1981-82 and 1982-83. From the 255 storms monitored for rainfall and runoff quality, 104 were analyzed for inorganic, biological, physical, and organic constituents. Most remaining storms were analyzed for pH and specific conductance only. Sixty-two of the 91 composite rain samples collected were analyzed for inorganic, physical, and organic constituents.

From the 49 storms monitored at the multiple(1) catchment for rainfall and runoff, 26 were used to calibrate and verify the rainfall-runoff model. Only rainfall events greater than 0.05 inch were classified as storms. The other models used 24 of 41 at the multiple(2) catchment, 23 of 42 at the single catchment, and 24 of 74 at the commercial catchment. Storms where peak discharges had to be estimated or the data-recording interval was greater than 2 minutes were not used in calibration and verification. Storms at the single catchment prior to December 21, 1982, were not used because discharges were affected by an external electromagnetic field. The 1982-83 storms at the commercial catchment were not used because stage records were affected by variable backwater conditions caused by new construction.

For the runoff-quality model simulations, four constituents were selected to represent a cross section of the water-quality data collected during the Fresno NURP study. The four constituents--dissolved solids, total recoverable lead, dissolved nitrite plus nitrate, and suspended sediment--also were selected to evaluate the accuracy of the runoff-quality model to similate storm-runoff loads. Thirteen of the 24 storms at the commercial catchment that were used to calibrate and verify the rainfall-runoff model had sufficient water-quality data to calibrate and verify the runoff-quality model.

The data used by the rainfall-runoff model are unit rainfall, daily rainfall, unit discharge, and daily evaporation. All the rainfall and runoff data were available from the Fresno NURP study on the Survey's National Water Data Storage and Retrieval System (WATSTORE). Daily evaporation data were compiled from published climatological data of the National Weather Service (NWS) and manually entered into a computer.

For modeling purposes, data were retrieved from WATSTORE and stored digitally on online computer disks as part of a comprehensive drainage basin data-management system called ANNIE (Lumb and Kittle, 1985). ANNIE is a system of software modules developed by the U.S. Geological Survey to simplify the tasks of storing, retrieving, and preparing data sets for the entry into the DR3M-II model. Watershed Data Management (WDM) files are used in ANNIE to store rainfall-runoff data.

Schematization

Each catchment was schematized into a series of segments that represented the physical features of the catchment. The types of segments available in DR3M-II are channel, overland-flow, junction, and reservoir. Only channel (gutters and pipes) and overland-flow segments were used in the rainfall-runoff models. Channel segments are defined by length, slope, roughness, and cross-sectional geometry. Overland-flow segments are rectangular planes defined by flow length, slope, and a roughness coefficient. Overland-flow plane width is determined by the length of the channel segment it flows into. Manning's n values were used for the roughness coefficients in all segments.

Segments were schematized using (1) surface drawings of streets and gutters, (2) subsurface drawings of storm-drain pipes, (3) aerial photographs of the catchments, and (4) field inspection of the catchments. A digitizer was used to determine the overall catchment area, and segment and pipe lengths. Aerial photographs of the catchments were used to estimate the percentage of effective and noneffective impervious areas of each overland-flow plane.

The surface drainage at the multiple(1) and multiple(2)-dwelling residential catchment was schematized into 11 overland-flow plane segments and 12 channel (gutter) segments (fig. 7). These were combined with 10 pipe segments to represent the final model schematization of the catchment (fig. 8).

The surface drainage at the single-dwelling residential catchment was schematized into 11 overland-flow plane and 9 channel (gutter) segments (fig. 9). These were combined with five pipe segments to represent the final model schematization of the catchment (fig. 10).

The storm-drain system at the commercial catchment was the most complex of the three catchments, and therefore required a more detailed schematization. The multiple and single catchments had six drop inlets, whereas the commercial catchment had 27 drop inlets and 10 pipes leading from the roof of the mall. The surface drainage was schematized into 32 overland-flow planes and four channel (gutter) segments (fig. 11). The final schematization was represented by 32 overland-flow plane, 4 channel (gutter), and 39 pipe segments (fig. 12).

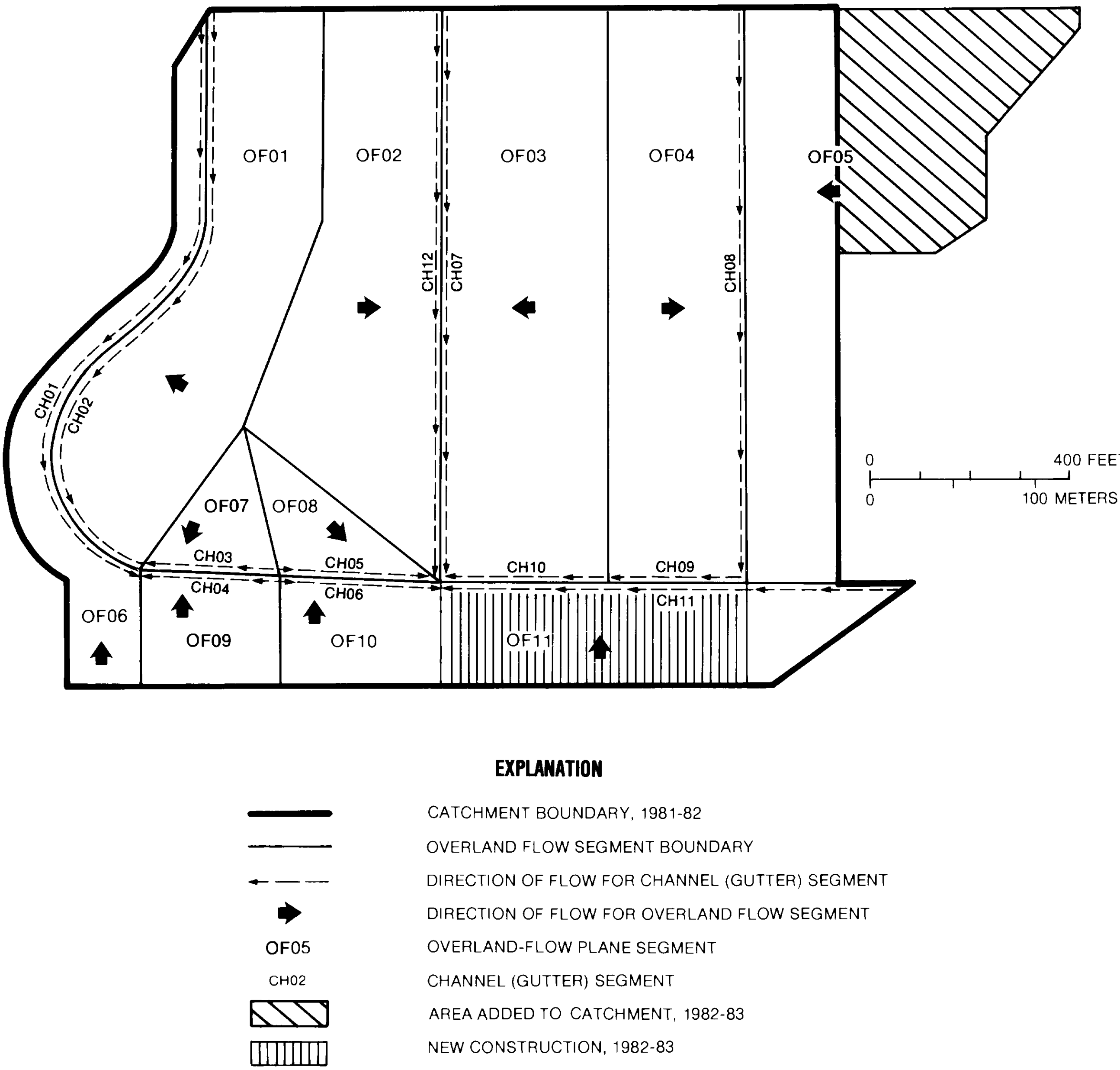
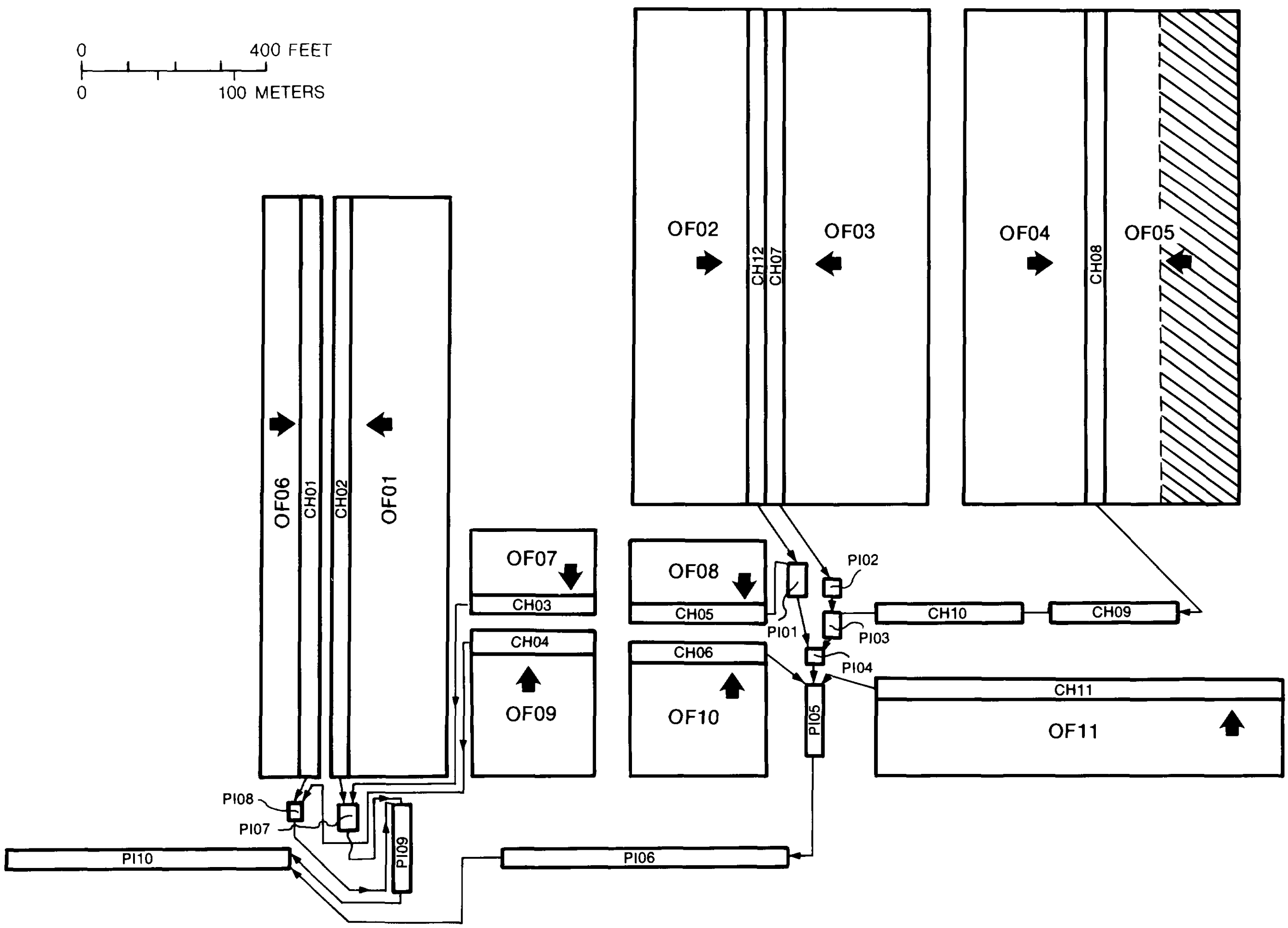


FIGURE 7. Schematization of overland-flow planes and channel (gutters) for the multiple(1)- and multiple(2)-dwelling residential catchment.



EXPLANATION

SEGMENT BOUNDARY

DIRECTION OF FLOW FOR CHANNEL (GUTTER) AND PIPE SEGMENTS

DIRECTION OF FLOW FOR OVERLAND FLOW SEGMENTS

OF05 — OVERLAND-FLOW PLANE SEGMENT

CH01 — CHANNEL (GUTTER) SEGMENT

PI10 — PIPE SEGMENT

AREA ADDED TO CATCHMENT, 1982-83

FIGURE 8. Segments for the multiple(1)- and multiple(2)-dwelling residential catchment.

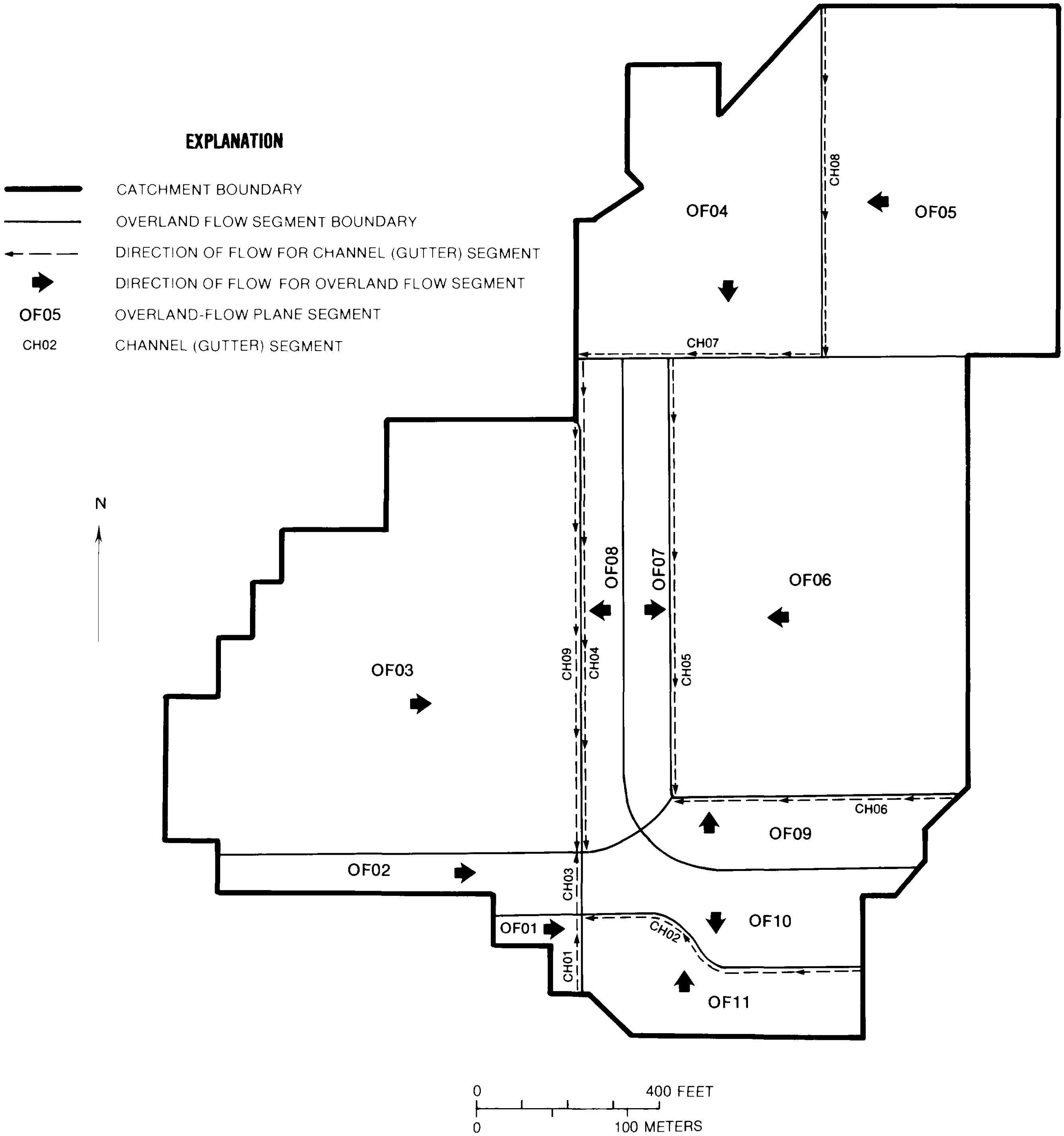
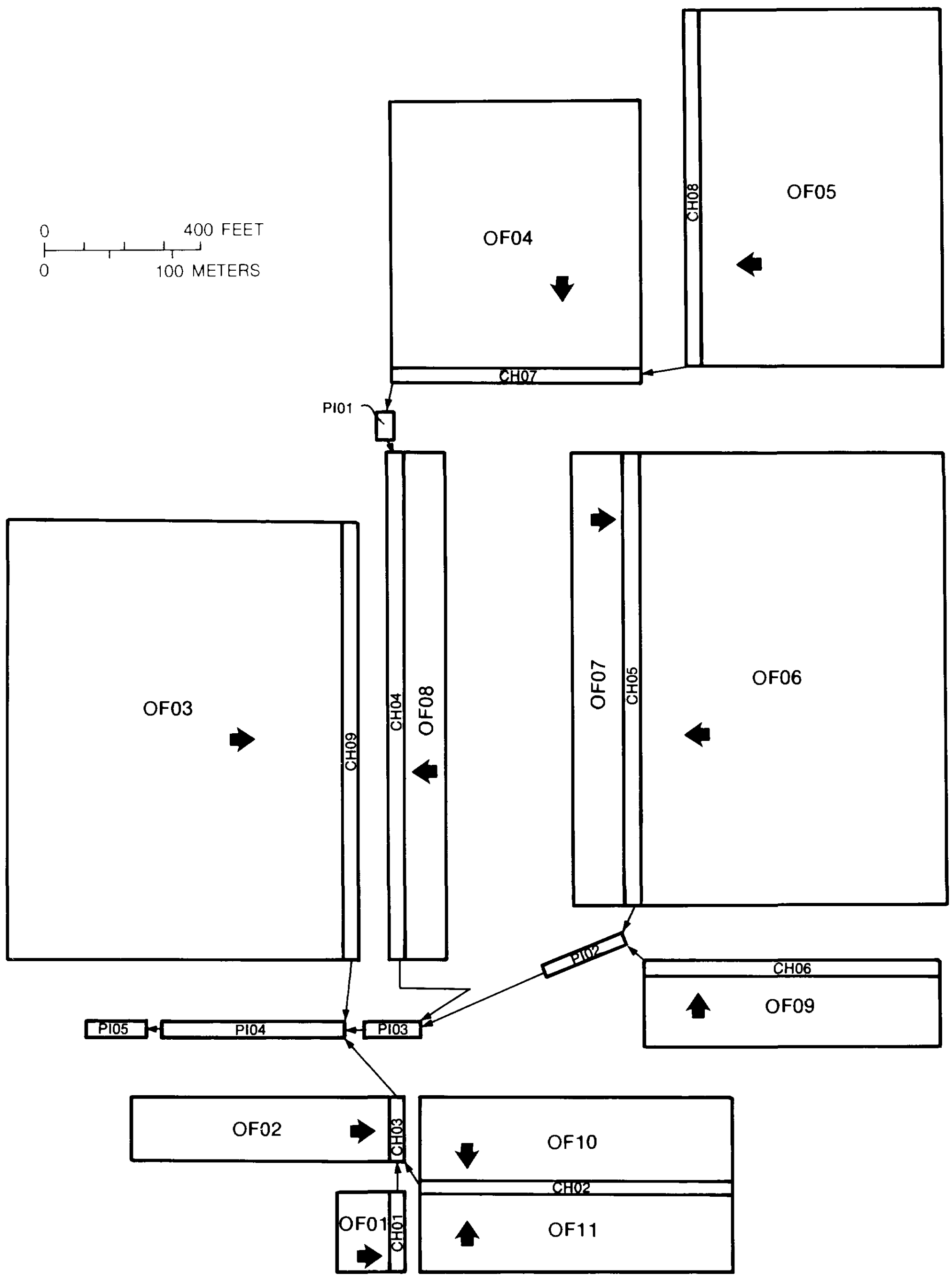


FIGURE 9. Schematization of overland-flow planes and channels (gutters) for the single-dwelling residential catchment.



EXPLANATION

(thick line)	SEGMENT BOUNDARY
(thin arrow)	DIRECTION OF FLOW FOR CHANNEL (GUTTER) AND PIPE SEGMENTS
(bold arrow)	DIRECTION OF FLOW FOR OVERLAND FLOW SEGMENTS
OF05	OVERLAND-FLOW PLANE SEGMENT
CH01	CHANNEL (GUTTER) SEGMENT
PI05	PIPE SEGMENT

FIGURE 10. Segments for the single-dwelling residential catchment.

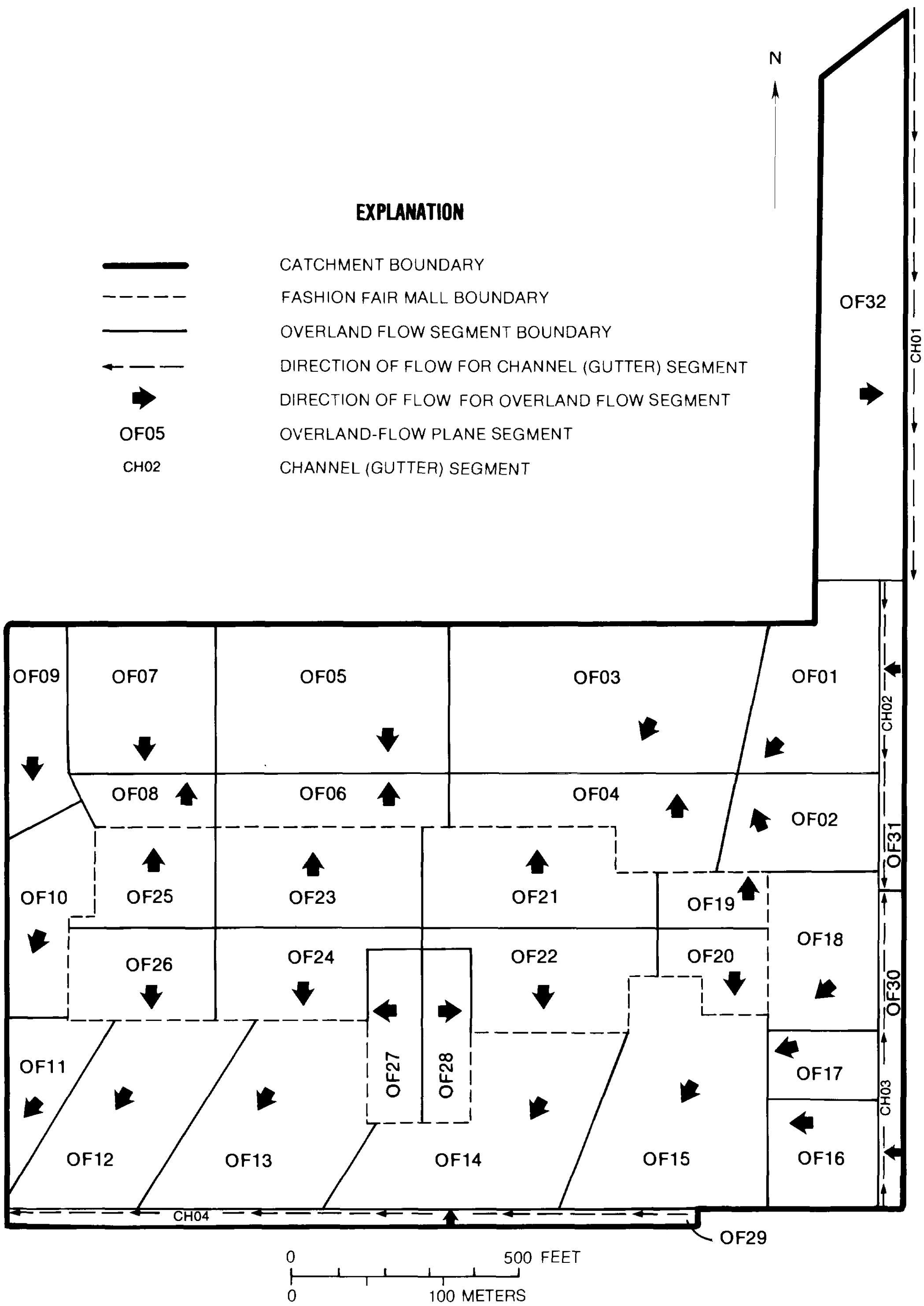
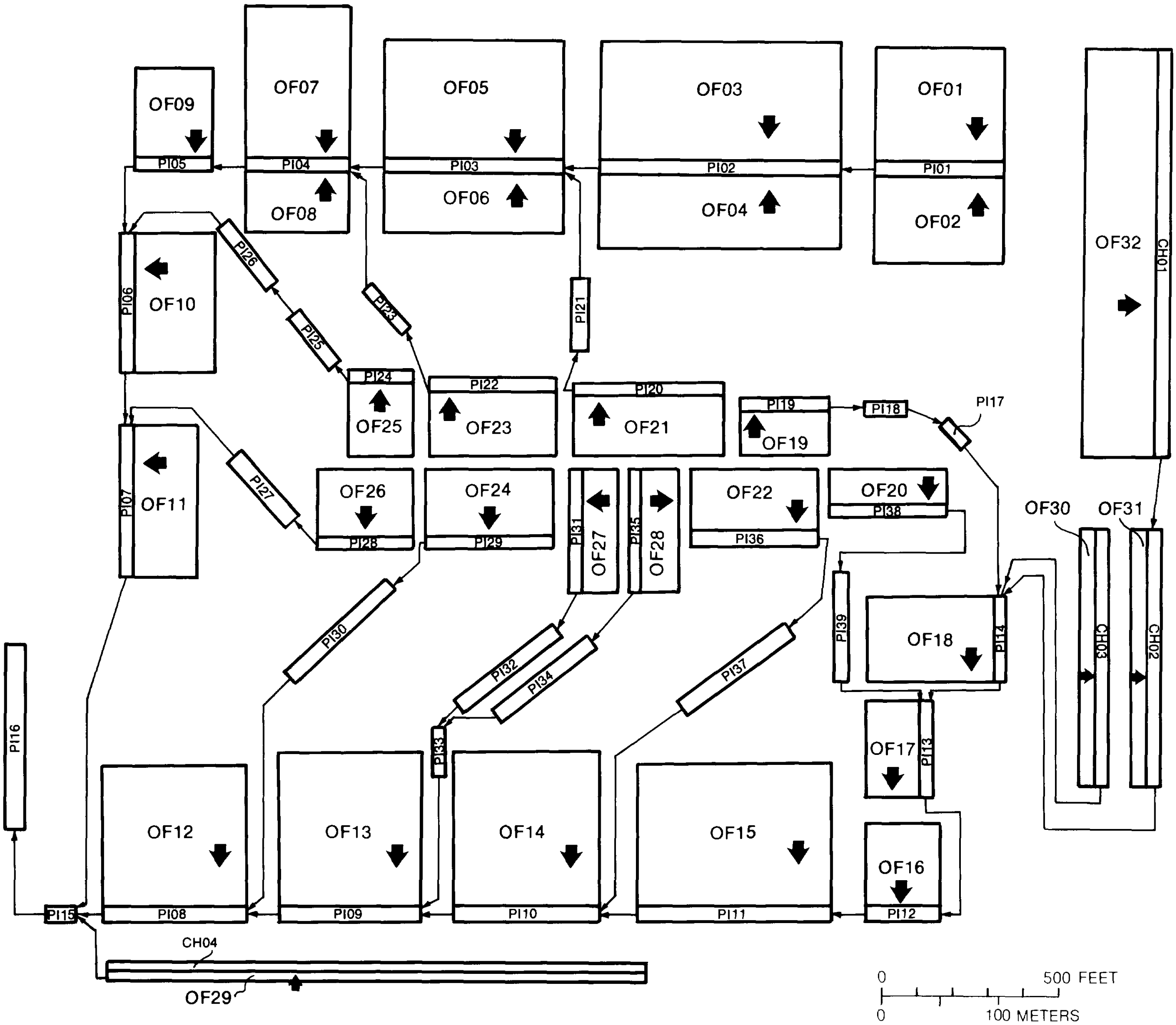


FIGURE 11. Schematization of overland-flow planes for commercial catchment.



