Calibration of a Distributed Routing Rainfall-Runoff Model at Four Urban Sites near Miami, Florida

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(2) A 58.3-acre highway area,
(3) A 20.4-acre commercial area, and
(4) A 14.7-acre multifamily residential area.

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METRIC CONVERSIONS

Inch-pound units used in this report may be converted to metric units by the following conversion factors:

Multiply inch-pound units	By	To obtain metric units
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
inch (in.)	25.4	millimeter (mm)
square mile (mi^2)	2.590	square kilometer (km^2)
acres	0.4047	hectares (ha)

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ABSTRACT

Urban stormwater data from four Miami, Fla. catchments were collected and compiled by the U.S. Geological Survey and were used for testing the applicability of deterministic modeling for characterizing stormwater flows from small land-use areas. A description of model calibration and verification is presented for:

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OBJECTIVES AND INTRODUCTION

The purpose of this report is to present mathematical modeling results of the rainfall-runoff process for urban stormwater data collected from January 1974 to June 1978, near Miami, Fla. A distributed routing rainfall-runoff model developed by Dawdy, Schaake, and Alley (1978) was calibrated and verified for four urban sites located near Miami in Broward and Dade Counties, Fla.

The report also describes the procedures used to achieve calibration and verification. Similar study areas could be modeled following report guidelines. The four sites were:

(1) A 40.8-acre single-family residential area,

(2) A 58.3-acre highway area,

(3) A 20.4-acre commercial area, and

(4) A 14.7-acre multifamily residential area.

The location of these sites is shown in figure 1.

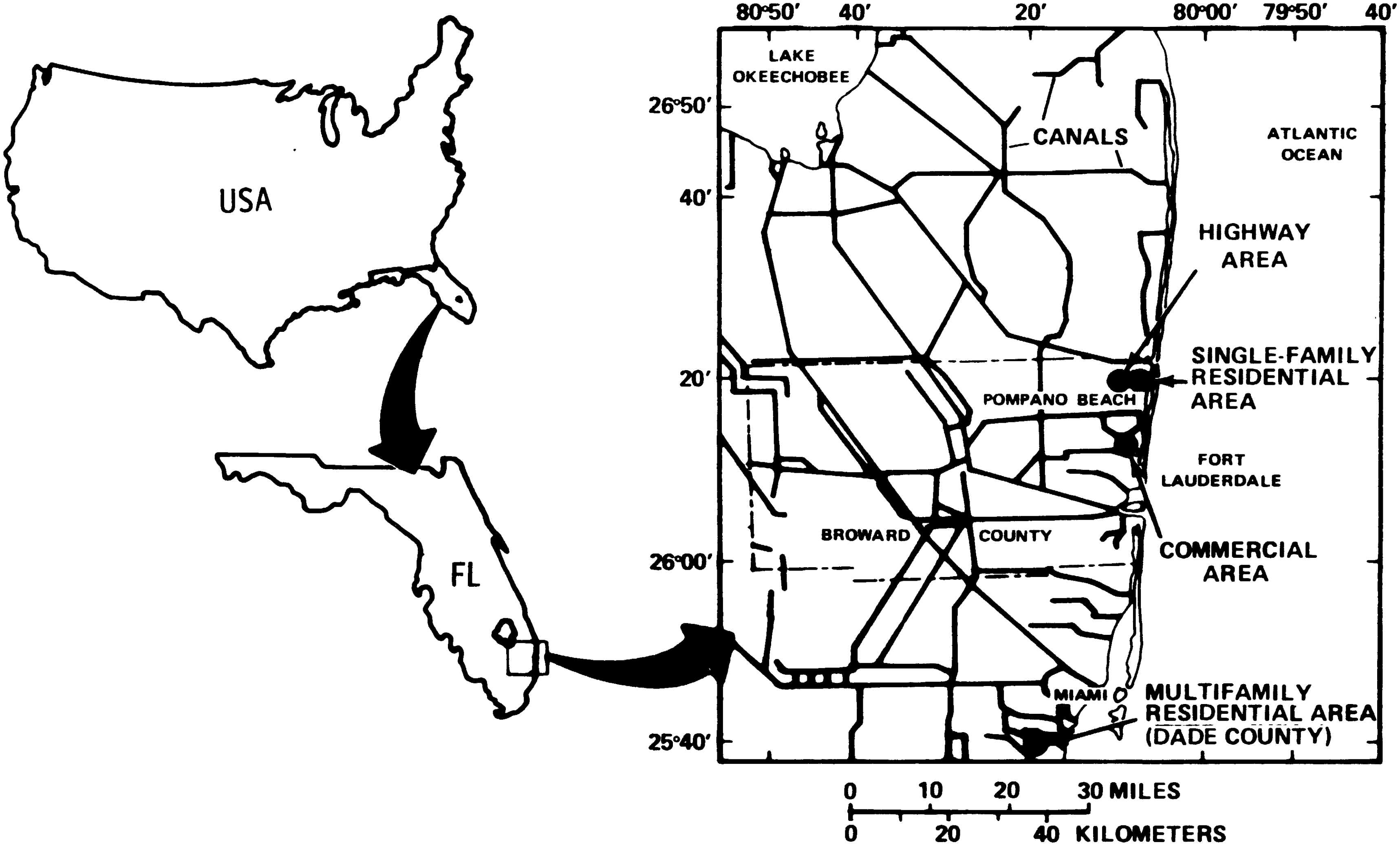

Figure 1.--Location map of four urban sites.

Rainfall-runoff data for 80, 108, 114, and 52 storms at sites 1, 2, 3, and 4, respectively, were collected and analyzed, and the results were stored on direct-access disk files. Rainfall and runoff data are available at 1-minute time intervals. This unique detailed sampling information provided a significant data base of hydrograph information for flow that was used for model calibration and verification.

DESCRIPTION OF MODEL

An urban watershed model developed by Dawdy, Schaake, and Alley (1978)--hereafter referred to as the DSA model--was adopted to route rainfall runoff to the outlet of each urban site. Modifications were made to the model (W. M. Alley, written commun., 1978) to accommodate 1-minute rainfall and runoff data recorded for these sites.

The model uses kinematic wave theory for routing flows over contributing areas through channels and (or) storm sewers that can be branched to the watershed outlet. A soil infiltration and moisture-accounting procedure (Dawdy and others, 1972) is used to determine the effect of antecedent conditions on the pervious watershed infiltration and to compute rainfall excess. The rainfall excess is then routed over pervious surfaces and two types of impervious surfaces: (1) hydraulically effective impervious areas (HEIA)--impervious areas draining directly into the channel drainage system, and (2) noneffective impervious areas (NIA)--impervious areas that drain onto pervious areas.

For a given modeling application, the drainage basin can be divided into as many as four types of segments:

(1) Overland-flow segments,

(2) Channel or pipe segments,

(3) Reservoir segments, and

(4) Nodal segments.

The DSA model was modified to accept as many as 99 total segments which provides the user a significant amount of flexibility for delineating the drainage basin. Channel segments are allowed to receive upstream inflow from as many as three segments, including any of types (2) to (4). In addition, a channel or pipe segment can receive uniformly distributed lateral inflow from overland-flow segments. The overland-flow segments receive uniformly distributed lateral inflow from excess precipitation. The model provides the option to use two types of reservoir routing (not tested in this report)--linear-storage routing or modified-Puls routing. It can also accept two types of nodal segments. These are junctions and input hydrographs.

Kinematic wave theory using a finite-difference solution scheme is applied to overland flow and channel or pipe routing. Kinematic wave equations are an approximation of the St. Venant equations in which the dynamic effects of flood wave movement are neglected. In this approximation the friction slope is assumed equal to the channel slope.

Pipe flow in the model is limited to nonpressurized flow. When the runoff is greater than the capacity of nonpressurized pipe flow, the excess water is stored and later released when the runoff is less than this capacity.

CALIBRATION AND VERIFICATION OF THE MODEL

Highway Site

The same procedure for calibrating and verifying the DSA model was utilized at each of the four sites. For continuity, the following detailed discussion will pertain only to the 58.3-acre highway site. Later sections of this report will summarize calibration and verification results for the other sites. The highway basin contains a 3,000-foot highway section and is 36 percent impervious (21 acres) and 64 percent pervious (37 acres). The impervious area includes 14 acres of roads and 1 acre of roof tops.

Data Management System

Rainfall and stage data were recorded at the highway site for the period April 1975 through July 1977. Discharge was computed from two stage readings in a U-shaped constriction and recorded using an urban-hydrology monitor at the site (Smoot and others, 1974). During the period of record, 397 rain storms were recorded at 36-second sampling intervals. Of these, data for 108 were digitized and stored in a data-management system at 1-minute intervals. Storms selected for computer storage generally exceeded 0.10 in. rainfall. Water-quality samples were obtained for 42 of the 108 storms, and these data are also stored in the data base.

The quality of the data was generally good. However, the following problems could be sources of error: (1) The discharge rating in the constriction at the outlet for the transition between open-channel flow and pressure flow is not well defined. This produces slightly questionable discharges in the 25 to 35 ft^3/s range. (2) Delineation of contributing drainage areas was difficult because of the flat topograpy, however, a field reconnaissance was made at all sites and the best values obtained.

A data management system was developed to store, edit, and retrieve the data collected in the Miami urban studies (Wilson and others, 1978). The data base, currently comprising 834 IBM[1/] 3350 disk tracks, is a random access file (360/370 direct access) designed as a user-oriented file for use with Fortran programs. Figure 2 shows the activity flow associated with acquiring model calibration and verification data from the data base.

[1/] The use of the brand name in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

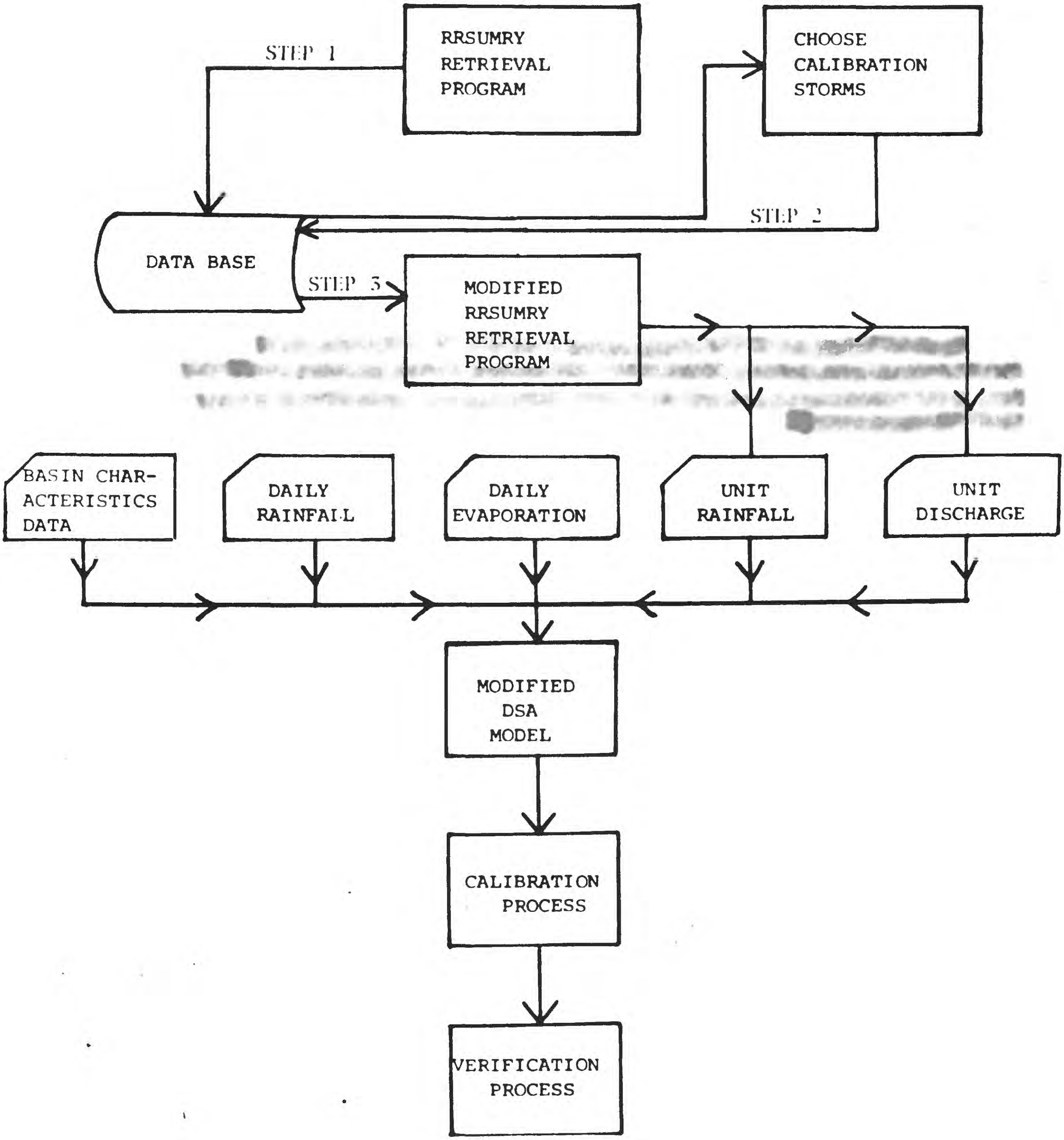

Figure 2.--Flow chart of model calibration and verification processes for Miami urban sites.

Rainfall and Soil-Moisture Analysis

A retrieval program "RRSUMRY", part of the data management system, was used to retrieve individual storm data for all 108 storms stored for the highway site. The retrieval format "RRSUMRY" generates (fig. 3) provides data needed to evaluate the storm. The observed rainfall (inches) versus the observed runoff (inches) were plotted (fig. 4). The graph was used as a guide for selecting a range of storms to use for an initial calibration data set. The number of storms selected was based upon how many the model could analyze during a run and also the total number of available storms. Twenty-eight representative storms were chosen. These included storms with rainfall ranging from 0.22 in. to 3.02 in. The observed peak discharge for these storms ranged from 0.32 to 43.9 ft^3/s.

The slope of the runoff versus rainfall relation (fig. 4) for storms having less than 1.5 in. of rainfall was 0.18. The total HEIA was estimated as 10.5 acres or about 18 percent of the total highway basin area. This implies that the HEIA is the source for a large percentage of the runoff for most storms which have rainfall up to 1.5 in. (Miller, 1978).

Antecedent soil-moisture conditions affect the actual runoff amount. A detailed analysis of the soil-moisture accounting process using observed rainfall and runoff data indicated that in addition to impervious runoff, pervious areas contributed some rainfall excess under certain antecedent conditions. The analysis resulted in initial estimated values for the seven soil-moisture-accounting parameters (table 1). The data (table 2) indicated a highly porous, rapidly infiltrating soil. Consequently, pervious surfaces yield little overland runoff for most storms with rainfall less than 1.5 in. if there were 3 or more days prior to a storm without any appreciable rainfall. This is considered typical of soil types prevalent in the study areas (R. A. Miller, oral commun., 1978).

Rainfall in any amount and intensity can occur at any time during the year in the Miami area. This creates wide fluctuations in antecedent soil-moisture conditions in the study area. Storm data illustrated that many storms were a part of very complex storm systems and not isolated events with preceding long dry periods. Runoff periods plotting near the 18 percent slope line of figure 4 represent drier conditions, and the resulting scatter of the data about the line verifies a fluctuating antecedent soil-moisture situation. Scatter at the low end is caused (in part) by the changing impervious retention while overall scatter is also the result of errors in precipitation and flow measurements.

There are two recording rain gages in the highway basin. One gage operated satisfactorily for all storms, while the other malfunctioned for many of the storms. An automobile ran into the problem-plagued gage in June 1976 and destroyed it. Therefore, rainfall data from only one gage were used as model input for all highway site storm simulations. This probably induced no additional error into the results because the two gages were in close proximity and when both gages were functioning, little areal variation in rainfall was observed.

SITE NO: 2
STORM NO: 29

STATION ID: 261629080072400 FROM MON DAY YR HR MN 10 -14 -75 13:15 TO MON DAY YR HR MN 10 -14 -75 16:0

NOTE: ***RAINFALL AND RUNOFF IN INCHES, DISCHARGE IN CUBIC FEET PER SECOND
TIME INTERVAL OF BASIC DATA: 1.0 MINUTE(S)
PRINT INTERVAL: EVERY 5 MINUTES

TIME	DISCHARGE	ACCUMULATED RUNOFF	RAINFALL GAGE 1	ACCUMULATED RAIN 1	RAINFALL GAGE 2	ACCUMULATED RAIN 2	RAINFALL GAGE 3	ACCUMULATED RAIN 3
13:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13:20	1.55	0.00	0.28	0.28	0.30	0.30	0.00	0.00
13:25	4.09	0.01	0.12	0.40	0.12	0.42	0.00	0.00
13:30	4.88	0.01	0.03	0.43	0.08	0.50	0.00	0.00
13:35	3.65	0.02	0.10	0.53	0.06	0.56	0.00	0.00
13:40	3.36	0.02	0.00	0.53	0.00	0.56	0.00	0.00
13:45	3.09	0.03	0.00	0.53	0.00	0.56	0.00	0.00
13:50	2.57	0.03	0.00	0.53	0.00	0.56	0.00	0.00
13:55	2.57	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:00	1.36	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:05	0.88	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:10	0.47	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:15	0.47	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:20	0.32	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:25	0.23	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:30	0.19	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:35	0.15	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:40	0.15	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:45	0.11	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:50	0.08	0.04	0.00	0.53	0.00	0.56	0.00	0.00
14:55	0.02	0.04	0.00	0.53	0.00	0.56	0.00	0.00
15:00	0.00	0.04	0.00	0.53	0.00	0.56	0.00	0.00

INCHES OF RUNOFF = 0.04
RUNOFF PERCENT, GAGE 1 = 8.05
GAGE 2 = 7.62
GAGE 3 = 0.00

Figure 3.--Format of "RRSUMRY" retrieval printout.

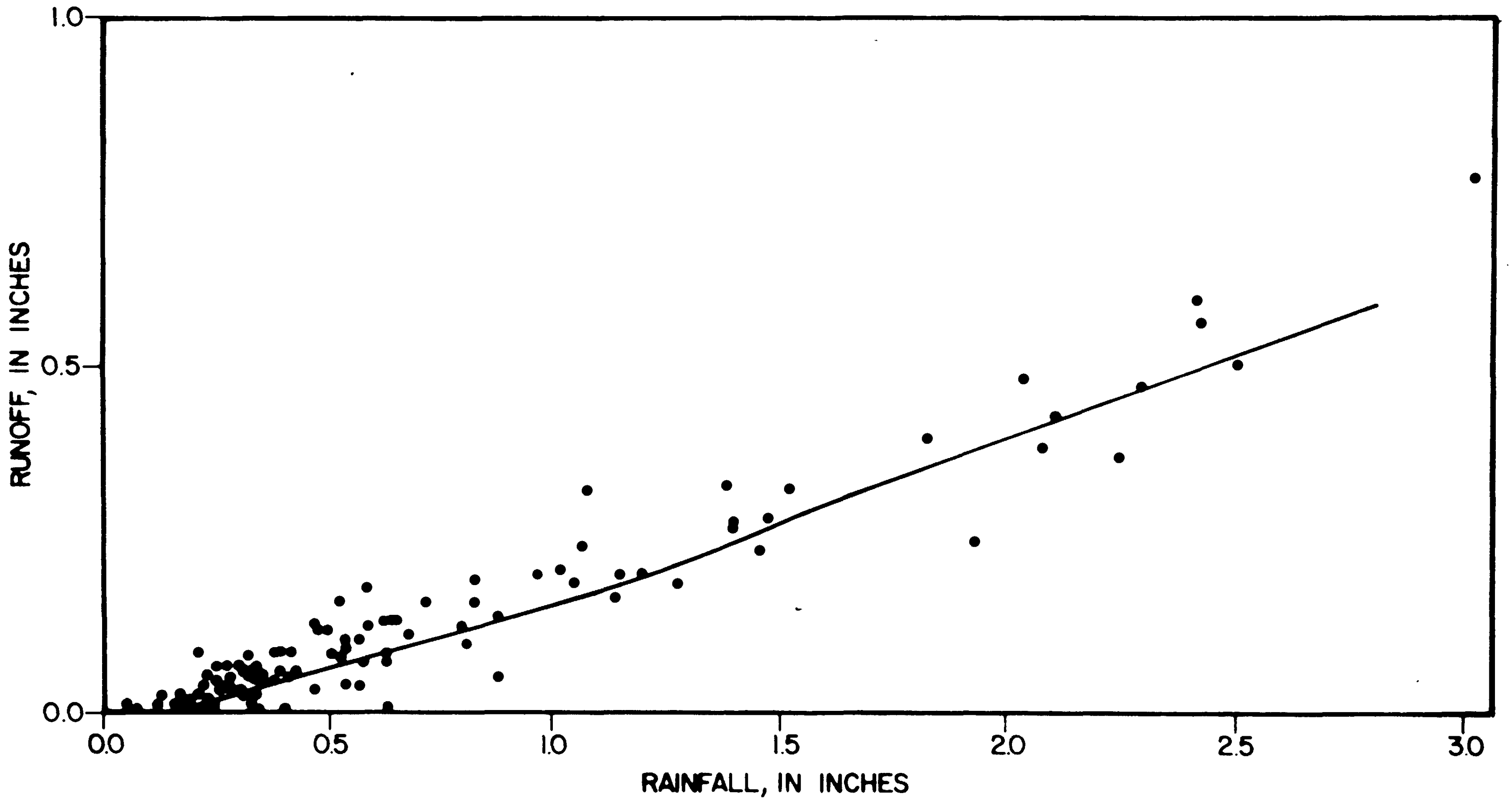

Figure 4.--Rainfall-runoff relation for highway site.

Table 1.--Parameters for soil-moisture accounting and infiltration

Soil-Moisture Accounting
Parameters:
DRN--A constant drainage rate for redistribution of soil moisture, in inches per day
EVC--A pan coefficient for converting measured pan evaporation to potential evapotranspiration
RR--The proportion of daily rainfall that infiltrates into the soil
BMSN--Soil-moisture-storage volume at field capacity, in inches
Infiltration
Parameters:
KSAT--The minimum (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 wetted front for soil moisture at field capacity, in inches of pressure

Table 2.--Parameter values for soil-moisture accounting and infiltration at the highway site

Parameter symbol	Range of values		Initial estimate	Optimized value
	Lower limit	Upper limit		
DRN	0.1	1.0	0.90	0.90
EVC	.5	1.0	0.90	.99
RR	.65	1.0	0.90	.71
BMSN	1.0	15.0	14.0	9.3
KSAT	0.01	1.0	0.9	.99
RGF	5.0	20.0	19.0	19.99
PSP	1.0	15.0	14.0	14.8

Input Data Requirements

The next step (see fig. 2), after selection of calibration storms, was to use a modified "RRSUMRY" program to retrieve the 1-minute unit-rainfall and unit-discharge data for each storm. Unit data refers to data collected or measured at specified intervals, for example, 1-minute, 5-minute, and so forth. This program produces 80-column data cards in the format required by the model. Daily rainfall and evaporation data for the entire period were retrieved from the data base by interface computer programs and used in the moisture-accounting routine of the model.

Figure 5 shows segmentation of the basin into 35 contributing areas. The areas ranged in size from 0.175 acres (CA-3) to 8.611 acres (CA-27). Table 3 lists the total, pervious, impervious, and hydraulically effective impervious areas for each contributing area. Figure 6 shows the impervious area of each subarea. Also available were topographic and drainage maps for the basin plus a sewer map documenting pipe lengths, diameters, and slopes. The model requires individual segment data that were obtained from these maps. Table 4 lists pipe lengths, diameters, and slopes used in the calibration.

Physical Representation of the Basin in the Model

The model will allow differentiation of the basin into as many as 99 segments. Three different sets of segments were used for the highway-site drainage area. One analysis employed a 10-segment representation; another, 25 segments; and a final analysis, 76 segments. The segments included all components of the system, such as overland flow segments, pipe or channel segments, and also junctions. There are no detention reservoirs in the drainage system. The effort associated with describing the basin in the analyses increased proportionally as the number of segments increased. Also, computer costs for the 76-segment representation were about three times the cost of the 25-segment representation. In general, the 25-segment analysis produced the best results, with the 76-segment analysis being the poorest. Figure 7 shows the 25-segment representation of the basin as chosen for general use in calibration and verification runs. Flow direction is indicated by the arrowhead symbols. Figure 7 also shows an expanded view of the model representation of pipe 7 and catchments J and G.

