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VERIFICATION OF THE RUNOFF BLOCK OF SWMM MODEL

by

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ABSTRACT

The Runoff Block of the Storm Water Management Model (SWMM) of the U.S. Environmental Protection Agency was verified for 14 rainfall/runoff events monitored in the Malvern catchment.

A good fit was obtained between measured and simulated runoff volumes, peak flow rates and times to peak flow.

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1.0 INTRODUCTION

One of the objectives of the Urban Drainage Subcommittee established under the Canada-Ontario Agreement on Great Lakes Water Quality was to provide fully operational verified computer models for simulation of quantity and quality of urban runoff. Towards this end, several existing models were combined in a complete modelling package and verified on a number of urban test catachments. The report which follows describes one of the verification studies - the verification of the RUNOFF Block of the Storm Water Management Model of the U.S. EPA on the Malvern test catchment.

The Malvern test catchment was established in 1973 and served for monitoring of urban rainfall/runoff events for a number of years. This report represents the third progress report on the SWMM verification studies on the Malvern catchment. Whenever possible, reference is made to the first progress report (8) to avoid unnecessary repetition.

2.0 BRIEF OVERVIEW OF THE SWMM MODEL

2.1 Description

The SWMM Model was developed in 1971 by a consortium of contractors under the sponsorship of the U.S. Environmental Protection Agency (EPA). It is a comprehensive mathematical model capable of simulating urban storm water runoff and combined sewer overflow phenomena by using a high-speed digital computer. The model has since been updated and maintained by the University of Florida. The version (7) of the model used in this study was released in May, 1976.

The model uses rainfall hyetographs along with system characteristics as inputs and then makes a step by step computation of infiltration, depression storage, surface runoff and in-sewer system routing to arrive an outflow hydrograph and pollutograph (if quality to be simulated). The computations can be carried out for any rainfall hyetograph, land use and topography.

The programming arrangement consists of an executive block and four major computational blocks: Runoff, Transport, Storage and Receiving Blocks.

2.1.1 Runoff Block

The Runoff Block simulates overland flow, surface runoff, and sewer flow routing for a given storm for each subcatchment and stores the results in the form of hydrographs at inlets to the main sewer system.

2.1.2 Transport Block

The Transport Block simulates the in-sewer flow routing. It sets up prestorm conditions by computing dry weather flow (i.e. in combined sewers) and infiltration and distributing them throughout the sewer system. The block then picks up the results of runoff hydrograph computed by the Runoff Block, and combined with the dry weather flow, produces flow hydrographs for the total drainage basin at selected points within the sewer system. The computations in the Transport Block employ the Manning's equation and continuity for the routing of flows under free-surface condition. When pipe capacity is exceeded, the excess flow is stored at manholes for subsequent release when capacity becomes available. Quality constituents can be also simulated in the Transport Block.

2.1.3 Storage Block

The Storage Block uses the output hydrographs and pollutographs generated by the Transport Block. Costs associated with the construction and operation of storage facilities are computed or simulated from input unit costs and indices.

Treatment is modelled by packages of selected standard treatment processes which are contained in the model forming a computational string. The sewage flows and treatment are simulated each time step according to the computation string. This block requires only minimal input data to describe the storage/treatment facilites.

2.1.4 Receiving Block

The Receiving Block accepts the output of the Transport Block or the modified output of the Storage Block and simulates dispersion and effects of the discharges in the estuaries, rivers, reservoirs, lakes or bays. The Receiving Block uses a system called "channel" and "nodes" to represent an open water body. Channels are assigned certain properties of length, width, slope and roughness to connect the nodes, representing a small portion of the water body. The nodes are assigned a volume, surface area and depth. The equations of motion and continuity are solved at each time step to determine the flow in each channel and the net transfer from one node to another.