EXPLANATION

(thick line)	SEGMENT BOUNDARY
(thin arrow)	DIRECTION OF FLOW FOR CHANNEL (GUTTER) AND PIPE SEGMENTS
(bold arrow)	DIRECTION OF FLOW FOR OVERLAND FLOW SEGMENTS
OF05	OVERLAND-FLOW PLANE SEGMENT
CH01	CHANNEL (GUTTER) SEGMENT
PI10	PIPE SEGMENT

FIGURE 12. Segments for the commercial catchment.

Calibration and Verification

The rainfall-runoff models were calibrated and verified by comparing measured and simulated storm runoff volumes, peak discharges, and hydrograph timing. The measured rainfall-runoff data were divided into two unbiased data sets: one for calibration and one for verification. During calibration, model parameters were adjusted so that model output best agreed with measured data. During verification, all model parameters were held constant.

Runoff volumes were calibrated using the model optimization procedure (Rosenbrock, 1960) to refine the estimates of effective impervious area obtained from aerial photographs and to determine the soil moisture and infiltration components that provided the best agreement between simulated and measured runoff volumes. When using the optimization procedure, only storms where runoff volumes are sensitive to the components being optimized are included in the objective function; otherwise, erroneous estimates of components are possible. The percentage of effective impervious area was optimized using only small storms that had little or no runoff occurring from pervious areas. The soil moisture and infiltration components (table 2) were optimized using only large storms (greater than 0.75 inch), which had a significant part of total runoff occurring from pervious areas.

Peak discharge and hydrograph timing were calibrated by adjusting the estimated slopes and roughnesses of the modeled overland-flow planes. Overland-flow planes consist of many types of land surfaces such as streets, sidewalks, driveways, parking lots, and roofs. The slopes and roughnesses of overland-flow planes are difficult to determine where many of these features are combined into a single model segment. For this reason, slopes and roughnesses are used as calibration parameters as long as the final values are physically realistic. The slopes and roughnesses initially assigned for channels (gutters) and pipes were not adjusted during calibration. The subsurface pipe segments used in the rainfall-runoff models are shown in table 3. The final calibration was made by choosing a slope of 0.035 and roughness of 0.020 for all of the overland-flow planes at the multiple(1), multiple(2), and single catchments. At the commercial catchment, a slope of 0.0075 and a roughness of 0.025 were used for all overland-flow planes in the parking lots of the Fashion Fair Mall.

TABLE 2.--*Components for soil-moisture accounting and infiltration*

[From Alley and Smith, 1982a]

Soil-Moisture Accounting
Component:
EVC--A coefficient for converting measured pan evaporation to potential evapotranspiration
RR--The proportion of daily rainfall that infiltrates into the soil for the period of simulation excluding unit days
BMSN--Available soil water at field capacity, in inches
Infiltration
Component:
KSAT--The effective saturated value of hydraulic conductivity, in inches per hour
RGF--Ratio of suction at the wetting front for soil moisture at wilting point to that at field capacity
PSP--Suction at wetting front for soil moisture at field capacity, in inches

TABLE 3.--*Subsurface pipe segments used in the rainfall-runoff models*

[Abbreviations: ft, feet; ft/ft, feet per foot]

Pipe segment	Length (ft)	Slope (ft/ft)	Roughness (Manning's n)	Diameter (ft)
		Multiple(1), Multiple(2) Catchments		
PI01	55	0.0044	0.013	1.50
PI02	38	.0042	.013	1.50
PI03	48	.0042	.013	1.50
PI04	30	.0020	.013	2.00
PI05	158	.0011	.013	2.07
PI06	646	.0018	.013	2.07
PI07	52	.0010	.013	1.50
PI08	30	.0010	.013	1.50
PI09	196	.0090	.013	1.50
PI10	640	.0018	.013	2.07
		Single Catchment		
PI01	80	0.0063	0.013	1.25
PI02	232	.0031	.013	1.50
PI03	154	.0031	.013	1.50
PI04	478	.0027	.013	2.07
PI05	166	.0128	.013	2.07
		Commerical Catchment		
PI01	343	0.0020	0.010	1.50
PI02	647	.0025	.010	1.70
PI03	494	.0012	.010	2.00
PI04	270	.0010	.010	2.00
PI05	200	.0014	.010	2.25
PI06	379	.0010	.010	2.25
PI07	400	.0020	.010	2.25
PI08	385	.0010	.010	2.50
PI09	389	.0020	.010	2.50
PI10	394	.0030	.010	2.50
PI11	517	.0020	.010	2.00
PI12	206	.0020	.010	2.00
PI13	146	.0010	.010	2.00
PI14	352	.0040	.010	1.50
PI15	72	.0270	.010	3.00
PI16	510	.0013	.011	3.00

Multiple(1)-Dwelling Residential Catchment

Rainfall and runoff data were used to calibrate and verify (13 storms each) the rainfall-runoff model for the multiple(1) catchment. A summary of these data is shown in table 4. The optimum values for effective impervious, noneffective impervious, and pervious areas are 31, 26, and 43 percent, respectively. Because little intense rainfall fell during the first year of the study, the catchment had little runoff from pervious areas. DR3M-II simulations indicated a maximum pervious area runoff of 10 percent, with

TABLE 4.--*Summary of rainfall and runoff data used to calibrate and verify the rainfall-runoff model for the multiple(1)-dwelling residential catchment*

[Time: Time from first rainfall to last measured discharge.

Total runoff: $\frac{\text{Total runoff volume (ft}^3\text{)}}{\text{Total area of catchment (acre)}} \cdot \frac{12 \text{ (in.)}}{43{,}560 \text{ (ft}^2\text{)}}$.

Simulated pervious area runoff: Determined from DR3M-II simulations. Number of dry hours since last storm: The number of hours between the last 0.01 inch of rainfall of the previous storm and the start of the storm drain flow (about 0.1 cubic foot per second) for the following storm. Abbreviations: in., inches; ft^3, cubic feet; ft^3/s, cubic feet per second; ft^2, square feet]

Storm date	Time	Total rainfall (in.)	Total runoff (in.)	Measured peak discharge (ft^3/s)	Simulated pervious area runoff (in.)	Runoff-rainfall ratio (percent)	Percent of total runoff originating on pervious areas	Maximum 20-minute rainfall (in.)	Number of dry hours since last storm
1981									
Dec. 20	0332-0958	0.09	0.01	0.41	0.000	11	0	0.03	241
Dec. 29	1354-2042	.24	.05	.94	.000	21	0	.07	198
Dec. 30	0146-0408	.14	.03	1.0	.000	21	0	.06	5
1982									
Jan. 1	0114-0354	0.08	0.01	0.72	0.000	13	0	0.05	46
Jan. 1-2	2330-0202	.09	.02	.65	.000	22	0	.07	21
Jan. 4	0656-2008	.83	.30	2.1	.001	36	0	.04	50
Jan. 4-5	2110-0304	.33	.14	3.1	.001	42	1	.06	2
Jan. 19-20	2202-0052	.14	.05	1.7	.000	36	0	.05	351
Jan. 20	0752-1306	.18	.06	1.4	.000	33	0	.03	9
Feb. 14	1740-2012	.11	.03	1.6	.000	27	0	.05	461
Feb. 15-16	2000-0102	.23	.11	2.0	.001	48	1	.05	19
Feb. 16	0338-0710	.10	.05	1.2	.000	50	0	.04	1
Mar. 9	1846-2320	.16	.03	.60	.000	19	0	.04	199
Mar. 10	0100-0700	.31	.11	5.1	.004	35	4	.11	2
Mar. 11	0626-0900	.05	.01	.46	.000	20	0	.03	3
Mar. 14	0146-1550	.92	.40	6.40	.026	43	7	.10	55
Mar. 16	0456-1316	.44	.16	3.8	.007	36	4	.07	37
Mar. 16-17	1948-0248	.30	.12	2.3	.002	40	2	.06	7
Mar. 18	0350-0910	.20	.06	1.2	.001	30	2	.04	6
Mar. 25-26	2100-0348	.26	.07	1.1	.001	27	1	.05	167
Mar. 28	1246-1510	.06	.02	1.6	.001	33	5	.06	1
Mar. 29	1104-1700	.27	.09	2.8	.002	33	2	.06	20
Mar. 31-Apr. 1	1630-1030	1.07	.56	5.2	.033	52	6	.12	44
Apr. 1	1602-1844	.15	.06	3.0	.006	40	10	.10	6
Apr. 10	0448-0920	.17	.04	.87	.000	24	0	.04	202
Apr. 10	1834-2332	.25	.09	1.7	.001	36	1	.04	4

most storms having 1 percent or less. The average pervious area runoff was 2 percent. For this reason, optimized infiltration values could not be determined; however, the rainfall and associated pervious area runoff at the multiple(2) catchment was much higher. Because the soils for both applications were similar, the optimized infiltration values determined for the multiple(2) catchment also could be used for the multiple(1) catchment. Final estimated and optimized values for soil moisture and infiltration components at each catchment in the study are shown in table 5.

A comparison of measured and simulated discharge for selected storms used in calibration and verification are shown in figures 13 and 14. Measured and simulated runoff volumes and peak discharges for all storms used in calibration and verification are shown in table 6.

TABLE 5.--*Final optimized values for soil-moisture and infiltration components*

[Model component: Definitions of model components are given in table 2. The commercial catchment was modeled as 100-percent impervious, therefore no soil-moisture or infiltration components were needed]

Model component	Multiple(1)-dwelling catchment	Multiple(2)-dwelling catchment	Single-dwelling catchment
EVC	0.70	0.70	0.70
RR	.89	.89	.89
BMSN	2.70	2.70	2.70
KSAT	.50	.50	.32
RGF	10.00	10.00	10.00
PSP	.50	.50	.56

TABLE 6.--*Measured and simulated runoff volumes and peak discharges for all storms used in calibration and verification for the multiple(1)-dwelling residential catchment*

[Runoff volume:

$$\frac{\text{Total runoff volume (ft}^3\text{)}}{\text{Total area of catchment (acre)}} \cdot \frac{12 \text{ (in.)}}{43{,}560 \text{ (ft}^2\text{)}}.$$

Peak discharge, in cubic feet per second. Abbreviations: in., inches; ft^3, cubic feet; ft^2, square feet]

Storm date	Runoff volume		Peak discharge	
	Measured	Simulated	Measured	Simulated
CALIBRATION				
1981				
Dec. 29	0.050	0.065	0.94	1.6
1982				
Jan. 1	0.015	0.026	0.65	1.2
Jan. 4	.30	.25	2.1	1.6
Jan. 19-20	.046	.036	1.7	1.4
Feb. 14	.029	.026	1.6	1.4
Feb. 16	.053	.024	1.3	.87
Mar. 10	.11	.093	5.1	3.8
Mar. 16	.16	.13	3.8	2.5
Mar. 18	.062	.056	1.2	1.3
Mar. 25-26	.065	.074	1.1	1.3
Mar. 28	.020	.019	1.6	1.3
Mar. 31-Apr. 1	.56	.36	6.3	4.5
Apr. 10 (am)	.037	.046	.87	.98
VERIFICATION				
1981				
Dec. 20	0.013	0.021	0.41	0.49
Dec. 30	.030	.033	1.0	1.6
1982				
Jan. 1-2	0.013	0.017	0.72	0.97
Jan. 4-5	.14	.10	3.1	1.9
Jan. 20	.056	.048	1.4	1.1
Feb. 15-16	.11	.065	2.0	1.2
Mar. 9	.029	.042	.60	.87
Mar. 11	.013	.010	.46	.41
Mar. 14	.40	.30	6.4	4.8
Mar. 16-17	.12	.093	2.3	1.6
Mar. 29	.094	.078	2.8	2.3
Apr. 1	.055	.048	3.0	3.0
Apr. 10 (pm)	.085	.077	1.8	1.5

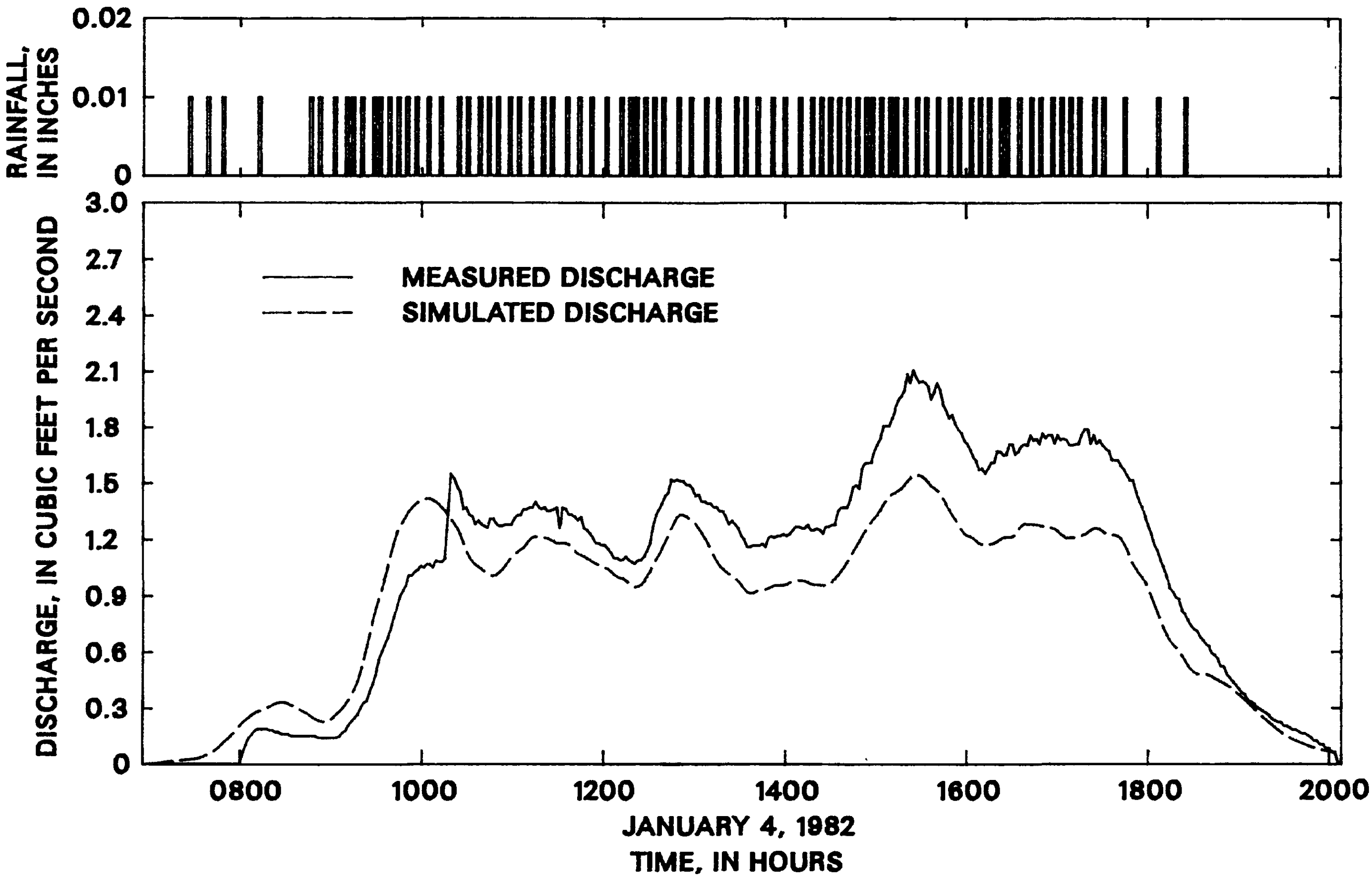


FIGURE 13. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model at the multiple (1)-dwelling residential catchment.

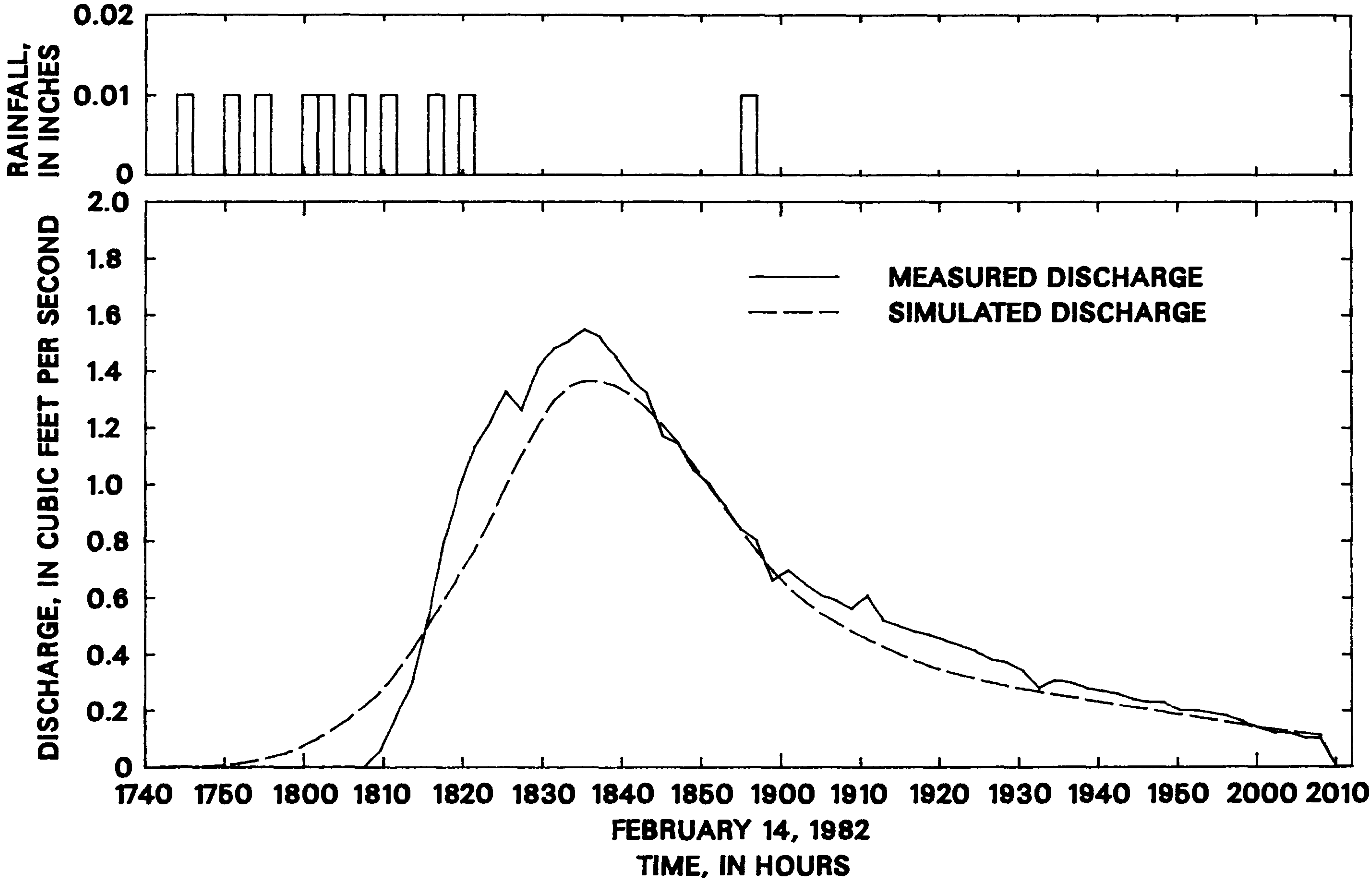


FIGURE 13. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model at the multiple (1)-dwelling residential catchment--Continued.

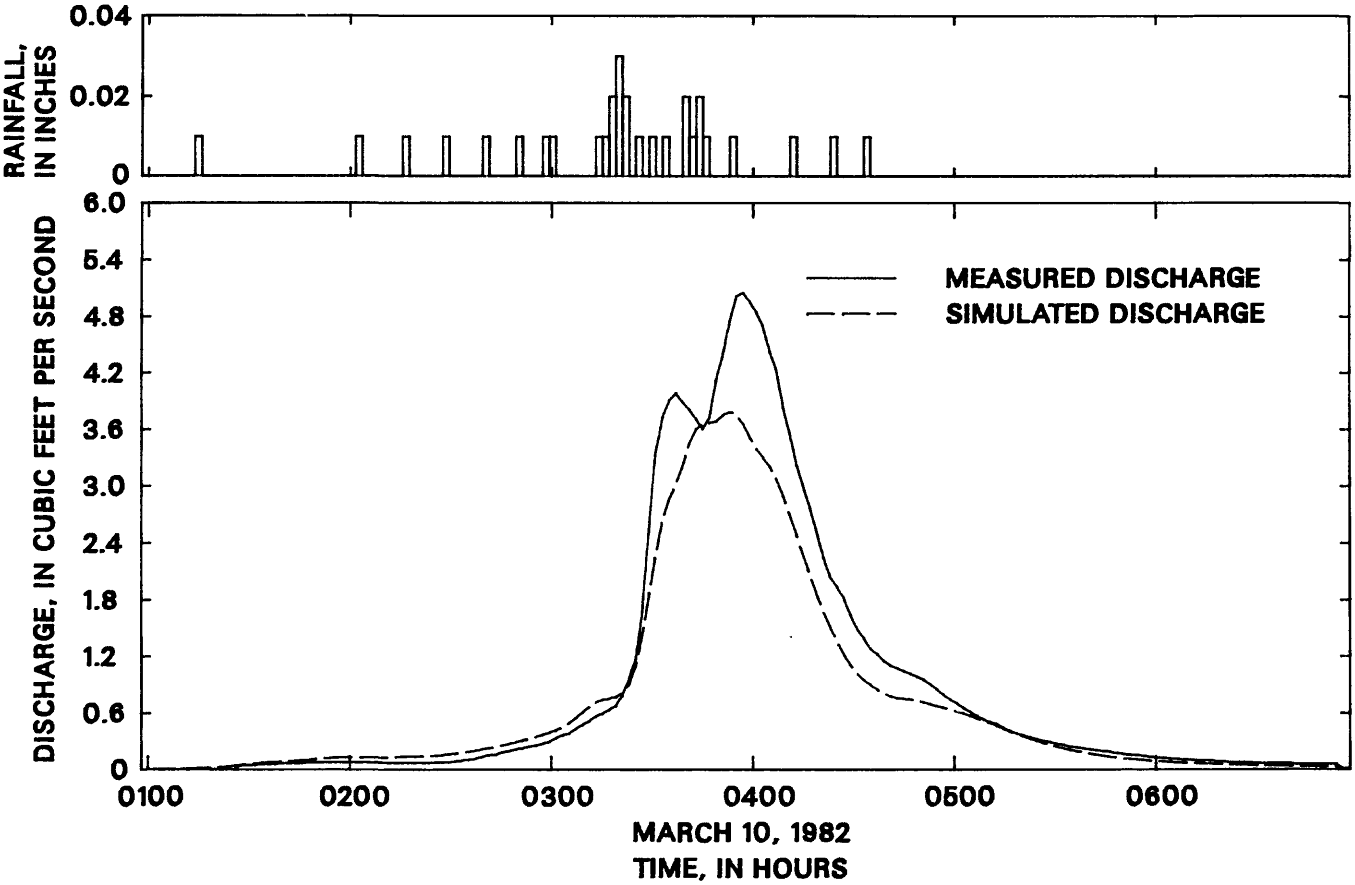


FIGURE 13. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model at the multiple(1)-dwelling residential catchment--Continued.

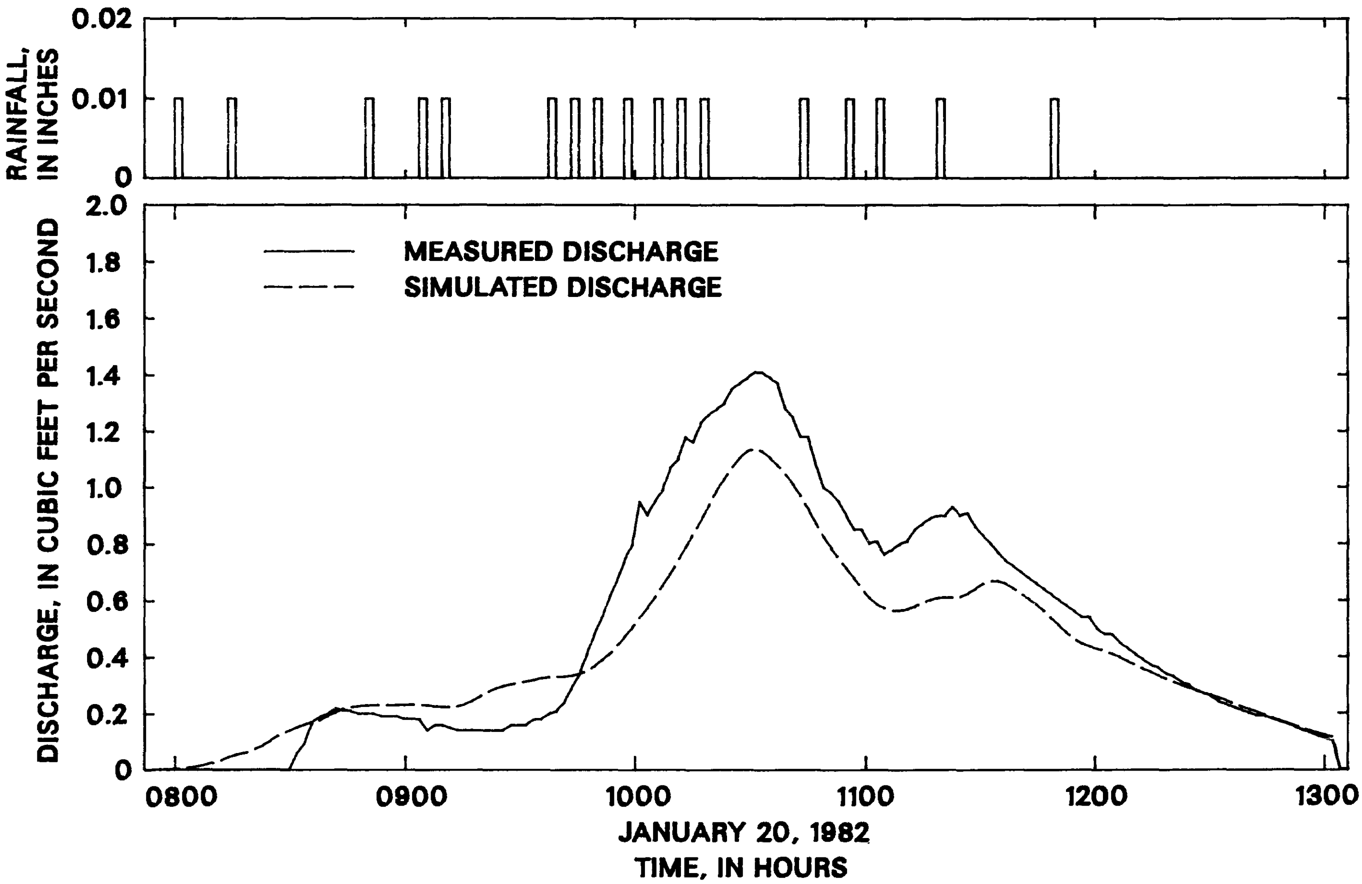


FIGURE 14. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the multiple(1)-dwelling residential catchment.