Calibration Option

The model has a calibration option to adjust the soil-moisture and infiltration parameters for drainage basins having observed rainfall-runoff data. The method of determining optimum values is based on an optimization technique devised by Rosenbrock (1960). The model will optimize any or all of seven soil-moisture accounting parameters using data for designated storms. All seven parameters were optimized for the 28 storms included in the calibration process. Because of the data measurement errors encountered and the relative unimportance of pervious area runoff, especially for smaller rainfall amounts, the optimization

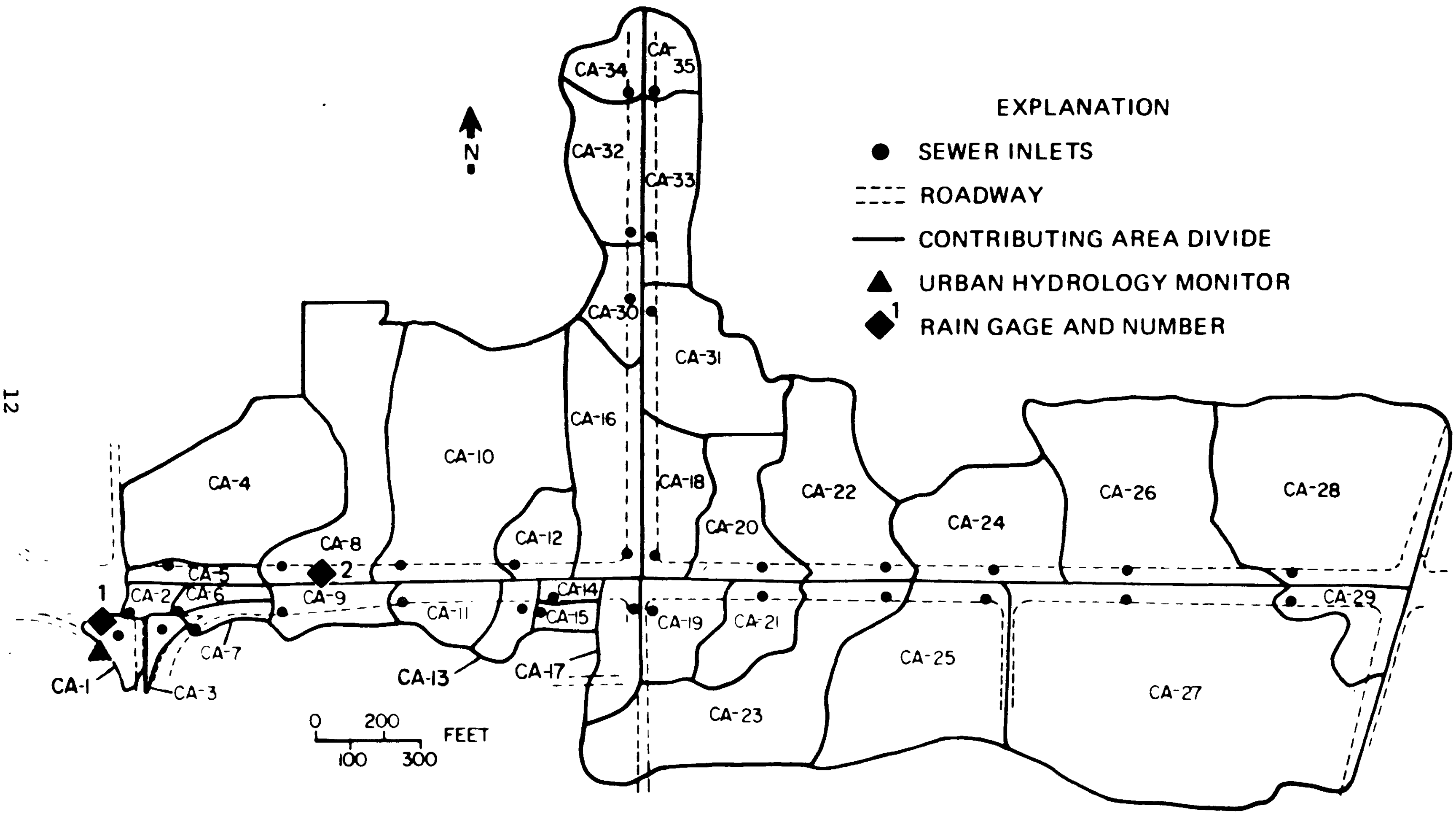

Figure 5.--Contributing areas (CA) map of highway site.

Table 3.--List of impervious, pervious, effective impervious, and total areas for highway site

Designation	Total area	Pervious area	Impervious area	Effective impervious area
CA-1	0.387	0.320	0.067	0.000
CA-2	.221	.095	.126	.126
CA-3	.175	.175	.000	.000
CA-4	3.387	2.517	.870	.000
CA-5	.341	.059	.282	.282
CA-6	.239	.105	.134	.134
CA-7	.212	.061	.151	.121
CA-8	2.713	1.466	1.247	.249
CA-9	.683	.325	.358	.358
CA-10	4.799	3.158	1.641	.372
CA-11	.710	.473	.237	.222
CA-12	.719	.569	.150	.150
CA-13	.443	.314	.126	.126
CA-14	.193	.055	.138	.138
CA-15	.239	.171	.068	.034
CA-16	2.058	1.361	.697	.617
CA-17	.738	.184	.554	.492
CA-18	1.118	.155	.963	.543
CA-19	.941	.637	.304	.273
CA-20	1.329	.506	.823	.490
CA-21	0.941	.789	.152	.152
CA-22	2.427	2.008	.419	.240
CA-23	3.452	1.742	1.710	.591
CA-24	2.196	1.856	.340	.340
CA-25	3.313	2.198	1.115	.502
CA-26	3.876	3.113	.763	.519
CA-27	8.611	5.335	3.276	.749
CA-28	4.753	3.221	1.532	.844
CA-29	0.876	.146	.730	.526
CA-30	.646	.400	.246	.215
CA-31	1.993	1.238	.755	.302
CA-32	1.209	.868	.341	.279
CA-33	1.238	.627	.611	.397
CA-34	.572	.508	.064	.038
CA-35	.507	.366	.141	.113
Totals	58.255	37.121	21.131	10.534
Percentage	100.0	63.7	36.3	18.08

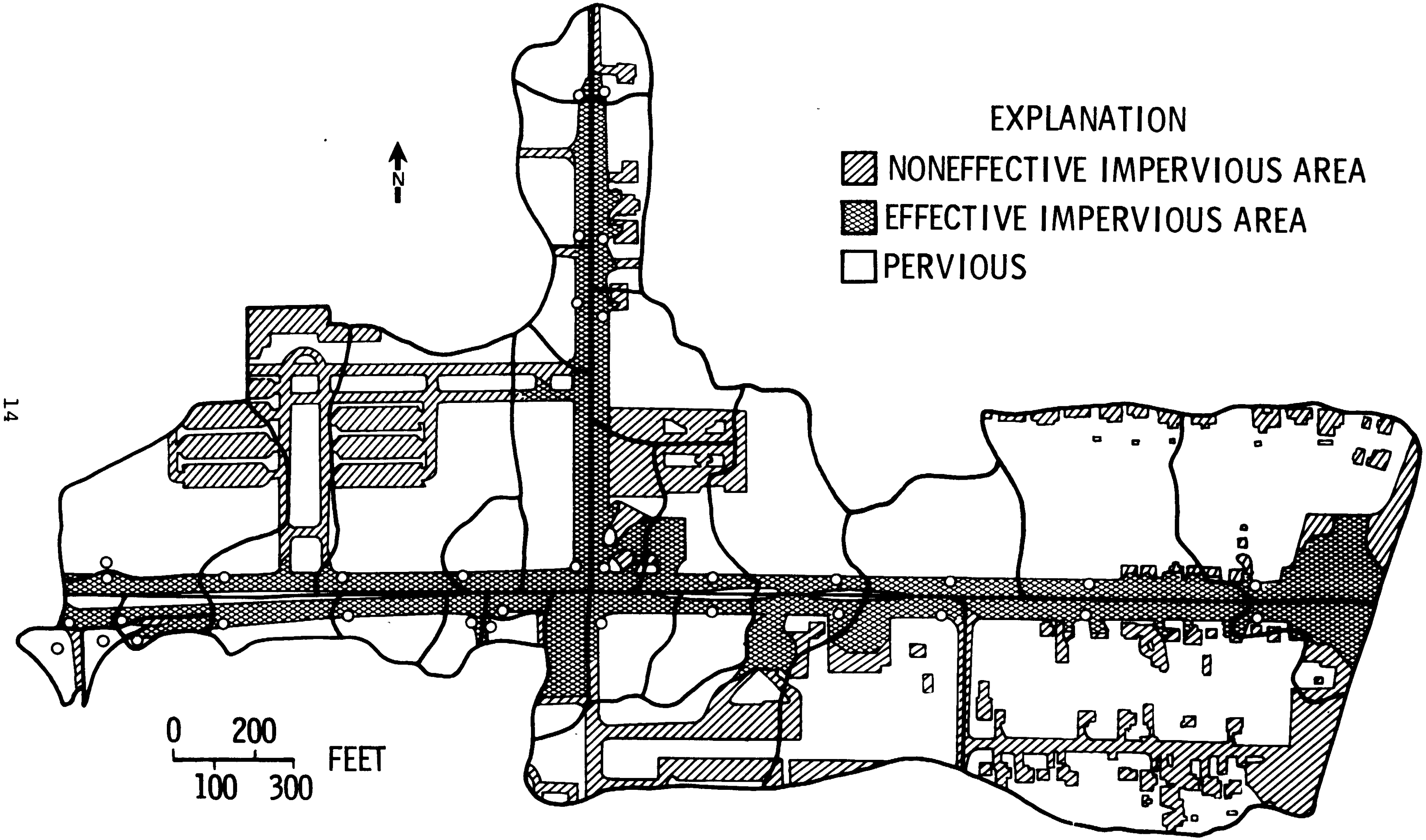

Figure 6.--Impervious and hydraulically connected impervious area of the highway site.

Table 4.--Highway site pipe-segment information

Segment	Length (ft)	Slope (ft/ft)	Diameter (ft)
P003	400	0.001	2.0
P004	350	.001	2.5
P005	250	.001	3.0
P006	600	.001	3.0
P007	810	.003	1.25
P008	390	.005	2.0
P009	555	.005	3.5
P010	660	.005	3.5
P011	55	.008	3.5
P012	25	.003	3.5

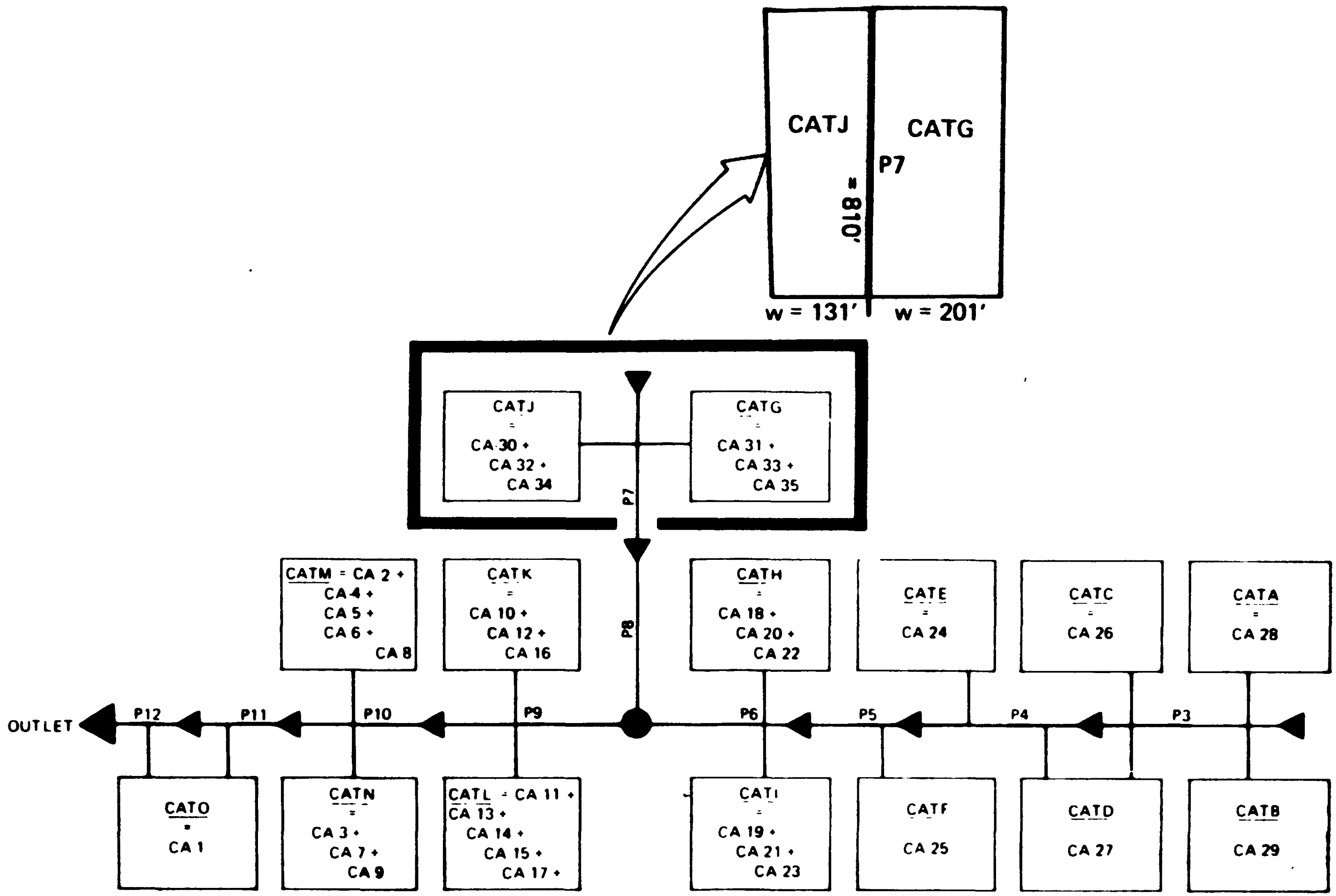

Figure 7.--Twenty-five segment representation of highway site and expanded view of the model representation of pipe 7 and catchment J and catchment G.

technique in the model was difficult to apply in the studied urban areas. The optimization results are significantly affected by the particular storms used. The sensitivity of the soil-moisture-accounting parameters determined in the optimization may be highly related to one event in which there is a significant data measurement error. The resulting soil-moisture-accounting parameters may not reflect the overall pervious area basin characteristics for most storms (Dawdy and others, p. B23, 1972).

The 28 calibration storms covered a range of antecedent conditions and rainfall-runoff events as suggested by Dawdy, Lichty, and Bergmann (p. B23, 1972). Thus, optimizing on all storms produced parameter values averaged over all antecedent conditions and data measurement errors. These values should fit average antecedent conditions closely, but large errors may result for simulation of some storms, particularly where antecedent soil-moisture conditions are highly variable. This condition was experienced during the calibration phase for the highway site when the model failed to adequately simulate the outflow hydrographs for some of the storms with unusually dry or wet antecedent conditions. The final set of seven soil-moisture accounting and infiltration parameters was used in all remaining runs.

Discussion of Calibration Results

The impervious area of the contributing areas is a measured and not an optimized value in the model; however, simulated runoff volumes and peaks can be grossly in error if incorrect estimates of imperviousness are used. The detailed delineation of pervious and effective and noneffective impervious areas (fig. 6) established fairly reliable estimates for this analysis. Therefore, the error in reproducing runoff volumes and peaks will probably depend to a large extent on chosen slopes, roughness coefficients, and impervious retention. These are the remaining parameters that can be adjusted within a reasonable range during calibration.

The DSA model will print out the outflow hydrograph for any designated section in the drainage system. During one of the calibration runs, a detailed output showed initial flow components occurring simultaneously at almost all segments and corresponded proportionately to the delineated HEIA of each segment. For example, an overland-flow segment with four times the HEIA of another segment produced four times the runoff initially as the smaller area.

Simplifications required by the model result in a few conceptional problems. The model assumes uniformly distributed lateral inflow from the overland-flow segments into the storm sewer system. However, in reality, overland flows are nonuniformily distributed and are rerouted through sewer inlets into the pipes. Also, flow in the pipe may be controlled by the inlets which restrict flow into the sewer to less than full-pipe flow. In addition, a storm sewer flowing under pressure has a greater discharge capacity than the flow predicted using kinematic wave theory.

Excellent pipe-slope and geometry data were available for most of the sewer system. A roughness coefficient of 0.012 was used for all pipes. Overland-flow roughness coefficients and slopes were varied until an acceptable simulation of outflow volumes and peaks was obtained. An overland-flow roughness coefficient of 0.015 was selected to represent each contributing area. Actual field overland roughness values for urbanized areas are usually about 0.02. An average overland slope of 0.027 produced the best calibration. This value is greater than field values derived from topographic maps which showed slopes varying from almost flat to about 0.01. The greater model overland slope values were necessary to compensate for the assumptions of kinematic-wave-routing theory. This theory neglects momentum effects which are important in cases where flow occurs on mild slopes. With mild slopes it is not likely that uniform flow exists where the friction slope, bed slope, and water-surface slope are all parallel.

Table 5 lists summary statistics for the 28 storms used to calibrate the DSA model at the highway site. The time interval (column 3) is expressed in 1-minute units which are counted from midnight (zero) to the beginning and end of the storm period. For example, a single storm beginning at 2 p.m. and lasting until 4 p.m. would have a time interval from 0840 to 0960. However, if the same storm occurred during the second day of a multisequence storm, the corresponding time intervals would originate on the first day and are computed by adding 1440 (that is, 60 x 24) to 0840 and 0960. Standard error of estimates (SEE) for computed volumes and peaks for all storms were 0.060 in. and 7.020 ft^3/s, respectively. No storms were dropped from the optimization process even though storms 2 and 9 appear to be anomalies (occurring after a very dry 2-month period).

Figure 8 shows the four best calibration storms, both observed (or measured) and simulated data. These storms cover a range of expected events, and include single peak small storms and more complex multipeak storms. After the initial calibration runs, acceptance criteria for further calibration and verification analyses were set as follows:

(1) Hydrograph timing--simulated peaks, rising limbs, and recessions occurring within several minutes of measured hydrographs.

(2) Hydrograph shape--approximately the same width and height as measured data.

(3) Runoff volume--within 50 percent of measured values if simulated less than measured and within 100 percent of measured if simulated greater than measured.

(4) Peak discharge--same criteria as stated for runoff volumes.

Model calibration at the highway site produced only 4 storms, 2, 9, 29, and 32 that were unacceptable. This amounts to 14 percent of the 28 calibration storms. Although hydraulically effective impervious area probably varies with storm size, the model uses one value for each

Table 5.--Model calibration results--highway site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
2	05-05-75	1170-1380	0.22	0.007	0.031	+343	0.32	2.65	+728
9	05-29-75	0810-0960	.88	.052	.155	+198	4.72	21.61	+358
11	07-14-75	0755-0870	.21	.029	.028	- 3	3.65	3.48	- 5
20	08-20-75	1302-1440	.30	.031	.047	+ 52	3.65	5.96	+ 63
21	08-21-75	2000-2220	.57	.071	.095	+ 34	7.03	9.30	+ 32
22	08-23-75	0947-1140	1.20	.202	.212	+ 5	18.74	22.62	+ 21
26	09-17-75	0850-1020	.41	.090	.067	- 25	8.64	4.59	- 47
29	10-14-75	0795-0960	.53	.043	.091	+111	4.38	11.19	+129
32	10-22-75	0555-0660	.33	.029	.053	+ 83	3.22	6.87	+113
34	10-31-75	0373-0480	.40	.051	.066	+ 29	5.22	9.64	+ 85
46	05-23-76	0680-0993	.83	.162	.144	- 11	14.04	11.75	- 16
47	05-28-76	0960-1380	2.25	.366	.405	+ 11	23.69	26.74	+ 13
48	05-29-76	2445-2640	2.04	.483	.376	- 22	36.99	24.78	- 33
49	05-29-76 to 05-30-76	2750-2940	.50	.088	.080	- 9	7.22	7.35	+ 2
51	06-07-76 to 06-08-76	1334-1560	.64	.137	.110	- 20	11.79	8.92	- 24
60	06-25-76	0240-0540	.62	.086	.106	+ 23	8.43	6.61	- 22
76	10-10-76 to 10-11-76	1320-1860	2.42	.559	.441	- 21	34.28	31.04	- 9
78	11-02-76 to 11-03-76	1265-1830	2.42	.595	.441	- 26	18.16	10.26	- 43

Table 5.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
81	12-06-76	0150-0360	0.25	0.065	0.033	- 49	4.09	2.62	- 36
82	12-06-76	0450-0660	.32	.080	.049	- 39	8.43	5.02	- 40
83	12-13-76 to 12-14-76	1170-1560	2.50	.500	.460	- 8	37.73	30.04	- 20
87	01-15-77	0540-0990	1.83	.397	.335	- 16	22.73	16.79	- 26
92	04-13-77	0841-1160	1.14	.170	.200	+ 18	12.04	12.12	+ 1
111	04-13-77 to 04-14-77	1185-1560	3.02	.697	.555	- 20	43.90	24.65	- 44
94	05-04-77	0670-1170	2.08	.383	.372	- 3	17.87	14.40	- 19
95	05-05-77	1710-1860	1.40	.275	.256	- 7	39.38	28.18	- 28
102	06-01-77 to 06-02-77	0960-1530	1.48	.283	.255	- 10	22.41	14.78	- 34
106	06-09-77	0740-1040	1.50	.275	.274	- 0	16.94	18.35	+ 8

28 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.060 in.	9 1/	40.7 1/	17 1/	17.0 1/
Computed peaks	7.020 ft^3/s	10 1/	46.7 1/	16 1/	27.8 1/

1/ Without storms 2 and 9.

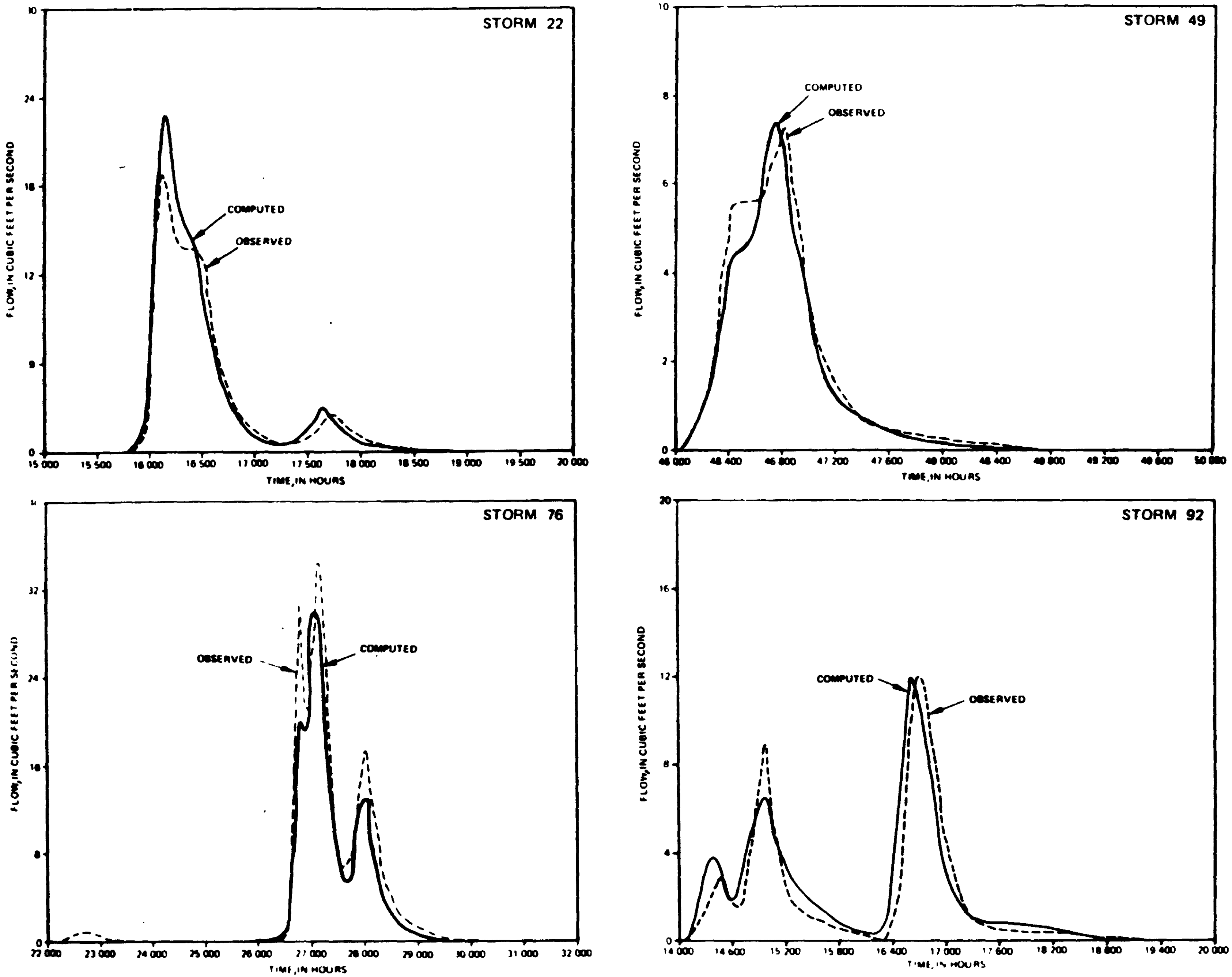

Figure 8.--Calibration storms for site 2, highway site.

overland flow segment. This factor plus possible data measurement errors could be factors in rejecting these four storms. The larger storms produced the best simulation results in spite of possible discharge-rating errors. This implies that after soil-moisture requirements are satisfied, the model reproduces the outflow within the limits of the criteria given for acceptance. Also, larger storms tend to yield more uniform rain over the basin.