2.2 Runoff Block Simulation Procedures

In this study, only the quantity aspects of the Runoff Block were considered. A brief summary of the Runoff Block simulation procedures dealing with quantity aspects follows:

Type of Simulation Procedures

Simulation : Noncontinuous

Simulation of Processes:

Interception : Neglected

Transpiration : Neglected

Evaporation : Neglected

Depression Storage : Fills up before overland flow begins. Some fraction of the impervious area is assigned a zero depression storage, thus allowing an immediate runoff. On pervious areas, the surface storage is depleted by infiltration.

Infiltration : Horton's equation. No time offset. Satisfied by water on the ground surface and rainfall independent of antecedent condition.

Overland Flow : Uniform depth of detention over pervious and impervious surfaces. Use Manning turbulent flow equation and continuity equation.

Gutter Flow : Quasi steady state to uniform flow storage routing.

Inlet Junction : Outflow=sum of inflows from subcatchments.

Conduit Flow : Quasi steady-state storage routing by Manning equation based on the slope of energy line.

Conduit Surcharge : Stored for subsequent release.

2.3 Quantity Input Parameters

a. Rainfall hyetograph

b. Subcatchment characteristics - areas, depression depths, width, slope, roughness, and infiltration rates.

c. Gutter/pipe characteristics - length, slope, Manning's n, width, side slope or pipe diameter.

3.0 DESCRIPTION OF THE MALVERN CATCHMENT

3.1 Description

A detailed description of the Malvern catchment has been given by Marsalek (8). The following is only a brief description of the catchment following the terms of reference proposed by the University of Florida for the urban rainfall runoff data base.

3.2 Location and Data Collection Period

The location of the Malvern drainage basin is shown in Figure 1. The outfall of the sewer system drains into the Tuck Creek which drains into Lake Ontario. The development of the Malvern catchment was completed in 1964. The entire area is zoned as single family residential. There are no vacant lots or parks in the area.

The Malvern catchment was instrumented and monitored by the Hydraulics Division of the National Water Research Institute in Burlington. Data collection started in September 1973 and has continued till 1979. The field season spans from late March to December.

3.3 Runoff Contributing Areas

The drainage boundaries of the Malvern catchment are shown in Figure 1. The total contributing area of the catchment is 57.6 acres* (23.3 Ha).

The contributing area of the Malvern catchment is divided into pervious and impervious areas. The breakdown of pervious and impervious areas is outlined in Table 1.

TABLE 1 PERVIOUS AND IMPERVIOUS CONTRIBUTING AREAS

	Pervious		Impervious	
	Acre	ha	Acre	ha
Total roof area (directly connected to the storm sewers)			8.1	3.28
Total road surface area			6.7	2.71
Total surface area of driveway			3.1	1.25
Total sidewalks area			1.63	0.66
Total Areas	38.1	15.4	19.5	7.9

* Note: Since the SWMM Model input and output is specified in British Engineering Units, these units are used in this report. Wherever, practical, metric equivalents are given in brackets.