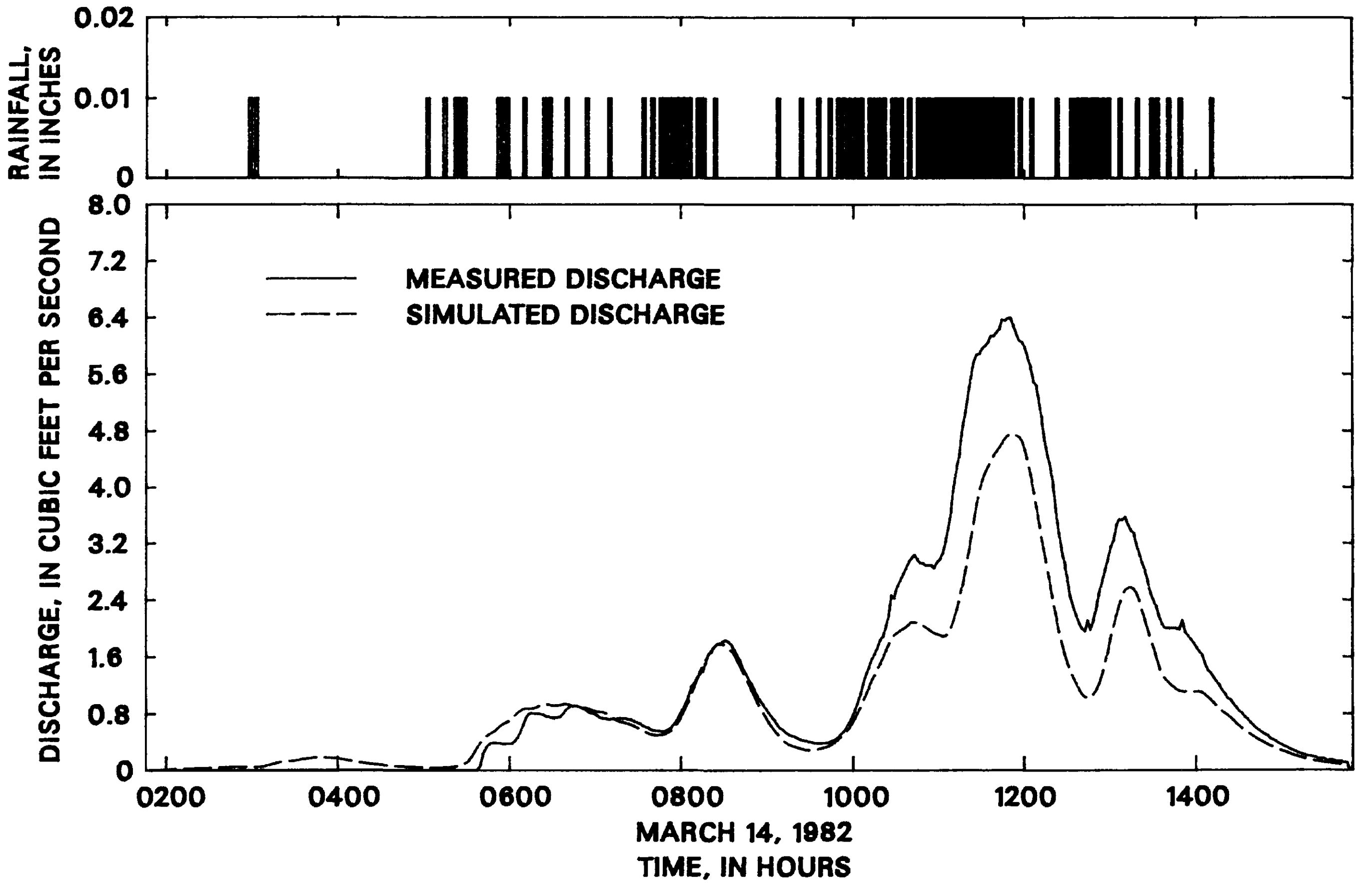


FIGURE 14. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the multiple(1)-dwelling residential catchment--Continued.

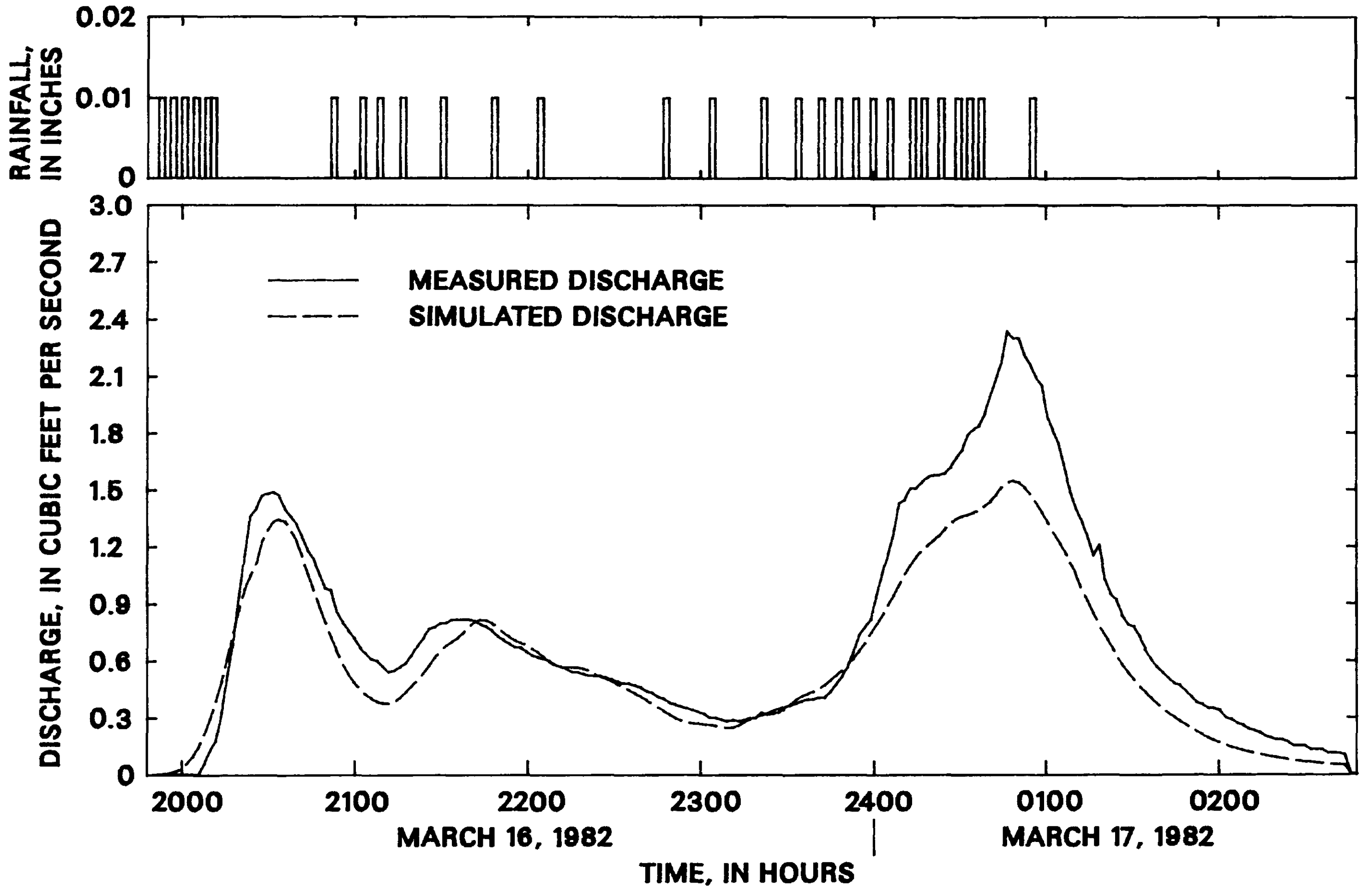


FIGURE 14. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the multiple (1)-dwelling residential catchment--Continued.

Multiple(2)-Dwelling Residential Catchment

Rainfall and runoff data were used to calibrate and verify (12 storms each) the rainfall-runoff model for the multiple(2) catchment. The optimum values for the effective impervious, noneffective impervious, and pervious areas are 36, 21, and 43 percent, respectively. The second year storms (1982-83) were characterized by shorter periods between storms (antecedent dry hours) and higher total rainfalls. Dry hours between storms and total inches of rainfall averaged 83 and 0.28 for 1981-82, and 46 and 0.49 for 1982-83. The pervious area runoff for 1982-83 storms averaged 7 percent, with a maximum of 19 percent. The rainfall and runoff data used in calibration and verification are summarized in table 7.

TABLE 7.--*Summary of rainfall and runoff data used to calibrate and verify the rainfall-runoff model for the multiple(2)-dwelling residential catchment*

[Time: Time from first rainfall to last measured discharge.

$$\text{Total runoff: } \frac{\text{Total runoff volume (ft}^3)}{\text{Total area of catchment (acre)}} \cdot \frac{12 \text{ (in.)}}{43{,}560 \text{ (ft}^2)}.$$

Simulated pervious area runoff: Determined from DR3M-II simulations. Number of dry hours since last storm: The number of hours between the last 0.01 inch of rainfall of the previous storm and the start of the storm drain flow (about 0.1 cubic foot per second) for the following storm. Abbreviations: in., inches; ft³, cubic feet; ft³/s, cubic feet per second; ft², square feet]

Storm date	Time	Total rainfall (in.)	Total runoff (in.)	Measured peak discharge (ft³/s)	Simulated pervious area runoff (in.)	Runoff-rainfall ratio (percent)	Percent of total runoff originating on pervious areas	Maximum 20-minute rainfall (in.)	Number of dry hours since last storm
1982									
Sep. 24	0144-0658	0.24	0.07	3.1	0.001	29	1	0.08	[1]
Sep. 25-26	1200-0232	1.00	.34	4.6	.002	34	1	.07	1
Oct. 30	0032-0956	.65	.23	3.2	.001	35	0	.06	89
Nov. 9	1028-1744	.45	.16	4.3	.001	36	1	.04	16
Nov. 18	0508-1212	.37	.12	4.7	.001	32	1	.07	192
Nov. 28	1704-2328	.51	.23	7.4	.014	45	6	.12	21
Nov. 29	1410-2238	.76	.34	11	.027	45	8	.16	10
Nov. 30	0356-0910	.45	.22	9.1	.041	49	19	.18	3
Dec. 21-22	1750-0006	.21	.06	1.7	.001	29	2	.04	4
Dec. 22	0124-1404	.74	.30	5.8	.013	41	4	.08	3
1983									
Jan. 18-19	1814-0204	0.95	0.41	7.2	0.061	43	15	0.11	56
Jan. 22	0320-1628	.89	.40	7.7	.057	45	14	.13	4
Jan. 23-24	2230-0840	.34	.15	3.8	.005	44	3	.10	27
Jan. 28-29	2138-0552	.47	.22	6.6	.012	47	5	.10	35
Feb. 7-8	1526-0320	.48	.27	8.5	.030	56	11	.12	17
Feb. 12-13	1016-0006	.40	.09	2.5	.002	23	2	.05	94
Feb. 13	0156-0438	.11	.04	2.1	.003	36	8	.08	4
Feb. 18	0718-1018	.24	.10	6.4	.013	42	13	.17	124
Feb. 25	1328-2158	.35	.12	3.0	.003	34	2	.05	173
Feb. 28	1624-2224	.23	.10	4.4	.013	43	13	.09	9
Mar. 16	1642-2218	.40	.18	6.3	.016	45	9	.10	74
Mar. 17-18	1552-0532	.57	.29	7.7	.025	51	9	.10	21
Mar. 20-21	1918-0128	.33	.13	4.6	.005	39	4	.05	65
Mar. 23-24	1918-0052	.57	.32	9.2	.058	56	18	.11	23

[1]Dry hours not computed for first storm of the year.

A comparison of measured and simulated discharge for selected storms used in calibration and verification are shown in figures 15 and 16. Measured and simulated runoff volumes and peak discharges for all storms used in calibration and verification are shown in table 8.

One storm, that of November 30, 1982, used in calibration had a simulated peak discharge that was limited to the calculated capacity of the storm-drain system. Calculated capacity is the maximum unpressurized flow in a pipe as calculated from known pipe diameters and slopes, and estimates of pipe roughness, using the Manning's formula. When full flowing pipes develop a differential hydraulic head, pressurized flows occur that exceed the calculated capacity of the pipe. The additional discharge caused by pressurized flows cannot be simulated by the DR3M-II. A mass balance of water volumes is maintained by storing the water that ponds upstream of the pipe, then releasing it when the flows decrease to less than the calculated capacity of the pipe. These overflow conditions, called surcharging, are simulated as horizontal lines in the hydrographs. Simulated peak discharges were not included in the error analysis if surcharging occurred. Simulated peak discharges for all verification storms were less than the calculated capacity of the storm-drain pipes.

TABLE 8.--*Measured and simulated runoff volumes and peak discharges for all storms used in calibration and verification for the multiple(2)-dwelling residential catchment*

[Runoff volume: $\frac{\text{Total runoff volume (ft}^3\text{)}}{\text{Total area of catchment (acre)}} \bullet \frac{\text{12 (in.)}}{\text{43,560 (ft}^2\text{)}}$.

Peak discharge, in cubic feet per second. Abbreviations: in., inch; ft^3, cubic feet; ft^2, square feet]

Storm date	Runoff volume		Peak discharge		Storm date	Runoff volume		Peak discharge	
	Measured	Simulated	Measured	Simulated		Measured	Simulated	Measured	Simulated
	CALIBRATION					VERIFICATION			
1982					1982				
Sep. 24	0.065	0.075	3.1	3.7	Sep. 25-26	0.34	0.35	4.6	3.5
Oct. 30	.23	.23	3.2	2.9	Nov. 9	.16	.16	4.3	3.3
Nov. 28	.23	.19	7.4	6.6	Nov. 18	.12	.13	4.7	3.7
Nov. 30	.22	.20	9.1	[1]11	Nov. 29	.34	.29	11	9.3
Dec. 21-22	.058	.067	1.7	1.5	Dec. 22	.30	.26	5.8	4.9
1983					1983				
Jan. 18-19	0.41	0.39	7.2	9.2	Jan. 22	0.40	0.36	7.7	8.0
Jan. 23-24	.15	.12	3.8	3.6	Jan. 28-29	.22	.17	6.6	5.6
Feb. 7-8	.27	.20	8.5	7.6	Feb. 13	.035	.032	2.1	1.9
Feb. 12-13	.094	.14	2.5	2.6	Feb. 25	.12	.12	3.0	2.5
Feb. 18	.10	.091	6.4	7.0	Feb. 28	.096	.082	4.4	4.1
Mar. 17-18	.29	.22	7.7	6.8	Mar. 16	.18	.15	6.3	6.5
Mar. 20-21	.13	.12	4.6	4.0	Mar. 23-24	.32	.26	9.2	8.2

[1]Surcharging, peak discharge not used in error analysis.

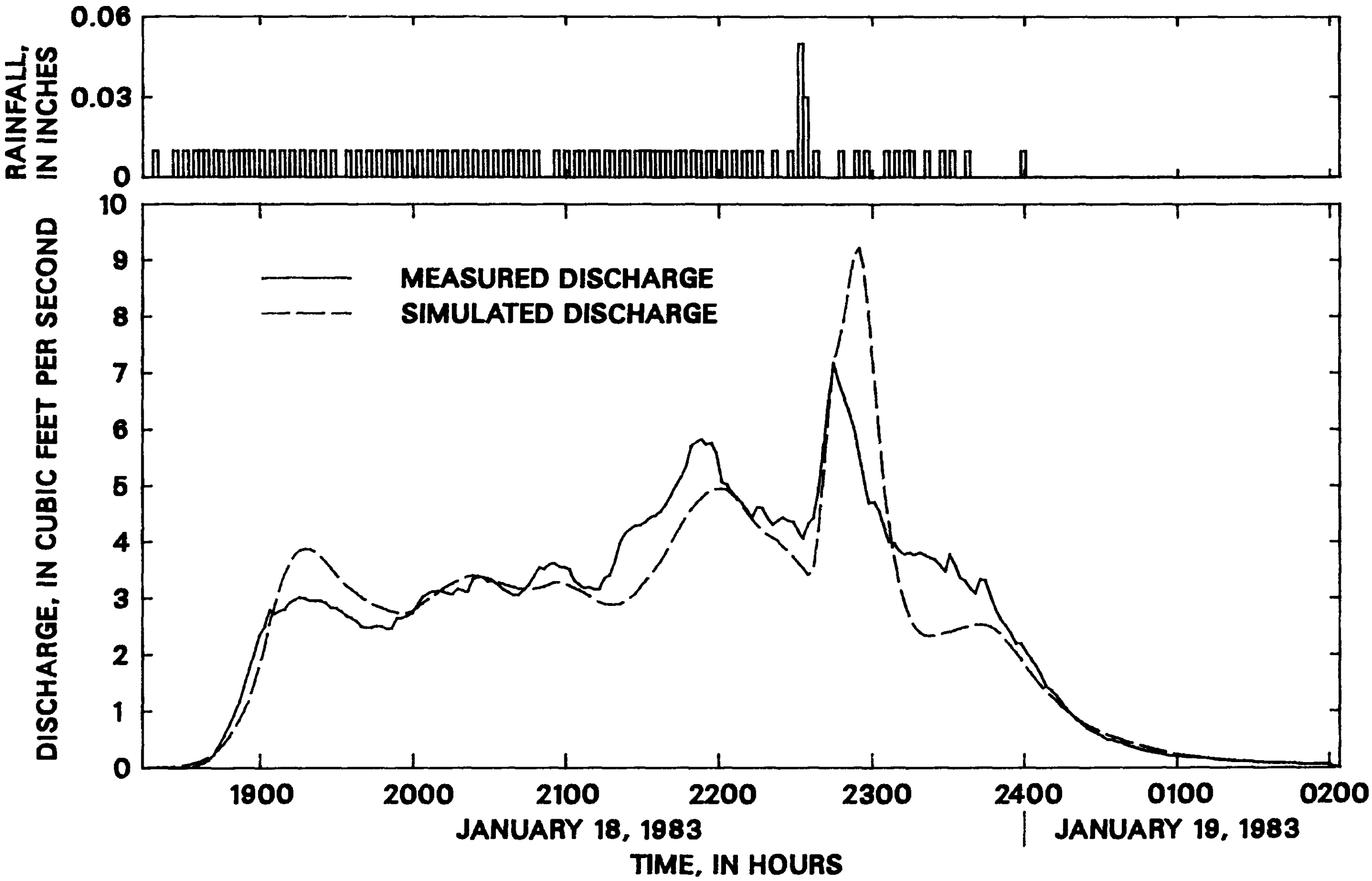


FIGURE 15. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the multiple (2)-dwelling catchment.

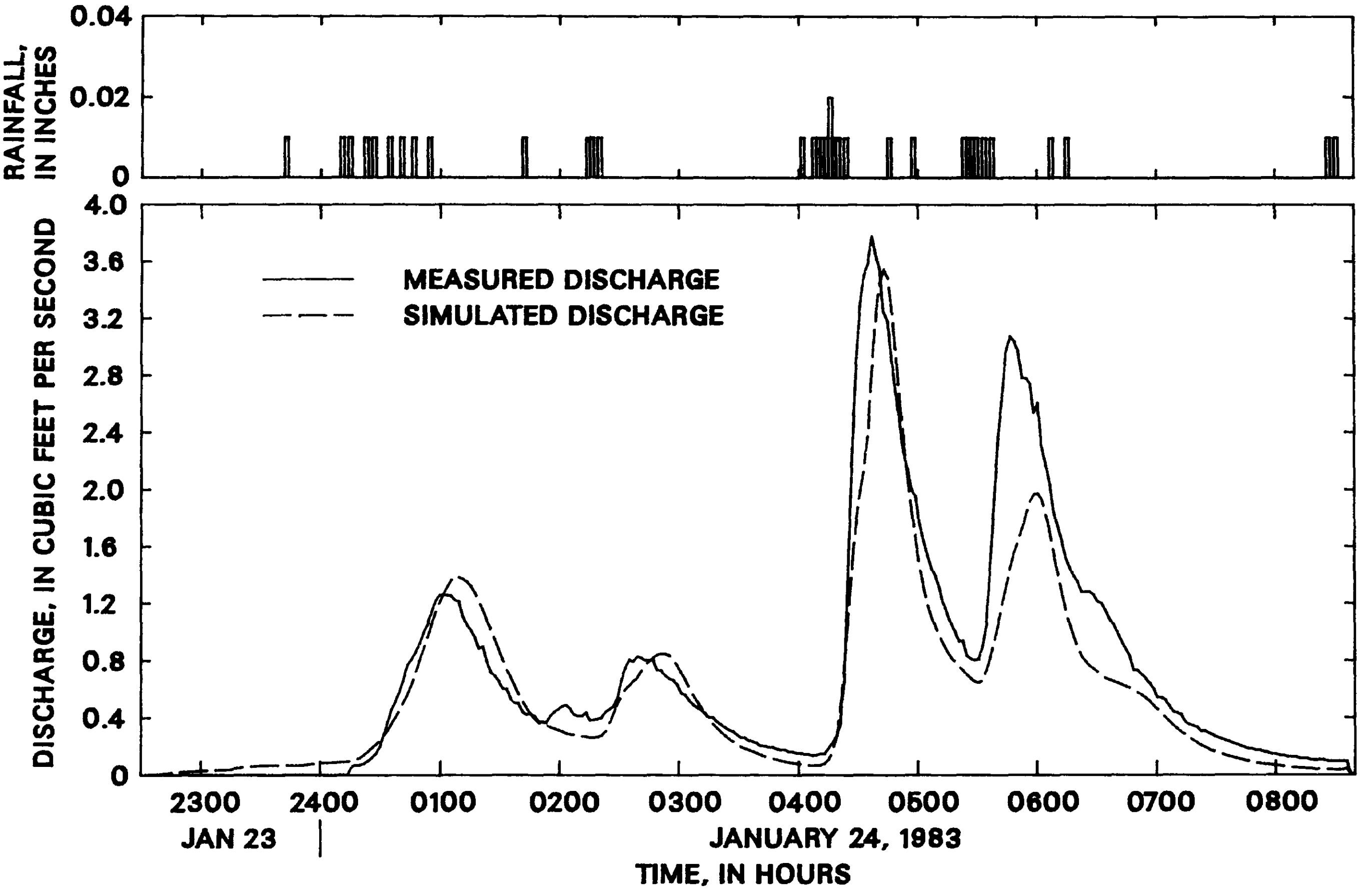


FIGURE 15. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the multiple (2)-dwelling catchment--Continued.

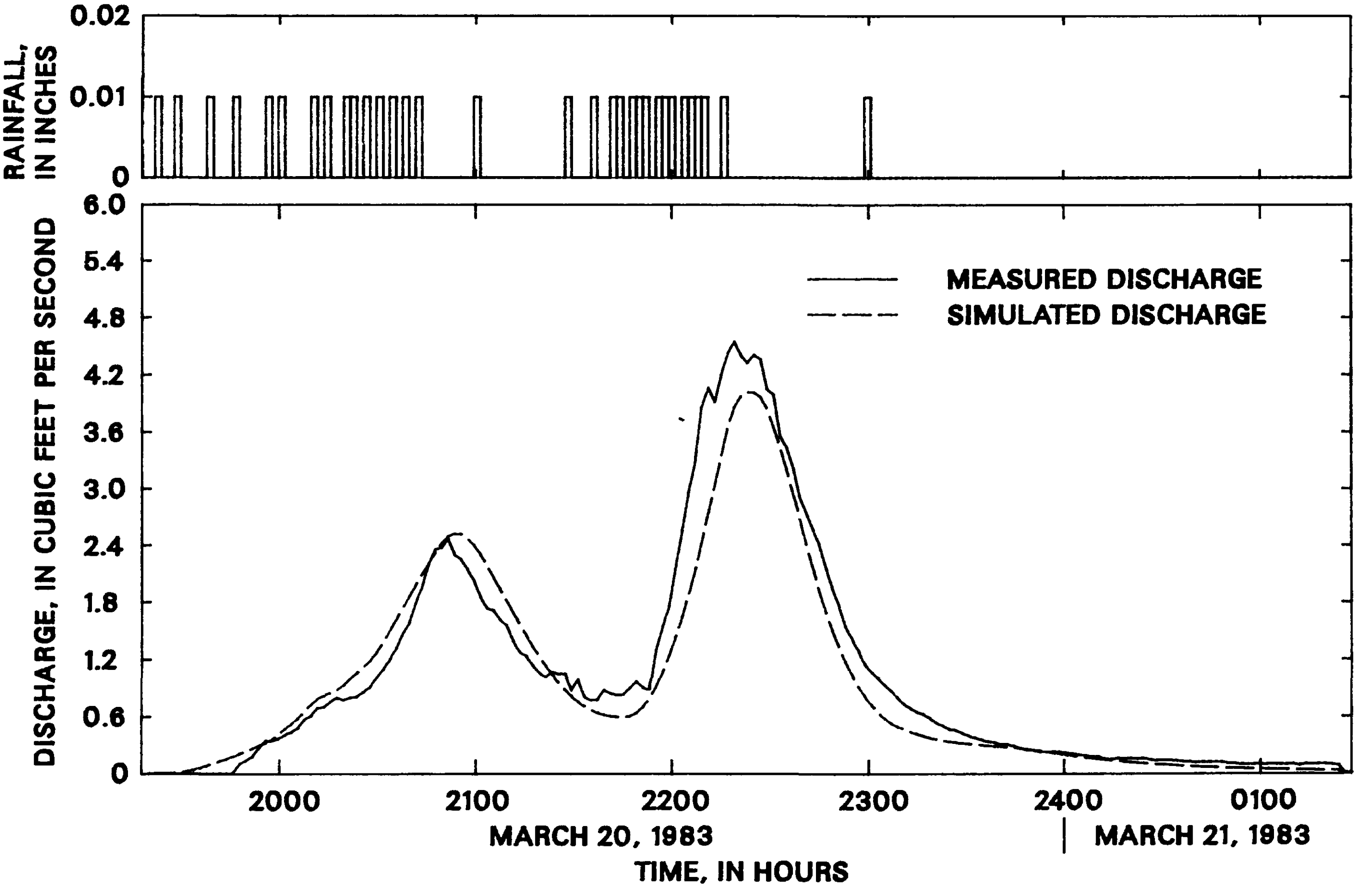


FIGURE 15. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the multiple (2)-dwelling catchment--Continued.