Verification of Model

Twenty storms were used for verification. These storms were selected because they also varied from small to large size storms. A preliminary verification analysis resulted in a recalibration of the model. The recalibration involved adjustments made to the overland roughnesses and slopes and pipe slopes so that better results would be obtained for model simulations. Thus, the verification data set influenced the recalibration process, thereby no longer providing a completely independent verification of the model. However, the analysis made on the remaining 59 storms in the data base did provide an independent verification. After "fine tuning" the model, the SEE for verification storm volumes and peaks for the 20 selected storms were 0.054 in. and 10.406 ft^3/s, respectively (table 6). Figure 9 shows six of the verification storms that were simulated.

Table 7 presents results for the remaining 59 storms collected at the highway site. The SEE for volumes and peaks were 0.086 in. and 5.791 ft^3/s, respectively. Figure 10 shows 11 of the 59 storms for which the best simulation results were obtained. Results for twelve storms were unacceptable which equals 20 percent of the 59 storms. The percentages of unacceptable results went from 14 to 20 percent as simulations progressed from the calibration to the verification phase. This is indicative of true modeling error as one goes from calibrating to verifying a model.

SINGLE-FAMILY RESIDENTIAL SITE

Physical Representation of the Basin in the Model

Figure 11 shows the segmentation of the 40.8-acre basin into 17 contributing areas. The areas ranged in size from 0.029 acres (CA-14) to 12.149 acres (CA-1). Table 8 lists for each contributing area the total, pervious, impervious, and HEIA areas. Figure 12 shows the impervious area of each subarea. Also available were topographic and sewer maps. Table 9 lists pipe lengths, diameters, and slopes used in the calibration phase. A 25-segment representation (fig. 13) of the single-family residential site was used in calibration and verification simulations.

Table 6.--Model verification results--highway site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
6	05-22-75	0590-0680	0.12	0.011	0.011	0	0.88	0.73	- 17
7	05-28-75	0720-0840	.16	.030	.021	- 30	4.56	1.92	- 58
18	08-07-75	0510-0600	.24	.013	.036	+176	2.20	4.67	+112
19	08-16-75	0385-0510	.28	.052	.043	- 17	6.84	5.86	- 14
23	08-29-75	0274-0420	.27	.038	.040	+ 5	5.05	5.12	+ 1
45	05-22-76	0070-0360	.54	.096	.086	- 10	9.72	8.36	- 14
54	06-11-76	0635-1200	.82	.191	.137	- 28	35.43	10.50	- 70
57	06-19-76	0676-0945	1.39	.269	.247	- 8	9.72	10.92	+ 12
58	06-23-76	0486-0840	.96	.202	.166	- 18	13.53	8.77	- 35
65	07-22-76	0647-0840	1.92	.245	.353	+ 44	14.83	19.21	+ 30
66	08-16-76	1060-1320	1.39	.326	.253	- 22	43.09	29.91	- 31
69	08-20-76	0750-0900	.46	.126	.077	- 39	24.67	11.66	- 53
72	09-12-76	0390-0600	2.30	.470	.428	- 9	53.67	56.21	+ 5
75	10-09-76	0815-0960	.37	.090	.060	- 33	14.83	8.75	- 41
77	10-18-76	0947-1260	.58	.178	.096	- 46	22.09	11.73	- 47
79	11-17-76	0238-0420	1.07	.244	.192	- 21	29.48	20.59	- 30
96	05-09-77	1050-1320	.88	.138	.147	+ 7	15.36	12.31	- 20
97	05-10-77	2205-2520	1.04	.190	.183	- 4	32.40	27.94	- 14
100	05-27-77	0862-1080	1.53	.322	.278	- 14	36.59	29.96	- 18
101	05-29-77	0960-1140	1.08	.318	.192	- 40	57.29	30.26	- 47

Table 6.--Continued

20 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.054 in.	4[1/]	14.0[1/]	15[1/]	22.6[1/]
Computed peaks	10.406 ft^3/s	4[1/]	12.0[1/]	15[1/]	33.9[1/]

[1/] Without storm 18.

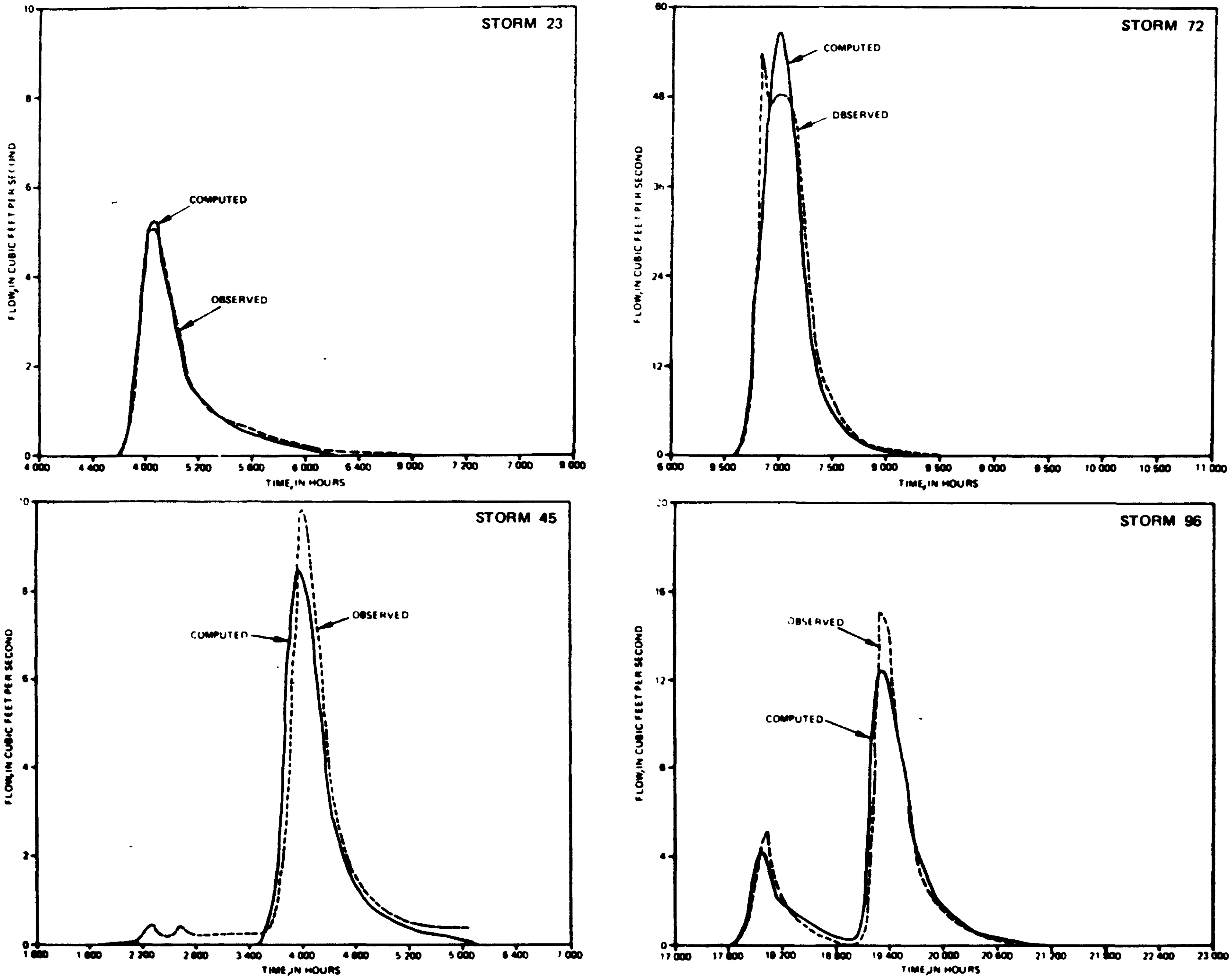

Figure 9.--Verification storms for site 2, highway site.

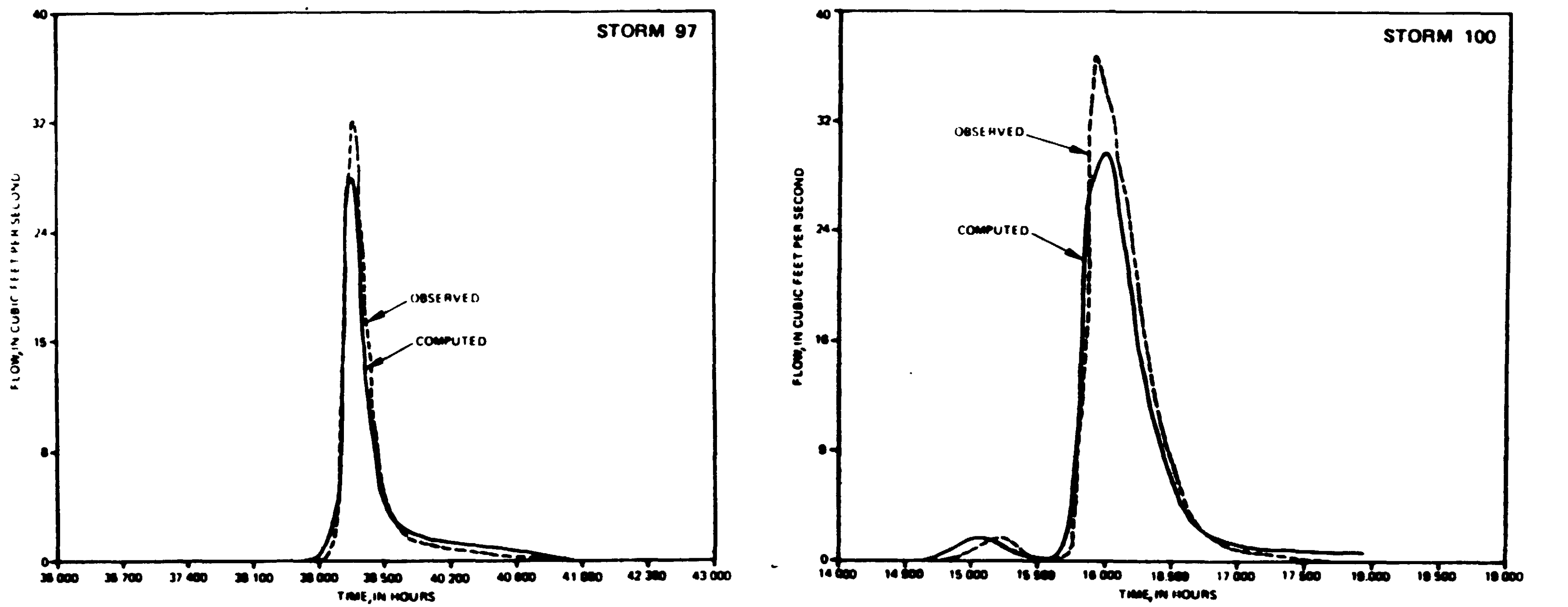

Figure 9.--Verification storms for site 2, highway site (Continued).

Table 7.--Remaining model verification results--highway site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
1	04-15-75	0857-0990	0.07	0.008	0.000	-100	0.47	0.00	-100
3	05-09-75	1030-1260	.33	.005	.052	+940	.32	4.39	+1272
5	05-13-75	1020-1200	.63	.008	.108	+1250	.53	7.72	+1357
10	07-11-75	0890-1080	.24	.045	.034	- 24	2.20	1.29	- 41
12	07-16-75	0090-0210	.17	.009	.021	+133	1.98	2.27	+ 15
13	07-16-75	0760-0870	.23	.019	.032	+ 68	1.76	3.43	+ 95
16	08-01-75	0025-0150	.22	.055	.032	- 42	11.32	4.11	- 64
17	08-04-75	0060-0300	.81	.098	.138	+ 41	6.46	20.18	+212
24	09-07-75	1005-1140	.62	.076	.106	+ 39	10.16	15.03	+ 48
25	09-09-75	0548-0780	.43	.062	.069	+ 11	7.61	7.25	- 5
27	09-18-75	0815-1320	4.38	.195	.815	+318	6.09	37.67	+519
28	10-03-75 to 10-04-75	1373-1560	.25	.019	.035	+ 84	.81	2.23	+175
30	10-18-75	0522-0660	.33	.014	.053	+279	.81	7.49	+825
31	10-19-75	2556-2700	.18	.020	.023	+ 15	1.20	1.38	+ 15
33	10-29-75	0886-1200	.38	.045	.056	+ 24	5.39	4.39	- 19
35	10-31-75	0650-0780	.52	.083	.088	+ 6	9.06	10.94	+ 21
36	11-04-75	0309-0450	.57	.037	.096	+159	2.69	13.43	+399
37	11-04-75	0726-0900	.28	.041	.042	+ 2	3.22	2.14	- 34
38	11-20-75	0252-0560	.47	.034	.072	+112	.64	1.75	+173

Table 7.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
39	01-05-76	0526-0720	0.27	0.057	0.040	- 30	5.05	3.12	- 38
40	01-05-76	0976-1260	.39	.059	.063	+ 7	1.41	2.10	+ 49
41	05-03-76	0666-0900	.29	.041	.044	+ 7	1.41	1.92	+ 36
42	05-15-76 to 05-16-76	1240-1560	.63	.134	.101	- 25	5.56	3.64	- 35
43	05-17-76	3679-3840	.30	.058	.044	- 24	4.72	2.71	- 43
44	05-21-76	0685-0900	.63	.134	.104	- 22	17.59	14.76	- 16
50	06-04-76 to 06-05-76	1390-1560	.38	.088	.061	- 31	8.64	4.47	- 48
52	06-10-76	0870-1080	.25	.031	.029	- 6	1.34	1.72	+ 28
53	06-10-76 to 06-11-76	1230-1695	.84	.152	.132	- 13	8.43	7.41	- 12
55	06-16-76	0648-0750	.05	.011	.000	-100	1.34	.00	-100
56	06-17-76	1245-1380	.31	.028	.046	+ 64	2.57	4.21	+ 64
59	06-23-76 to 06-24-76	1285-1680	1.28	.187	.225	+ 20	14.57	15.87	+ 9
61	06-27-76	0150-0330	.20	.087	.027	- 69	9.50	2.43	- 74
62	07-06-76	1084-1230	.18	.018	.024	+ 33	1.41	2.10	+ 49
63	07-07-76	2279-2490	.53	.160	.087	- 45	24.34	9.34	- 62
64	07-13-76	0977-1140	.13	.026	.011	- 58	1.41	.71	- 50
67	08-18-76	0730-1080	.56	.108	.089	- 18	7.61	5.32	- 30
68	08-18-76 to 08-19-76	1380-1950	1.45	.234	.254	+ 9	12.77	7.85	- 39
109	08-19-76	1951-2460	1.01	.198	.182	- 8	5.31	5.27	- 1
70	09-01-76	0606-0900	.54	.110	.083	- 25	7.81	6.29	- 19
71	09-08-76	0533-0660	.35	.045	.055	+ 22	7.81	7.83	0

Table 7.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
73	09-12-76	1100-1320	0.79	0.125	0.135	+ 8	7.81	7.63	- 2
74	09-23-76	0880-1020	.34	.066	.054	- 18	9.28	7.09	- 24
80	12-01-76	0620-0960	.50	.119	.080	- 33	2.57	2.13	- 17
84	12-21-76	0110-0360	.26	.039	.033	- 15	2.44	2.13	- 13
85	12-23-76 to 12-24-76	1020-1560	.59	.130	.097	- 25	1.45	1.27	- 12
110	12-24-76	1561-2040	.47	.111	.087	- 22	2.77	2.35	- 15
86	12-25-76	3330-3660	.21	.039	.022	- 44	2.09	1.26	- 40
88	02-08-77	0400-0890	.71	.163	.118	- 28	8.64	7.09	- 18
89	02-14-77	0822-1020	.32	.058	.050	- 14	4.09	2.47	- 40
90	04-10-77	1000-1260	.32	.052	.044	- 15	4.40	3.32	- 25
91	04-12-77	1055-1260	.27	.030	.039	+ 30	2.95	2.58	- 13
93	04-24-77	0370-0505	.16	.016	.019	+ 19	2.09	1.61	- 23
98	05-12-77	1305-1440	.67	.113	.116	+ 3	13.78	10.11	- 27
99	05-25-77	1275-1440	.33	.048	.050	+ 4	8.02	6.36	- 21
103	06-02-77	0705-0990	1.14	.200	.201	0	9.28	9.31	0
104	06-03-77	2110-2310	.35	.051	.055	+ 8	2.20	2.53	+ 15
105	06-08-77	1030-1140	.27	.064	.040	- 38	12.04	5.00	- 58
107	06-09-77 to 06-10-77	2480-2940	2.10	.392	.380	- 3	11.28	10.37	- 9
108	07-01-77	0528-0650	.30	.064	.044	- 31	7.81	4.52	- 42

Table 7.--Continued

59 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.086 in.	28 1/	54.5 1/	29 1/	31.9 1/
Computed peaks	5.791 ft^3/s	20 1/	137.4 1/	37 1/	33.2 1/

1/ Without storms 3 and 5.

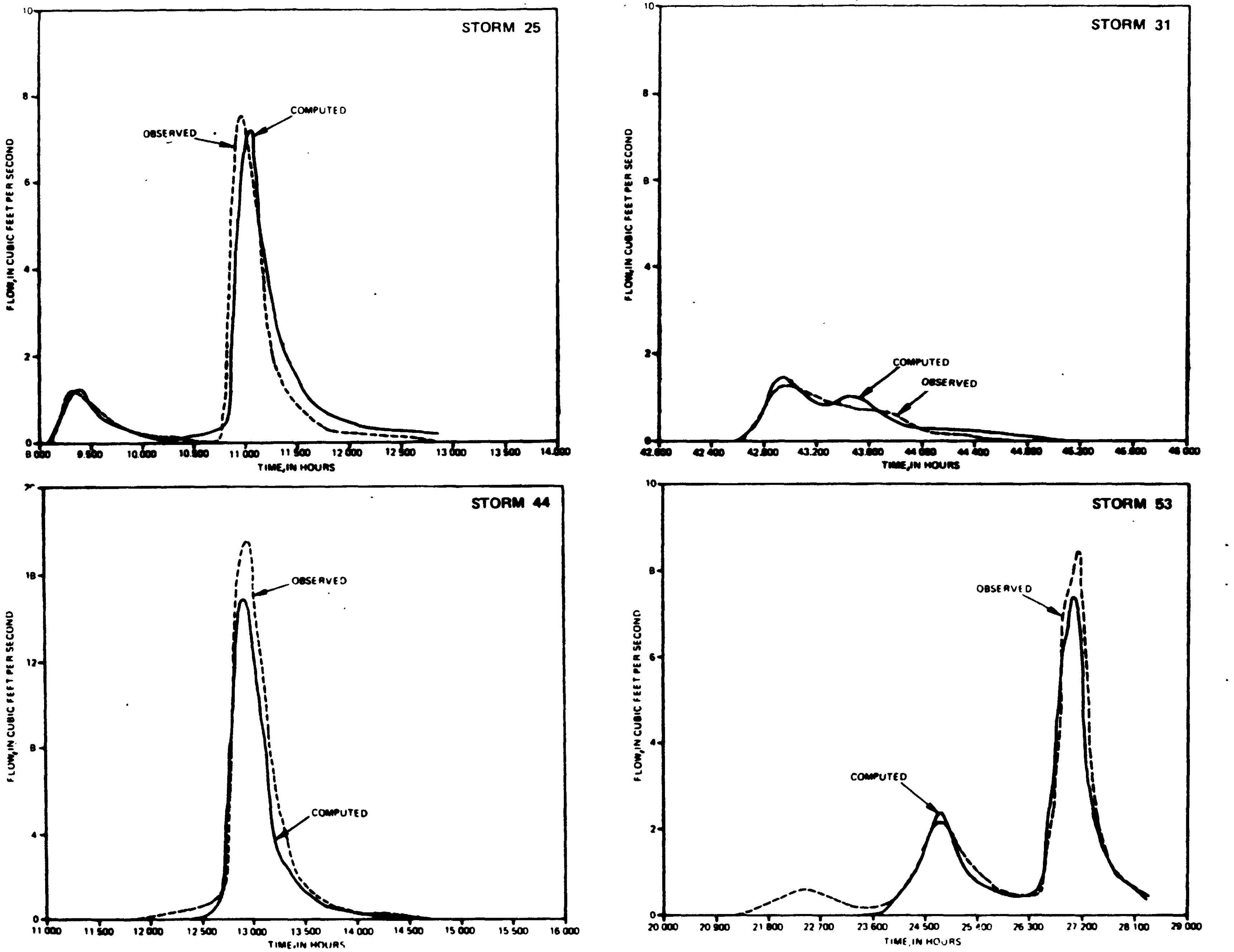

Figure 10.--Verification storms for site 2, highway site.

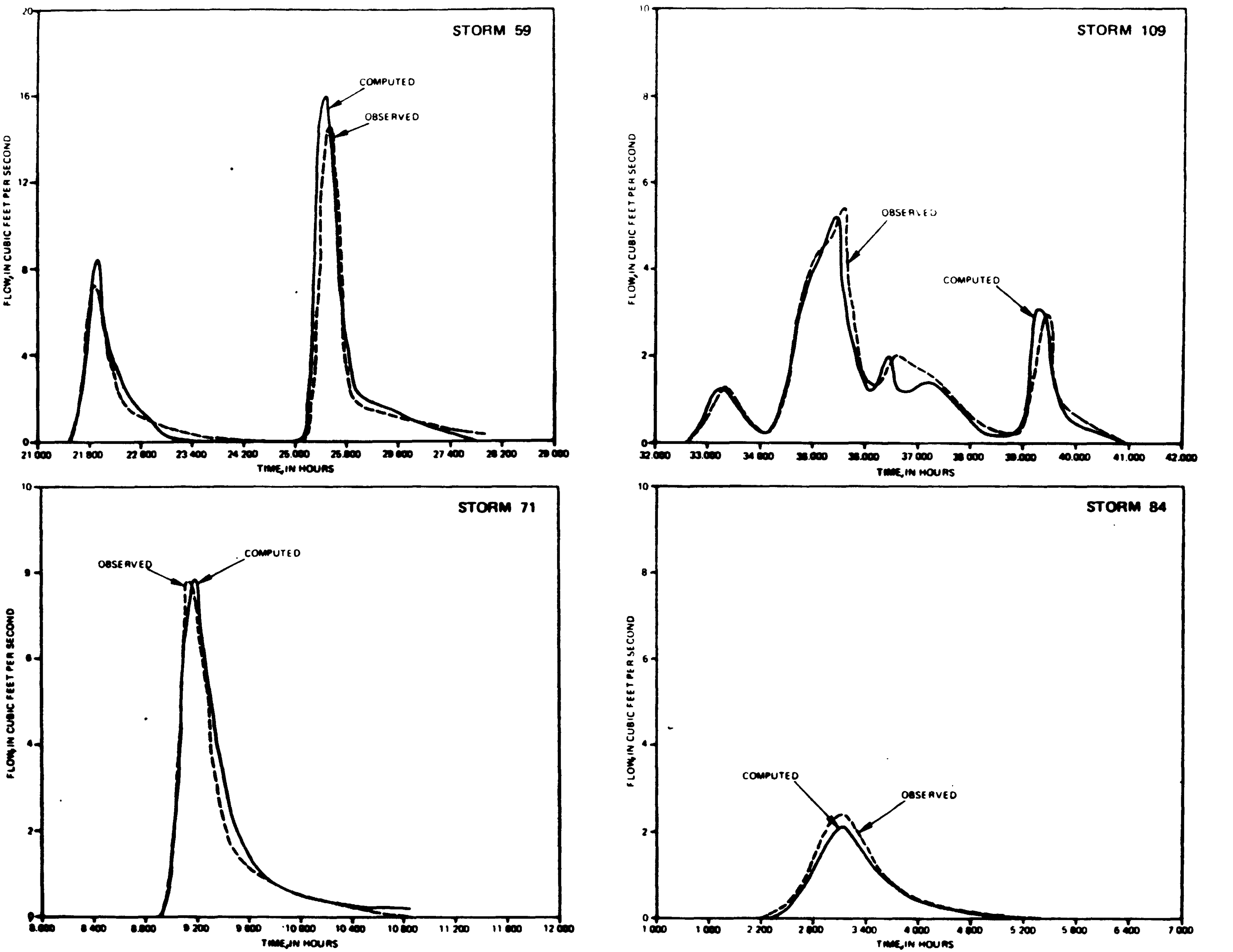

Figure 10.--Verification storms for site 2, highway site (Continued).