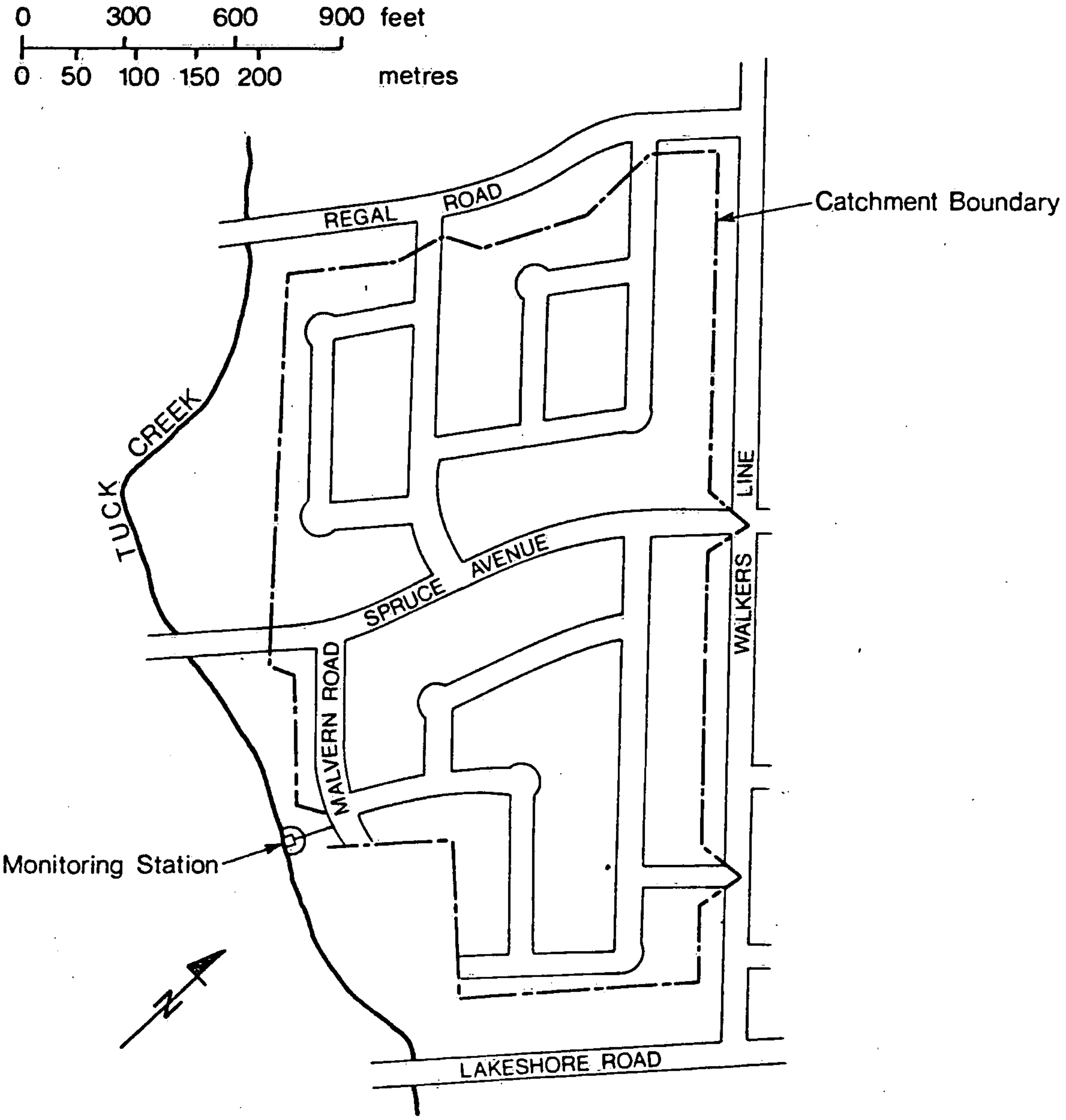
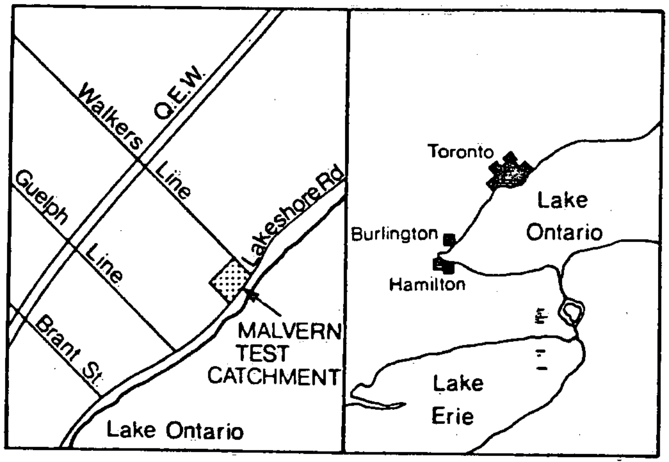


Figure 1. LOCATION MAP OF MALVERN TEST CATCHMENT



Key Map

The total catchment imperviousness of the Malvern catchment was expressed as 19.5/57.6=34%. If one considers only the directly connected impervious areas, the corresponding catchment imperviousness is 19.87/57.6=31%.