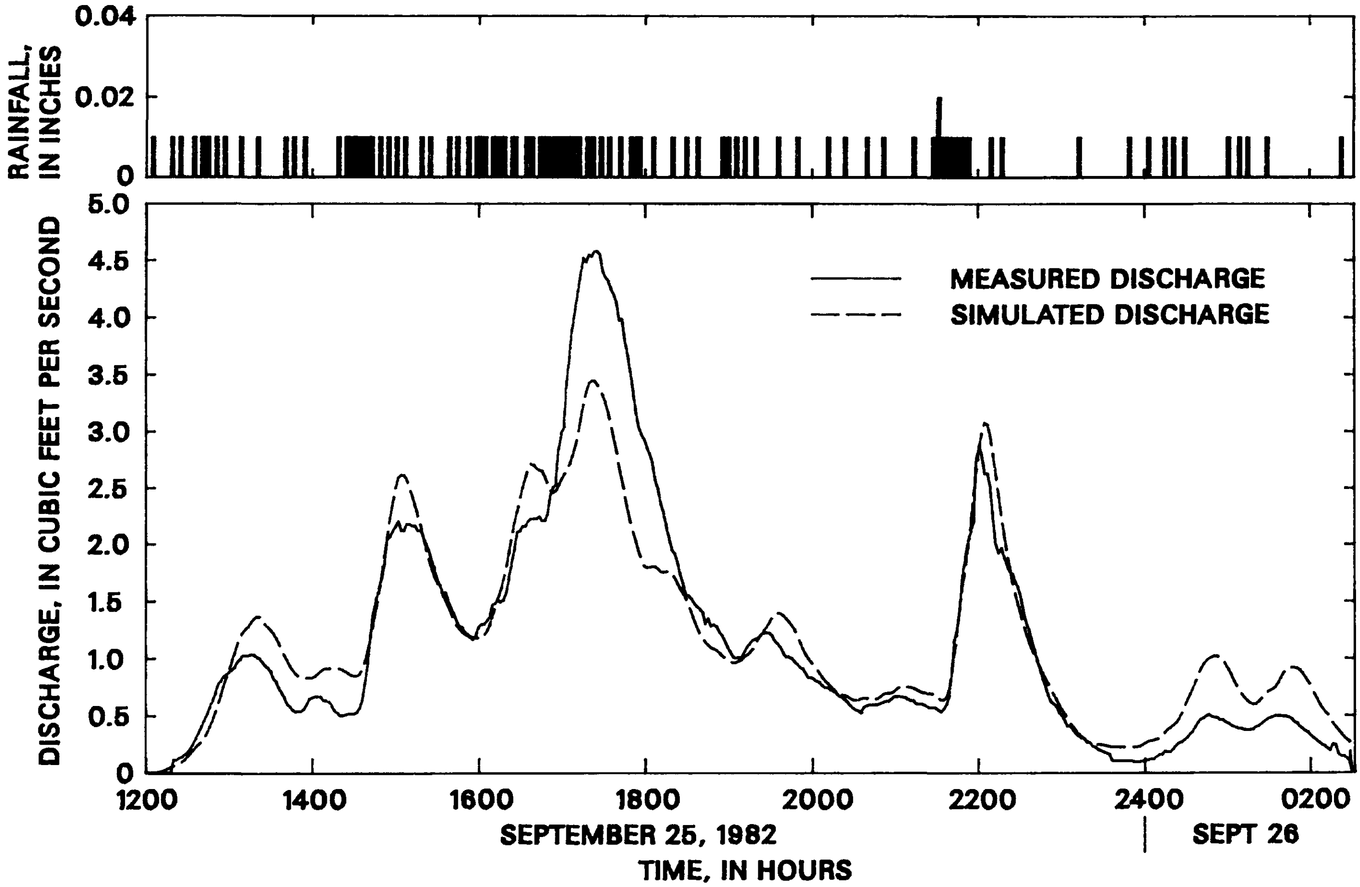


FIGURE 16. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the multiple (2)-dwelling residential catchment.

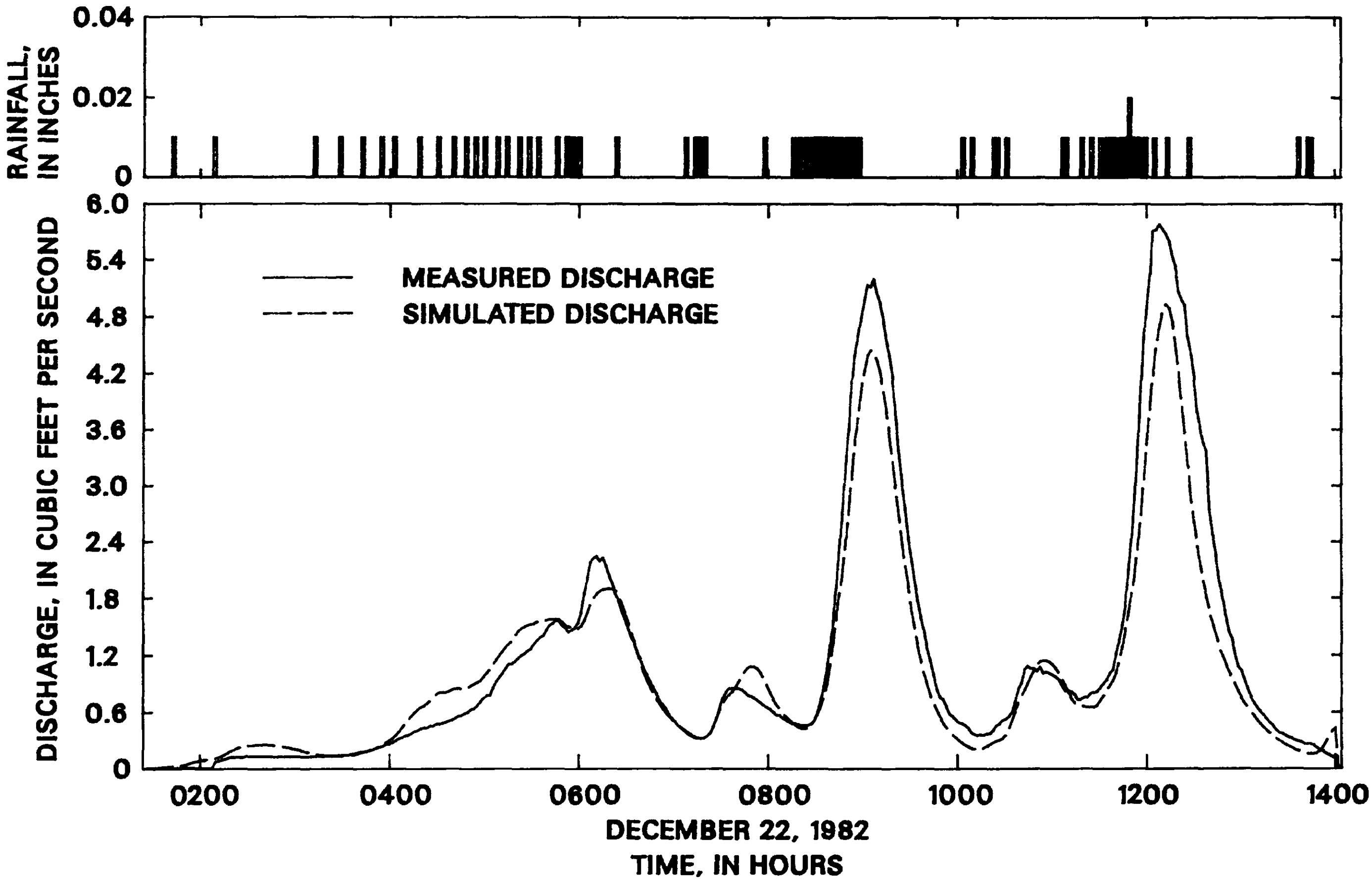


FIGURE 16. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the multiple (2)-dwelling residential catchment--Continued.

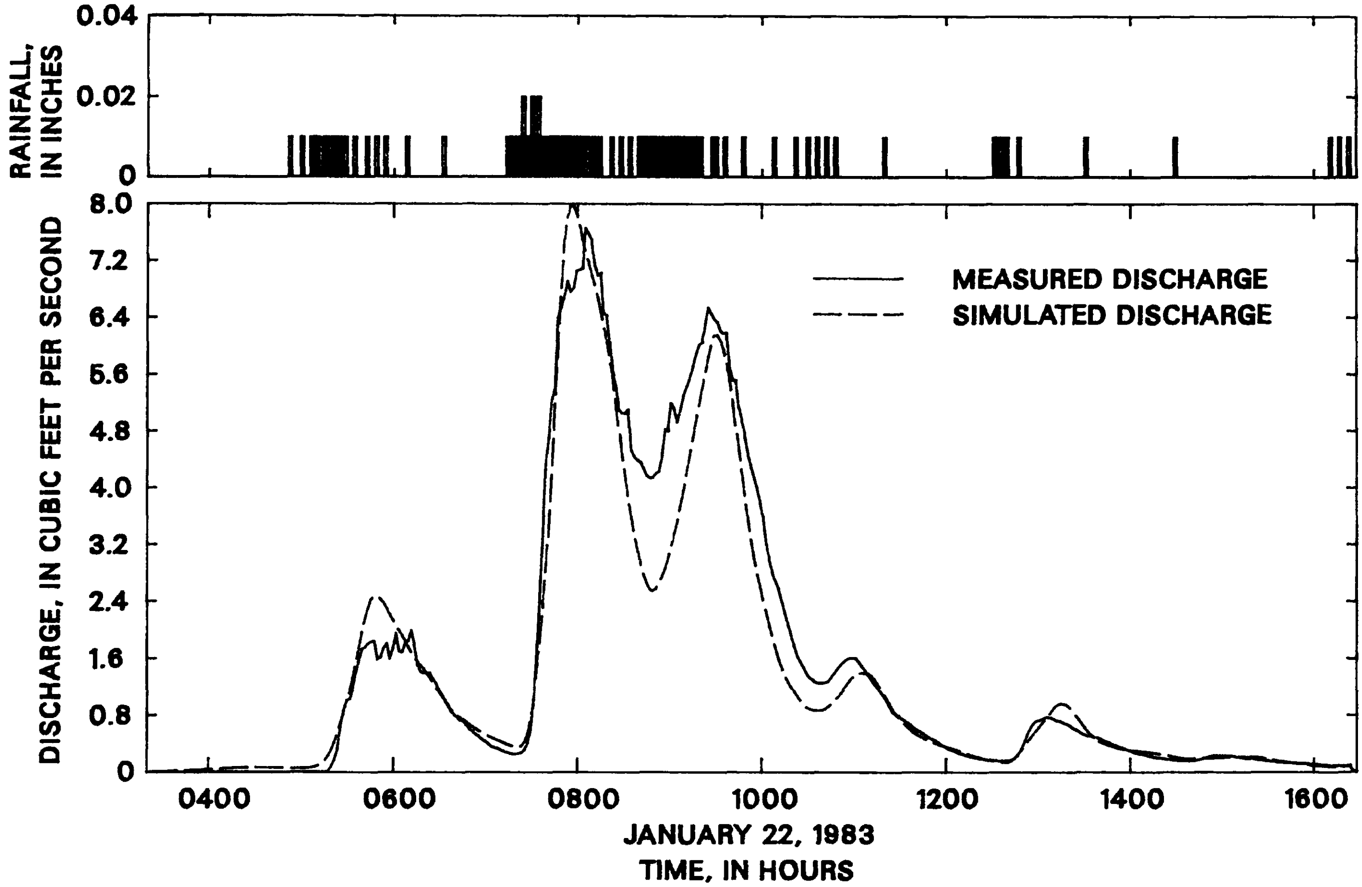


FIGURE 16. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the multiple (2)-dwelling residential catchment--Continued.

Single-Dwelling Residential Catchment

Rainfall and runoff data were used to calibrate and verify (12 storms each) the rainfall-runoff model for the single catchment. The optimum values for the effective impervious, noneffective impervious, and pervious areas are 19, 25, and 56 percent, respectively. The single-dwelling catchment had the highest percentage of pervious area runoff because the soils were the least permeable. The average pervious area runoff was 18 percent; the maximum was 59 percent. The rainfall and runoff data used in calibration and verification are summarized in table 9.

TABLE 9.--*Summary of rainfall and runoff data used to calibrate and verify the rainfall-runoff model for the single-dwelling residential catchment*

[Time: Time from first rainfall to last measured discharge.

Total runoff: $\frac{\text{Total runoff volume (ft}^3)}{\text{Total area of catchment (acre)}} \cdot \frac{12 \text{ (in.)}}{43{,}560 \text{ (ft}^2)}$.

Simulated pervious area runoff: Determined from DR3M-II simulations. Number of dry hours since last storm: The number of hours between the last 0.01 inch of rainfall of the previous storm and the start of the storm drain flow (about 0.1 cubic foot per second) for the following storm. Abbreviations: in., inches; ft^3, cubic feet; ft^3/s, cubic feet per second; ft^2, square feet]

Storm date	Time	Total rainfall (in.)	Total runoff (in.)	Measured peak discharge (ft^3/s)	Simulated pervious area runoff (in.)	Runoff-rainfall ratio (percent)	Percent of total runoff originating on pervious areas	Maximum 20-minute rainfall (in.)	Number of dry hours since last storm
1983									
Jan. 18-19	1734-0106	0.85	0.17	5.5	0.034	20	20	0.11	56
Jan. 21-22	2100-0110	.10	.01	1.1	.000	10	0	.03	71
Jan. 22	0450-1354	.73	.17	6.9	.034	23	20	.11	5
Jan. 24	0006-0710	.27	.06	2.5	.002	22	3	.06	29
Jan. 24	0830-1136	.47	.17	19	.101	36	59	.36	3
Jan. 26-27	1938-1138	1.39	.40	8.8	.056	29	14	.12	58
Feb. 6	0530-2400	.85	.14	3.6	.005	16	4	.07	195
Feb. 7-8	2142-0104	.44	.11	8.5	.038	25	35	.14	16
Feb. 12	1114-2124	.33	.06	2.4	.001	18	2	.04	108
Feb. 25	1340-1802	.22	.02	1.1	.000	9	0	.05	168
Feb. 28-Mar. 1	1610-0438	1.11	.30	16	.147	27	49	.16	31
Mar. 1	1806-2018	.11	.02	2.7	.002	18	10	.08	15
Mar. 7	0038-0420	.14	.02	0.74	.000	14	0	.03	100
Mar. 10	1932-2348	.19	.03	2.7	.004	16	13	.11	88
Mar. 13	0554-1700	.70	.19	12	.064	27	34	.27	55
Mar. 16	1640-2040	.40	.08	5.1	.017	20	21	.10	74
Mar. 17-18	1836-0028	.46	.09	5.0	.018	20	20	.09	2
Mar. 20	1908-2352	.29	.04	2.5	.002	14	5	.05	64
Mar. 22	0844-1252	.14	.02	1.0	.000	14	0	.03	34
Mar. 22	1634-1818	.08	.01	1.2	.002	13	20	.08	5
Mar. 23	1924-2346	.57	.13	8.2	.055	23	42	.10	27
Mar. 24	0750-1010	.30	.07	8.4	.035	23	50	.25	10
Mar. 24	1358-1808	.16	.04	2.4	.001	25	3	.06	6

Measured and simulated discharge for selected storms used in calibration and verification are shown in figures 17 and 18. Surcharging was observed for one of the calibration storms (March 13, 1983), and two of the verification storms (January 24, 1983, and February 28 to March 1, 1983). Measured and simulated runoff volumes and peak discharges for all storms used in calibration and verification are shown in table 10.

TABLE 10.--*Measured and simulated runoff volumes and peak discharges for all storms used in calibration and verification for the single-dwelling residential catchment*

[Runoff volume: $\frac{\text{Total runoff volume (ft}^3)}{\text{Total area of catchment (acre)}} \cdot \frac{12 \text{ (in.)}}{43{,}560 \text{ (ft}^2)}$.

Peak discharge, in cubic feet per second. Abbreviations: in., inches; ft^3, cubic feet; ft^2, square feet]

Storm date	Runoff volume		Peak discharge		Storm date	Runoff volume		Peak discharge	
	Measured	Simulated	Measured	Simulated		Measured	Simulated	Measured	Simulated
	CALIBRATION					VERIFICATION			
1983					1983				
Jan. 21-22	0.014	0.012	1.1	0.79	Jan. 18-19	0.17	0.18	5.5	6.9
Jan. 24 am	.063	.044	2.5	1.6	Jan. 22	.17	.16	6.9	5.6
Jan. 26-27	.40	.30	8.8	6.1	Jan. 24	.17	.18	19	[1]13
Feb. 6	.14	.15	3.6	2.6	Feb. 7-8	.11	.11	8.5	11
Feb. 12	.061	.054	2.4	2.0	Feb. 28- Mar. 1	.30	.35	16	[1]13
Feb. 25	.023	.031	1.1	1.6	Mar. 10	.027	.033	2.7	2.9
Mar. 1	.024	.016	2.7	1.6	Mar. 17-18	.091	.094	5.0	5.4
Mar. 7	.016	.019	.74	.91	Mar. 20	.044	.048	2.5	2.3
Mar. 13	.19	.18	12	[1]13	Mar. 22 am	.022	.019	1.0	.84
Mar. 16	.077	.085	5.1	6.0	Mar. 22 pm	.012	.014	1.2	1.5
Mar. 23	.13	.16	8.2	10	Mar. 24 am	.068	.084	8.4	12
					Mar. 24 pm	.036	.027	2.4	2.0

[1]Surcharging, peak discharge not used in error analysis.

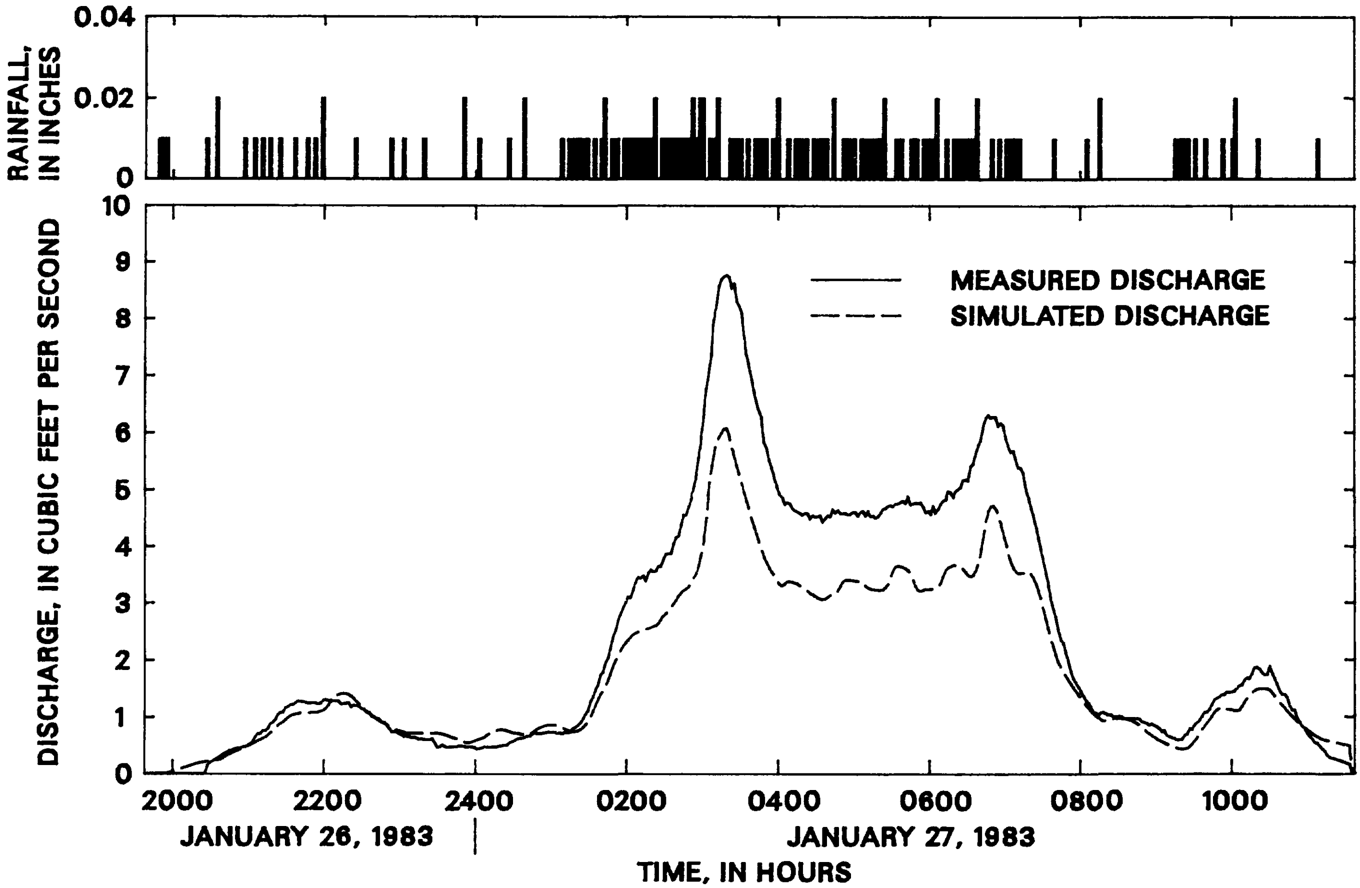


FIGURE 17. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the single-dwelling residential catchment.

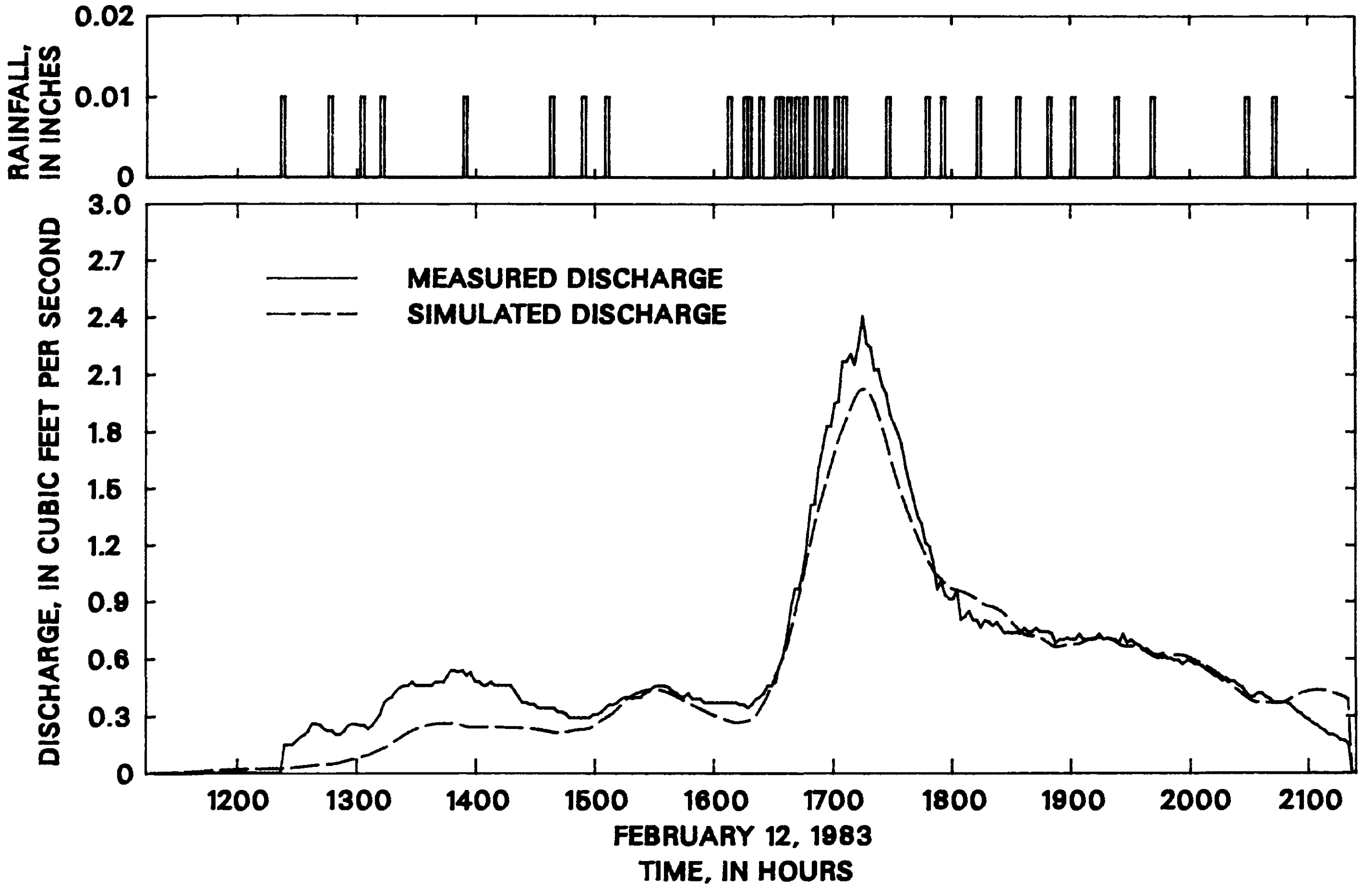


FIGURE 17. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the single-dwelling residential catchment--Continued.

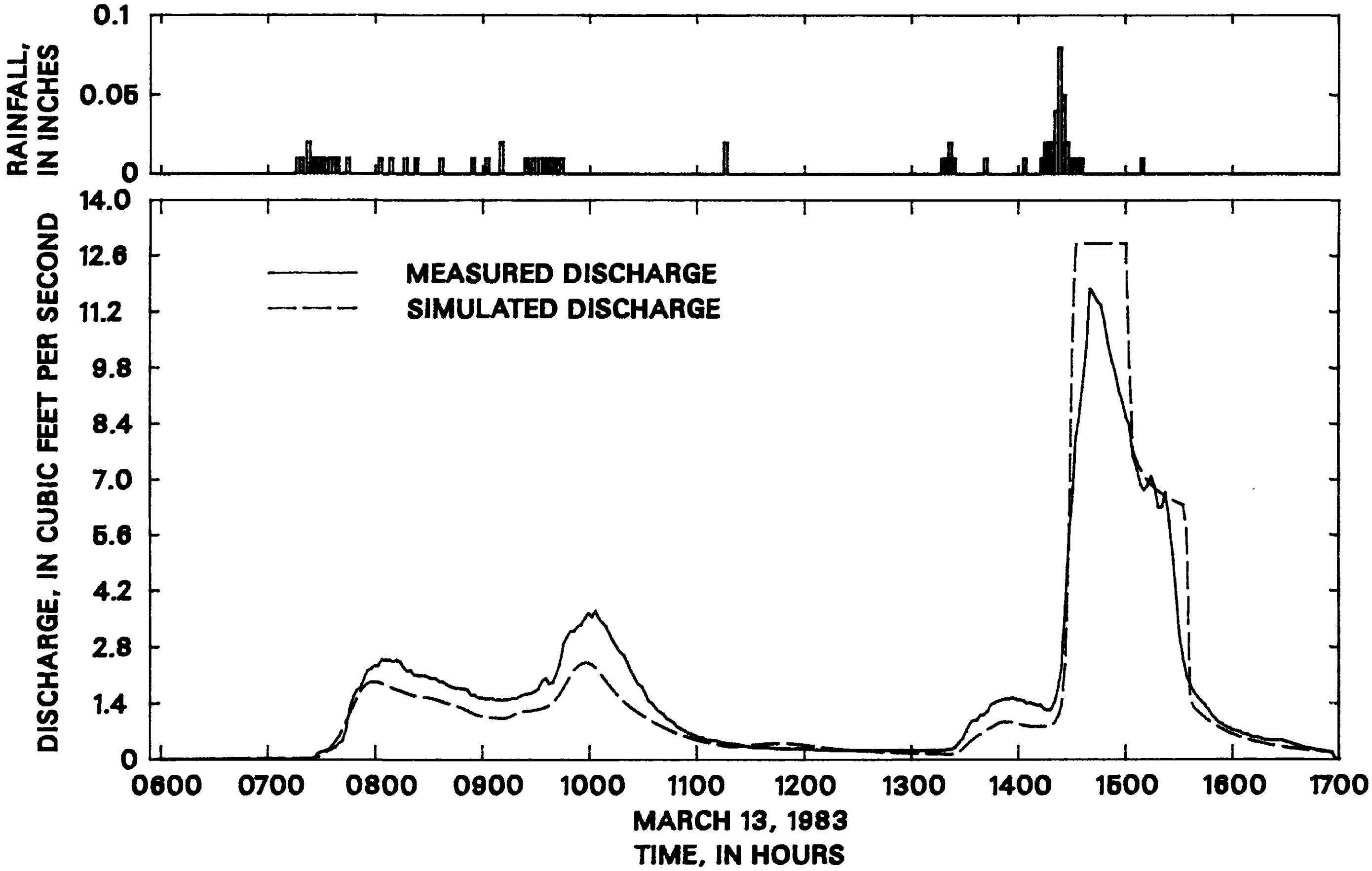


FIGURE 17. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the single-dwelling residential catchment--Continued.