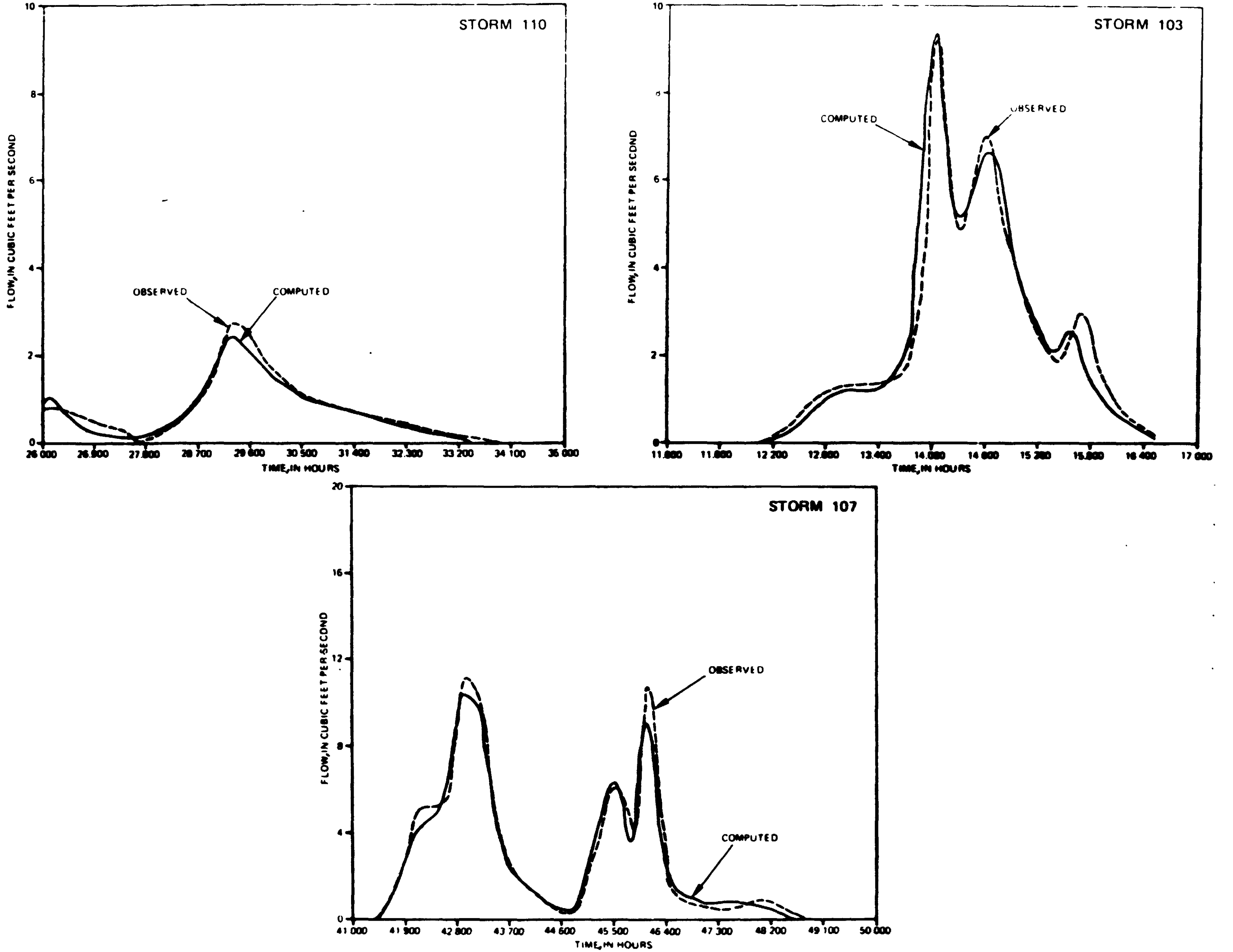

Figure 10.--Verification storms for site 2, highway site (Continued).

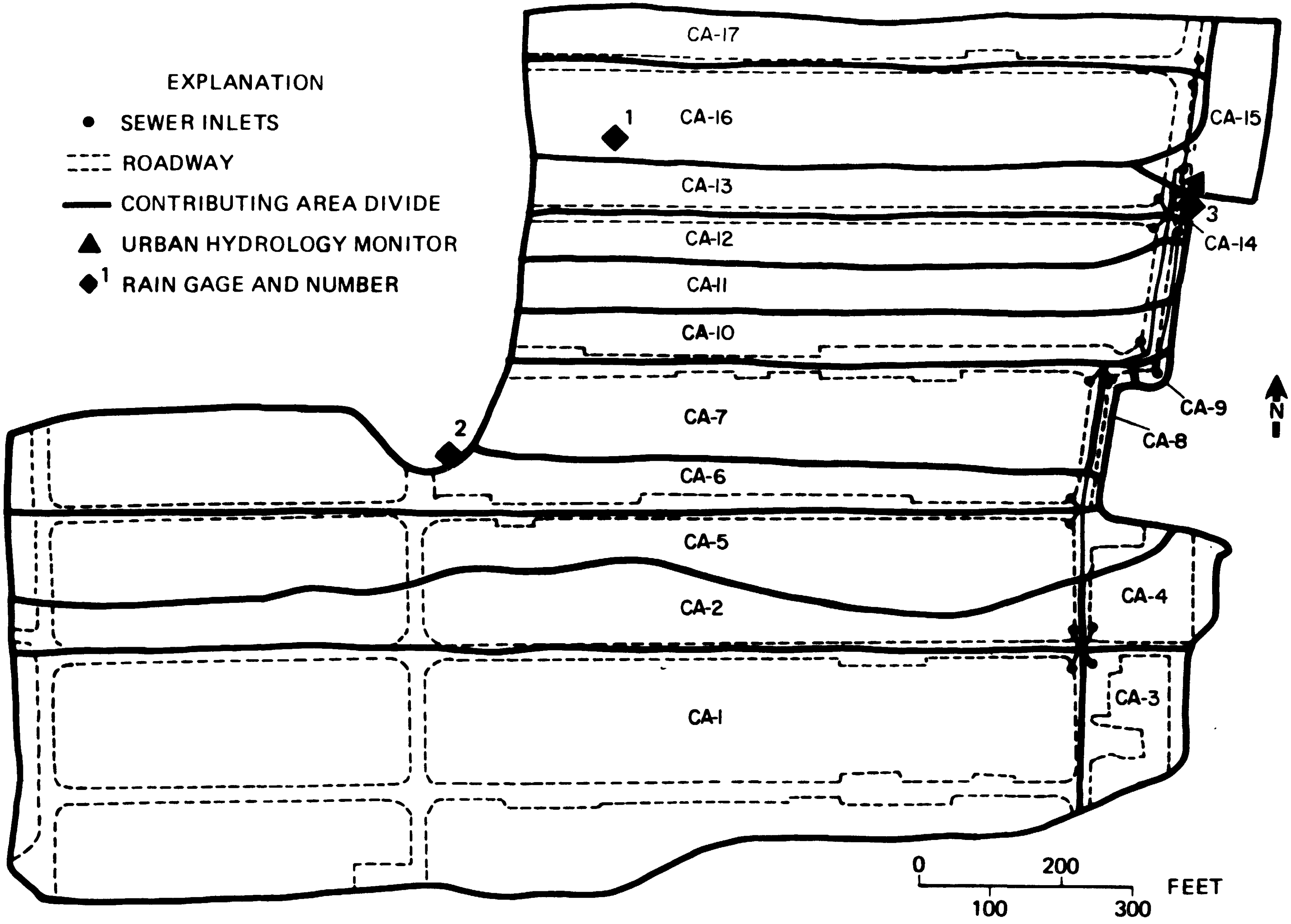

Figure 11.--Contributing-areas (CA) map of single-family residential site.

Table 8.--List of impervious, pervious, effective impervious, and total areas for single-family residential site

Designation	Total area	Pervious area	Impervious area	Effective impervious area
CA-1	12.149	6.905	5.092	0.152
CA-2	3.422	1.751	1.579	.092
CA-3	.712	.329	.187	.196
CA-4	.650	.375	.202	.073
CA-5	4.506	2.529	1.809	.168
CA-6	3.666	1.993	1.565	.108
CA-7	3.220	1.989	1.081	.150
CA-8	.119	.064	.000	.055
CA-9	.042	.029	.000	.013
CA-10	1.605	.823	.561	.221
CA-11	1.851	1.249	.541	.061
CA-12	1.470	.864	.512	.094
CA-13	1.533	.848	.561	.124
CA-14	.029	.018	.000	.011
CA-15	.675	.045	.000	.630
CA-16	3.408	2.079	1.182	.147
CA-17	1.701	.966	.618	.117
Totals	40.758	22.856	15.490	2.412
Percentage	100.0	56.1	43.9	5.92

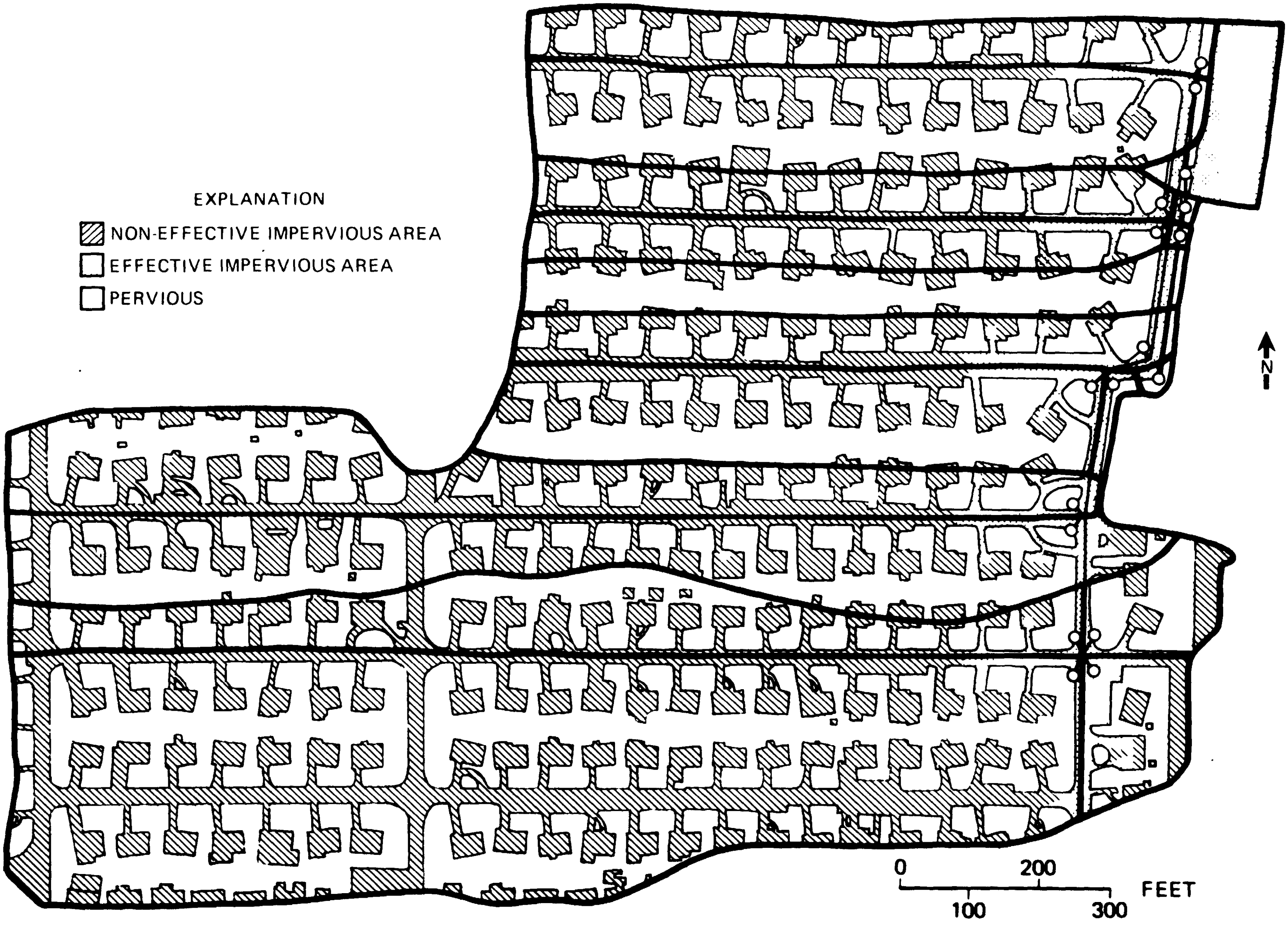

Figure 12.--Impervious and hydraulically connected impervious areas of the single-family residential site.

Table 9.--Single-family residential site pipe-segment information

Segment	Length (ft)	Slope (ft/ft)	Diameter (ft)
P001	336	0.001	1.25
P002	95	.001	2.25
P003	125	.001	2.25
P03A	101	.001	2.25
P004	160	.001	2.25
P005	78	.001	2.25
P006	235	.001	3.00
P007	165	.001	2.00
P008	82	.001	2.00
P009	20	.001	3.50
P010	110	.0048	3.50

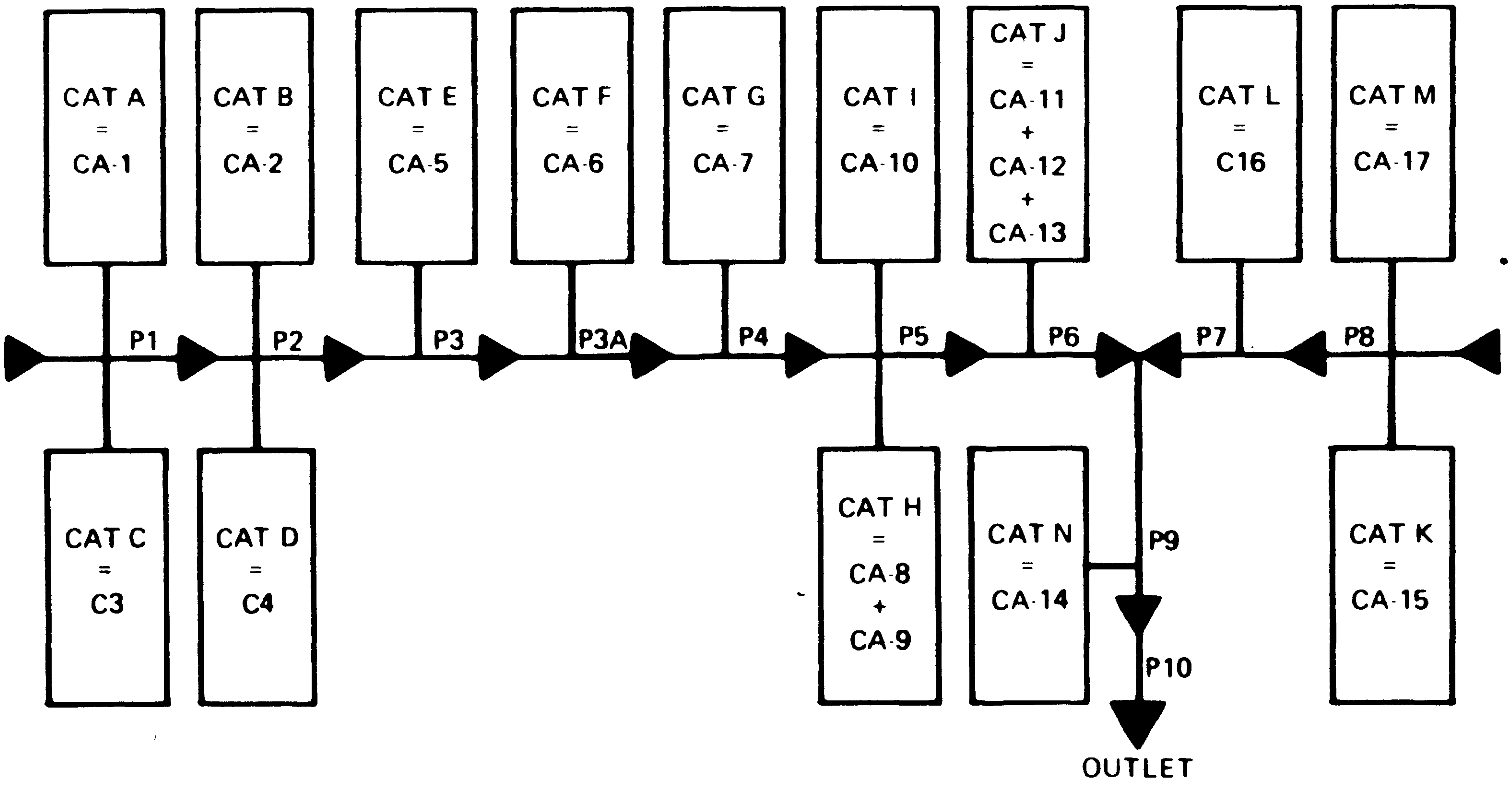

Figure 13.--Twenty-five segment representation of single-family residential site.

Rainfall and Soil-Moisture Analysis

Rainfall at three gages and stage data for 231 storms were recorded at the single-family residential site for the period January 1974 to September 1975. There are data for 80 storms that have been digitized and stored in the data base for the site at 1-minute intervals. Water-quality samples were obtained and stored in the data base for 32 of the 80 storms.

Individual storm data for all storms were retrieved ("RRSUMRY," example, fig. 3) and observed rainfall (inches) versus observed runoff (inches) were plotted (fig. 14). The graph was used as a guide and 14 calibration storms were selected. Rainfall for the 14 storms varied from 0.20 in. to 4.37 in. Measured peak discharges ranged from 0.24 to 37.75 ft^3/s while measured runoff volumes ranged from 0.003 to 0.800 in.

The slope of the runoff versus rainfall relationship was 0.07 (fig. 14) for storms of less than about 0.8 in. rainfall. As with the highway site the 0.07 slope is approximately equal to the total HEIA area. Figure 14 shows greater data scatter above 0.8 in. rainfall. Below this figure the source for runoff is mostly the HEIA while above 0.8 in., a significantly greater amount of the runoff is contributed from the pervious part of the basin. Possible sources of error as stated previously probably account for most of the scatter above 0.8 in.

The seven soil-moisture accounting parameters (table 1) were optimized for all 14 storm events. Again, the results of the optimization were difficult to apply. Eight to nine computer simulations were made varying the seven parameters from low to medium to high to recommended starting values. As many as 75 iterations were performed on a single parameter during some of the runs. Table 10 shows the final optimized value for each parameter which was used in calibration and verification analyses.

Calibration Results

There were three recording rain gages operating in the basin from January 1974 to September 1975. At least one gage was operating for all storm events. Missing rain gage data was extrapolated from the nearest rain gage so that rainfall data was available for all storms at each gage for the entire period of record. These data were averaged together, since little aerial variation occurred, and a mean value was used to represent storm rainfall data for input to the modified DSA model although the model can accept data from three rain gages.

Initially, there was a timing problem when simulating storm-runoff data. CAT K, which is CA-15 (fig. 11) is unusual in that 93 percent of the area is HEIA, or about one-fourth of the total HEIA for the entire 40.8-acre site is being generated from CAT K. An adjustment was made to that catchment's overland slope and overland roughness to slow down the runoff from CAT K. An overland slope of 0.005 and an overland roughness

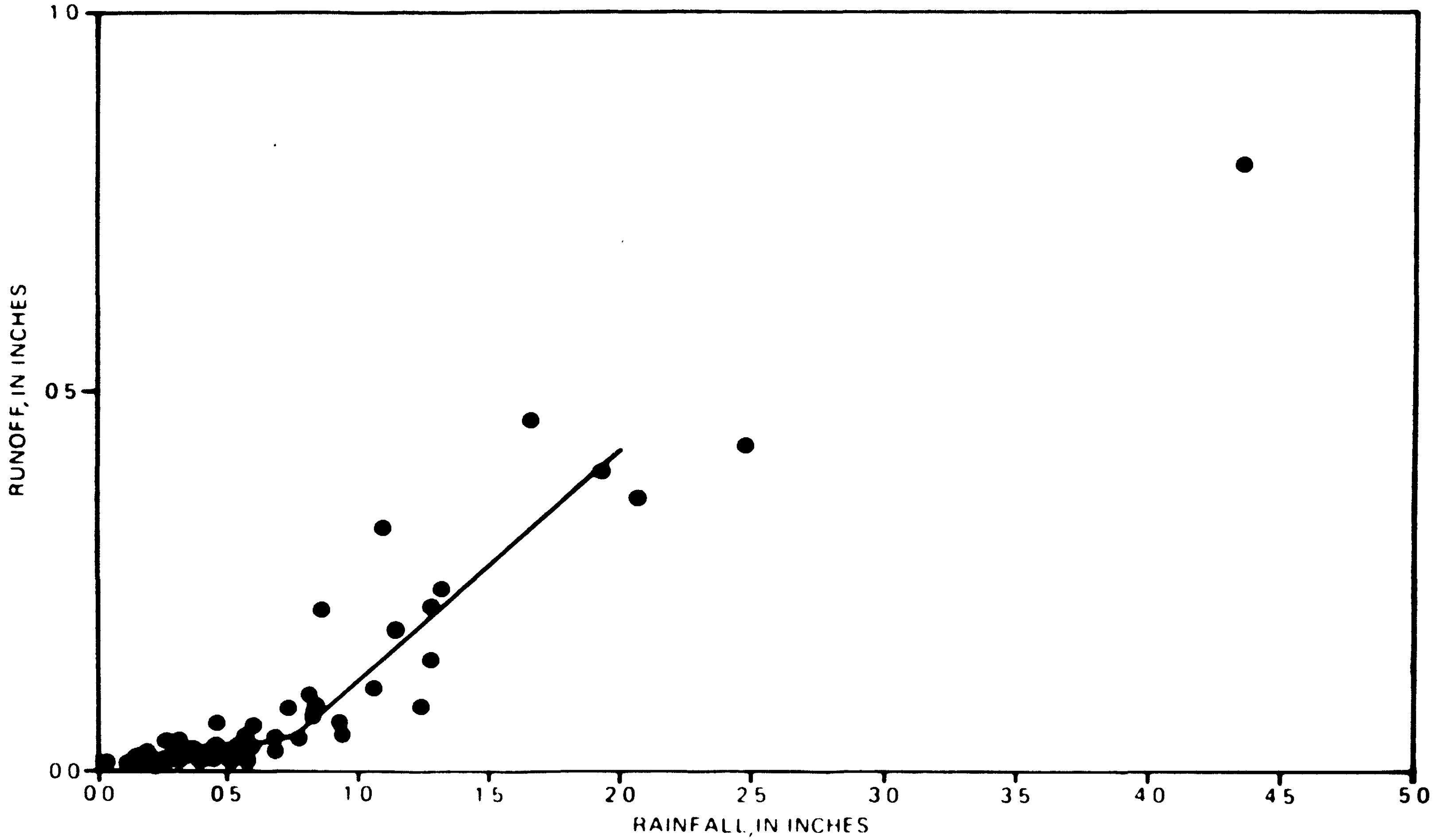

Figure 14.--Rainfall-runoff relation for single-family residential site.

Table 10.--Parameter values for soil-moisture accounting and infiltration at the single-family residential site

Parameter symbol	Range of values		Optimized value
	Lower limit	Upper limit	
DRN	0.1	1.0	0.80
EVC	.5	1.0	.60
RR	.65	1.0	.80
BMSN	1.0	15.0	14.99
KSAT	.01	1.0	.62
RGF	5.0	20.0	5.08
PSP	1.0	15.0	1.25

equal to 0.025 produced the best results for the calibration phase while a slope of 0.027 and a roughness of 0.015 were used on all other overland subareas. Many other values for slope (0.005 to 0.027) and roughness (0.015 to 0.025) were tried. The best combination was the 0.027 slope and 0.015 roughness. Except for CAT K it can be noted that these values were the same as selected for the highway site. This is expected since the areas are topographically similar and the runoff is occurring at both sites on overland-flow sections draining into sewer-collector systems.

The pipe data (table 9) used for model calibration was adjusted from actual pipe data. Some of the pipe sections were not round so that equivalent round pipe diameters were computed and used to satisfy model requirements. A common pipe roughness of 0.012 was used for all sewer pipe sections while the slope value was 0.001 for all pipes except the last section at the outlet. Also, an impervious retention value of 0.02 in. provided the best calibration results.