3.4 Surface Characteristics

The basic surface characteristic values are summarized in Table 2.

TABLE 2 SURFACE CHARACTERISTICS OF MALVERN CATCHMENT

Ground slope		0.01 - 0.03 ft/ft	(pervious & impervious)
Manning's n:	Impervious area	0.013	SWMM Default Value
	Pervious area	0.250	SWMM Default Value
Infiltration rates for pervious areas:			
	Maximum rate	3.0 in/hr	
	Minimum rate	0.52 in/hr	SWMM Default Values
	Decay rate	0.00115/sec	
Surface Depression Storage:			
	Pervious area	0.184 in	
	Impervious area	0.020 in	SWMM Default Value

3.5 Catchment Discretization

For modelling purposes, the Malvern catchment was discretized into ten subcatchments whose characteristics are listed in Table 3. Such a discretization was found satisfactory in the previous progress reports (8, 9). Subcatchment boundaries are shown in Fig. 2.

Earlier estimates (8) of the time of concentration for front yards and backyards indicated that while the runoff from front yards could reach the drainage outlet in 20-40 minutes, the runoff from backyards was considerably delayed. For typical observed events, the runoff from the backyards would reach the drainage outlet long after the occurrence of the peak flow. Thus the runoff hydrograph peak would not be affected by the backyard runoff.

TABLE 3

SUBCATCHMENT CHARACTERISTICS
(after reference 8)

Subcatchment Number	1	2	3	4	5	6	7	8	9	10
Sewer pipe for drainage	3	6	10	13	18	21	25	30	34	22
Area (acres)	5.64	6.23	3.87	6.01	6.12	2.26	9.47	6.62	8.14	2.14
Impervious area (acres)	1.89	2.21	1.66	2.81	1.89	1.22	2.74	2.11	1.87	1.07
Pervious area (acres)	3.75	4.02	2.21	3.20	4.23	2.14	6.73	4.51	6.27	1.07
Imperviousness (%)	33.8	35.7	42.5	46.8	31.0	36.0	28.8	32.0	23.1	50.9
Catchment SWMM width (ft)	1400	2400	1390	1930	1930	1060	2550	2050	2180	1100
Length of curb (100 ft)	17.48	23.18	15.42	22.07	20.33	11.25	30.47	21.75	24.76	10.77
Number of catchbasins	8	4	7	7	7	5	11	7	8	4

3.6 Sewer System

The Malvern catchment is drained by a storm sewer system. Characteristics of individual sewer pipes are listed in Table 4.

Only 21 out of the 36 pipes listed in Table 4 were used in runoff simulations described later. Such a procedure was found acceptable in the previous progress report.