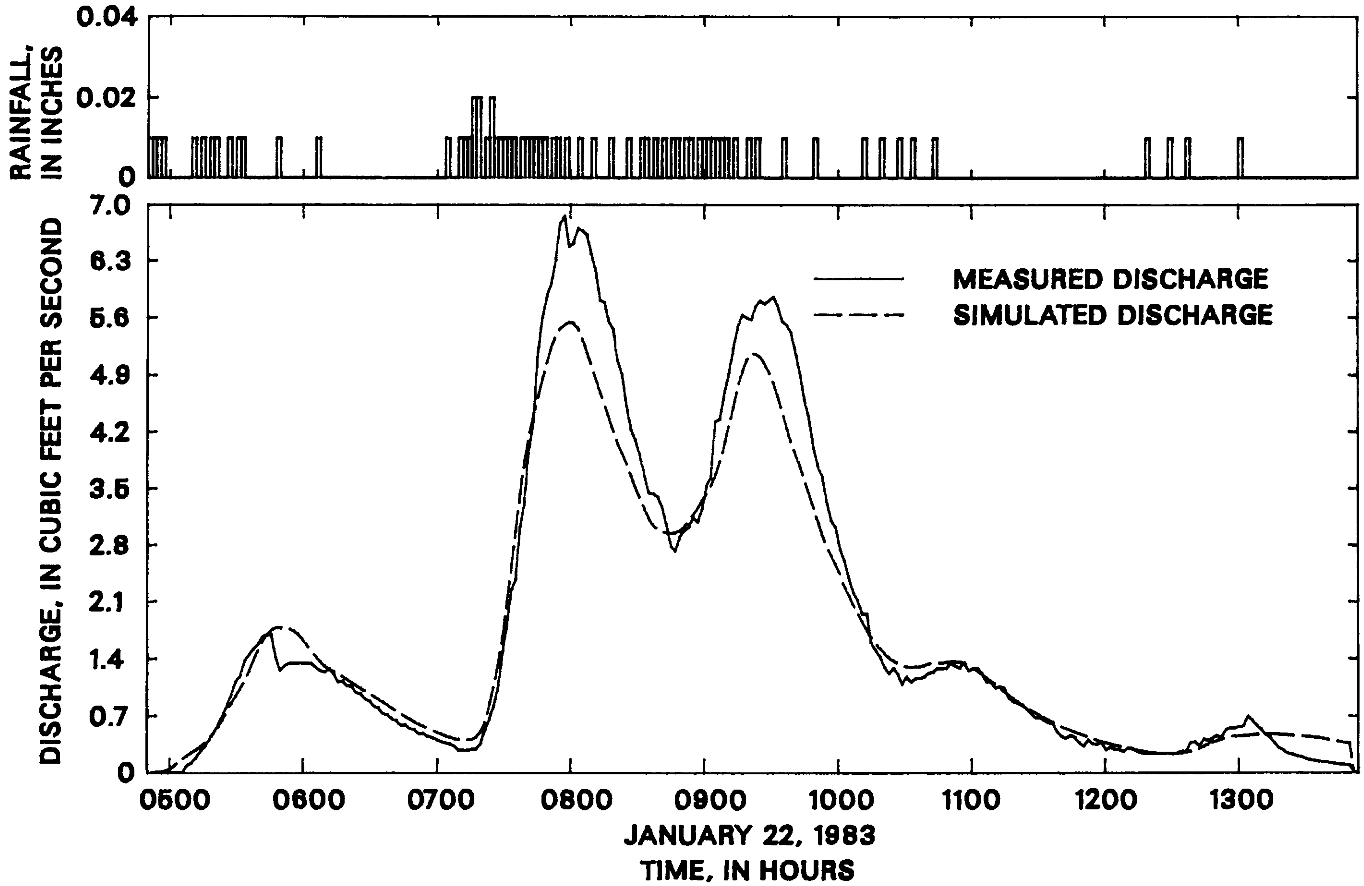


FIGURE 18. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the single-dwelling residential catchment.

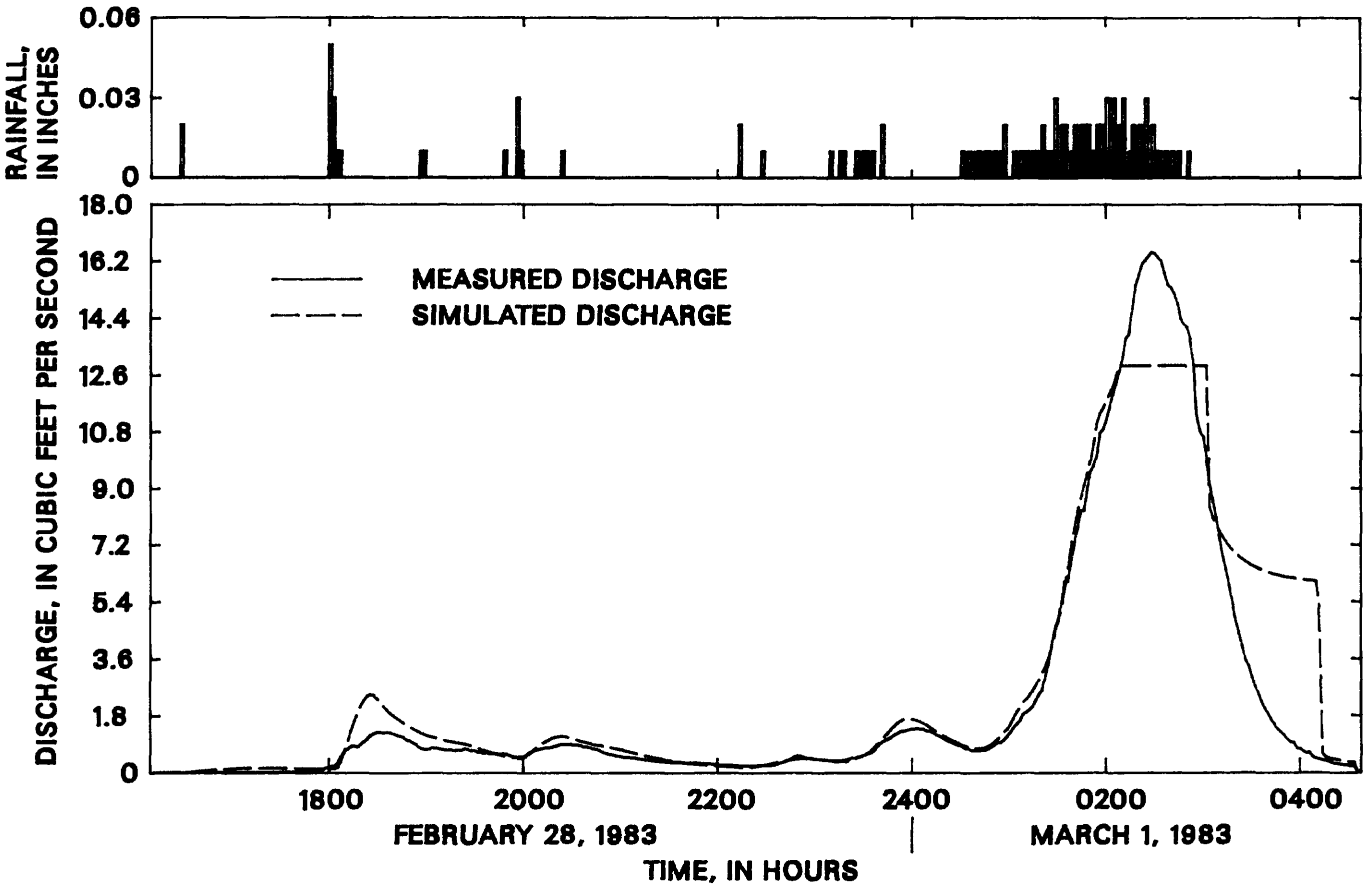


FIGURE 18. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the single-dwelling residential catchment--Continued.

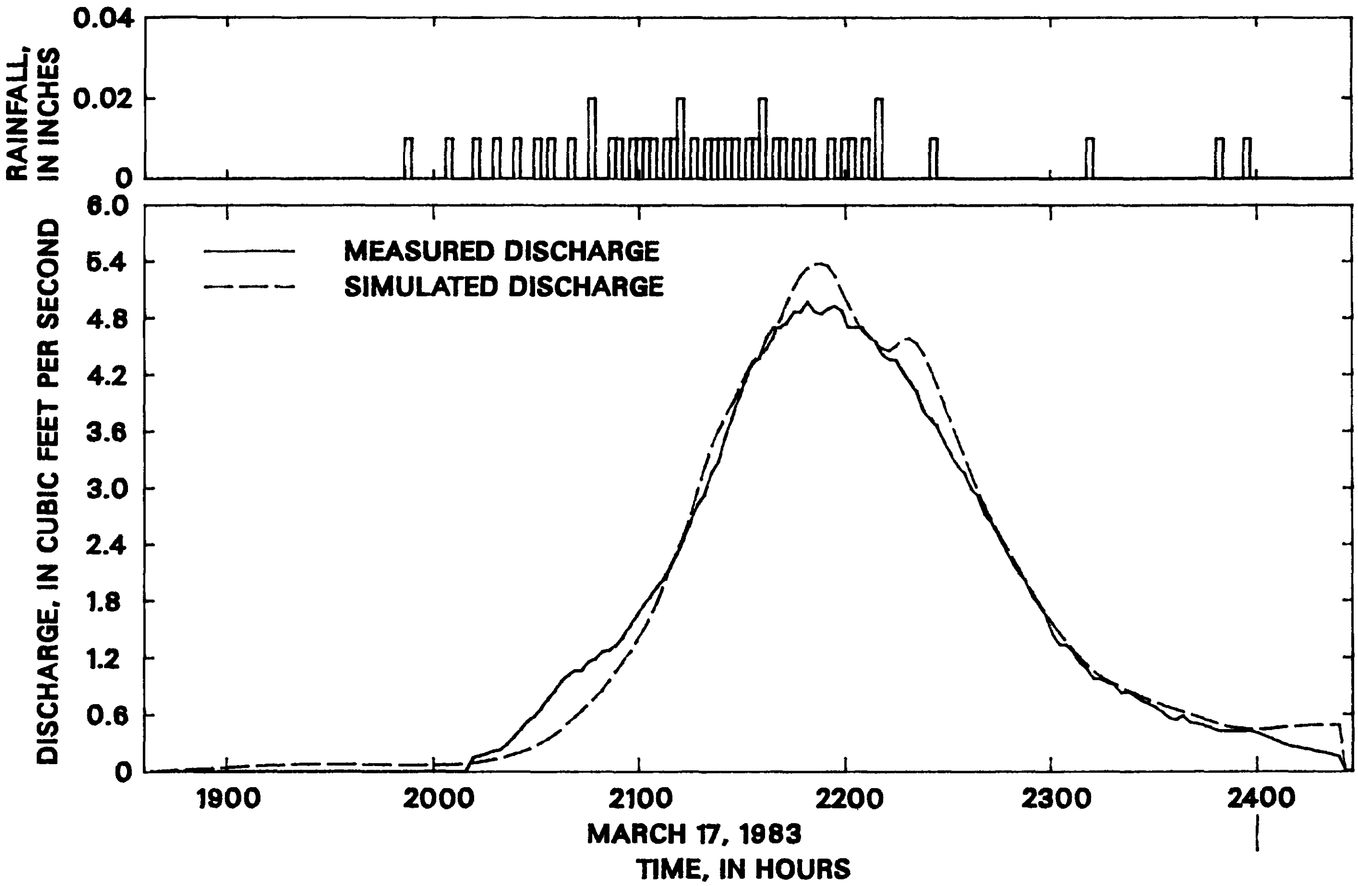


FIGURE 18. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the single-dwelling residential catchment--Continued.

Commercial Catchment

Rainfall and runoff data were used to calibrate and verify (12 storms each) the rainfall-runoff model for the commercial catchment. The catchment was simulated as 100-percent effective impervious; therefore, soil-moisture accounting and infiltration optimization was not necessary. Rainfall and runoff data used for calibration and verification are summarized in table 11.

TABLE 11.--*Summary of rainfall and runoff data used to calibrate and verify the rainfall-runoff model for the commercial catchment*

[Time: Time from first rainfall to last measured discharge.

Total runoff: $\frac{\text{Total runoff volume (ft}^3\text{)}}{\text{Total area of catchment (acre)}} \cdot \frac{12 \text{ (in.)}}{43{,}560 \text{ (ft}^2\text{)}}$.

Simulated pervious area runoff: Determined from DR3M-II simulations. Runoff-rainfall ratio: Some rainfall totals may not be representative of the average rainfall over the catchment due to the spatial variation of rainfall and the location of the rain gage. Number of dry hours since last storm: The number of hours between the last 0.01 inch of rainfall of the previous storm and the start of the storm drain flow (about 0.1 cubic foot per second) for the following storm. Abbreviations: in., inches; ft^3, cubic feet; ft^3/s, cubic feet per second; ft^2, square feet]

Storm date	Time	Total rainfall (in.)	Total runoff (in.)	Measured peak discharge (ft^3/s)	Simulated pervious area runoff (in.)	Runoff-rainfall ratio (percent)	Percent of total runoff originating on pervious areas	Maximum 20-minute rainfall (in.)	Number of dry hours since last storm
1981									
Dec. 20	0326-1718	0.14	0.17	3.7	0.000	186	0	0.02	240
Dec. 29	1414-2150	.21	.18	7.0	.000	86	0	.04	199
Dec. 30	0142-0444	.13	.13	9.3	.000	100	0	.05	6
1982									
Jan. 4	0732-2100	0.71	0.77	7.2	0.000	108	0	0.04	42
Jan. 4-5	2112-0450	.26	.31	9.8	.000	119	0	.06	3
Jan. 20	0754-1300	.13	.12	5.4	.000	92	0	.03	9
Jan. 21	1326-1718	.20	.21	20	.000	105	0	.09	10
Feb. 14	1744-2046	.12	.10	7.9	.000	83	0	.05	453
Feb. 14-15	2032-0248	.18	.21	4.2	.000	117	0	.03	1
Feb. 15-16	1958-0140	.22	.27	7.9	.000	123	0	.05	11
Feb. 16	0314-1002	.15	.19	6.4	.000	127	0	.04	4
Mar. 10-11	2258-0330	.29	.29	10	.000	100	0	.06	18
Mar. 14	0312-1630	.89	.96	28	.000	108	0	.15	58
Mar. 16	0512-1338	.46	.44	11	.000	96	0	.06	39
Mar. 16-17	1946-0222	.24	.32	15	.000	133	0	.08	8
Mar. 18	0348-0956	.22	.21	5.9	.000	95	0	.04	5
Mar. 25-26	2208-0250	.19	.15	4.9	.000	79	0	.04	170
Mar. 28	1548-1724	.11	.08	12	.000	73	0	.11	3
Mar. 29	1140-1702	.19	.21	9.5	.000	111	0	.05	13
Mar. 31-Apr. 1	1630-0920	1.05	1.18	12	.000	112	0	.12	49
Apr. 10	0444-0934	.18	.17	8.0	.000	94	0	.05	216
Apr. 10	1112-1434	.17	.16	11	.000	94	0	.07	5
Apr. 10-11	1846-0020	.22	.23	8.1	.000	105	0	.04	8
Apr. 11	0516-0836	.12	.12	7.4	.000	100	0	.07	5

All storms used in calibration and verification had simulated peak discharges less than the calculated capacity (28.5 cubic feet per second) of the outfall pipe (see table 12). A comparison of measured and simulated discharges for selected storms used in calibration and verification are shown in figures 19 and 20.

TABLE 12.--*Measured and simulated runoff volumes and peak discharges for all storms used in calibration and verification for the commercial catchment*

[Runoff volume: $\frac{\text{Total runoff volume (ft}^3\text{)}}{\text{Total area of catchment (acre)}} \cdot \frac{\text{12 (in.)}}{\text{43,560 (ft}^2\text{)}}$.

Peak discharge, in cubic feet per second. Abbreviations: in., inches; ft^3, cubic feet; ft^2, square feet]

Storm date	Runoff volume		Peak discharge	
	Measured	Simulated	Measured	Simulated
	CALIBRATION			
1981				
Dec. 20	0.17	0.12	3.7	2.9
1982				
Jan. 4	0.77	0.69	7.2	6.4
Jan. 4-5	.31	.26	9.8	9.0
Jan. 20	.12	.11	5.4	4.7
Feb. 15-16	.27	.20	7.9	6.2
Feb. 16	.19	.15	6.4	4.7
Mar. 16	.44	.41	11	9.5
Mar. 18	.21	.20	5.9	6.8
Mar. 25-26	.15	.17	4.9	6.4
Mar. 28	.079	.087	12	11
Apr. 10 (pm)	.16	.15	11	8.8
Apr. 10-11	.23	.22	8.1	7.3

Storm date	Runoff volume		Peak discharge	
	Measured	Simulated	Measured	Simulated
	VERIFICATION			
1981				
Dec. 29	0.18	0.19	7.0	6.0
Dec. 30	.13	.13	9.3	9.3
1982				
Jan. 21	0.21	0.18	20	12
Feb. 14	.098	.080	7.9	6.6
Feb. 14-15	.21	.18	4.2	4.0
Mar. 10-11	.29	.27	10	9.6
Mar. 14	.96	.87	28	26
Mar. 16-17	.32	.22	15	6.6
Mar. 29	.21	.15	9.5	7.3
Mar. 31-Apr. 1	1.2	1.0	20	16
Apr. 10 (am)	.17	.16	8.0	6.8
Apr. 11	.12	.12	7.4	7.8

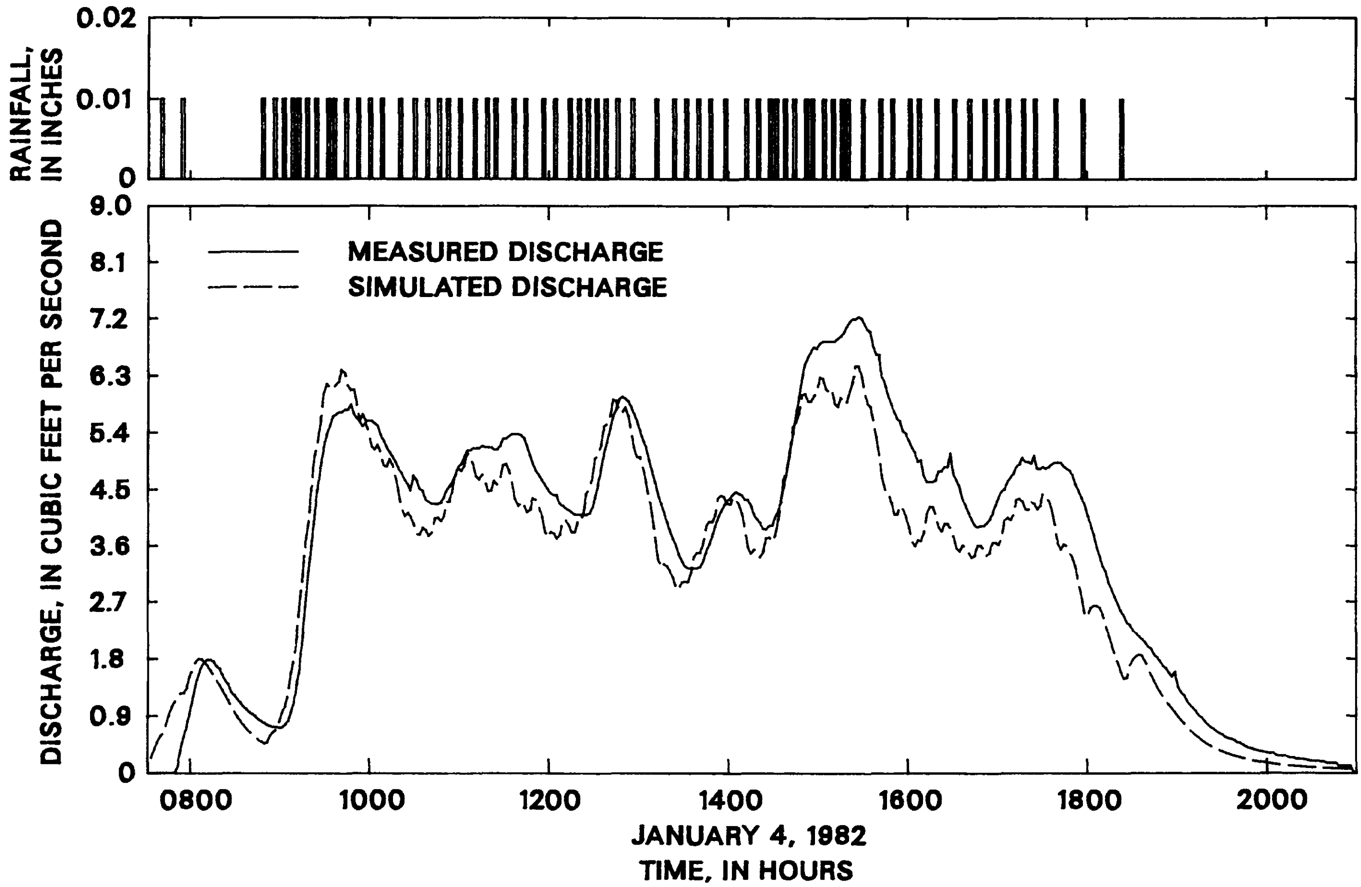


FIGURE 19. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the commercial catchment.

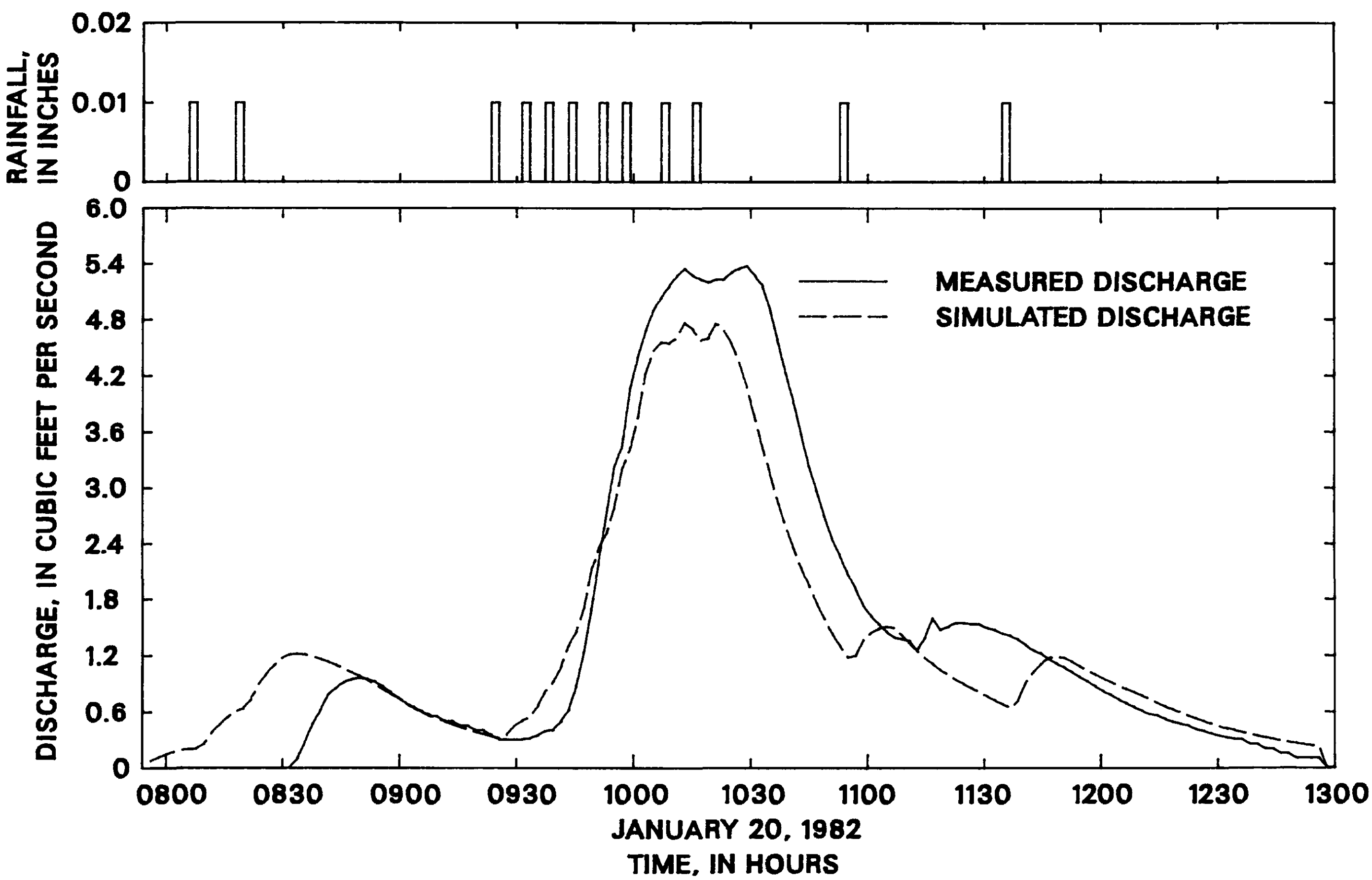


FIGURE 19. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the commercial catchment--Continued.