Table 11 lists summary statistics for the 14 calibration storms. The SEE for simulated volumes and peaks were 0.081 in. and 5.358 ft^3/s, respectively.

Observed and simulated data are shown in figure 15 for four of the best calibration storms. Acceptance criteria as stated previously for the highway site were used to determine when the model was calibrated.

Verification Results

Fourteen verification storms were selected. The first simulation produced a successful verification of the model with the SEE for simulated volumes and peaks of 0.032 in. and 2.389 ft^3/s, respectively (table 12). The SEE for verification plus the average positive and negative errors were lower than the calibration results. Figure 16 shows some of the various simulated versus observed storms used for verification. Table 13 lists statistics on the remaining 49 storms in the data base for the single-family residential site.

COMMERCIAL SITE

Physical Representation of the Basin in the Model

Figure 17 shows the segmentation of the 20.4-acre basin into 25 contributing areas which ranged in size from 0.067 acres (CA-3) to 1.870 acres (CA-13). Table 14 lists for each contributing area the total, pervious, impervious, and HEIA areas. The commercial site is different from the other three sites for several reasons. First, it contains a smaller range of individual subdivided areas, from 0.067 to 1.870 acres. Second, it contains a very small percentage of pervious area, 2.1 percent.

Table 11.--Model calibration results--single-family residential site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
11	06-03-74	1235-1362	0.22	0.003	0.012	+300	0.24	0.40	+ 67
12	06-05-74	0860-1005	.58	.033	.045	+ 36	2.81	2.35	- 16
15	06-15-74	0862-0990	.54	.030	.039	+ 30	1.60	1.65	+ 3
16	06-16-74	2038-2190	1.15	.185	.164	- 11	18.56	14.06	- 24
21	07-05-74	0780-0870	.45	.035	.039	+ 11	3.95	2.41	- 39
34	09-05-74	1120-1320	1.70	.464	.338	- 27	37.75	27.87	- 26
35	09-06-74	2078-2168	.24	.014	.015	+ 7	1.48	.76	- 49
36	09-24-74 to 09-25-74	1168-1458	2.08	.361	.439	+ 21	32.84	28.95	- 12
55	05-17-75	0070-0180	.20	.025	.012	- 52	1.72	.72	- 58
56	05-17-75	0930-1200	.88	.213	.092	- 57	19.61	6.73	- 66
57	06-17-75	0667-0840	1.25	.084	.184	+119	7.17	15.01	+109
73	07-19-75	0305-0630	1.92	.396	.337	- 15	21.75	22.09	+ 2
84	09-18-75	0860-1440	4.37	.800	.981	+ 23	27.12	30.04	+ 11
85	09-26-75	1297-1440	.73	.083	.106	+ 28	8.34	8.60	+ 3

14 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.081 in.	9	63.9	5	32.4
Computed peaks	5.358 ft^3/s	6	32.5	8	36.2

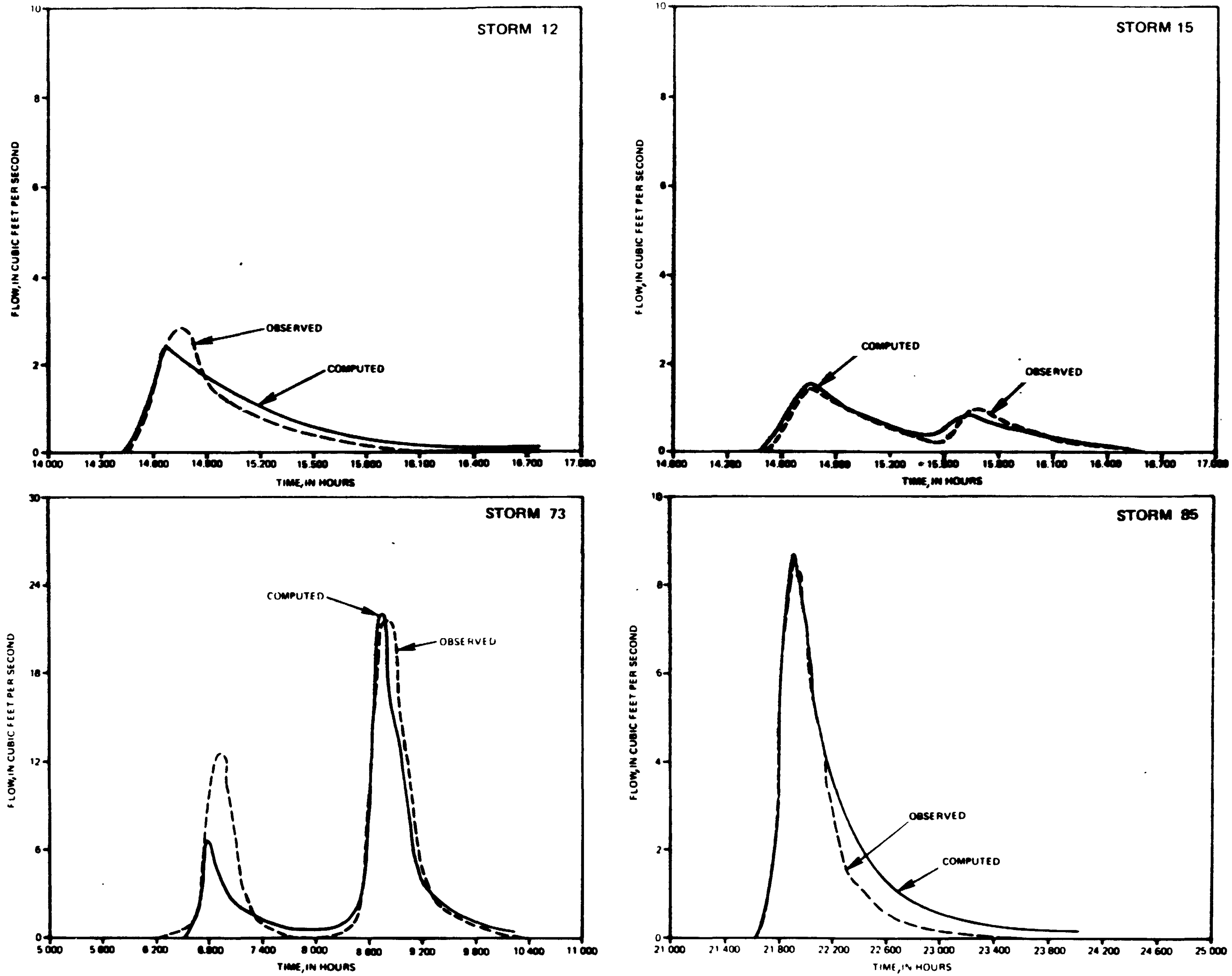

Figure 15.--Calibration storms for site 1, single-family residential site.

Table 12.--Model verification results--single-family residential site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
6	05-05-74	1035-1200	1.07	0.111	0.127	+ 14	9.09	8.21	- 10
7	05-07-74	1223-1438	.40	.011	.030	+172	1.16	1.88	+ 62
8	05-08-74	2420-2552	.44	.026	.028	+ 8	1.26	1.03	- 18
17	06-17-74	0812-0882	.41	.020	.032	+ 60	2.23	2.07	- 7
18	07-01-74	1112-1288	1.32	.242	.184	- 24	20.29	13.96	- 31
19	07-02-74	2110-2197	.47	.034	.039	+ 15	3.12	2.41	- 23
24	07-18-74	0125-0300	.85	.072	.088	+ 22	4.31	4.94	+ 15
29	08-17-74	1154-1260	.68	.043	.063	+ 47	3.78	3.44	- 9
86	09-25-74 to 09-26-74	1200-1620	1.38	.217	.181	- 17	14.36	11.93	- 17
40	09-30-74	0850-1380	2.49	.429	.511	+ 19	32.08	29.27	- 9
41	10-03-74	0930-1140	.19	.021	.010	- 52	.89	.37	- 58
42	10-05-74	0470-0540	.31	.014	.032	+128	2.23	2.09	- 6
61	06-25-75	1040-1380	.92	.078	.075	- 4	7.18	2.98	- 58
66	07-11-75	0860-1050	1.28	.146	.160	+ 10	10.38	10.41	0

14 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.032 in.	10	49.5	4	23.4
Computed peaks	2.389 ft^3/s	3	25.7	11	22.4

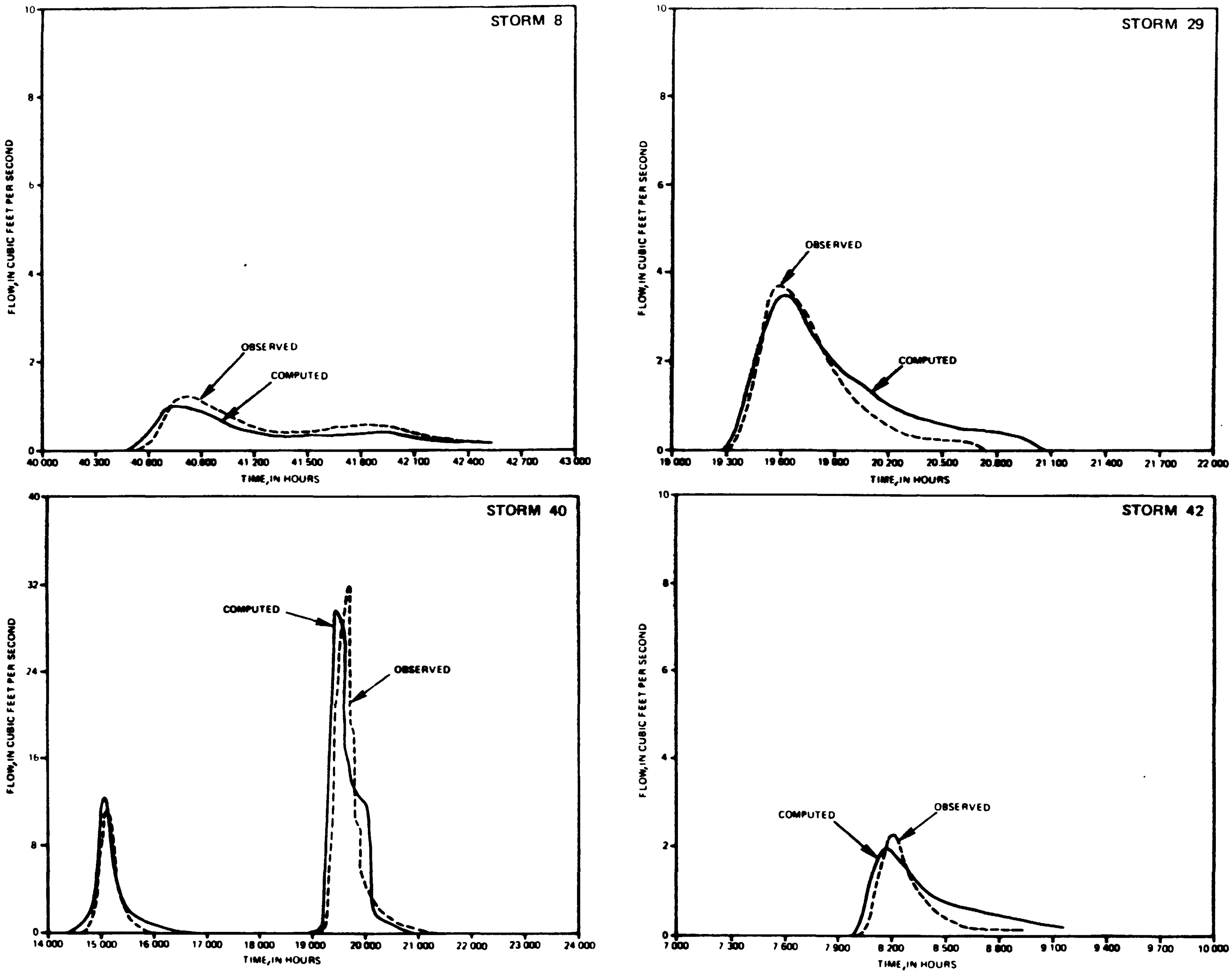

Figure 16.--Verification storms for site 1, single-family residential site.

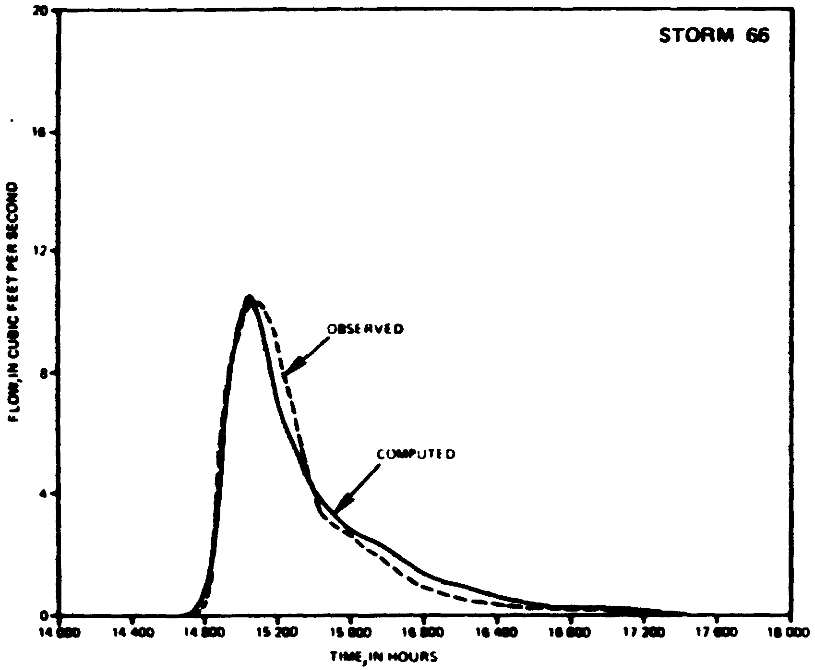

Figure 16.--Verification storms for site 1, single-family residential site (Continued).

Table 13.--Remaining model verification results--single-family residential site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
1	01-13-74	0720-0990	0.81	0.098	0.051	- 48	2.82	1.05	- 63
3	04-15-74	0364-0480	.60	.059	.045	- 24	3.79	1.60	- 58
4	04-16-74	2220-2340	.22	.006	.012	+100	.63	.46	- 27
5	04-16-74 to 04-17-74	2820-2940	.19	.009	.012	+ 33	.96	.57	- 41
9	05-14-74 to 05-15-74	1215-1560	.45	.015	.026	+ 73	.76	.94	+ 24
10	05-28-74	1160-1260	.18	.001	.009	+800	.15	.24	+ 60
20	07-04-74	0368-0450	.27	.016	.017	+ 6	.96	.65	- 32
23	07-15-74 to 07-16-74	1356-1456	.42	.018	.031	+ 72	1.84	1.82	- 1
25	07-21-74	1032-1170	.32	.016	.019	+ 18	.82	.66	- 20
26	07-31-74	0860-0960	.16	.004	.009	+125	.51	.47	- 8
27	08-03-74	0330-0540	.77	.043	.077	+ 79	4.31	4.67	+ 8
28	08-12-74	1200-1335	.58	.012	.041	+241	.57	1.30	+128
30	08-23-74	0334-0480	.32	.031	.023	- 26	2.23	1.23	- 45
32	08-25-74	0590-0690	.30	.030	.025	- 17	3.12	1.69	- 46
33	09-05-74	0668-0780	.11	.007	.005	- 29	.39	.20	- 49
37	09-25-74	0740-1200	.46	.035	.026	- 26	.76	.53	- 30
38	09-26-74	0980-1200	.88	.087	.088	+ 1	5.66	5.11	- 10
39	09-29-74	0990-1140	.32	.024	.022	- 8	2.10	1.17	- 44
45	12-26-74	1271-1380	.14	.010	.008	- 20	.57	.36	- 37

Table 13.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
46	02-05-75	0809-0900	0.14	0.010	0.008	- 20	0.90	0.42	- 53
47	02-10-75	0786-0900	.37	.018	.024	+ 33	1.37	1.05	- 23
48	02-24-75	1263-1380	.45	.035	.031	- 11	1.97	1.16	- 41
49	04-12-75	0655-0750	.14	.017	.008	- 53	1.16	.37	- 68
50	05-05-75	1170-1320	.26	.038	.016	- 58	3.95	.80	- 80
51	05-07-75	1142-1260	.31	.041	.020	- 51	3.79	1.18	- 69
52	05-09-75	1023-1200	.23	.013	.012	- 8	.39	.34	- 13
53	05-10-75	2410-2700	1.09	.322	.116	- 64	22.86	6.68	- 71
54	05-13-75	1035-1260	.45	.063	.028	- 56	3.12	1.08	- 65
58	06-19-75	0450-0540	.10	.002	.005	+150	.19	.24	+ 26
60	06-24-75	0932-1080	.95	.047	.081	+ 72	2.37	3.10	+ 31
62	06-26-75	0855-0940	.58	.045	.080	+ 78	6.72	6.95	+ 3
63	07-04-75	0885-1020	.46	.026	.035	+ 35	2.37	1.99	- 16
64	07-05-75	0320-0480	.22	.007	.013	+ 86	.89	.61	- 31
65	07-06-75	1441-1560	.52	.026	.040	+ 54	1.97	1.99	+ 1
67	07-13-75	0380-0480	.26	.010	.020	+100	1.05	1.27	+ 21
68	07-14-75	2189-2280	.25	.010	.016	+ 60	.96	.96	0
69	07-14-75	1330-1410	.21	.011	.014	+ 27	1.05	.89	- 15
70	07-15-75	0810-0900	.29	.016	.022	+ 38	2.10	1.36	- 35
71	07-17-75	0420-0505	.33	.020	.021	+ 5	1.37	.91	- 34
72	07-18-75	1890-1980	.37	.022	.028	+ 27	2.10	1.63	- 22

Table 13.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
74	07-31-75	0645-0750	0.38	0.028	0.036	+ 29	3.28	2.46	- 25
75	08-01-75	1460-1560	.29	.029	.025	- 14	4.13	1.66	- 60
77	08-12-75	0552-0630	.23	.011	.015	+ 36	1.15	.75	- 35
76	08-16-75	0535-0600	.20	.013	.012	- 8	1.37	.63	- 54
78	08-21-75	0660-0750	.20	.014	.013	- 7	1.97	.75	- 62
79	08-23-75	0937-1080	.93	.065	.088	+ 35	4.31	3.77	- 13
81	09-07-75	0994-1080	.52	.027	.059	+119	3.78	4.64	+ 23
82	09-09-75	0642-0720	.68	.023	.070	+204	2.37	4.25	+ 79
83	09-17-75	0845-0960	.50	.014	.037	+164	.83	1.16	+ 40

49 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.034 in.	30	96.7	19	28.8
Computed peaks	2.554 ft^3/s	13	34.9	36	38.8

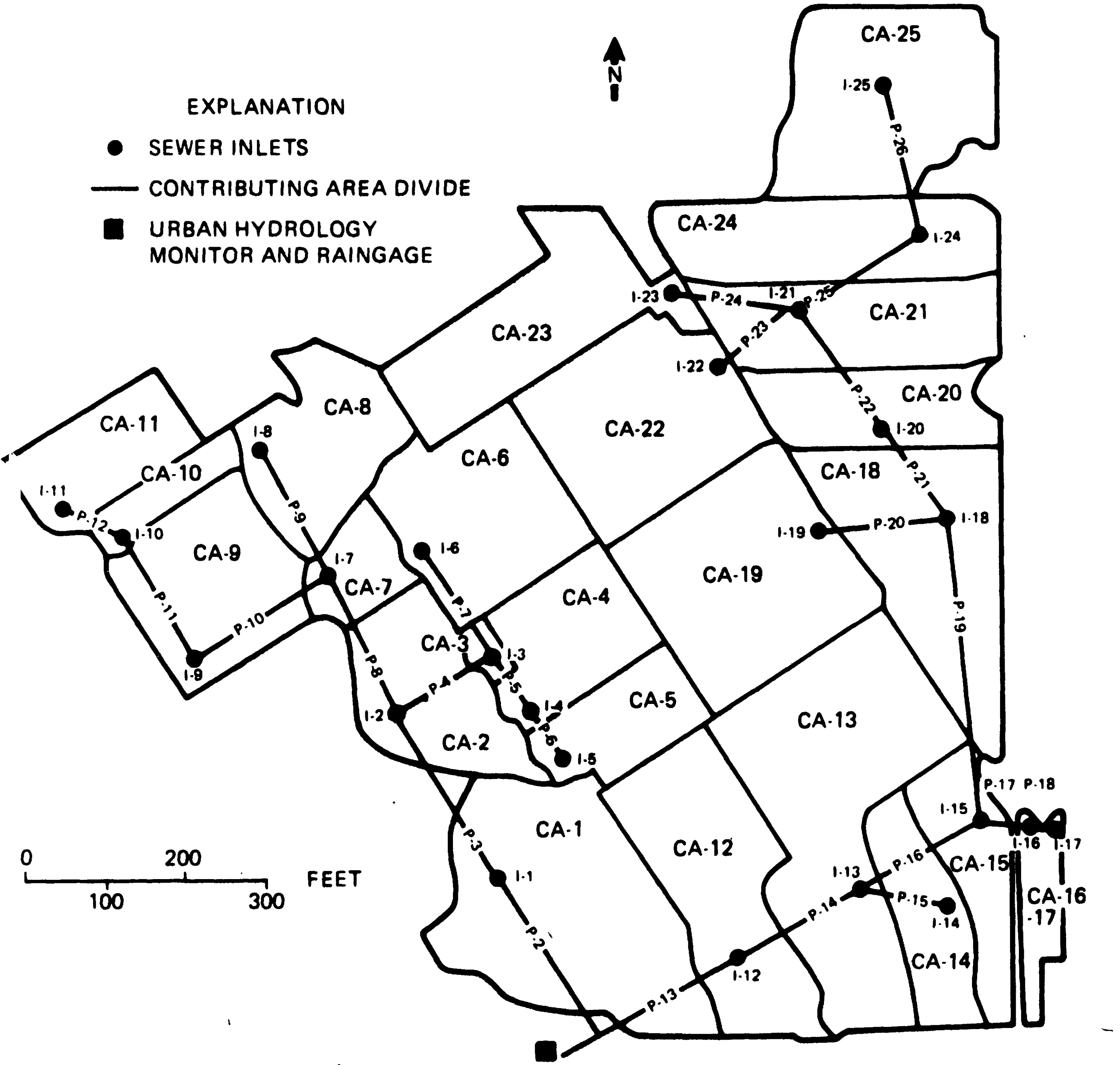

Figure 17.--Contributing-areas (CA) map of commercial site.

Table 14.--List of impervious, pervious, effective impervious, and total areas for commercial site

Designation	Total area	Pervious area	Impervious area	Effective impervious area
CA-1	1.747	0.039	1.708	1.708
CA-2	.087	.031	.776	.776
CA-3	.067	---	.067	.067
CA-4	.647	---	.647	.647
CA-5	.489	---	.489	.489
CA-6	.999	---	.999	.999
CA-7	.288	.010	.278	.278
CA-8	.769	.007	.762	.762
CA-9	.931	.027	.904	.904
CA-10	.222	---	.222	.222
CA-11	.551	.040	.511	.511
CA-12	1.166	.015	1.151	1.151
CA-13	1.870	.024	1.846	1.846
CA-14	.560	.031	.529	.529
CA-15	.514	.016	.498	.498
CA-16 } CA-17 }	.257	---	.257	.257
CA-18	1.240	.069	1.171	1.171
CA-19	1.435	---	1.435	1.435
CA-20	.609	.020	.589	.589
CA-21	.847	.028	.819	.819
CA-22	1.211	---	1.211	1.211
CA-23	1.028	---	1.028	1.028
CA-24	.918	.025	.893	.893
CA-25	1.232	.046	1.186	1.186
Totals	20.404	.428	19.976	19.976
Percentage	100.0	2.1	97.9	97.9

Finally, all the impervious areas are HEIA areas. Figure 18 shows how the pervious and the HEIA areas are distributed. Additional maps showing roof drains, sewer inlets, pipes, and basin flow patterns were also available. Table 15 lists pipe lengths, diameters, and slopes used in the calibration phase. A 42-segment representation (fig. 19) of the commercial site was used in calibration and verification runs.

Rainfall and Soil-Moisture Analysis

Rainfall at one gage and stage data for 284 storms were recorded at the commercial site for the period May 1975 to June 1977. There are data for 114 storms that have been digitized and stored in the data base at 1-minute intervals. Water-quality samples were collected, analyzed, and the data stored in the computer for 32 of the 114 storms.