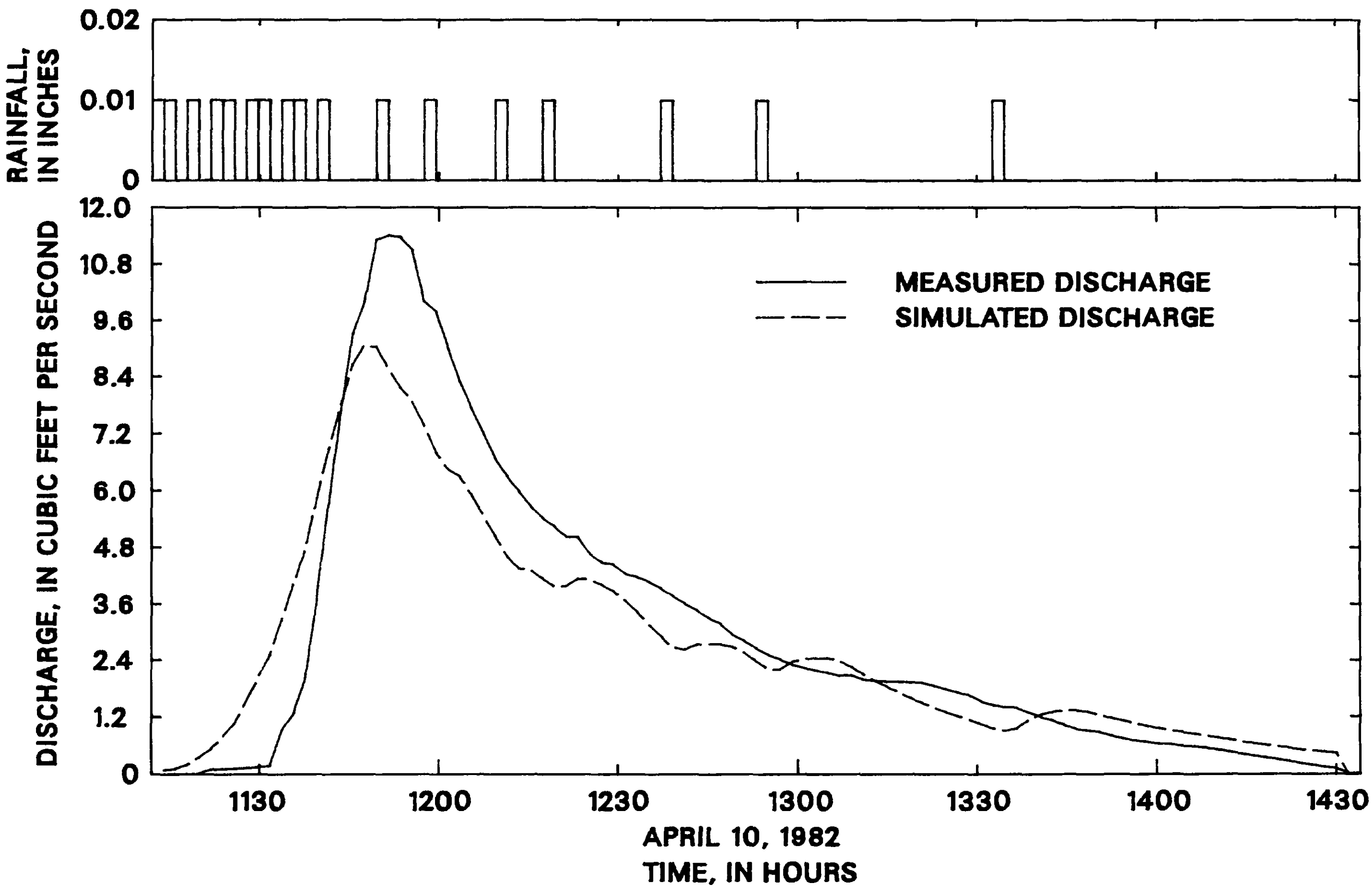


FIGURE 19. Comparison of measured and simulated discharge for selected storms used to calibrate the rainfall-runoff model for the commercial catchment--Continued.

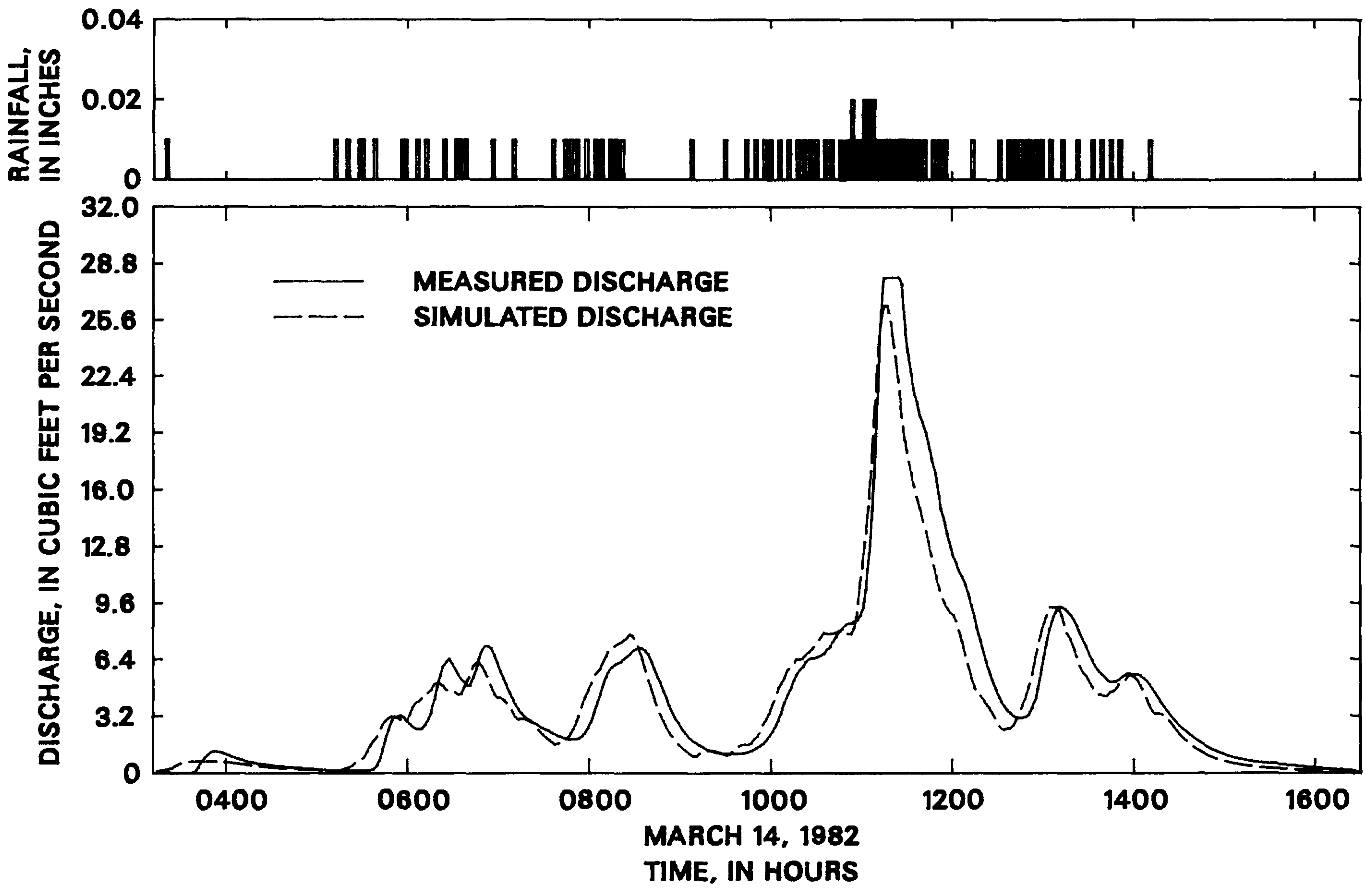


FIGURE 20. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the commercial catchment.

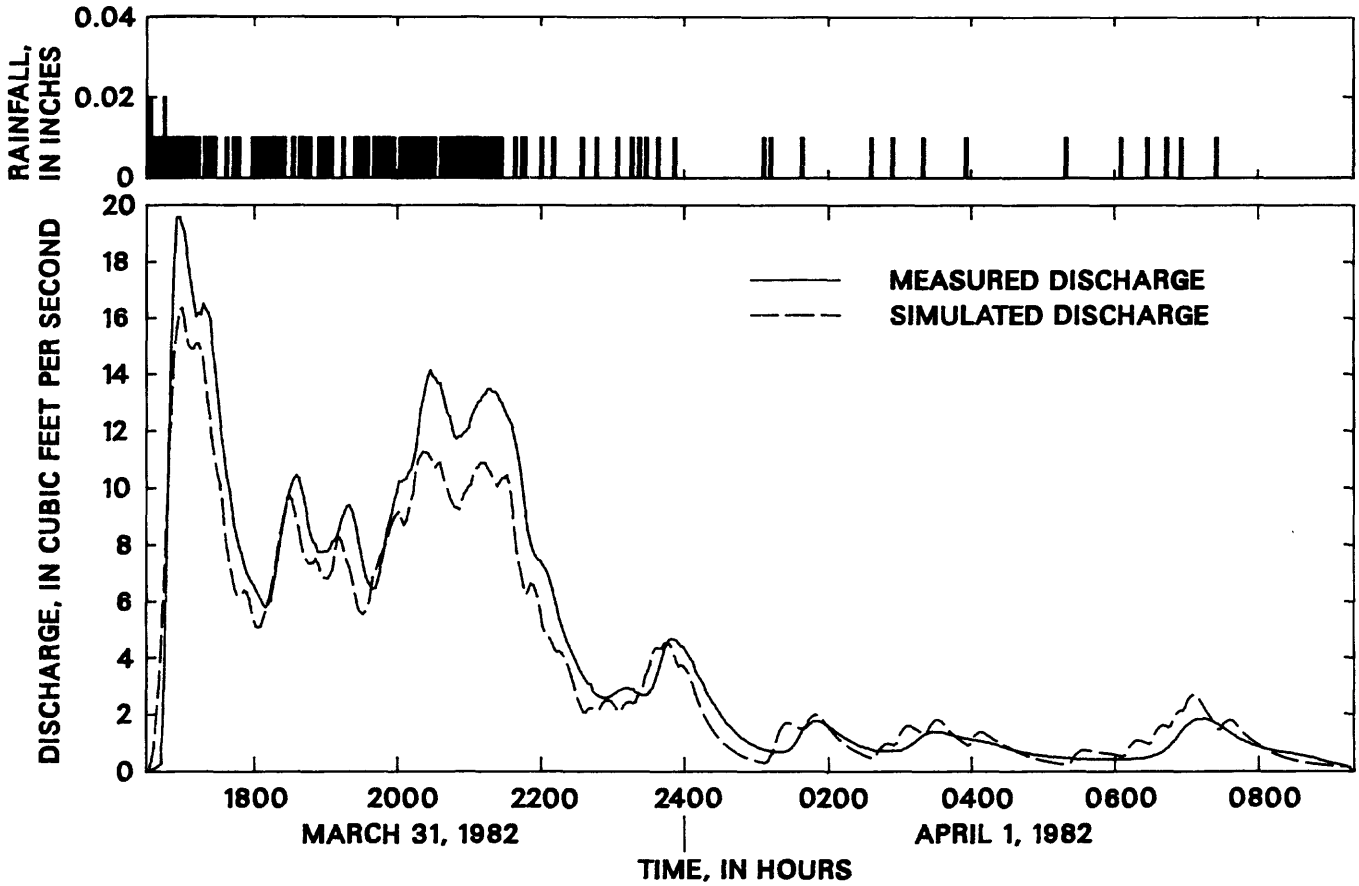


FIGURE 20. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the commerical catchment--Continued.

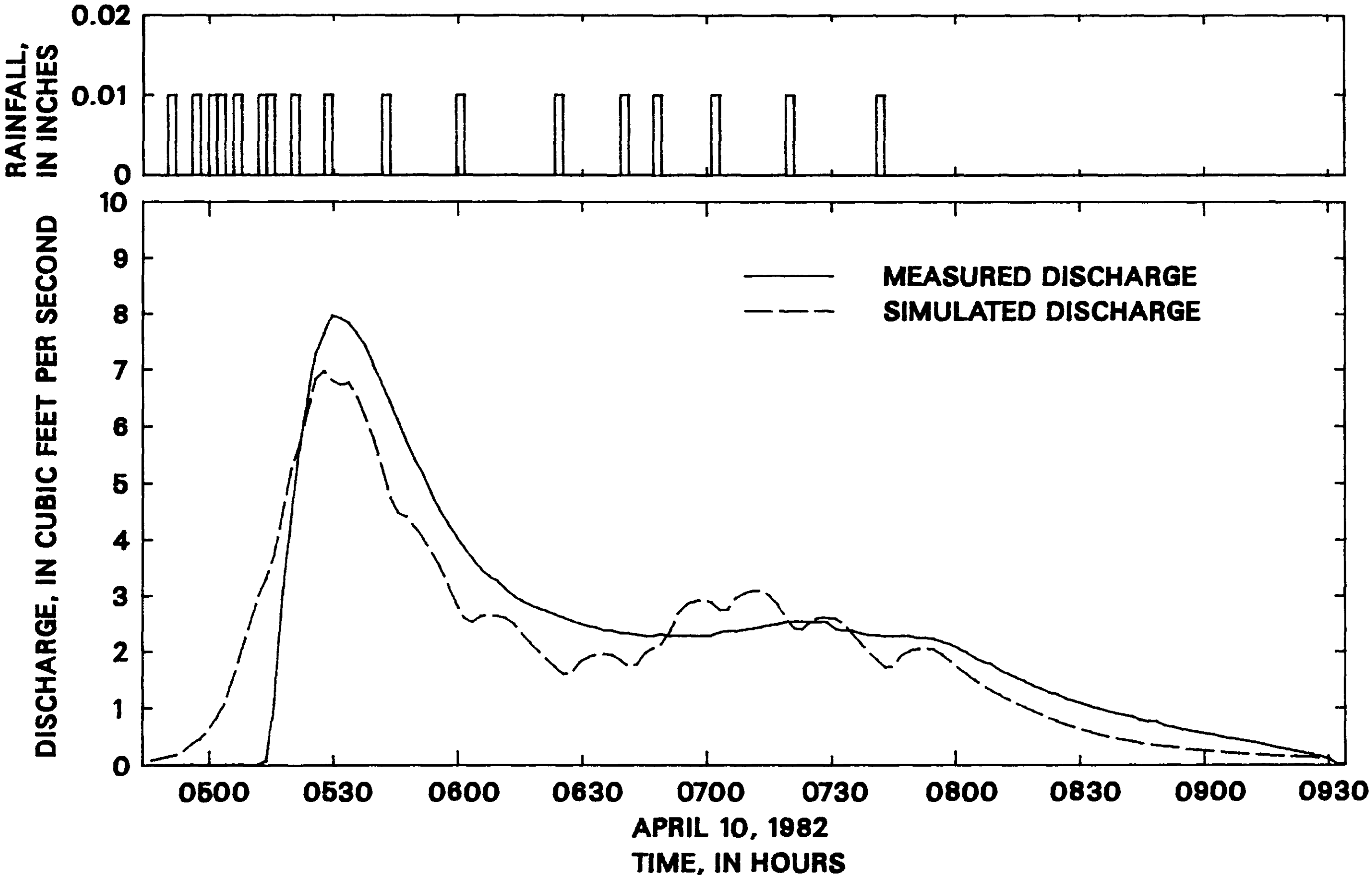


FIGURE 20. Comparison of measured and simulated discharge for selected storms used to verify the rainfall-runoff model for the commerical catchment--Continued.

Error Analysis

Simulation errors were summarized using the median absolute deviation (mad) in percent.

$$\text{mad} = 100 \cdot \{\text{median}|e_i|\} \qquad (1)$$

where

e_i is $(x_i - \hat{x}_i)/x_i$, and

x_i and $\hat{x}_i$ are the i^{th} measured and simulated values, respectively.

The mad criteria was used to summarize errors for two reasons. First, the mad criteria has the advantage of being insensitive to outliers. Second, comparisons could be made to another study (Alley, 1986), which summarized the mad errors for calibration and verification of DR3M and DR3M-II at 37 catchments. The overall mad errors reported by Alley (1986) for runoff volumes and peak discharges were 19 and 20 percent during calibration, and 24 and 21 percent during verification. The average mad errors for all four models were 15 and 20 percent for calibration of runoff volumes and peak discharges, and 14 and 18 percent for verification of runoff volumes and peak discharges (see table 13). Simulation errors for calibration and verification runoff volumes and peak discharge are shown in figures 21 and 22.

TABLE 13.--*Median absolute deviation (mad) errors for calibration and verification of runoff volumes and peak discharges*

	Calibration errors (percent)		Verification errors (percent)	
Catchment	Runoff volumes	Peak discharge	Runoff volumes	Peak discharge
Multiple(1)	18	25	23	26
Multiple(2)	16	11	11	15
Single	16	29	11	19
Commercial	10	16	10	14
Average, all catchments	15	20	14	18
Nationwide average, (Alley, 1986)	19	20	24	21

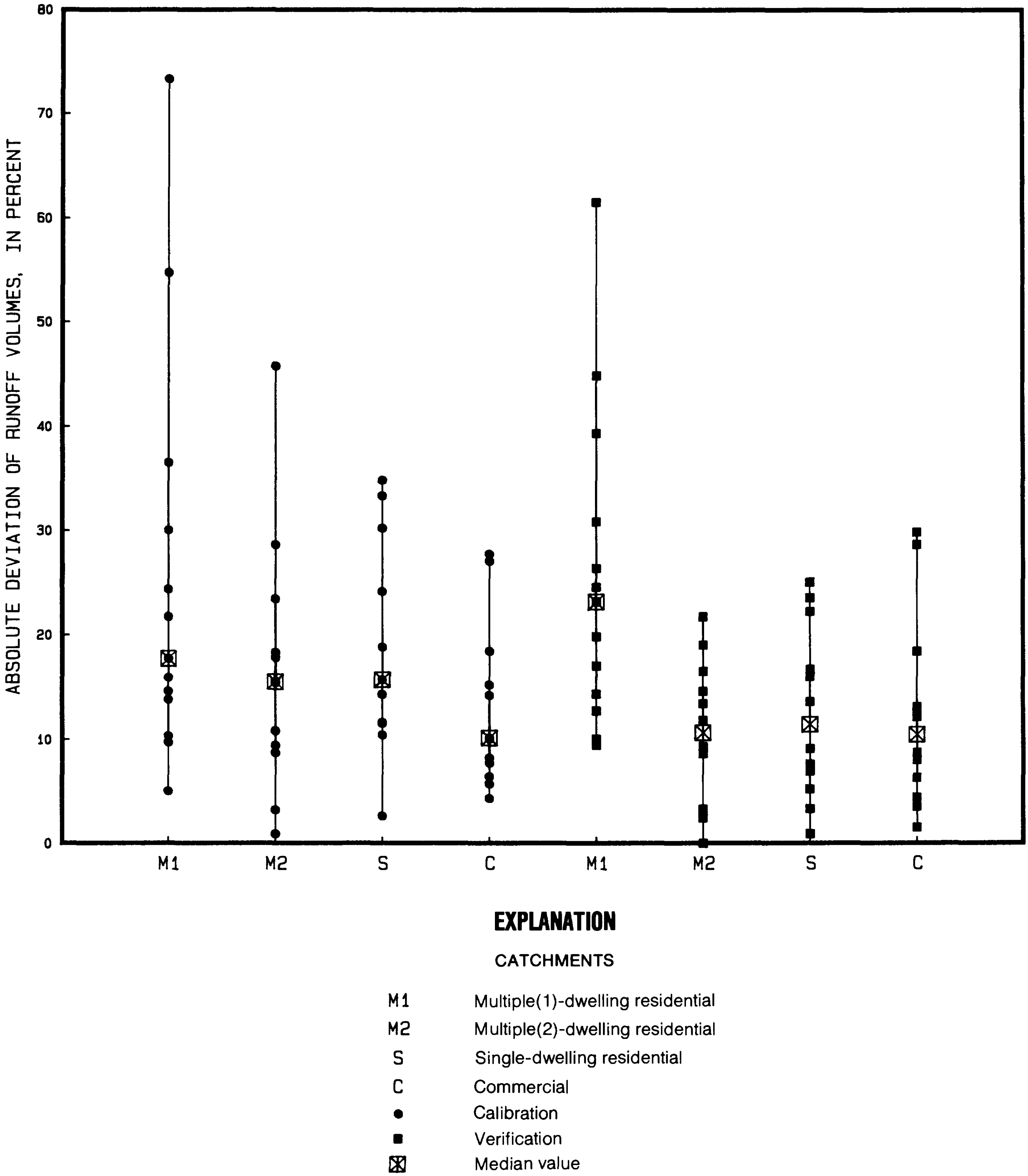
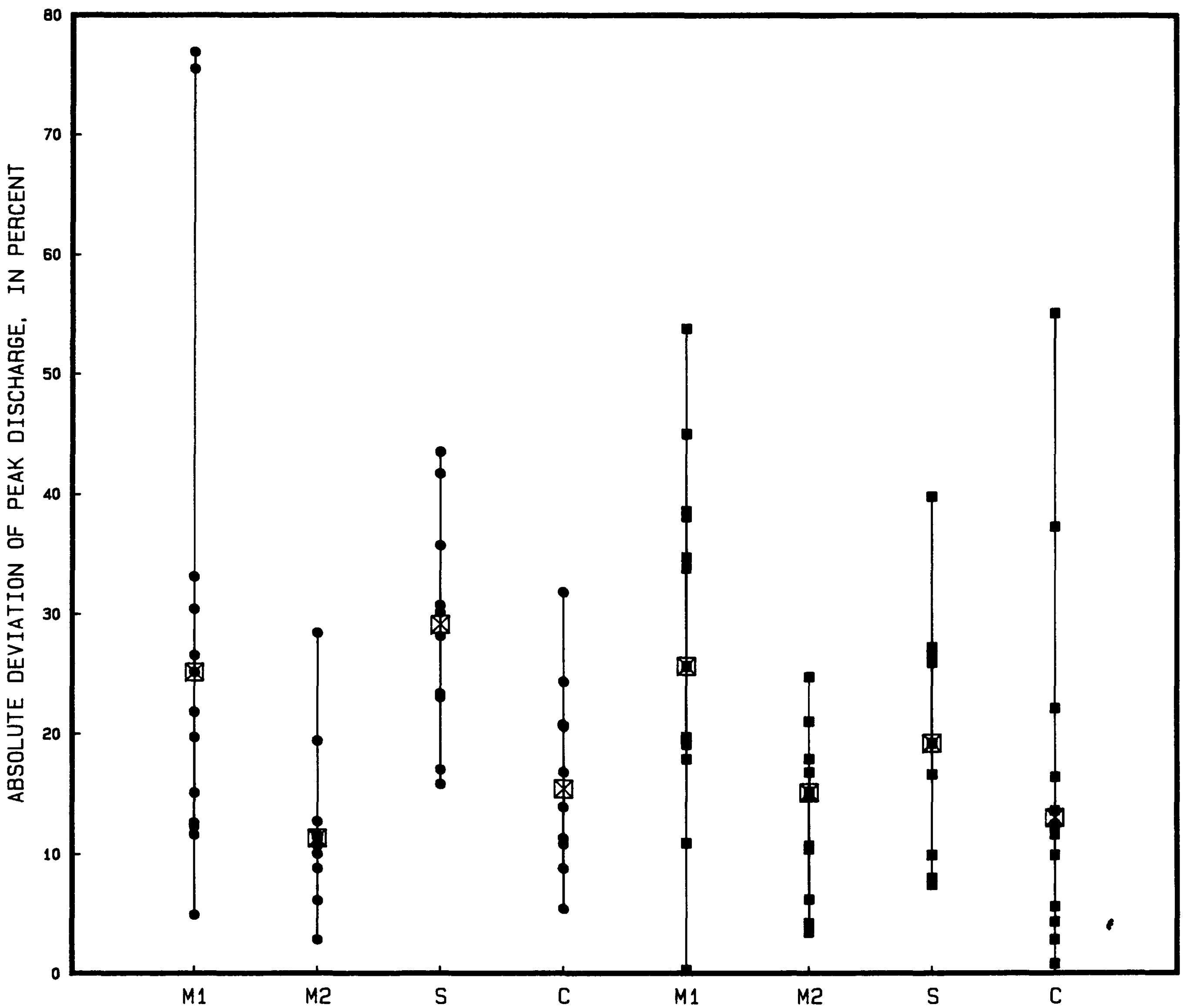


FIGURE 21. Simulation errors for calibration and verification of runoff volumes.



EXPLANATION

CATCHMENTS

M1	Multiple(1)-dwelling residential
M2	Multiple(2)-dwelling residential
S	Single-dwelling residential
C	Commercial
●	Calibration
■	Verification
⊠	Median value

FIGURE 22. Simulation errors for calibration and verification of peak discharge.

Applications

Storm-Drain Analysis

The storm-drain systems at the multiple(1), single, and commercial catchments were analyzed by entering 2-year design storm rainfall (fig. 23) to DR3M-II. The multiple(1) application was selected over the multiple(2) because more data for catchment characteristics were available. Because this catchment has gone through extensive development since 1983, neither application would reflect current conditions.

A design storm is derived from statistical analyses of rainfall from historical storms and represents a typical storm for a given return period. The design storm used in this study was developed from rainfall intensity and duration data from manuals used by the Fresno Metropolitan Flood Control District (Blair, 1960). Rainfall depth and duration were plotted on log-log paper to smooth the data and extract the accumulated rainfall depths at 5-minute intervals. The design storm is developed by placing the highest incremental rainfall value in the center of the hyetograph, next highest to the left, next highest to the right, and so forth. A 2-year return period was selected for the design storm because the storm-drain pipes at the three catchments were designed to pass the 2-year runoff event. A duration of 90 minutes was selected because any greater duration caused little increase in the peak discharge. For this study, the design storm was assumed to produce the design runoff.

Two of the 10 pipe sections simulated at the multiple(1) catchment surcharged from the 2-year design storm (fig. 24). The rainfall-runoff model does not simulate pressurized flows, but does indicate how long each simulated pipe section flows full assuming nonpressurized conditions. These times indicate the degree to which ponding occurs behind a pipe. Simulated pipe section PI05 surcharged for 15 minutes, and the outfall pipe PI10 surcharged for 25 minutes (fig. 8). Ponding behind PI05 could cause flooding near the drop inlets at North Woodrow and East Alamos Avenues (fig. 4).

The 2-year design storm caused two of the five simulated pipe sections at the single catchment to surcharge (fig. 25). Simulated pipe section PI02 surcharged for 10 minutes and PI03 surcharged for 20 minutes (fig. 10). Surcharging of these two pipes could cause flooding near the drop inlets at the corner of Hayston and Ashcroft Avenues (fig. 5).

The 2-year design storm caused the commercial storm-drain system to surcharge at four locations (fig. 26). Simulated pipe section PI07 surcharged for only 5 minutes. The highest surcharging occurred at simulated pipe sections PI03 (20 minutes), PI08 (25 minutes) and outfall pipe PI16 (45 minutes). Water backing up in these last three pipes could cause flooding at the north parking lot of the Fashion Fair Mall and the southwest corner of the catchment.

Two-year peak discharges also were determined at each catchment using the rational formula method described by Kibler (1982) to compare with DR3M-II. The rational formula method uses the following equation to compute peak discharge:

$$Q_t = C\, i_t\, A \qquad (2)$$

where

- Q_t is peak discharge, in cubic feet per second, for return period, t-years;
- C is a runoff coefficient dependent on land use;
- i_t is design rainfall intensity, in inches per hour, for return period of t-years and duration equal to the time of concentration for the basin; and
- A is drainage, in acres.