Individual storm data were retrieved from the data base and observed rainfall (inches) versus observed runoff (inches) were plotted (fig. 20). By using figure 20 as a guide, 14 calibration storms were selected. Rainfall for the 14 storms varied from 0.19 in. to 4.41 in. Observed peak discharges ranged from 3.29 to 48.64 ft^3/s while observed runoff volumes ranged from 0.133 to 4.195 in.

The slope of the runoff versus rainfall relationship for all the data was very close to 1.0. This is expected since 98 percent of the basin is HEIA. The slight offset of the data points to the right of the curve in figure 20 is due to impervious retention. This effect is shown in figure 21 for storms less than 1.0 in. The two lines A and B in the figure represent a lower and higher limit of impervious retention, 0.05 and 0.1 respectively. At point C a value of 0.075 was chosen for the average impervious retention in the basin. This is higher than values used at sites 1 and 2, but the roof top drainage systems accent impervious retention because of very flat surfaces usually coated with an asphalt and small grain mixture.

Even though the basin contains only 2 percent pervious area, which will have essentially no significant contribution to the total runoff, all seven soil-moisture-accounting parameters were optimized for all 14 storm events. Site 1 final optimized values (table 10) were used as starting values and table 16 shows the resulting optimized values.

Calibration Results

There was only one rain gage in the commercial site study area. If additional rain gages were available, a verification of areal rainfall distribution could have been made.

It was necessary to make a few preliminary calibration runs to adjust timing, runoff volume, and peak discharge errors. The 98 percent HEIA results in little contribution, if any, from the 2 percent pervious area. In other analyses involving larger pervious areas, the runoff contribution from these areas created more problems during model calibration. Again as at sites 1 and 2, the overland slope of 0.027 and roughness equal to 0.015 were used in the analyses. A common pipe roughness of 0.012 was used and a pipe slope of 0.002 was used for most pipes. Table

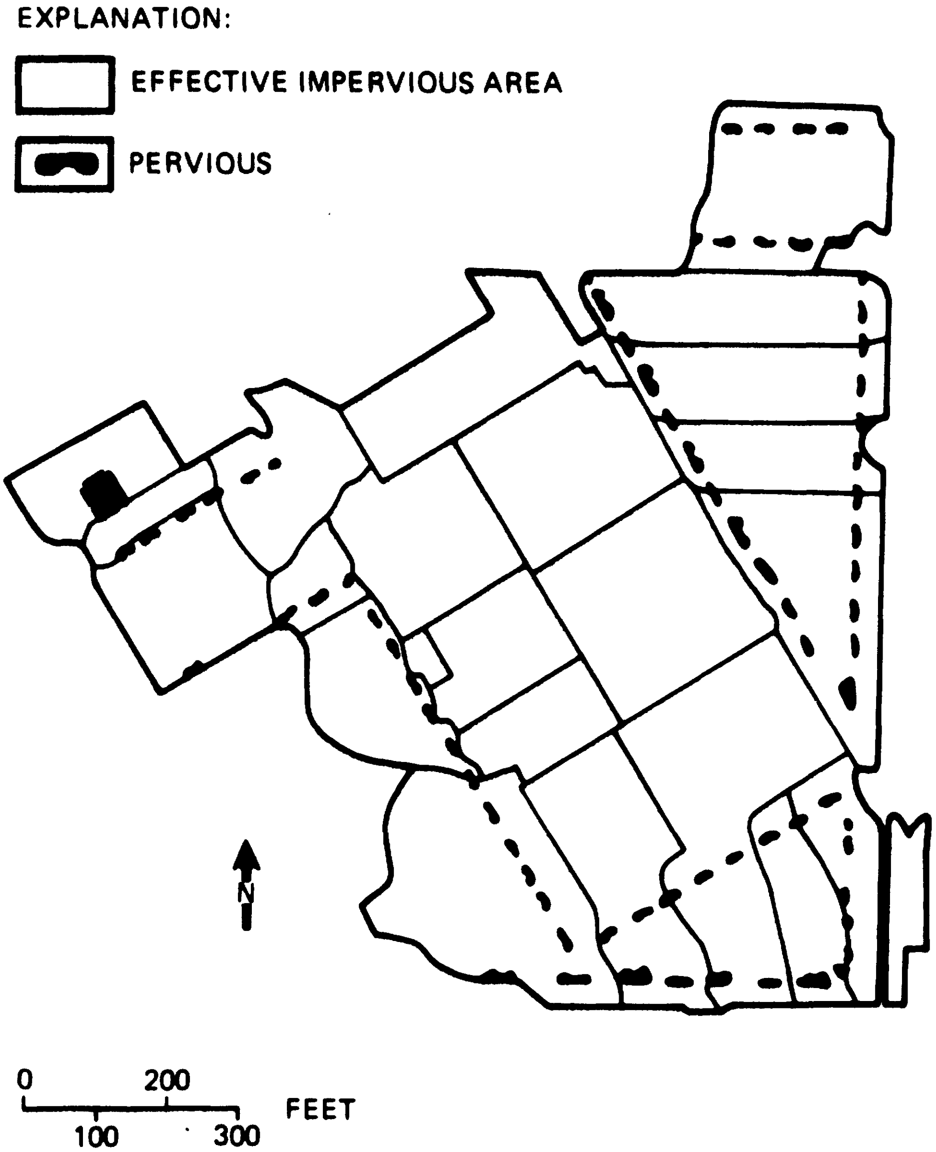

Figure 18.--Impervious and hydraulically connected impervious areas of the commercial site.

Table 15.--Commercial site pipe-segment information

Segment	Length (ft)	Slope (ft/ft)	Diameter (ft)
P001	80	0.007	3.00
P002	448	.002	2.00
P003	203	.002	1.50
P004	145	.002	1.00
P005	152	.002	1.00
P006	167	.008	1.00
P007	145	.002	1.25
P008	175	.002	1.25
P009	78	.002	1.00
P010	559	.002	2.25
P011	488	.002	1.75
P012	68	.002	1.00
P013	240	.002	1.00
P014	180	.002	1.50
P015	180	.002	1.00
P016	60	.002	1.00
P017	128	.002	1.00
P018	160	.002	1.00
P019	188	.002	1.00
P020	180	.002	1.00
P021	146	.002	1.25

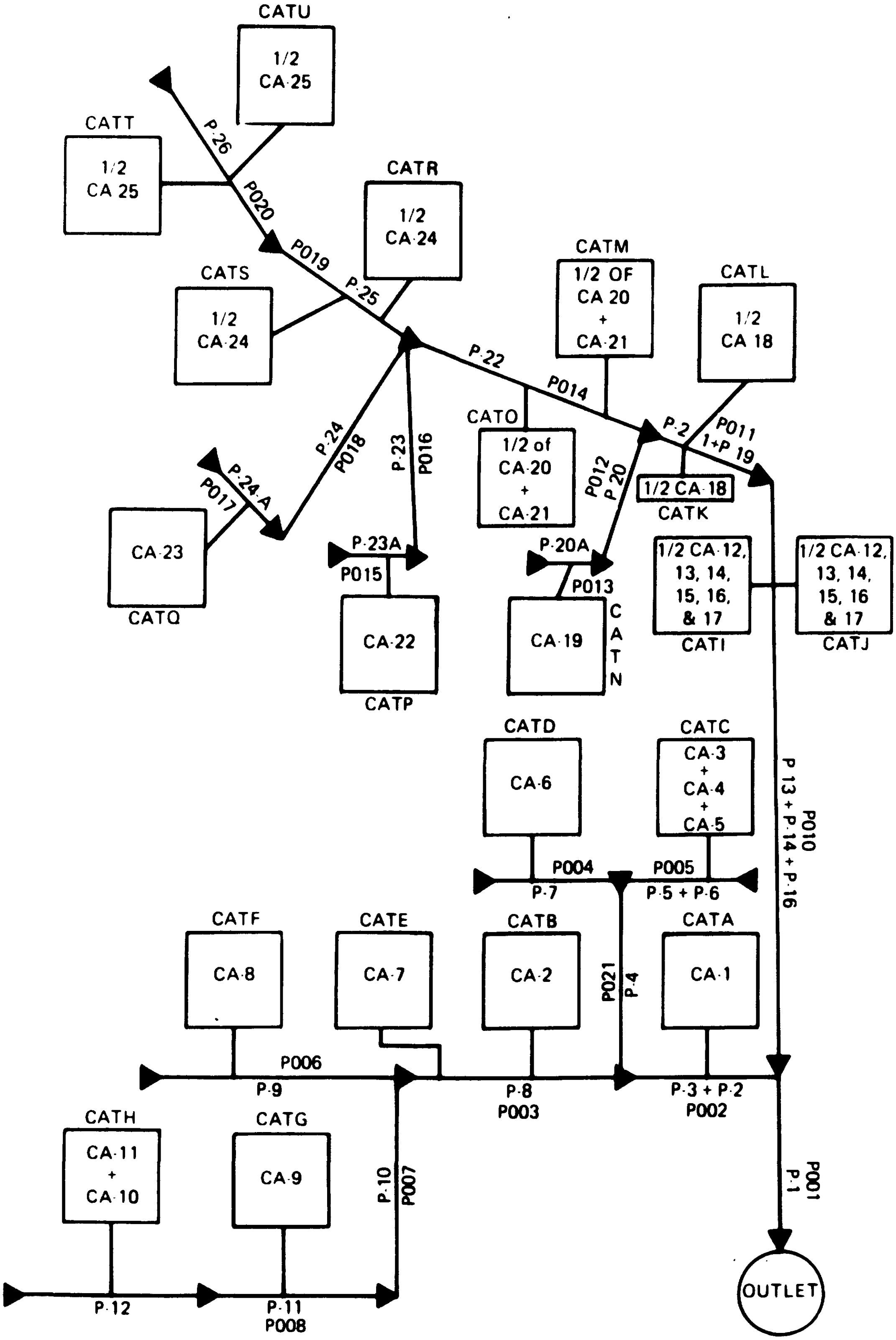

Figure 19.--Forty-two segment representation of commercial site.

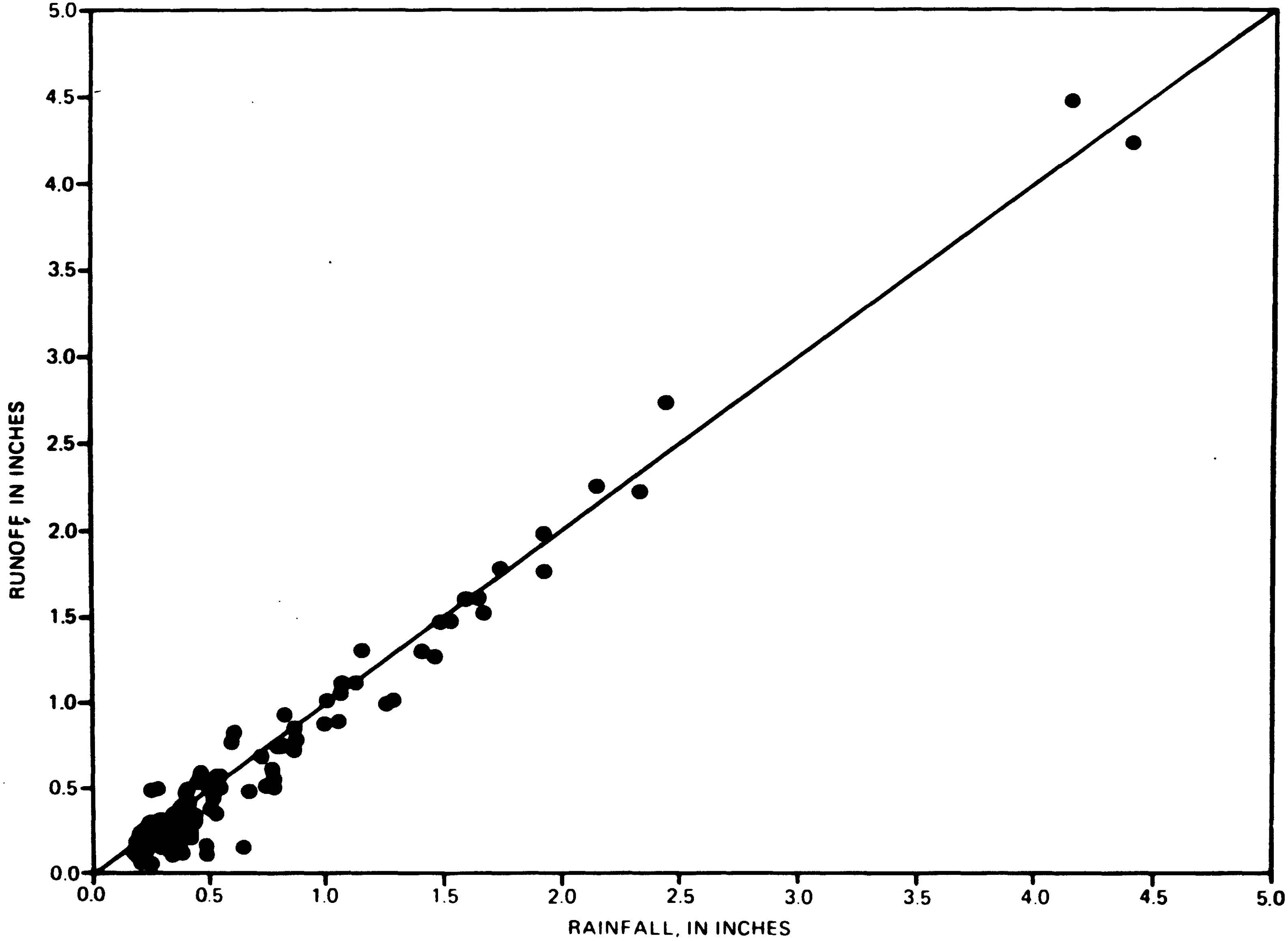

Figure 20.--Rainfall-runoff relation for commercial site.

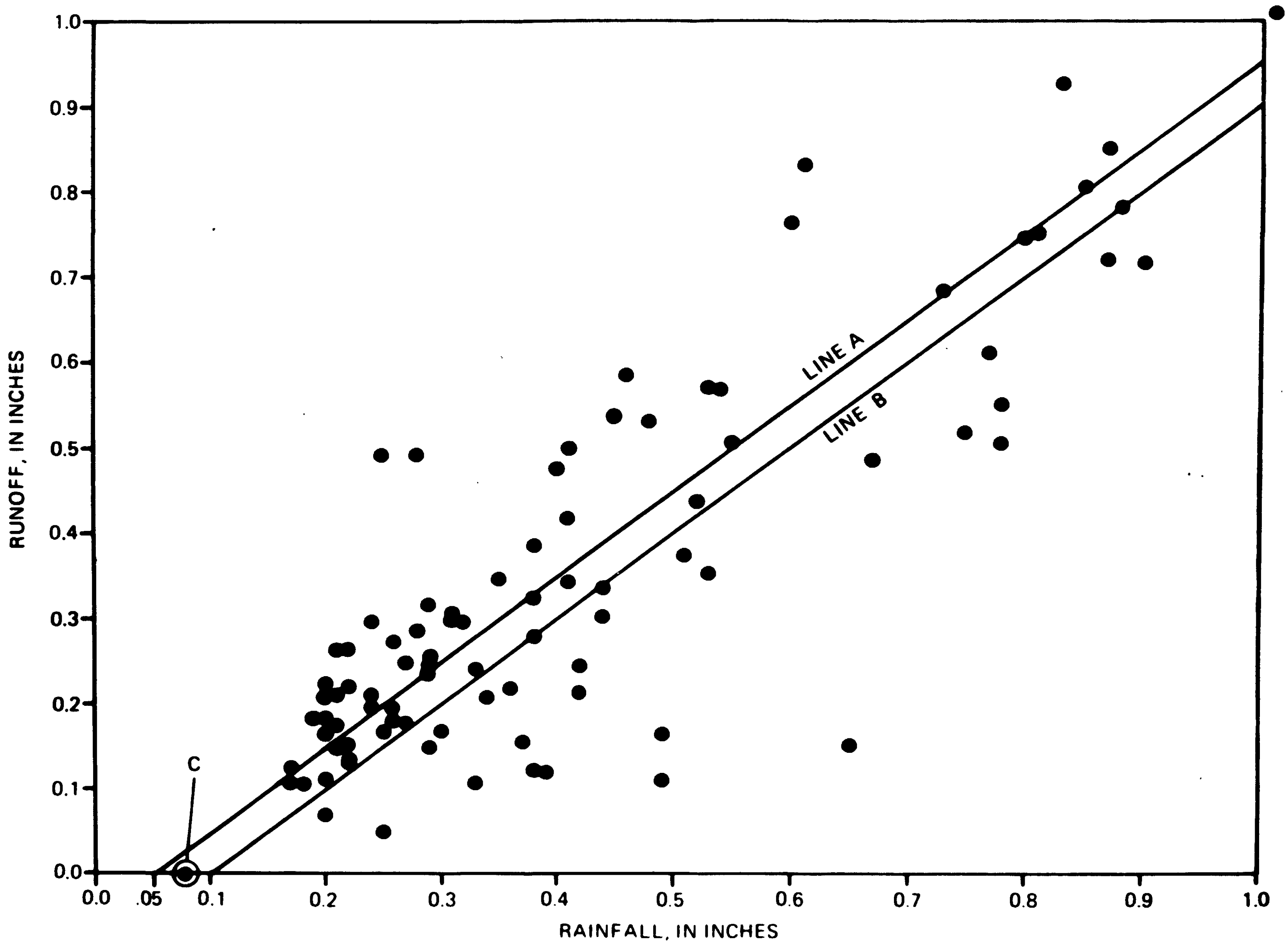

Figure 21.--Site 3, Smaller storms showing effect of impervious retention.

Table 16.--Parameter values for soil-moisture accounting and infiltration at the commercial site

Parameter symbol	Range of values		Initial value	Optimized value
	Lower limit	Upper limit		
DRN	.1	1.0	0.80	0.53
EVC	.5	1.0	.60	.50
RR	.65	1.0	.80	.99
BMSN	1.0	15.0	14.99	9.52
KSAT	.01	1.0	.62	.08
RGF	5.0	20.0	5.08	5.01
PSP	1.0	15.0	1.25	1.04

17 lists summary statistics for the 14 calibration storms. The SEE for simulated volumes and peaks were 0.082 in. and 6.569 ft^3/s, respectively.

Figure 22 shows the five best calibration storms--both observed and simulated storm hydrographs. Various type storms, small to large and single and multiple peaks, were analyzed. Results for two storms, 1 and 25, were determined as unacceptable.

Verification Results

Fourteen storms were used for verification. The first run was successful with the SEE for simulated volumes and peaks equal to 0.171 in. and 7.458 ft^3/s, respectively (table 18). None of the 14 verification storms were determined to be unacceptable. Figure 23 shows four of the verification storms.

Table 19 lists storm data and statistics on the remaining 84 storms for the commercial site. The wide variability in storm systems resulted in larger volume and peak errors than the calibration and verification analyses. About 20 of the 84 storms are questionable as to acceptance criteria.

MULTIFAMILY RESIDENTIAL AREA

Physical Representation of the Basin in the Model

Figure 24 shows the segmentation of the 14.7-acre basin into 13 contributing areas. The areas ranged in size from 0.352 acres (CA-2) to 2.798 acres (CA-10). Table 20 lists for each contributing area the total, pervious, impervious, and HEIA areas. Figure 25 shows the impervious area of each subarea. Topographic, sewer, and drainage maps were also available for the site. Table 21 lists pipe lengths, diameters, and slopes, and figure 26 shows the 28-segment representation used for the multifamily site during calibration and verification runs.

Rainfall and Soil-Moisture Analysis

Rainfall at two gage locations (for all but three storms which used data from one gage only) and discharge information for 146 storms were recorded at the multifamily residential site for the period May 1977 to June 1978. There are data for 52 storms that have been digitized and stored in the data base at 1-minute intervals. Water-quality data for 16 of the storms are also stored in the data base.

At site 4 the outflow for storms 1 to 32 was monitored by measuring the water levels in a canal receiving the basin runoff and in an inlet box 215 ft upstream from the canal. Flow equations describing type IV culverts (Bodhaine, 1968) were programmed to compute the discharge. It was found that because water-level differences of .001 ft significantly affected the computed discharge and the stormwater flow was highly unsteady, that the type IV steady-state flow equations provided a poor

Table 17.--Model calibration results--commercial site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
1	05-29-75	0795-0900	0.53	0.352	0.444	+ 26	11.20	20.79	+ 86
9	07-04-75	0745-0900	.87	.852	.777	- 9	45.62	39.94	- 12
17	08-25-75	0088-0210	.21	.147	.125	- 15	8.47	7.78	- 8
25	10-06-75	0090-0195	.19	.181	.107	- 41	11.18	4.90	- 56
35	11-20-75	0359-0515	.81	.753	.717	- 5	22.74	23.81	+ 5
43	02-28-76	0262-0480	.73	.682	.637	- 7	25.74	19.97	- 22
51	05-21-76	0662-0960	.22	.136	.126	- 7	3.29	3.25	- 1
59	06-23-76	0506-0840	1.13	1.123	1.022	- 9	22.49	19.05	- 15
61	07-07-76	0429-0780	1.67	1.520	1.556	+ 2	40.00	40.90	+ 2
67	08-02-76	0417-0550	.22	.133	.142	+ 7	9.60	13.50	+ 40
80	10-09-76	0870-1200	.44	.336	.345	+ 3	36.11	21.05	- 42
83	11-02-76 to 11-03-76	1230-1800	4.41	4.195	4.271	+ 2	48.64	39.90	- 18
100	04-13-77 to 04-14-77	1261-1680	1.41	1.296	1.289	- 1	41.99	38.11	- 9
111	06-09-77	0404-0900	2.16	2.253	2.035	- 10	44.47	40.43	- 9

14 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.082 in.	5	8.0	9	11.6
Computed peaks	6.569 ft^3/s	4	33.2	10	19.2

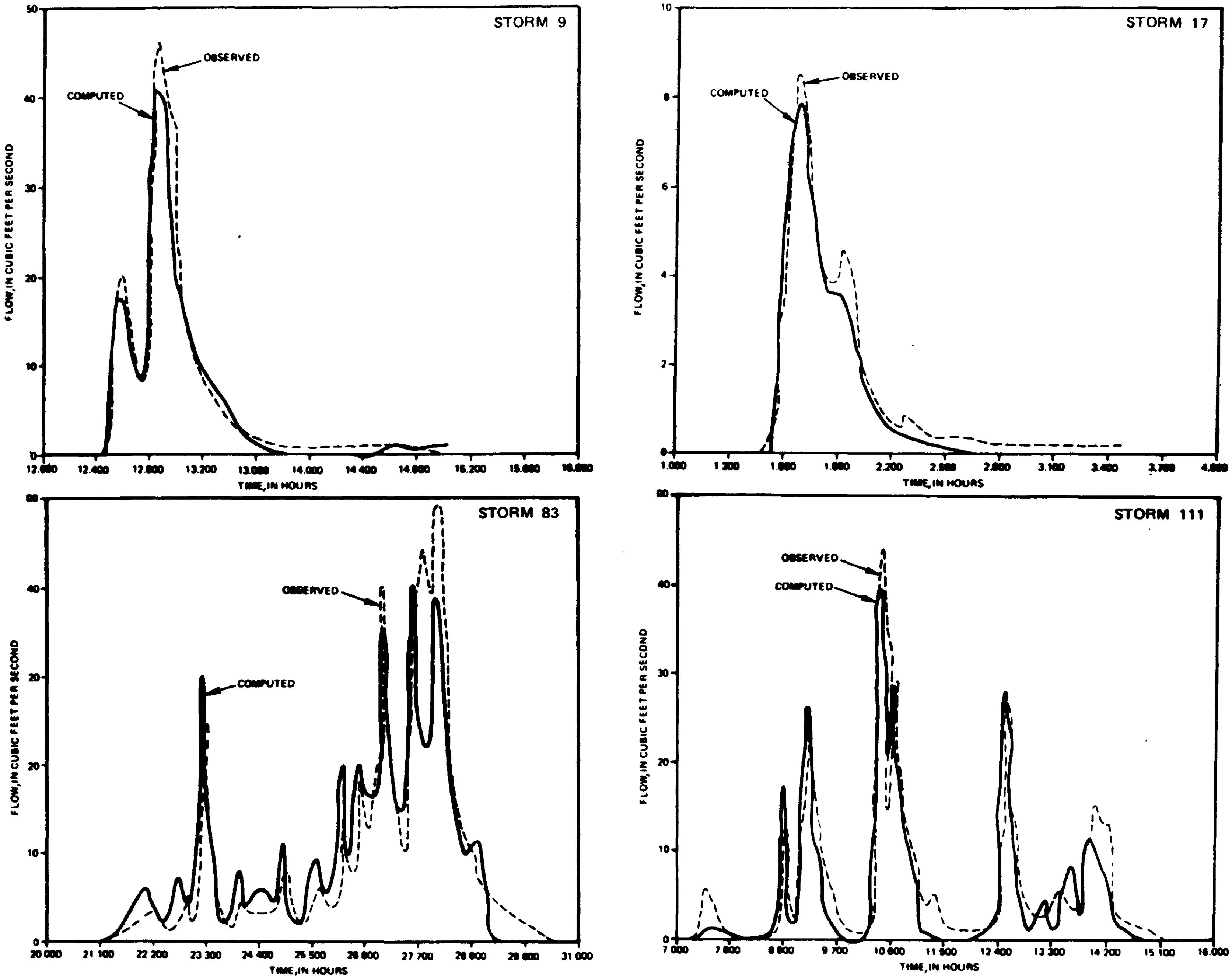

Figure 22.--Calibration storms for site 3, commercial site.

Table 18.--Model verification results--commercial site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
2	06-03-75	0975-1220	1.29	1.016	1.191	+ 17	43.04	59.14	+ 37
5	06-20-75	0835-1080	.28	.284	.191	- 33	16.26	10.13	- 38
13	07-19-75	0147-0345	.20	.223	.117	- 48	3.73	3.85	+ 3
22	09-18-75 to 09-19-75	0984-1500	4.15	4.381	4.010	- 8	48.49	60.13	+ 24
29	10-22-75	0642-0850	.45	.537	.362	- 33	38.85	33.86	- 13
39	02-01-76	0964-1112	.22	.264	.138	- 48	17.54	10.66	- 39
46	05-01-76	0347-0450	.18	.104	.101	- 3	8.56	7.48	- 13
55	06-07-76 to 06-08-76	1279-1550	1.65	1.603	1.539	- 4	51.67	48.48	- 6
60	06-23-76 to 06-24-76	1205-1460	2.34	2.196	2.231	+ 2	45.73	50.11	+ 10
63	07-11-76	0630-0840	.77	.612	.680	+ 11	37.43	29.85	- 20
70	08-18-76 to 08-19-76	1435-1917	1.47	1.267	1.348	+ 6	27.58	23.21	- 16
81	10-11-76	0125-0510	.78	.497	.681	+ 37	15.84	16.45	+ 4
105	05-20-77	1153-1440	1.16	1.306	1.052	- 19	47.04	41.42	- 12
113	06-10-77	0960-1110	.83	.926	.751	- 19	42.81	33.89	- 21

14 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.171 in.	5	14.6	9	23.9
Computed peaks	7.458 ft^3/s	5	15.6	9	19.8

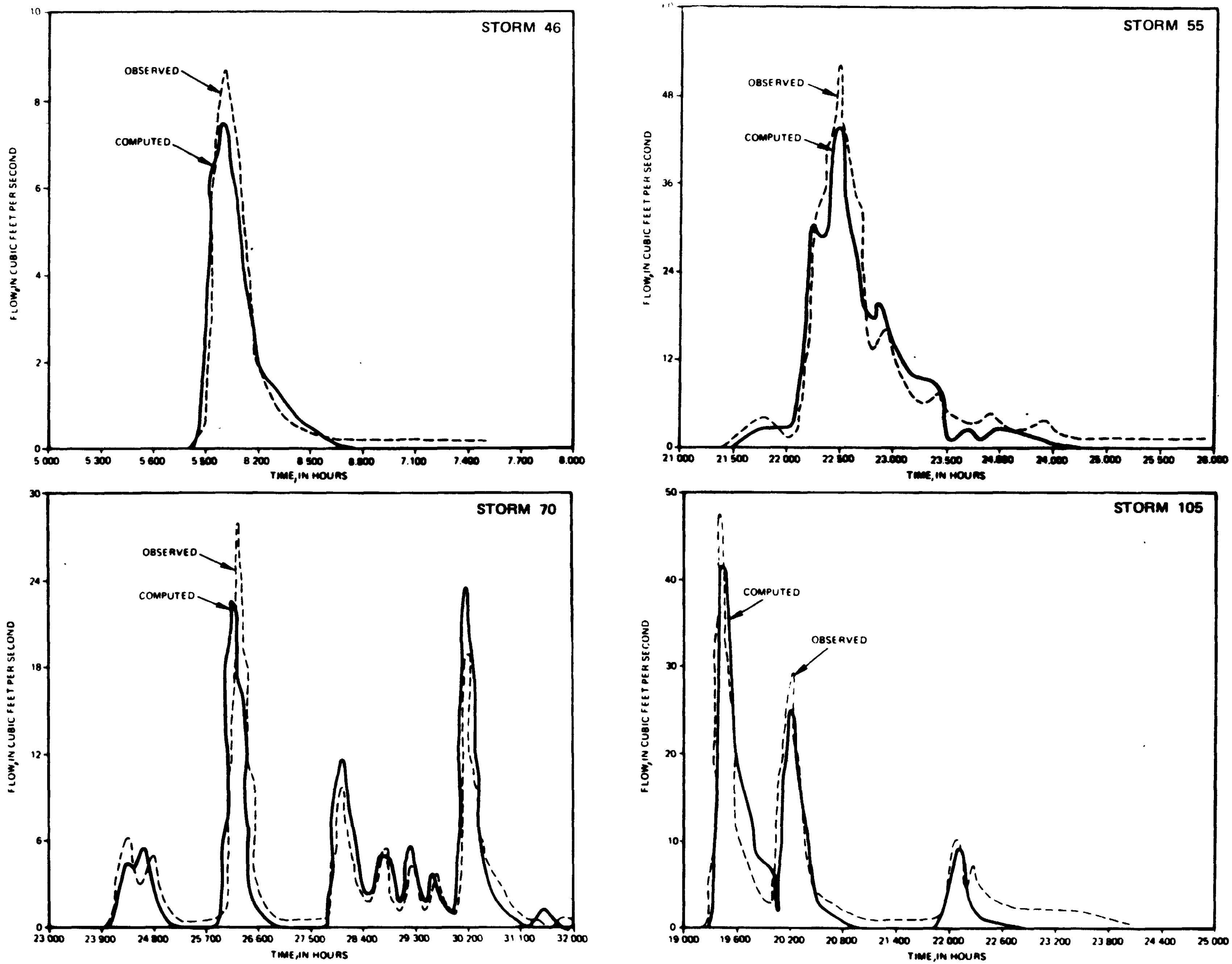

Figure 23.--Verification storms for site 3, commercial site.

Table 19.--Remaining model verification results--commercial site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
3	06-04-75	1100-1200	0.20	0.110	0.122	+ 11	7.01	11.34	+ 62
4	06-17-75	0655-0840	.54	.569	.443	- 22	28.83	24.69	- 14
6	06-23-75	0947-1260	1.74	1.778	1.629	- 8	52.42	46.25	- 12
7	06-26-75	1121-1380	.31	.299	.206	- 31	2.54	3.31	+ 30
8	07-02-75	0689-0900	1.07	1.115	.968	- 13	49.31	44.35	- 10
10	07-05-75	0207-0420	.60	.765	.509	- 33	37.27	28.67	- 23
11	07-05-75 to 07-06-75	1409-1530	.22	.152	.160	+ 5	9.72	12.01	+ 24
12	07-11-75	0883-1050	2.45	2.735	2.346	- 14	51.46	58.92	+ 14
14	08-02-75	0114-0320	.53	.570	.438	- 23	44.72	33.64	- 25
15	08-04-75	0260-0360	.26	.195	.180	- 8	12.72	13.13	+ 3
16	08-07-75	1395-1515	.35	.346	.270	- 22	32.38	23.14	- 29
18	09-01-75	1245-1390	.38	.325	.298	- 8	14.26	11.65	- 18
19	09-06-75	0509-0720	.37	.155	.285	+ 84	12.41	19.27	+ 55
20	09-07-75	0980-1110	.33	.241	.249	+ 3	24.79	25.27	+ 2
21	09-17-75	0861-0970	.25	.166	.170	+ 2	10.09	10.42	+ 3
23	09-19-75	1147-1395	.25	.492	.158	- 68	12.44	16.65	+ 34
24	09-27-75 to 09-28-75	1261-1500	.61	.832	.524	- 37	32.98	26.79	- 19
26	10-19-75	0381-0540	.24	.296	.160	- 46	4.51	5.04	+ 12
27	10-20-75	2697-2820	.20	.209	.159	- 24	9.98	7.57	- 24
28	10-21-75	3508-3615	.20	.068	.122	+ 79	5.82	12.03	+107

Table 19.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
30	10-27-75	1123-1260	0.46	0.587	0.378	- 36	29.58	25.15	- 15
31	10-29-75	0975-1080	.25	.048	.171	+256	7.91	15.36	+ 94
32	11-04-75	1282-1440	.50	.110	.412	+275	5.22	13.76	+164
36	12-08-75	0148-0360	.34	.208	.255	+ 23	8.65	19.74	+128
37	12-08-75	0581-0780	.20	.183	.182	- 1	5.57	10.23	+ 84
38	02-01-76	0693-0900	.38	.385	.294	- 24	11.43	12.00	+ 5
40	02-24-76 to 02-25-76	1319-1680	.24	.195	.143	- 27	1.92	2.20	+ 15
41	02-25-76	0205-0653	.87	.680	.760	+ 12	10.36	13.18	+ 27
42	02-26-76	2501-2660	.17	.105	.094	- 10	3.08	2.93	- 5
44	02-28-76	0556-1020	.29	.244	.176	- 28	2.77	3.12	+ 13
45	04-06-76	0431-0660	.42	.245	.322	+ 31	16.31	21.69	+ 33
47	05-01-76	0771-0915	.26	.273	.180	- 34	13.63	13.82	+ 1
48	05-01-76	0982-1220	.51	.376	.467	+ 24	17.08	17.49	+ 2
49	05-03-76	0644-0900	.41	.500	.325	- 35	5.28	5.31	+ 1
50	05-15-76 to 05-16-76	1225-1705	.88	.784	.748	- 5	9.03	9.81	+ 9
52	05-22-76	0025-0420	.24	.211	.146	- 31	4.88	7.49	+ 53
53	05-23-76	2361-2580	.55	.505	.462	- 9	44.03	41.84	- 5
54	06-05-76	1280-1440	1.01	1.010	.907	- 10	52.88	42.34	- 20
56	06-10-76 to 06-11-76	1160-1740	1.06	.895	.919	+ 3	24.70	26.38	+ 7
57	06-11-76	2075-2460	.27	.178	.238	+ 34	4.67	6.99	+ 50

Table 19.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
58	06-19-76	0648-0900	0.44	0.302	0.327	+ 8	8.57	14.35	+ 67
62	07-09-76	0748-1020	.48	.531	.393	- 26	17.24	15.86	- 8
64	07-25-76	0192-0370	.17	.124	.093	- 25	5.13	6.28	+ 22
65	07-31-76	0660-0840	.33	.108	.251	+132	11.47	24.76	+116
66	08-01-76	2490-2760	.90	.718	.801	+ 12	38.80	36.57	- 6
68	08-11-76	1053-1242	.21	.174	.126	- 28	13.90	12.01	- 14
69	08-18-76	0740-1020	.29	.255	.199	- 22	3.16	3.35	+ 6
72	08-23-76	1015-1170	.67	.486	.582	+ 20	46.01	40.30	- 12
73	09-10-76	1199-1320	.38	.121	.290	+140	10.79	22.94	+113
74	09-12-76	0360-0540	.40	.477	.307	- 36	35.10	24.40	- 30
75	09-12-76	0598-0945	.29	.238	.263	+ 11	17.49	19.45	+ 11
76	09-12-76	1153-1350	.26	.178	.201	+ 13	12.05	11.60	- 4
77	09-14-76	0958-1200	1.06	1.050	.970	- 8	43.32	32.62	- 25
78	09-15-76	2197-2530	1.26	1.000	1.163	+ 16	43.28	43.38	0
79	09-23-76	1189-1360	.36	.217	.276	+ 27	9.48	11.69	+ 23
82	10-18-76	0967-1210	.31	.307	.222	- 28	14.10	14.41	+ 2
85	11-12-76	0810-1080	.27	.249	.187	- 25	5.63	5.35	- 5
84	11-17-76	0184-0360	.38	.278	.299	+ 8	11.30	13.85	+ 23
86	12-01-76	0695-1080	.29	.148	.198	+ 34	3.06	4.76	+ 56
87	12-06-76	0082-0750	1.93	1.764	1.785	+ 1	48.13	57.15	+ 19

Table 19.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
88	12-13-76 to 12-14-76	1230-1560	1.93	1.982	1.829	- 8	46.25	38.36	- 17
89	12-14-76	1939-2160	.30	.168	.262	+ 56	5.64	9.28	+ 65
90	12-23-76 to 12-24-76	1224-1643	.49	.151	.399	+164	1.51	2.84	+ 88
115	12-24-76	1650-2040	.39	.107	.379	+254	2.06	4.05	+ 97
91	12-31-76	1035-1320	.20	.164	.118	- 28	10.14	9.56	- 6
92	01-03-77	0537-0840	.75	.518	.662	+ 28	20.62	23.90	+ 16
93	01-15-77	0708-1080	.78	.553	.693	+ 25	34.55	30.90	- 11
94	01-29-77	0361-0495	.29	.315	.213	- 32	24.43	20.32	- 17
95	01-31-77	0933-1280	.28	.491	.190	- 61	16.13	14.63	- 9
96	02-08-77	0428-1080	.85	.806	.743	- 8	29.64	34.73	+ 17
97	02-14-77	0817-1080	.41	.416	.326	- 22	10.62	11.81	+ 11
98	02-15-77 to 02-16-77	2800-3180	.21	.264	.145	- 45	3.26	4.16	+ 28
99	04-13-77	0805-1080	.21	.211	.118	- 44	8.80	4.86	- 45
101	04-24-77	0748-1015	.32	.296	.226	- 24	20.85	19.86	- 5
102	05-09-77	1058-1410	1.00	.877	.892	+ 2	42.76	51.81	+ 21
103	05-10-77	2216-2640	.41	.342	.324	- 5	4.94	7.53	+ 52
104	05-12-77	0645-0960	.22	.221	.130	- 41	3.83	3.22	- 16
106	05-27-77	0905-1200	.80	.749	.708	- 5	25.40	25.54	+ 1
107	05-29-77	1005-1280	1.60	1.602	1.511	- 6	70.26	60.59	- 14
108	06-01-77 to 06-02-77	0930-1640	1.49	1.462	1.350	- 8	30.72	30.97	+ 1

Table 19.--Continued

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
109	06-02-77	2140-2550	1.53	1.476	1.447	- 2	40.90	34.34	- 16
110	06-03-77	3727-4150	.52	.438	.444	+ 1	11.23	12.91	+ 15
112	06-09-77	0900-1225	.65	.151	.551	+265	3.19	6.20	+ 94
114	06-20-77	0565-0750	.42	.212	.331	+ 56	11.92	19.74	+ 66

84 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.136 in.	35	60.4	49	23.3
Computed peaks	5.216 ft^3/s	53	38.9	31	15.5

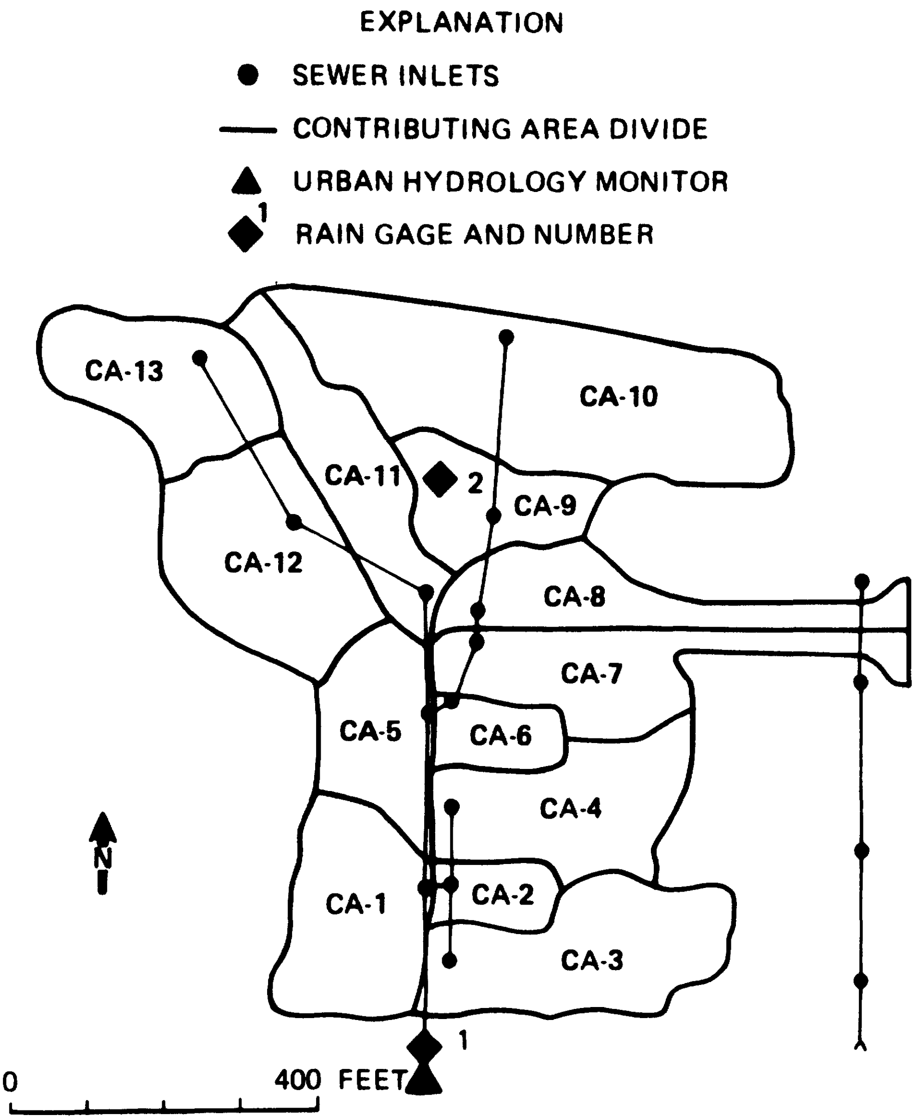

Figure 24.--Contributing areas (CA) map of multifamily residential site.

Table 20.--Lists of impervious, pervious, effective impervious, and total areas for multifamily residential site

Designation	Total area	Pervious area	Impervious area	Effective impervious area
CA-1	1.157	0.460	0.698	0.415
CA-2	.352	.043	.309	.109
CA-3	1.412	.626	.786	.568
CA-4	1.236	.380	.855	.459
CA-5	.842	.187	.655	.397
CA-6	.395	.093	.303	.126
CA-7	1.204	.315	.889	.585
CA-8	1.006	.310	.696	.513
CA-9	.761	.179	.582	.241
CA-10	2.798	.601	2.197	1.380
CA-11	1.049	.524	.525	.374
CA-12	1.452	.287	1.164	.864
CA-13	1.079	.293	.786	.444
Totals	14.743	4.298	10.445	6.475
Percentage	100.0	29.2	70.8	43.9

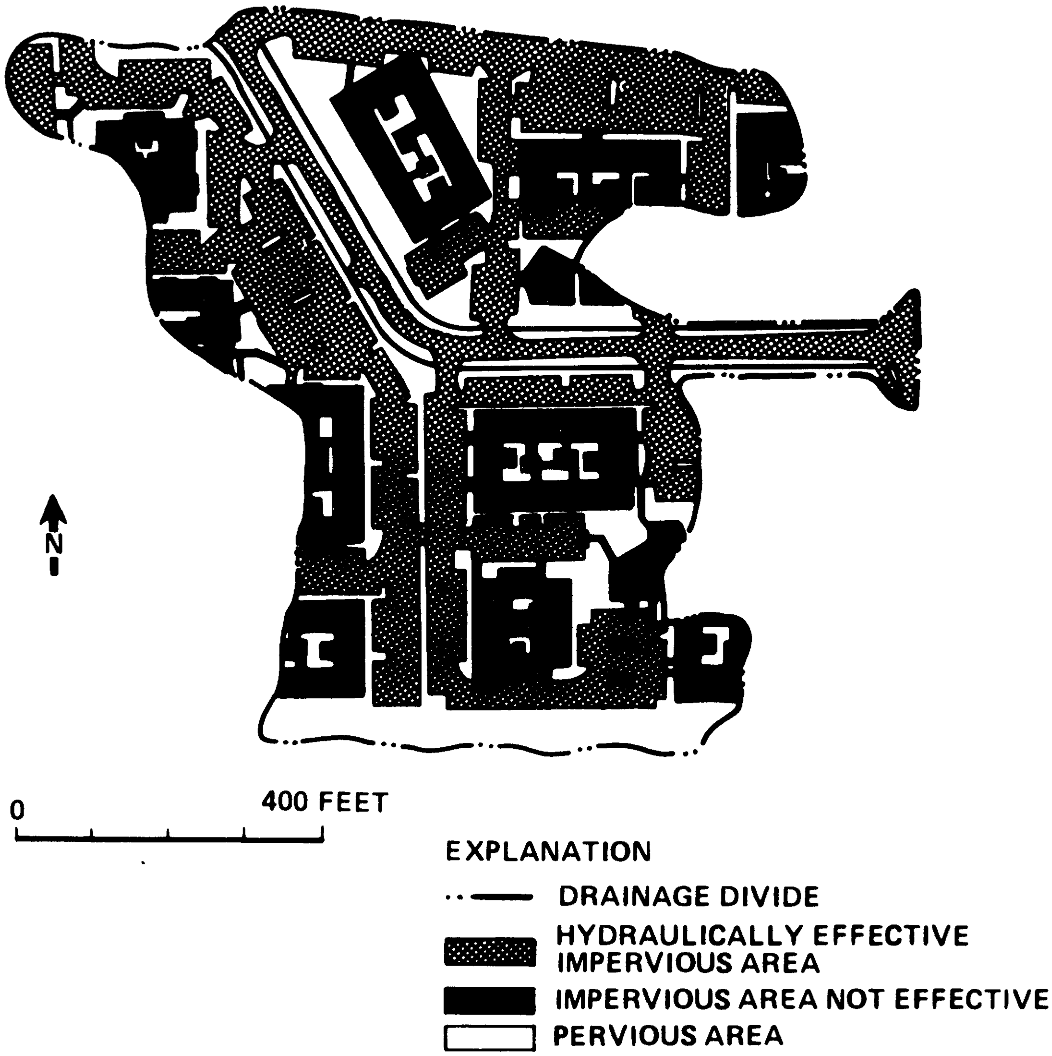

Figure 25.--Impervious and hydraulically connected impervious areas of the multifamily residential site.