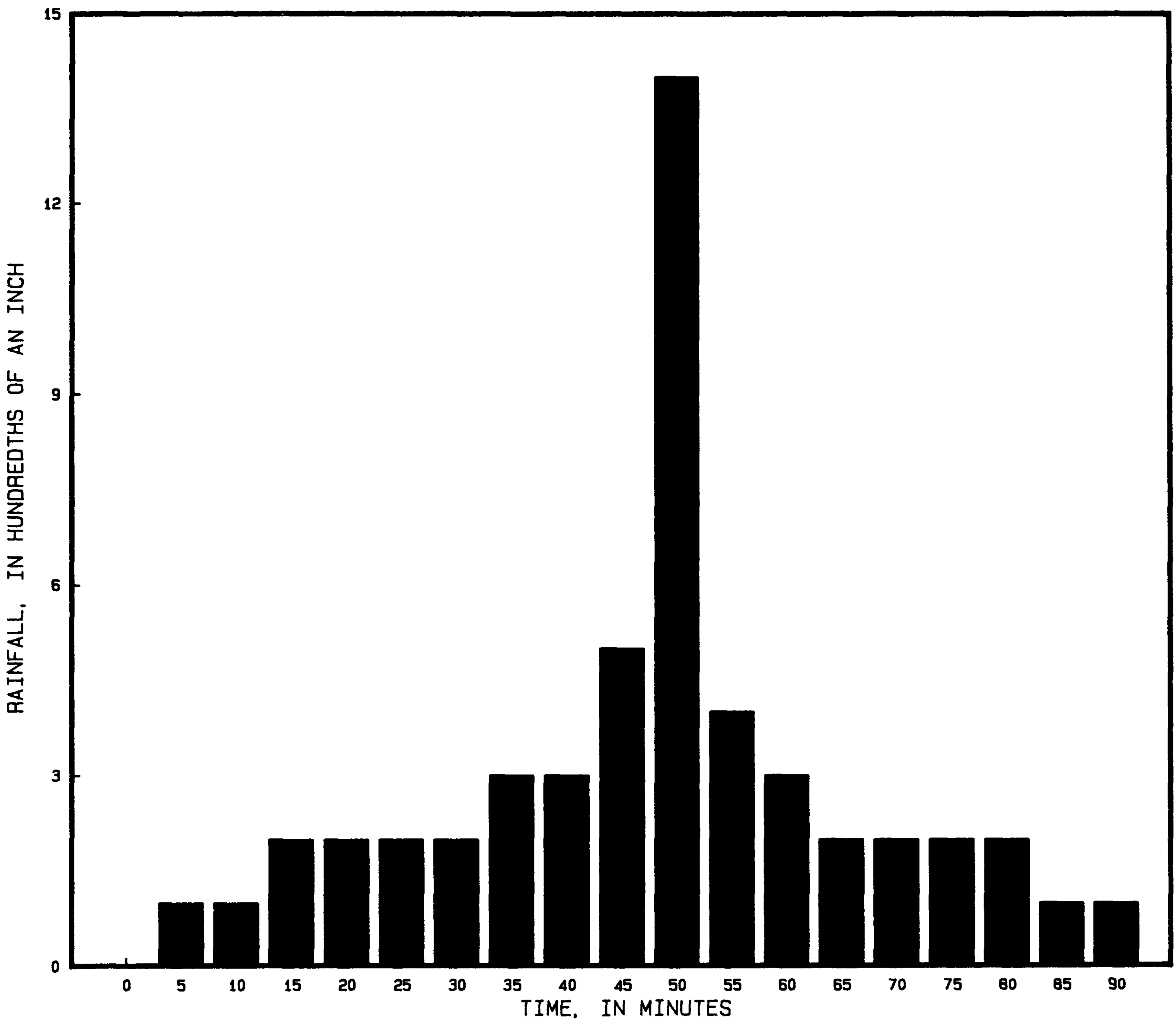


FIGURE 23. Two-year design storm rainfall.

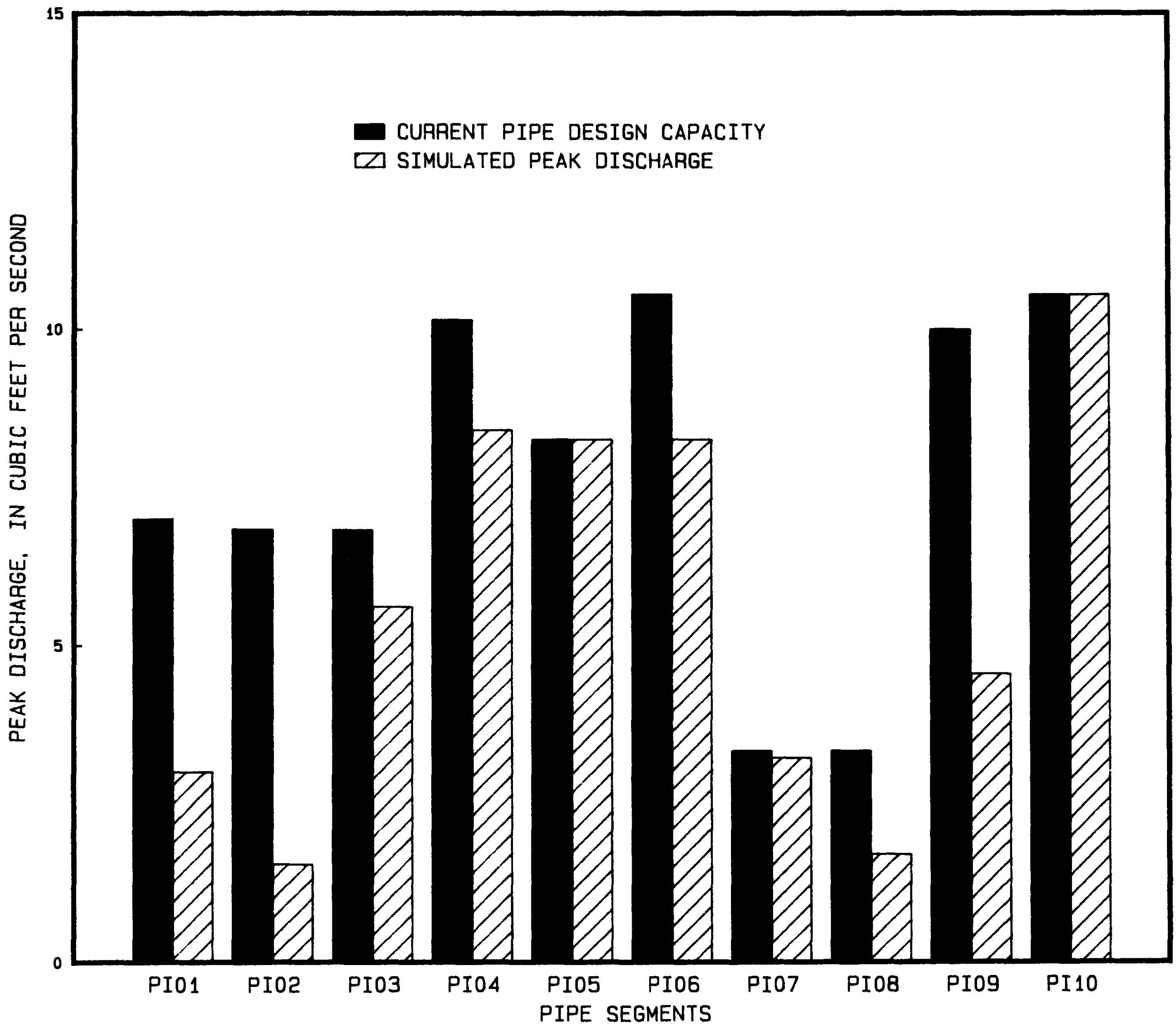


FIGURE 24. Current design capacity of storm-drain pipes and simulated peak discharge from 2-year design storm rainfall at the multiple (1)-dwelling residential catchment.

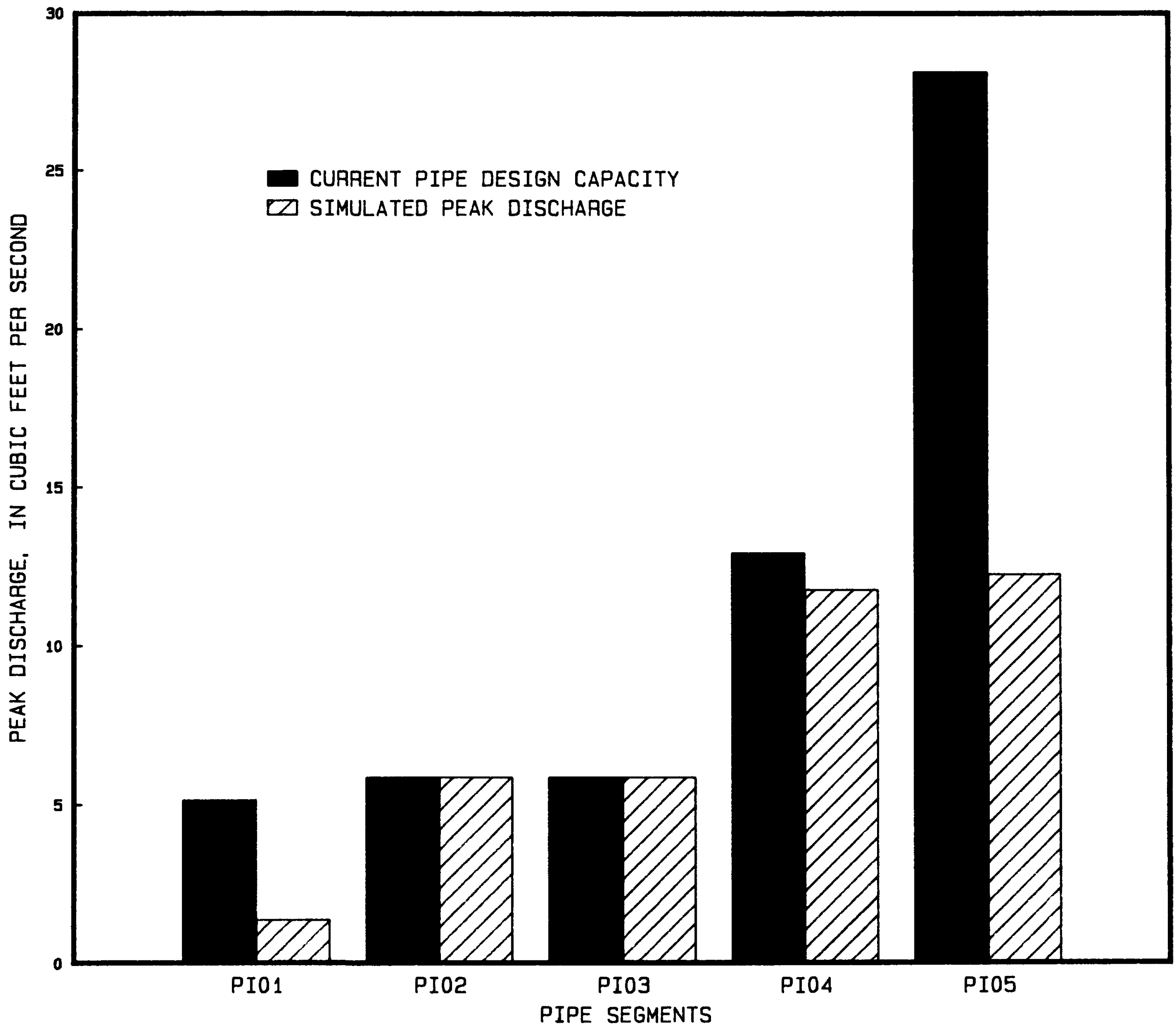


FIGURE 25. Current design capacity of storm-drain pipes and simulated peak discharge from 2-year design storm rainfall at the single-dwelling residential catchment.

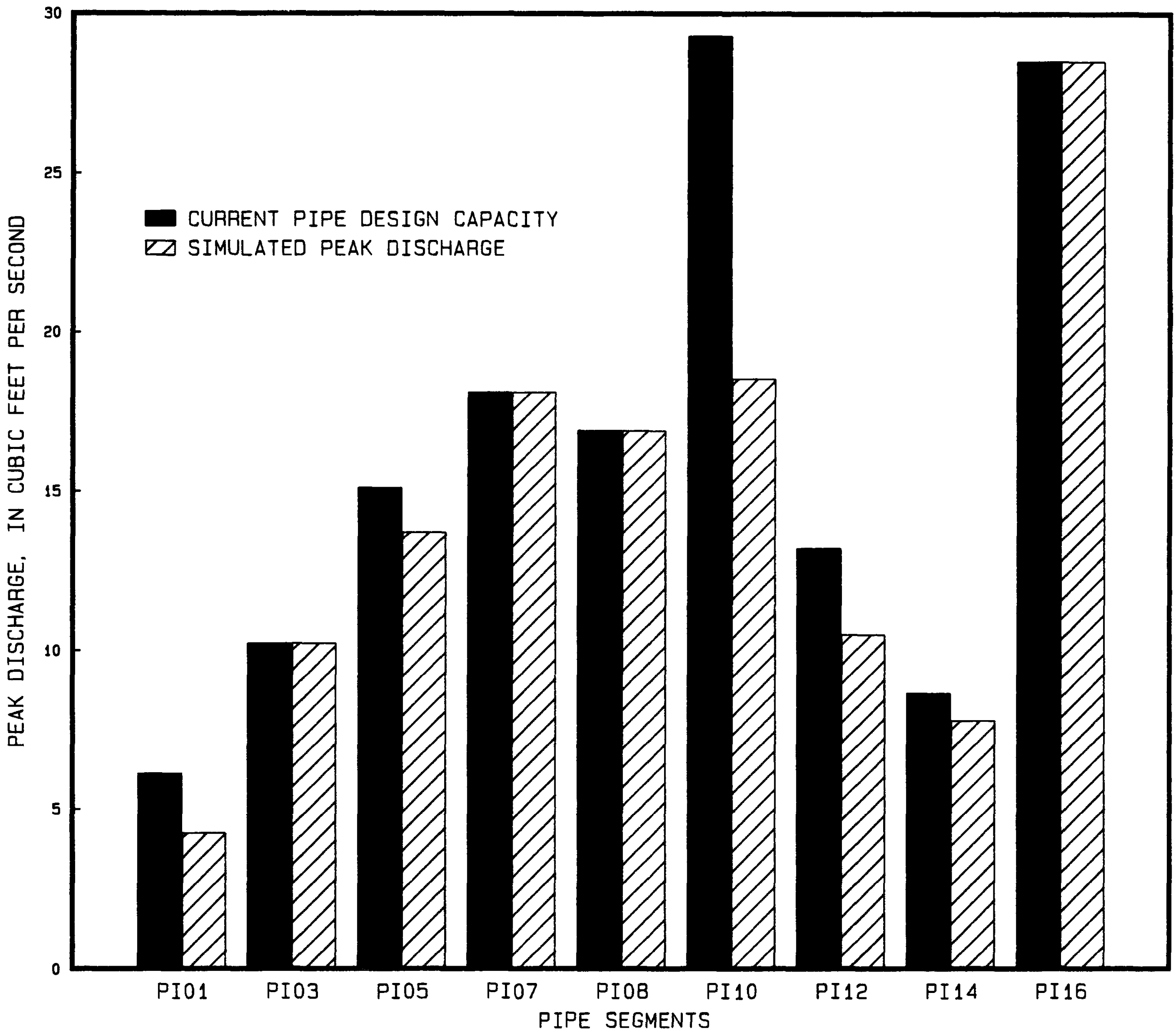


FIGURE 26. Current design capacity of selected storm-drain pipes and simulated peak from 2-year design storm rainfall at the commerical catchment.

The time of concentration for each catchment was calculated by determining the travel times of the pipes and overland-flow planes simulated in the models. Time of concentration is defined as the time required for runoff from all parts of the catchment to be contributing to the outflow. The travel times in pipes were calculated using Manning's formula. The overland-flow plane travel times were calculated using the following formula from Kibler (1982):

$$t_0 = \frac{1.8(1.1 - C)D^{\frac{1}{2}}}{S^{1/3}} \qquad (3)$$

where

t_0 is overland flow time, in minutes;
C is runoff coefficient;
D is travel distance, in feet; and
S is overland slope, in percent.

Two-year design rainfall intensities (i_t), using the time of concentration of each catchment, and runoff coefficients (C) were taken from Fresno Metropolitan Flood Control District manuals (Blair, 1960). Both methods produced 2-year peak discharges within a cubic foot per second of the calculated outfall capacity (table 14). But DR3M-II, using the same statistical rainfall used in the rational formula method, determined that many of the pipes would not pass the 2-year event without ponding occurring behind certain pipes. The outflow peak discharges of the two methods are similar only because the DR3M-II model limited the maximum discharge in the pipes to the nonpressurized flow capacity. If pressure heads were allowed to develop and increase the maximum flows through the surcharging pipes, then flows simulated by the DR3M-II model would be higher.

TABLE 14.--*Final values used in comparing 2-year peak discharges determined by the rational formula method and DR3M-II*

Rational formula	Multiple(1)	Single	Commercial
Peak discharge (Q_t)[1], in cubic feet per second	10.8	13.9	28.6
Runoff coefficient (C)[1]	.53	.32	.70
Design rainfall intensity (i_t)[1], in inches per hour	.45	.46	.66
Drainage area (A)[1], in acres	45.1	94.2	61.9
Rainfall-runoff model (DR3M-II)			
Peak discharge, in cubic feet per second	10.6	12.5	28.5
Calculated outfall capacity for non pressurized flows, in cubic feet per second	10.6	12.9	28.5

[1]Refers to the rational formula ($Q_t = C\ i_t\ A$), equation 2 in text.

As a result, the 2-year peak discharges determined by the DR3M-II model probably are low. The results from the rational formula method also probably are low, but for a different reason. The rational formula method, when applied to an entire catchment, does not consider the hydraulics of the drainage system except to the extent that it is reflected in the time of concentration used for choosing the design rainfall intensity. If the estimates using the rational formula are low, it is most likely the result of the choice for the runoff coefficient C. The values of C used in the rational formula applications were those selected from manuals used by the Fresno Metropolitan Flood Control District.

Because the rain season 1982-83 was very wet, the estimated 2-year event was probably equaled or exceeded during the second year of the study. The measured rainfall and runoff data and observations of storm runoff were used to determine if runoff from the 2-year event would produce pressurized flows and/or ponding. The storm-drain pipes under each monitoring station were constructed with an access space down to the invert of the pipe. The distance from the invert of the pipe to the land surface ranged from 6 to 7 feet at the multiple(1) catchment, and 10 to 12 feet at the single and commercial catchments. If pressurized flows did occur, water could be observed rising into these crawl spaces. Ponding behind pipes could be observed in the streets and gutters.

The runoff from the 2-year event probably would produce little or no pressurized flow or ponding at the multiple(1) catchment. Even with the additional 5-percent effective impervious area at the multiple(2) catchment, flows greater than full pipe were not observed during the second year. Therefore, both methods probably provided reasonable estimates of the 2-year peak discharge.

Runoff from the 2-year event probably would produce pressurized flows and ponding behind some pipes at the single catchment. Numerous times during the second year of the study, water rose 8 to 10 feet into the crawl space above the outfall pipe. A measured flow of 19 cubic feet per second on January 1983 and 16 cubic feet per second on March 1, 1983, were recorded, both of which exceeded the 12.9 cubic feet per second nonpressurized flow capacity of the outfall pipe. Flooding also was observed many times during the 1982-83 rain season. As a result, the estimates of the 2-year peak discharge at the single catchment are probably low.

Runoff from the 2-year event also probably would produce pressurized flows and ponding at the commercial catchment. Storms during the second year were not used because of backwater effects, but high flows largely unaffected by backwater were observed during the 1982-83 rain season. A few flows forced water 8 to 10 feet into the crawl space above the storm-drain pipe. During one storm, the manhole cover at the southwest corner of the catchment was forced open by pressure head in the pipe. Ponding on the southwest corner of the catchment was observed many times during the 1982-83 rain season. Consequently, the estimates for the 2-year peak discharge at the commercial catchment also probably are low.

RUNOFF-QUALITY MODEL

Description of Model

DR3M-qual is a runoff-quality model that simulates the concentrations and loads of water-quality constituents in runoff from urban areas. DR3M-qual simulates the quality of storm runoff during days when short-time interval (1-minute to hourly) runoff data are input to the program (unit days). Between unit days, daily precipitation data are used to perform a daily accounting of constituent accumulation on the effective impervious areas of the drainage basin.

DR3M-qual can be used as a lumped or distributed parameter model. As a lumped parameter model, parameters are taken as constant over the entire drainage basin. Constituent loads in runoff are assumed to originate entirely as washoff from the effective impervious areas of the drainage basin and from constituent loads in precipitation. The lumped parameter model assumes that constituent loads originating from noneffective impervious areas or pervious areas on the drainage basin are negligible. The lumped parameter input requires runoff hydrographs and estimates of precipitation quality for each of the selected storms. Between storms, daily rainfall is required. If streetsweeping is considered, then additional input data are needed to define frequency of sweeping, base residual load, efficiency of streetsweeper, and percentage of area swept. Base residual load is defined as the load that cannot be removed by the streetsweeper because it is too fine, located in inaccessible cracks, or cemented to the surface by dissolved minerals. The efficiency of the streetsweeper is the fraction of load coming from effective impervious areas that is in excess of the base residual load removed by the streetsweeper. The input hydrographs needed by DRM3M-qual can be either data simulated by DR3M-II, or measured data.

As a distributed parameter model, DR3M-qual can simulate impervious and pervious area contributions to runoff loads as well as precipitation contributions. For distributed parameter modeling, the drainage basin is represented by overland-flow and channel segments in an identical manner as DR3M-II. Each overland flow segment can be assigned an individual set of parameters for constituent accumulation and washoff. Because the models in this report use lumped parameters, no further discussion of distributed parameter algorithms will be given.

The constituent accumulation on effective-impervious areas is simulated by:

$$L = K_1[1-\exp(-K_2T)] \quad (5)$$

where

- L is the amount of constituent on the effective-impervious area, in pounds per acre;
- T is the equivalent accumulation time, in days (Alley and Smith, 1982b);
- K_1 is the maximum amount of the constituent which can accumulate on the effective impervious area, in pounds per acre; and
- K_2 is the rate constant for constituent removal, in $days^{-1}$.

The constituent washoff from effective impervious areas is simulated by:

$$W = L_0[1-\exp(-K_3 R \Delta T)] \quad (6)$$

where

- W is the amount of constituent removed from the effective impervious area during a time step, in pounds;
- L_0 is the amount of constituent on the effective impervious area at the beginning of the time step;
- K_3 is a washoff coefficient, in $inches^{-1}$;
- R is the runoff rate, in inches per hour; and
- ΔT is the time step, in hours.

Data Description and Management

At the time this study was done (1987), the data-management system that was used with the rainfall-runoff models did not include software for interfacing with the runoff-quality model (DR3M-qual). As a result, an earlier data-management system described by Doyle and Lorens (1982) was used.

The runoff-quality model was applied using daily rainfall, unit discharge, constituent concentrations, and estimates for precipitation quality and street-sweeping criteria. Discharge data were retrieved from WATSTORE, a U.S. Geological Survey water storage and retrieval system. The daily rainfall data were obtained from a National Weather Service gage at the Fresno airport and entered manually into the computer. Data for estimates of monthly precipitation quality and constituent loads were obtained from the Fresno NURP study.

Calibration and Verification

Storm runoff loads for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended sediment were simulated using the runoff-quality model in the lumped parameter mode. The commercial catchment is divided into three approximately equal sections--a north parking lot, a south parking lot, and the roof of the shopping center. Each parking lot was swept every other day Monday through Friday; both parking lots were swept on Sunday. The streetsweeping schedule was simulated in the model by a daily sweeping of one-third of the catchment. An estimate of 40 percent was used for the efficiency of the streetsweeper. The base residual load was estimated at 60 percent of the maximum constituent load (K_1) that could accumulate on the catchment--2.25, 0.022, 0.013, and 6.12 pounds per acre of effective impervious area for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended sediment. The rainfall-quality data used in the model are shown in table 15.

The model was calibrated and verified for the 1981-82 rain season by determining accumulation and washoff parameters K_1, K_2, and K_3, and comparing the measured and simulated storm-runoff loads. The quality model theory and calibration procedures are discussed in detail by Alley and Smith (1982b). The final values for the accumulation and washoff parameters K_1, K_2, and K_3 are shown in table 16. Measured and simulated constituent storm loads for calibration and verification, as well as the total runoff and peak discharge associated with each storm, are shown in table 17.

TABLE 15.--*Summary of average monthly rainfall-quality data used in the runoff-quality model*

Constituent	Concentration, in milligrams per liter				
	Nov.	Dec.	Jan.	Feb.	Mar.
Solids, sum of constituents, dissolved	6.0	6.0	6.7	7.5	8.9
Nitrogen, nitrite plus nitrate, dissolved (as N)	.10	.14	.09	.17	.28
Lead, total recoverable	.0051	.0065	.0030	.0023	.0058
Sediment, suspended	3.0	2.0	1.0	.5	2.5

TABLE 16.--*Calibrated values for the accumulation and washoff parameters used in the runoff-quality model*

[K_1, The maximum amount of the constituent which can accumulate on the effective impervious area, in pounds per acre; K_2, the rate constant for constituent removal, in 1/days; K_3, the washoff coefficient, in 1/inches]

Washoff or accumulation parameter dissolved	Solids, sum of constituents (as N)	Nitrogen, nitrite plus nitrate (as N)	Lead, total recoverable	Sediment, suspended
K_1	3.75	0.037	0.022	10.2
K_2	.40	.65	.24	.25
K_3	1.50	3.00	1.50	1.00

TABLE 17.--*Measured and simulated constituent storm loads for calibration and verification of the runoff-quality model*

[Total runoff: $\frac{\text{Total runoff volume (ft}^3\text{)}}{\text{Total area of catchment (acre)}} \cdot \frac{\text{12 (in.)}}{\text{43,560 (ft}^2\text{)}}$.

Storm runoff loads are in pounds per acre of effective impervious area. --, no data available]
Abbreviations: in., inches; ft^3, cubic feet; ft^3/s, cubic feet per second; ft^2, square feet]

Storm date	Total runoff (in.)	Peak discharge (ft^3/s)	Storm-runoff loads: Solids, sum of constituents, dissolved		Nitrogen, nitrite plus, nitrate (as N)		Lead, total recoverable		Sediment, suspended	
			Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
CALIBRATION										
1982										
Jan. 4	0.77	7.2	3.2	3.7	0.040	0.044	0.013	0.012	5.4	4.5
Feb. 14	.26	4.5	1.3	1.5	.025	.027	.0032	.0058	.71	2.0
Feb. 15	.46	7.9	2.2	2.0	.027	.032	.0053	.0065	1.8	2.6
Mar. 10	.28	10	1.8	1.6	.017	.036	.0052	.0061	1.9	2.2
Mar. 11	.067	3.7	.42	.50	.0094	.0071	.00065	.0011	--	.47
Mar. 25	.15	4.9	.79	.99	.021	.022	.023	.0039	1.2	1.3
Mar. 29	.21	9.5	.52	1.1	.011	.025	.0047	.0039	2.2	1.4
VERIFICATION										
1981										
Nov. 11	0.23	14	1.2	1.2	0.019	0.022	0.0061	0.0050	7.3	1.8
Dec. 29	.31	9.3	1.9	1.7	.065	.032	.011	.0076	4.3	2.5
1982										
Jan. 4	0.31	9.8	1.2	1.3	0.013	0.021	0.0047	0.0039	3.4	1.6
Mar. 9	.15	14	1.8	1.0	.030	.023	.0044	.0040	1.2	1.4
Mar. 14	.96	30	4.0	4.2	.058	.091	--	.012	--	5.1
Mar. 29	.10	12	.23	.53	.0040	.0013	.0048	.0018	2.4	.66

Error Analysis

Simulation errors for the runoff-quality model at the commercial catchment were summarized as the median absolute deviation in percent (mad) between measured and simulated values. The mad errors during calibration were 22 percent for dissolved solids, 23 percent for dissolved nitrite plus nitrate, 13 percent for total recoverable lead, and 26 percent for suspended sediment. The mad errors during verification were 20 percent for dissolved solids, 51 percent for dissolved nitrite plus nitrate, 11 percent for total recoverable lead, and 54 percent for suspended sediment. Simulation errors for calibration and verification of storm-runoff loads at the commercial catchment are shown in figure 27.

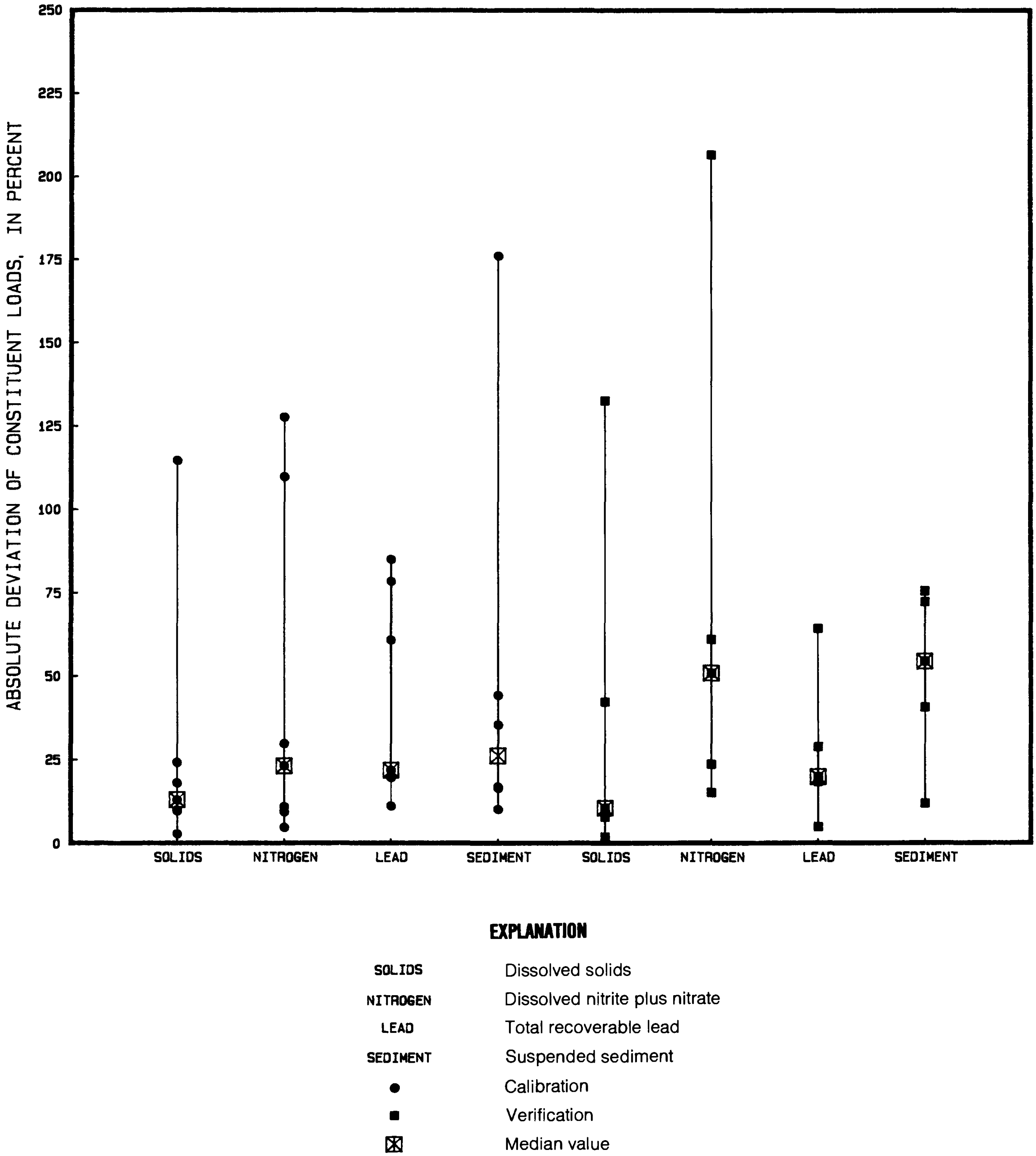


FIGURE 27. Simulation errors for calibration and verification of storm runoff loads at the commercial catchment.

Applications

Frequency Analysis of Storm-Runoff Loads

Long-term time series of annual storm-runoff loads for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended sediment at the commercial catchment were produced by using the runoff-quality model with 34 years of hourly simulated discharges as input. The discharges were simulated by entering hourly rainfall for 1948-82 to the rainfall-runoff model. Return periods for annual storm-runoff loads were determined by fitting a log-Pearson type III distribution to the time series of annual storm loads. The estimated annual storm-runoff load, in pounds per acre of effective impervious area, for dissolved solids that would occur on the average every 2 years is 41 pounds; the annual storm runoff load that would occur on the average every 100 years is 95 pounds. The 2- and 100-year storm runoff loads are 0.68 and 1.6 pounds for dissolved nitrite plus nitrate, 0.16 and 0.31 pounds for total recoverable lead, and 56 and 120 pounds for suspended sediment. The annual storm-runoff loads for return periods of 2, 5, 10, 25, 50, and 100 years at the commercial catchment are summarized in table 18.

Streetsweeping Analysis

A recent study (Pitt, 1979, p. 70) of the effectiveness of streetsweeping concluded that

> "Frequent street cleaning on smooth asphalt streets (once or twice per day) can remove up to 50 percent of the total solids and heavy metal yields of urban runoff. Typical street cleaning programs (once or twice a month) remove less than 5 percent of the total solids and heavy metals in the runoff. Organics and nutrients in the runoff cannot be effectively controlled by intensive street cleaning--typically much less than 10 percent removal, even for daily cleaning."

Because streetsweeping does not effectively reduce storm-runoff loads for nutrients and organics, only the effectiveness of streetsweeping on runoff loads for dissolved solids and total recoverable lead were studied. The effects of streetsweeping at the commercial catchment were evaluated by entering the long-term time series of discharges into the runoff-quality model with various estimates for the streetsweeping criteria--frequency of sweeping, base residual load, efficiency of the streetsweeper, and percentage of area swept.

TABLE 18.--*Annual storm-runoff loads for return periods of 2, 5, 10, 25, 50, and 100 years at the commercial catchment*

[Storm runoff loads are in pounds per acre of effective impervious area]

Constituent	Return period, in years					
	2	5	10	25	50	100
Solids, sum of constituents, dissolved	41	54	63	76	85	95
Nitrogen, nitrite plus nitrate, dissolved (as N)	0.68	0.89	1.1	1.2	1.4	1.6
Lead, total recoverable	0.16	0.19	0.22	0.26	0.28	0.31
Sediment, suspended	56	73	81	96	110	120

Because actual base residual loads were unknown, estimates of 2.25 and 1.13 pounds per acre of effective impervous area for dissolved solids, and 0.013 and 0.0066 pound per acre of effective impervious area for total recoverable lead were used. The numbers represent a base residual load of 60 and 30 percent of the maximum constituent load (K_1) that could accumulate on the catchment. K_1 was estimated to be 3.75 pounds per acre of effective impervious area for dissolved solids, and 0.022 pound per acre of effective impervious area for total recoverable lead. The inputs for area swept were either 33 percent (one parking lot) or 67 percent (both parking lots), because sweeping obviously could not occur on the roof area.

The average annual decrease of dissolved solids and total recoverable lead by streetsweeping is shown in figure 28. Figure 28A shows the percentage of the annual storm-runoff load that could be decreased by streetsweeping when the base residual load is 2.25 pounds per acre of effective area for dissolved solids and 0.013 pound per acre of effective area for total recoverable lead, and 33 percent of the catchment is swept. By using a 50-percent efficient sweeper as an example, the average annual runoff load could be decreased about 1.5 percent if the catchment were swept once a week, and about 10 percent if swept everyday. When the area swept is increased to 67 percent (fig. 28B), the annual storm-runoff loads are decreased about 2.2 percent when swept once a week, and about 14 percent when swept everyday. Figure 28C shows the effects of streetsweeping when the base-residual loads are 1.13 and 0.0066 pounds per acre of effective impervious area for dissolved solids and total recoverable lead, and 33 percent of the catchment is swept. A weekly cleaning from a 50-percent efficient sweeper would result in a 19-percent decrease. Increasing the area swept to 67 percent (fig. 28D) would result in about a 5-percent decrease of the average annual load when the catchment is swept once a week, and 27 percent when swept every day.

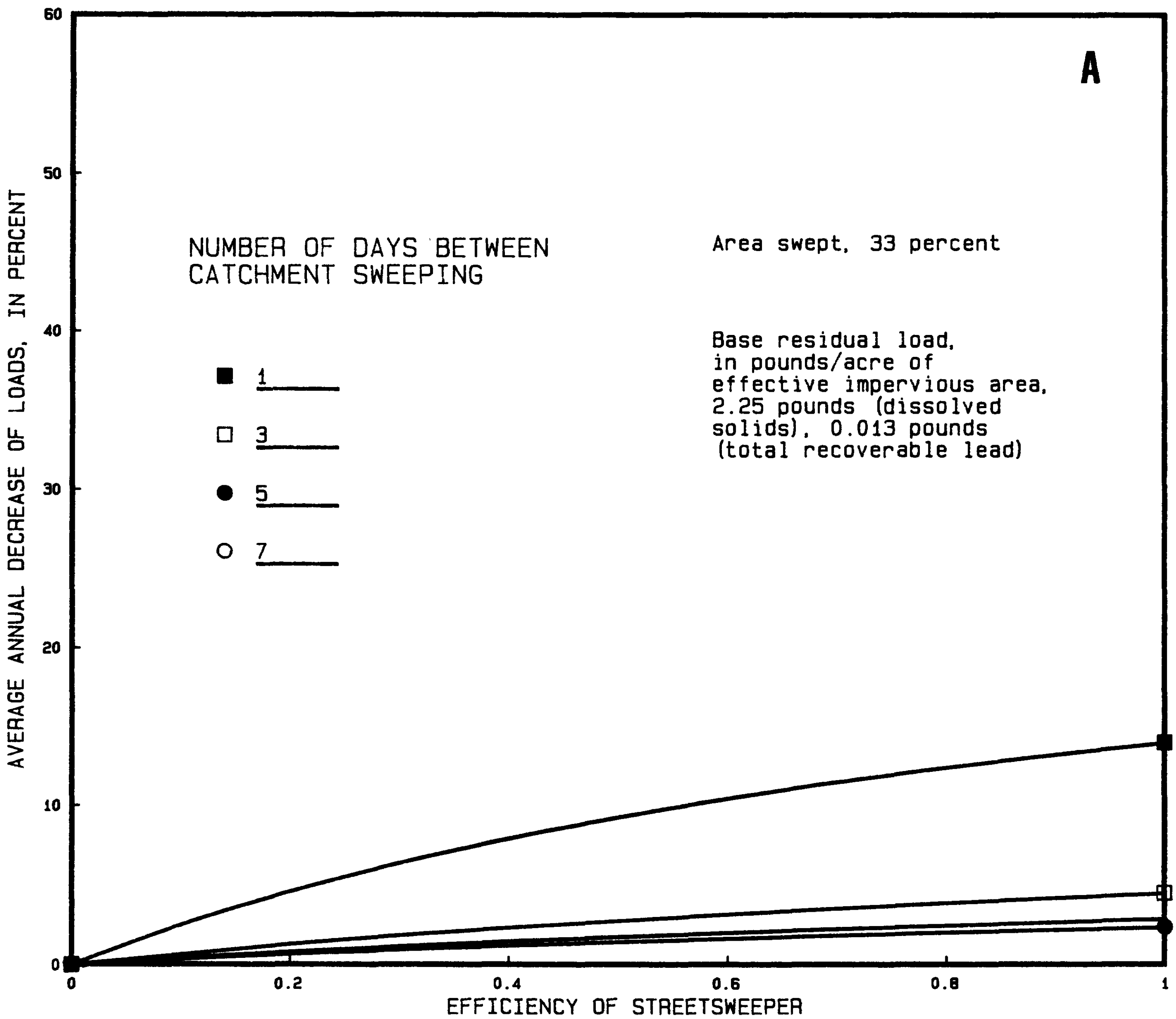


FIGURE 28. Average annual decrease of dissolved solids and total recoverable lead from streetsweeping.

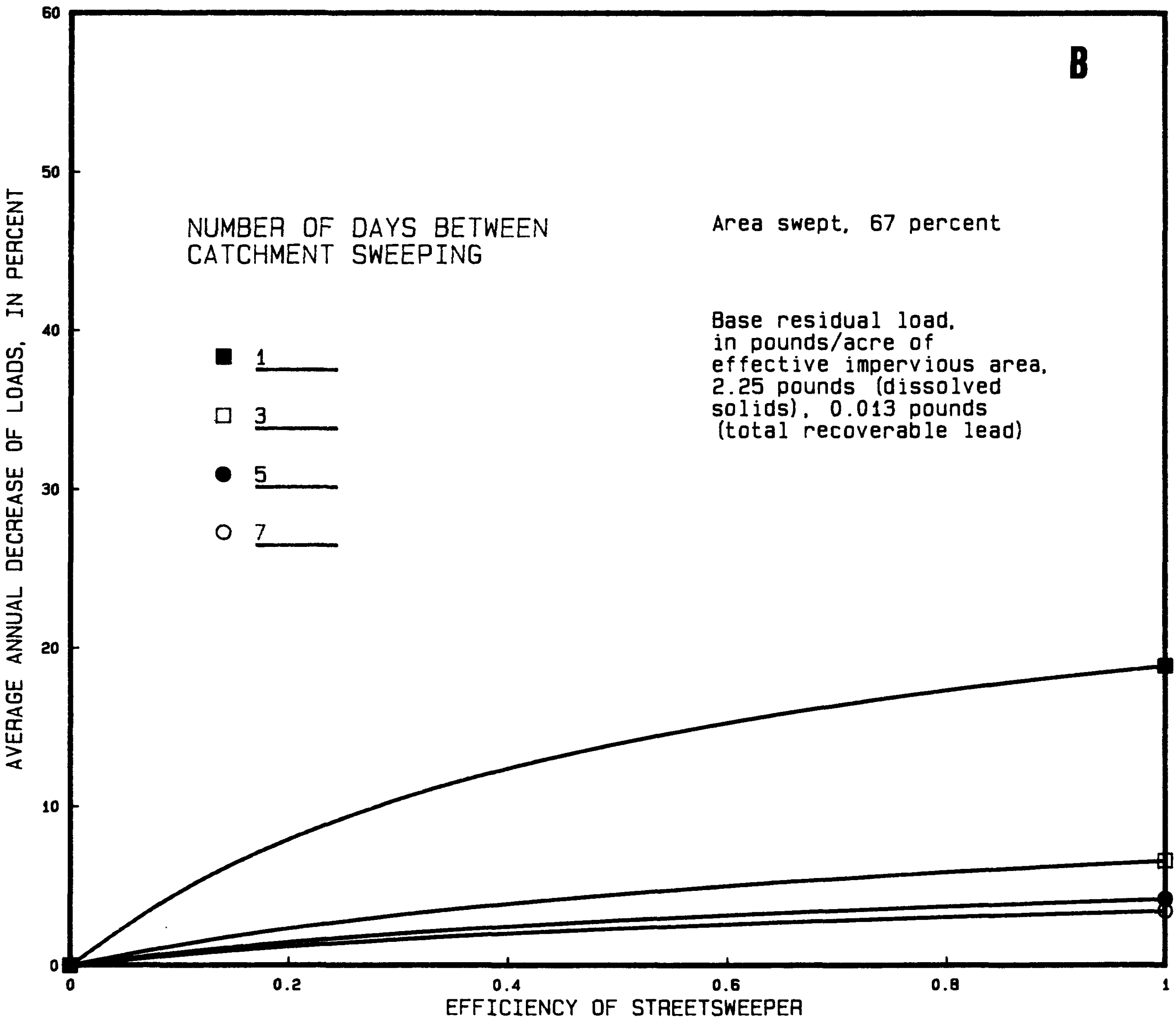


FIGURE 28. Average annual decrease of dissolved solids and total recoverable lead from streetsweeping--Continued.

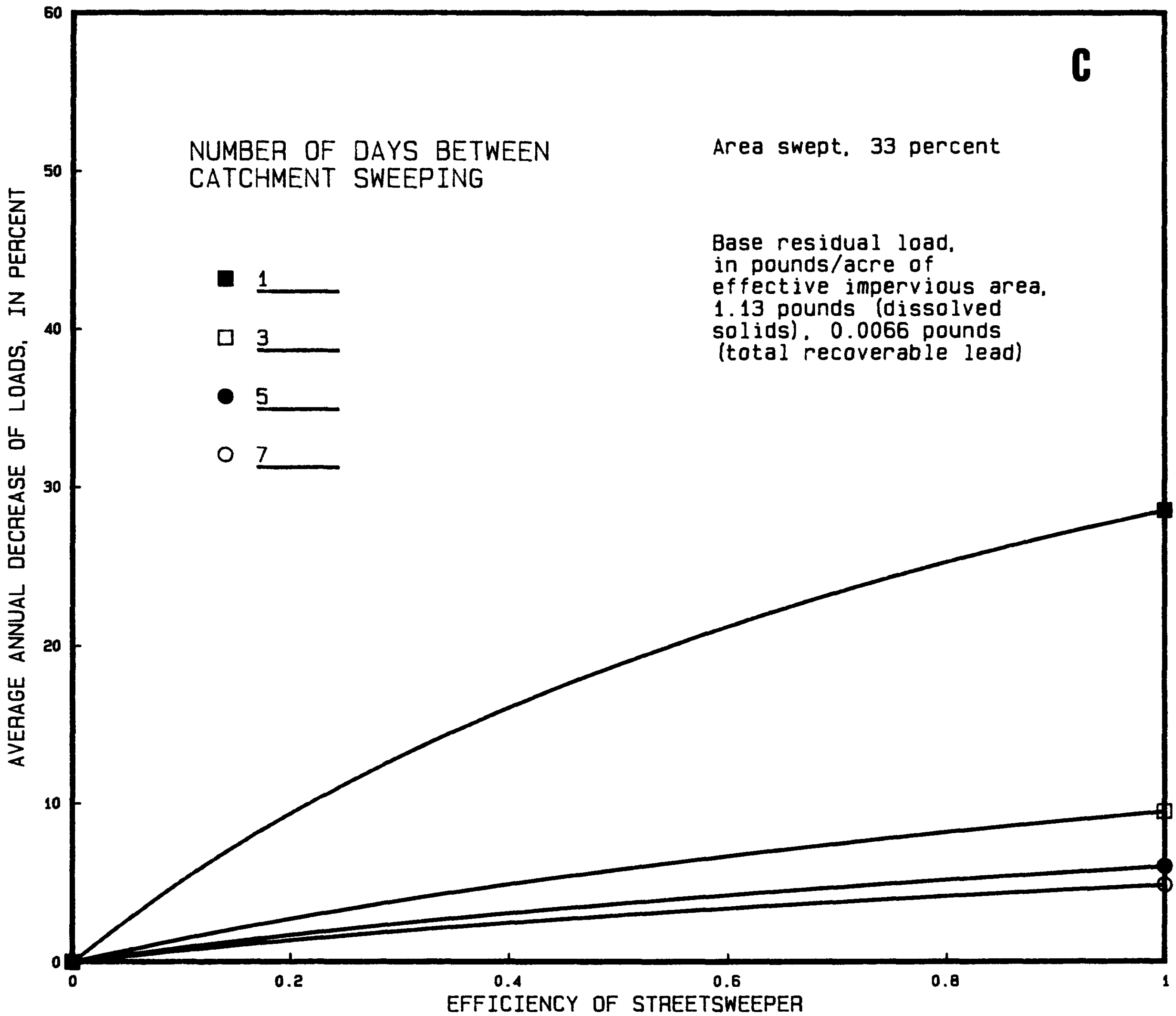


FIGURE 28. Average annual decrease of dissolved solids and total recoverable lead from streetsweeping--Continued.

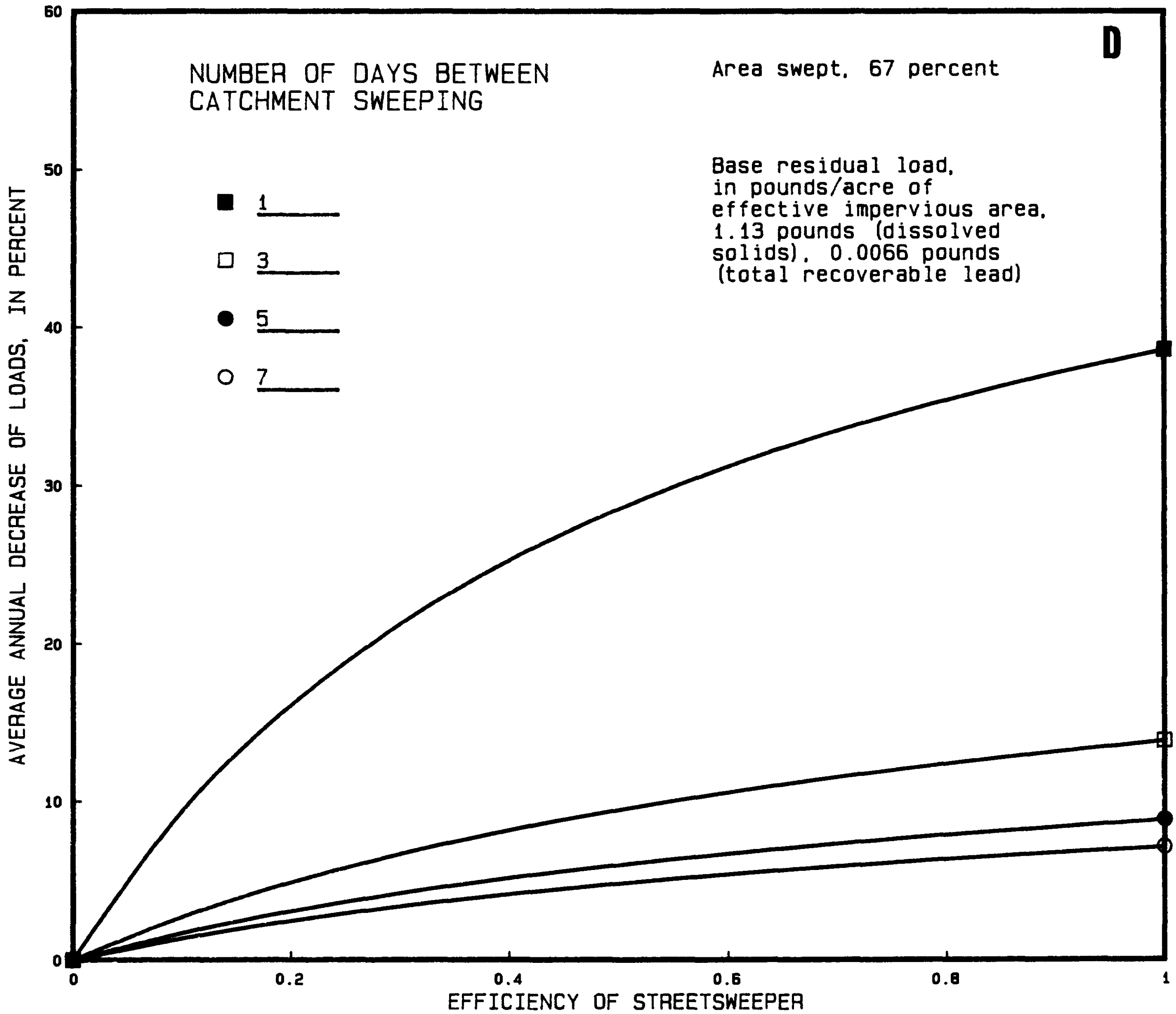


FIGURE 28. Average annual decrease of dissolved solids and total recoverable lead from streetsweeping–Continued.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey's rainfall-runoff model (DR3M-II) was applied to a multiple-dwelling residential catchment (2 applications), a single-dwelling residential catchment, and a commercial catchment. The average simulation errors for the four model applications were equal to or better than the nationwide average reported by Alley (1986). Calibration errors for runoff volumes and peak discharges for the Fresno catchments were 15 and 20 percent. Alley reported a nationwide calibration error of 19 percent for runoff volumes and 20 percent for peak discharges. The Fresno verification errors for runoff volumes and peak discharges were 14 and 18 percent; the nationwide average was 24 and 21 percent.

The storm-drain systems at each catchment were analyzed by inputing the 2-year design storm to DR3M-II. The model results then were compared to those computed by the rational formula. The rational formula method determined a 2-year discharge of 10.8 cubic feet per second at the multiple(1) catchment, 13.9 at the single catchment, and 28.6 at the commercial catchment. The rainfall-runoff models estimated 2-year discharges of 10.6, 12.5, and 28.5 cubic feet per second at the multiple(1), single, and commercial catchments.

The rainfall-runoff models showed surcharging at all three catchments for the 2-year event. The peak discharges determined by each method were similar only because the rainfall-runoff model cannot simulate flows greater than the calculated capacity of the pipes, and the runoff coefficients used in the rational formula method were too low. On the basis of measured rainfall and runoff data and field observation, the runoff from the 2-year event would probably cause little or no pressurized flow or ponding at the multiple(1) catchment, but probably would cause pressurized flow and ponding at the single and commercial catchments. Therefore, the estimated 2-year peak discharges probably are reasonable at the multiple(1) catchment, but underestimated at the single and commercial catchments.

The Survey's runoff-quality model (DR3M-qual) was used at the commercial catchment to simulate storm-runoff loads for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended sediment. The quality model simulation errors for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended sediment were 22, 23, 13, and 26 percent, respectively, for calibration; and 20, 51, 11, and 54 percent, respectively, for verification. For the level of accuracy normally expected in the runoff-quality modeling, these simulation errors are acceptable. Simulation errors in runoff-quality modeling usually are much larger than in rainfall-runoff modeling.

Hourly rainfall for 1948-82 was used with the rainfall-runoff and runoff-quality models to simulate a long-term record of annual storm-runoff loads for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended sediment at the commercial catchment. The estimated annual loads, in pounds per acre of effective impervious area that would occur on the average every 2 years, were 41 pounds for dissolved solids, 0.68 pound for dissolved nitrite plus nitrate, 0.16 pound for total recoverable lead, and 56 pounds for suspended sediment. On the basis of the simulation errors, the runoff-quality model should provide reasonable estimates of the annual storm-runoff loads for dissolved solids and total recoverable lead. The estimates for dissolved nitrite plus nitrate and suspended sediment would be less accurate.

A streetsweeping analysis also was completed for the commercial catchment. Assuming a 50-percent efficient streetsweeper as an example, annual storm-runoff loads for dissolved solids and total recoverable lead could be decreased 1.5 percent when 33 percent of the catchment was swept once a week, and base residual loads for dissolved solids and total recoverable lead were 2.25 and 0.013 pounds per acre of effective impervious area. The same streetsweeper could decrease 27 percent of the annual loads if 67 percent of the catchment is swept every day with base residual loads of 1.13 and 0.0066 pounds per acre of effective impervious area for dissolved solids and total recoverable lead. Because measured data for base residual loads and streetsweeper efficiency were not available, the effects of streetsweeping could only be estimated. If or when measured data become available, these estimates might improve. Even with daily sweeping of 68 percent of the catchment, streetsweeping seems to be ineffective in reducing storm-runoff loads.

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