Table 21.--Multifamily residential site pipe-segment information

Segment	Length (ft)	Slope (ft/ft)	Diameter (ft)
P001	220	0.005	4.00
P002	32	.030	1.50
P003	105	.002	1.50
P004	105	.002	1.50
P005	240	.002	3.00
P006	40	.002	3.00
P06A	90	.002	1.50
P007	90	.007	3.00
P008	40	.024	2.50
P009	165	.004	2.25
P010	210	.002	2.00
P011	165	.002	2.50
P11A	90	.002	2.50
P12A	250	.002	2.25
P13A	150	.002	2.00

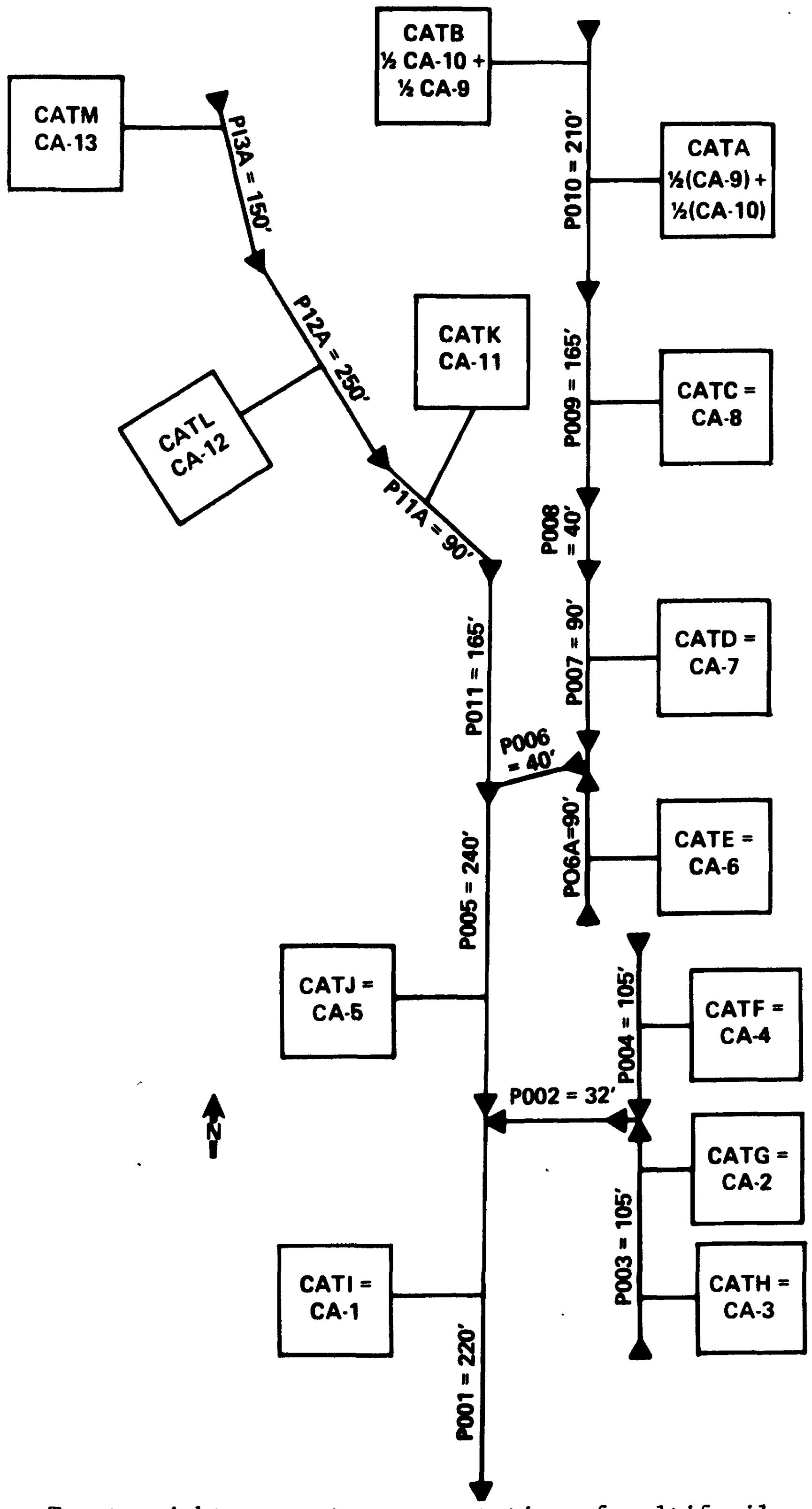

Figure 26.--Twenty-eight segment representation of multifamily residential site.

approximation of actual discharges during rapidly changing flows. An alternate method of computing discharge was selected and an electromagnetic velocity meter was installed in the storm drain pipe near the outlet for flow measurements during storms 33 to 52. The meter provided calibration and verification data for the development of an unsteady flow model of the storm drain pipe (Land and Jobson, 1979). Discharge data for storms 1 to 32 were recomputed using the unsteady flow model.

Because data on storms 33 to 52 included flow velocity measurements, these storms were used for calibration and verification of the stormwater model. Observed rainfall (inches) versus observed runoff (inches) were plotted (fig. 27). Nine calibration storms were selected using figure 27 as a guide. Rainfall for the nine storms varied from 0.18 in. to 2.06 in. Observed peak discharges and runoff volumes were in the ranges of 1.66 to 27.13 ft^3/s and 0.061 to 0.712 in., respectively.

The seven soil-moisture-accounting parameters were optimized using 20 iterations and all nine storms. Additionally, parameters KSAT and RGF were allowed to optimize for 50 more iterations each. Table 22 shows the resulting optimized values used in calibration and verification analyses.

Calibration Results

Data from two rain gages were averaged for each time increment during a storm. There was some aerial variation in rainfall, however, total rainfall amounts were closely related for most storms. Also, this site was the smallest of the four urban sites (14.7 acres), and the two gages were both functioning for all storms except three.

Initial calibration runs showed some timing, volume, and peak discharge errors. This resulted in additional optimization of the soil-moisture-accounting parameters KSAT and RGF. These two parameters affect the supply of rainfall excess and influence any simulated peak discharges and volumes more than any of the other soil-moisture-accounting parameters. Also, the impervious retention was decreased from 0.05 to 0.02 in.

Again, as at the other sites the overland slope of 0.027 and roughness equal 0.015 were used in the analysis. Available pipe slope data (table 21) and roughness values reflective of corrugated and smooth metal pipes were selected. An adjustment was made to the smallest pipe slopes (0.001 increased to 0.002 in table 21) to eliminate some of the timing errors. Final adjustments to slope data are listed in table 21.

Table 23 lists summary statistics for the nine calibration storms. The SEE for simulated volumes and peaks were 0.080 in. and 1.491 ft^3/s, respectively. It was noted that the smaller peaks simulated produced the greatest errors. Digitizing or shift application errors could produce a change as much as $\pm$ 1 ft^3/s, which would be greater than model simulation errors for small storms. Figure 28 shows four of the best calibration storms--both observed and simulated storm hydrographs. No storms were determined to be unacceptable.

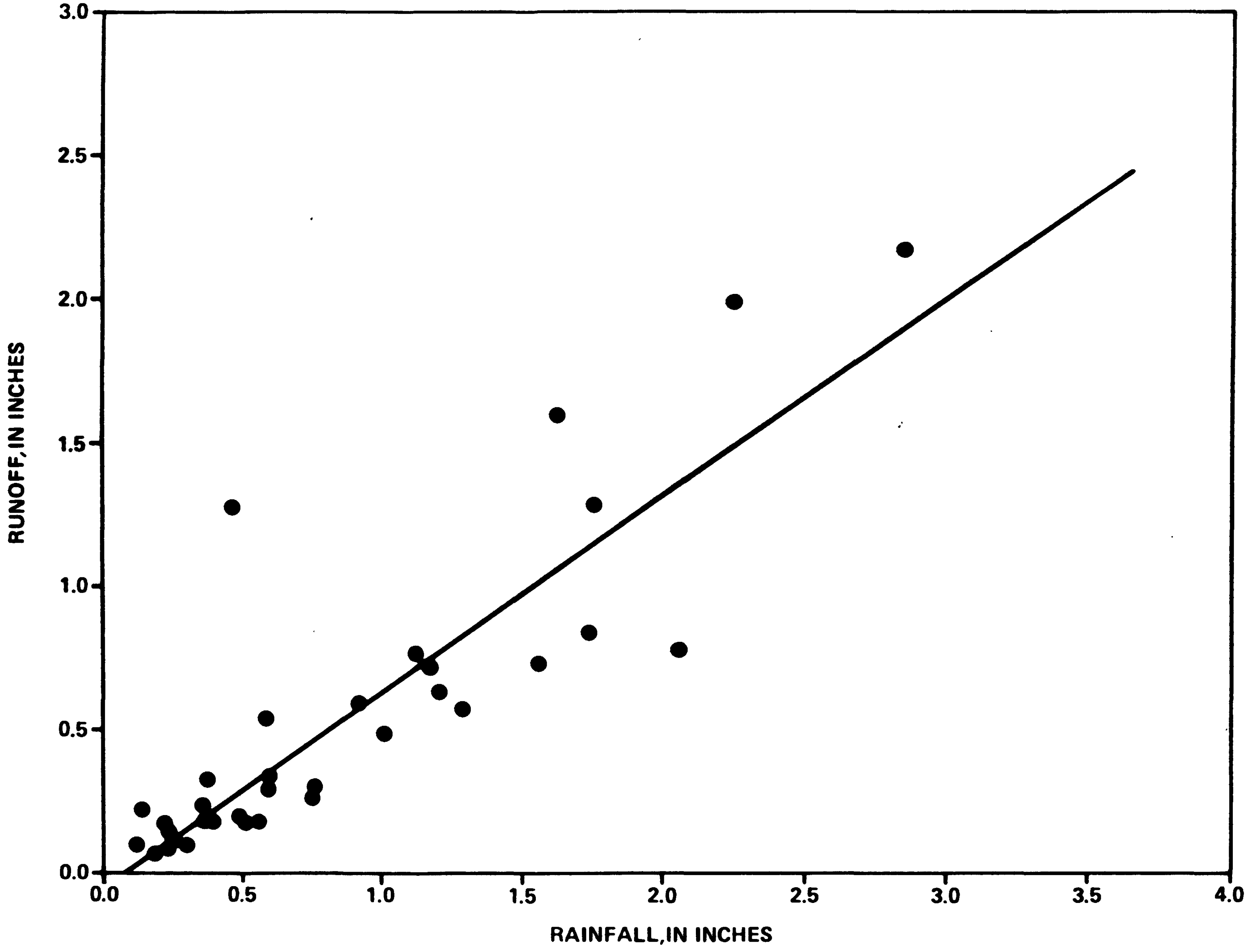

Figure 27.--Rainfall-runoff relation for multifamily residential site.

Table 22.--Parameter values for soil-moisture accounting and infiltration at the multifamily residential site

Parameter symbol	Range of values		Initial value	Optimized value
	Lower limit	Upper limit		
DRN	.1	1.0	0.50	0.51
EVC	.5	1.0	.70	.51
RR	.65	1.0	.90	.73
BMSN	1.0	15.0	5.00	6.80
KSAT	.01	1.0	.10	.99
RGF	5.0	20.0	10.00	19.72
PSP	1.0	15.0	5.00	4.70

Table 23.--Model calibration results--multifamily residential site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
33	12-06-77	0635-0785	0.75	0.309	0.323	+ 5	15.57	12.86	- 17
36	01-04-78	1220-1440	.25	.111	.101	- 9	2.81	1.86	- 34
37	01-13-78	0855-0960	.26	.125	.103	- 18	5.49	3.49	- 36
38	01-19-78 to 01-20-78	1215-1620	.76	.281	.331	+ 18	11.88	10.06	- 15
39	02-18-78	0905-1380	2.06	.712	.916	+ 29	16.20	16.00	- 1
42	03-28-78	0660-0905	.20	.061	.072	+ 18	1.66	1.30	- 22
48	05-18-78	0690-0920	.74	.238	.319	+ 34	8.50	7.35	- 14
49	05-25-78	1210-1350	.18	.069	.065	- 6	2.33	1.97	- 30
52	06-12-78	0933-1000	1.01	.443	.442	0	27.13	27.07	0

9 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.080 in.	5	20.8	4	8.2
Computed peaks	1.491 ft^3/s	0	0.0	9	18.3

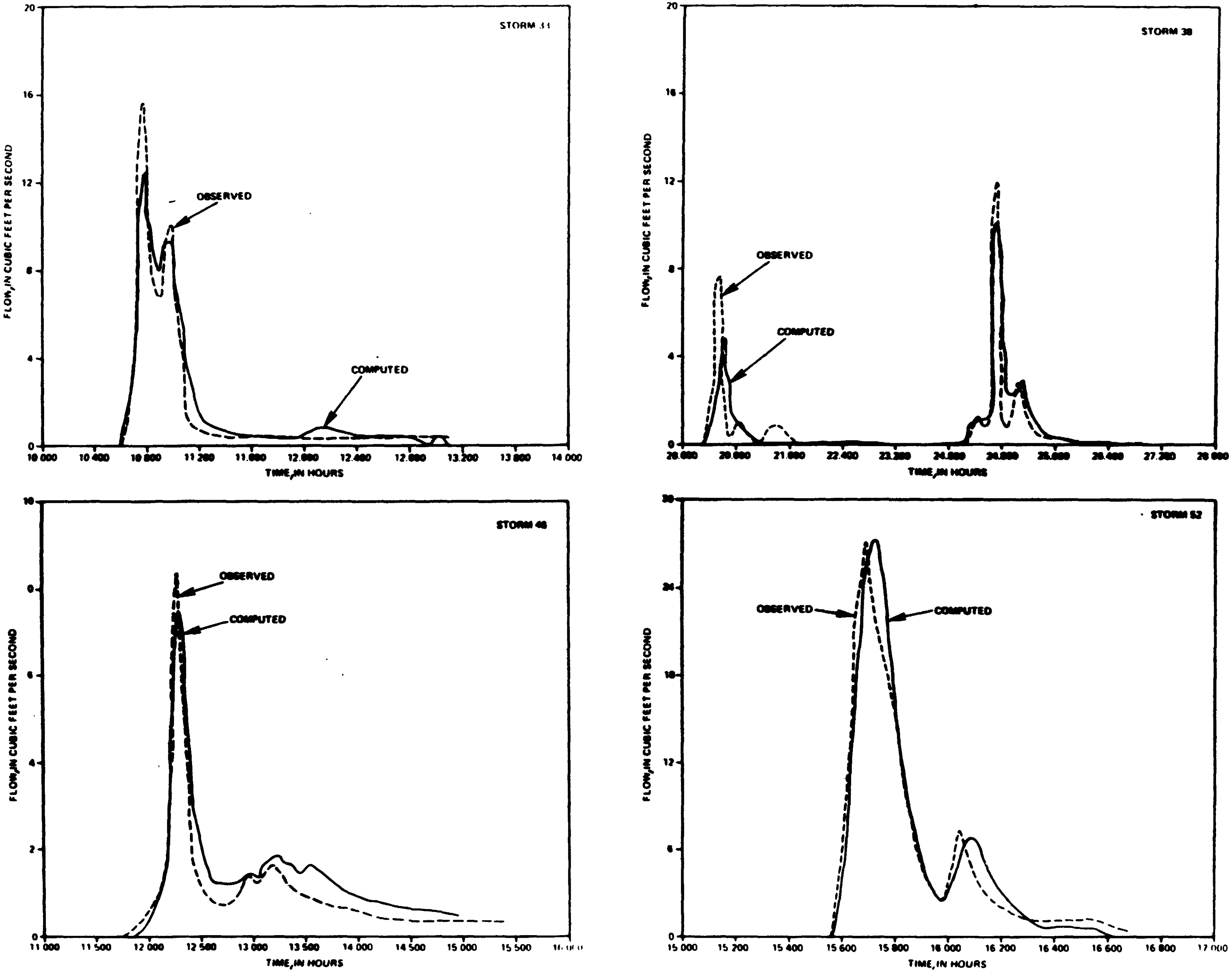

Figure 28.--Calibration storms for site 4, multifamily residential site.

Verification Results

Eight storms were used for verification. These were the remaining storms in the 33-52 range for which velocity data were available. The SEE for volumes and peaks (table 24) were 0.036 in. and 2.086 ft^3/s, respectively. Storm 34 was unacceptable as the peak discharge error indicates. This storm had the smallest measured rainfall of any of the calibration or verification storms. Small storms, as shown at the other three sites, tend to produce largely variable runoff amounts. Figure 29 shows four of the eight verification storms.

Table 25 lists storm data and statistics for storms 1-32. Some of the storms not listed, such as 4, 11, and so forth, were not included in the analysis because the data was not ready for use from the data management system for various reasons. The SEE for volumes and peaks were 0.449 in. and 5.541 ft^3/s, respectively. About 4 of the 20 storms were unacceptable. This site was more accurately modeled than any of the previous three sites probably because the flow data for site 4 included velocity measurements and the unsteady flow analysis, plus the basin was the smallest in size and had two rain gages.

SUMMARY AND CONCLUSIONS

Deterministic flow model calibration and verification results have been presented for four urban catchments near Miami, Fla. The sites were:

(1) A 40.8-acre single-family residential area,

(2) A 58.3-acre highway area,

(3) A 20.4-acre commercial area, and

(4) A 14.7-acre multifamily residential area.

One-minute time interval rainfall and runoff data were available for 80, 108, 114, and 52 storms at sites 1, 2, 3, and 4, respectively. A preliminary calibration was performed, verification attempted, and a final model recalibration completed, if necessary. A verification was performed using a separate set of data in each case.

This study also demonstrated which data need to be collected in order to define rainfall-runoff processes. Additional information is needed to define the relationship between soil types and soil-moisture-accounting parameters. When pervious-area runoff is small as compared to total basin runoff, data measurement errors can often be larger than the total effect of pervious area runoff. In this case the optimization technique provided in the DSA model cannot determine soil-moisture-accounting parameters with any degree of confidence. This also points out the importance of an accurate measurement of discharge. Accurate rainfall data with complete basin coverage are needed for modeling requirements. It is recommended that every basin have a minimum of

Table 24.--Model verification results--multifamily residential site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
34	12-27-77	0987-1020	0.17	0.090	0.066	- 27	7.35	2.73	- 63
35	01-03-78	0395-0680	.28	.080	.115	+ 44	1.83	1.77	- 3
41	03-09-78	0079-0425	.57	.186	.234	+ 26	8.37	7.90	- 6
43	03-31-78	0668-0780	.49	.177	.204	+ 15	7.06	6.36	- 10
46	05-10-78	0855-0960	.30	.099	.122	+ 23	5.13	4.51	- 12
47	05-11-78	2285-2460	.52	.160	.217	+ 36	6.67	7.42	+ 11
50	05-26-78	0140-0270	.60	.269	.252	- 6	12.46	10.94	- 12
51	05-28-78	0245-0615	1.74	.773	.760	- 2	22.72	24.99	+ 10

8 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.036 in.	5	28.8	3	11.7
Computed peaks	2.086 ft^3/s	2	10.5	6	17.7

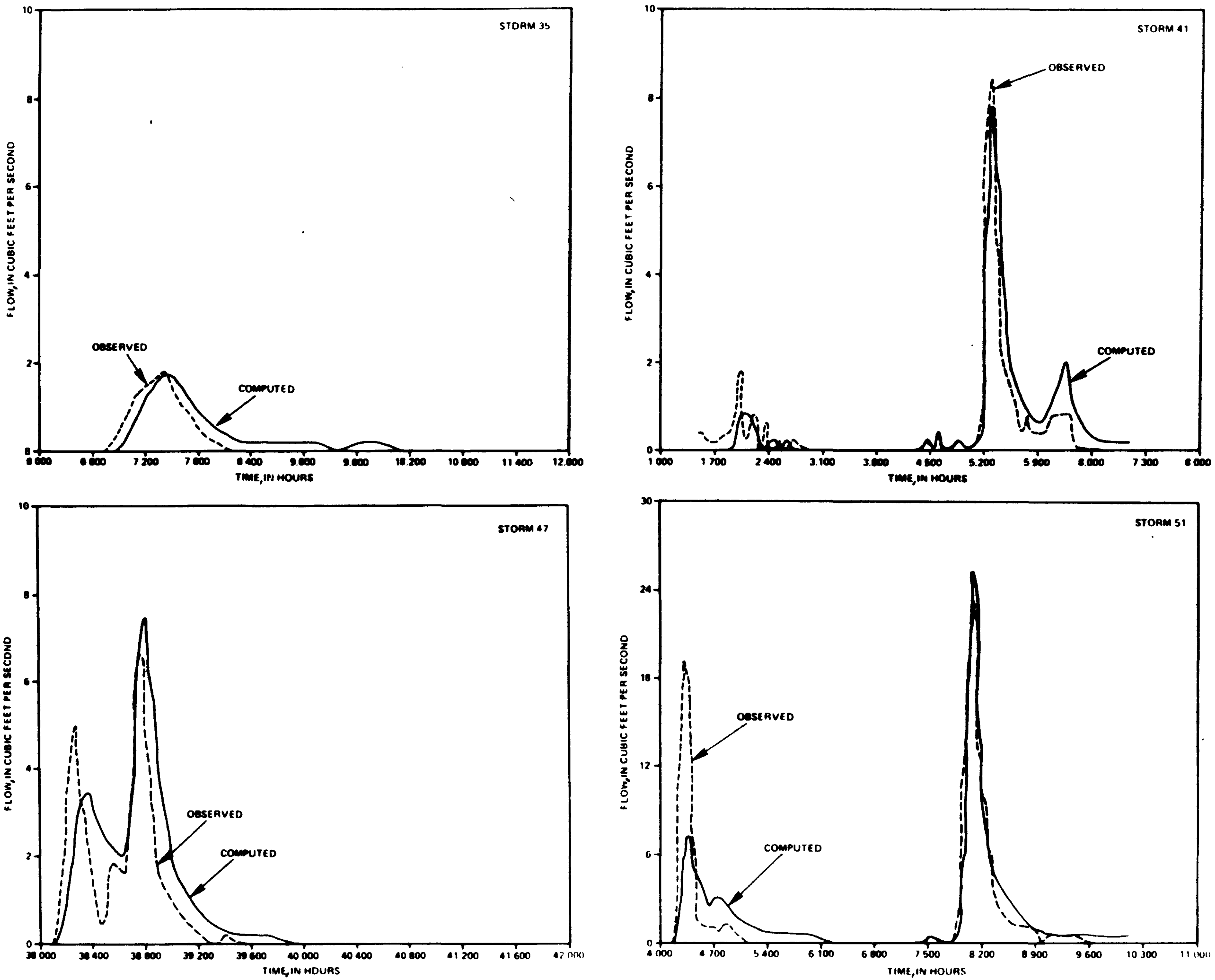

Figure 29.--Verification storms for site 4, multifamily residential site.

Table 25.--Remaining model verification results--multifamily residential site, Miami, Fla.

Storm	Storm date	Time interval	Rainfall (in.)	Observed runoff (in.)	Simulated runoff (in.)	Percent error	Observed peak Q (ft^3/s)	Simulated peak Q (ft^3/s)	Percent error
1	05-04-77	0454-0810	2.85	1.983	1.248	- 37	21.22	15.63	- 26
2	05-04-77	0817-1230	3.80	2.725	1.712	- 37	21.82	15.45	- 29
3	05-11-77	0280-0418	1.21	.657	.571	- 13	31.95	32.00	0
5	06-01-77	0955-1380	2.24	1.176	.986	- 16	17.61	18.69	+ 6
6	06-02-77	2054-2366	2.33	1.819	1.086	- 40	15.74	11.30	- 28
7	06-04-77	0282-0360	0.40	.162	.171	+ 6	13.97	10.72	- 23
8	06-20-77	0720-0990	1.12	.705	.491	- 30	16.12	10.51	- 35
9	07-15-77	0390-0580	1.56	.668	.682	+ 2	16.07	14.21	- 12
10	07-16-77	1970-2355	1.63	1.460	.718	- 51	17.87	12.42	- 30
12	07-23-77	0865-1200	1.24	.579	.552	- 5	15.76	19.55	+ 24
14	08-06-77	0605-0695	.35	.216	.144	- 33	10.17	7.61	- 25
15	08-06-77	1130-1185	.22	.157	.088	- 44	8.43	4.91	- 42
17	08-08-77	1065-1380	.94	.541	.407	- 25	13.88	14.65	+ 6
19	08-16-77	1375-1430	.24	.127	.092	- 28	5.26	4.67	- 11
20	08-22-77	0905-1020	1.29	.523	.581	+ 11	12.18	16.09	+ 32
21	08-24-77	0100-0330	.39	.296	.157	- 47	6.46	5.24	- 19
28	09-07-77	0275-0450	.60	.492	.253	- 49	18.68	5.51	- 71
29	09-11-77	0865-0960	.43	.164	.183	+ 12	17.83	9.06	- 49
31	09-27-77	0770-0825	.14	.203	.051	- 75	9.22	2.29	- 75
32	10-06-77	1090-1265	.47	1.169	.193	- 83	12.87	4.75	- 63

Table 25.--Continued

20 storms	Standard error of estimate	Number of high cases	Average + error percent	Number of low cases	Average - error percent
Computed volumes	0.449 in.	4	7.8	16	38.3
Computed peaks	5.541 ft^3/s	5	13.6	15	35.9

two rain gages, not only for defining areal variation in rainfall but also for backup capabilities. The drainage areas should be accurately delineated, especially the hydraulically effective impervious areas.

A summary of specific sources of errors identified in this study is as follows:

1. Rainfall data errors, including measurement and areal distribution;
2. Streamflow data measurement errors;
3. Shift application errors when used to compute discharges;
4. Digitizing errors when preparing the rainfall-runoff data for computer storage;
5. Varying antecedent soil-moisture conditions from storm to storm;
6. Varying impervious retention;
7. Varying hydraulically effective impervious areas as size of storms increase;
8. Delineation of drainage areas, impervious areas, and HEIA;
9. Kinematic wave theory neglecting the momentum effects of flow which are very important where mild slopes are prevalent; and
10. Last, but not least, the errors in the model that result from the stochastic nature of parametric modeling.

No attempt is made to quantify the actual amount of error that the above sources contribute to model error. It varies from storm to storm and from application to application.

The applicability of a verified model of one basin to another has not been tested at this point in model development. Values for overland roughnesses and slopes used in the model were the same at each site and probably reflect inadequacies in the kinematic wave routing method. This indicates a limited potential for model transferability within the same geographic area. Although soil-moisture-accounting parameters determined for each site were inadequate, they were indicative of the highly pervious, rapidly infiltrating soil found in the study area. Given a proper analysis of soil perviousness and adjustments to the kinematic wave routing method, the transferability of the model might be possible.

The results of this study showed that within the limits given an acceptable verification of the DSA model can be achieved with adequate data. Procedures for rainfall-runoff modeling and application of the DSA model have been developed and the important data collection needs for modeling purposes have been identified.

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