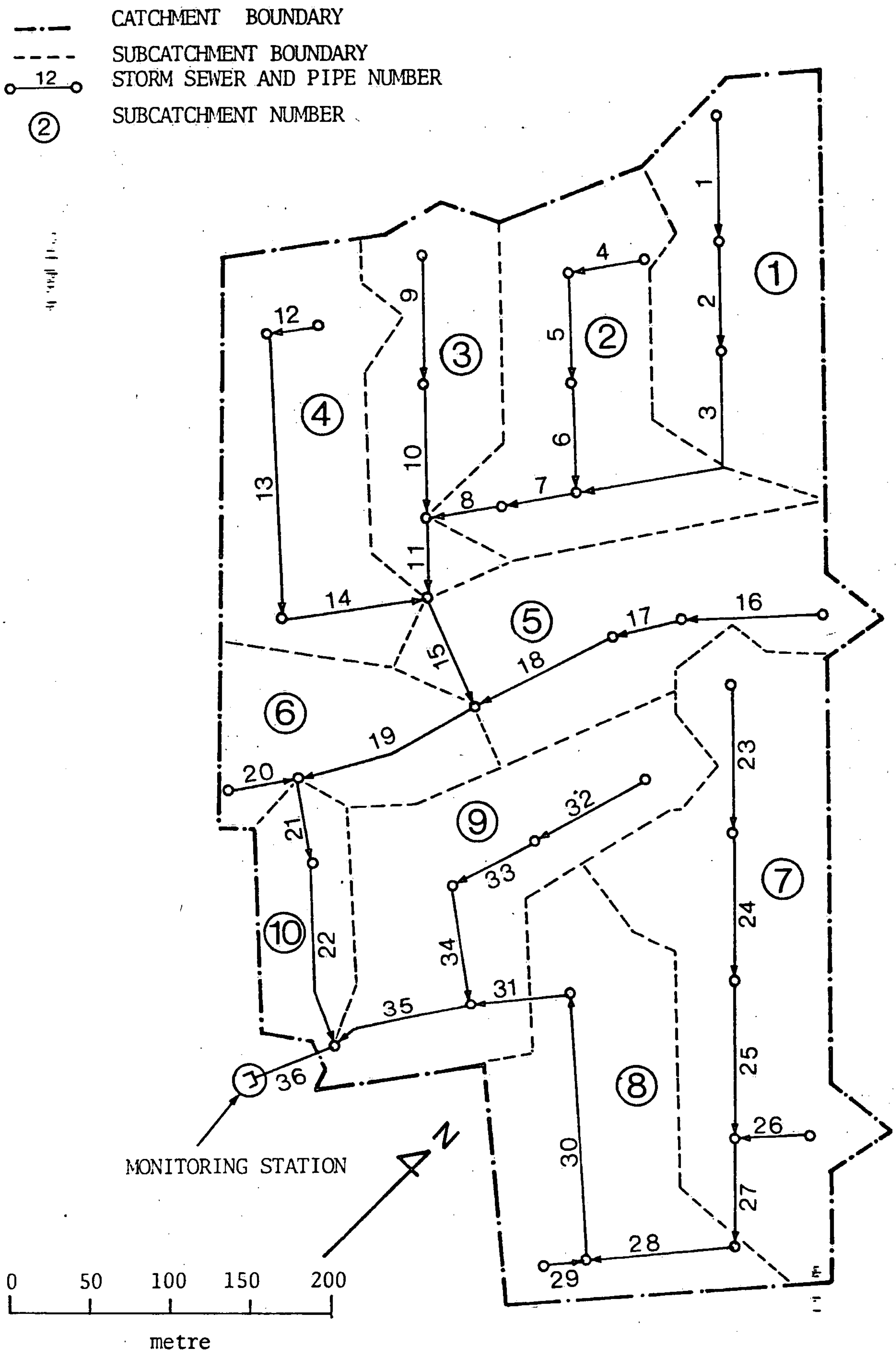


FIGURE 2. MALVERN CATCHMENT DISCRETIZATION AND SEWER SYSTEM

TABLE 4

SEWER PIPES - BASIC DATA
(after reference 8)

Pipe No.	Used in Simulations	Drains into Pipe	Pipe Diameter (in)	Invert Slope (ft/ft)	Pipe Length (ft)	Full Pipe Capacity (cfs)	Full Pipe Vel. (fps)	Full Pipe Time of Travel (sec)
1		2	12	.008	295	3.2	4.1	70.0
2		3	15	.007	220	5.8	4.7	46.6
3	x	7	18	.005	525	7.4	4.2	124.7
4		5	12	.005	149	2.5	3.2	46.3
5		6	12	.008	210	3.2	4.1	51.6
6	x	7	12	.013	213	3.9	5.0	42.8
7	x	8	18	.010	151	10.5	6.0	25.2
8	x	11	18	.0132	148	12.5	7.0	21.0
9		10	12	.008	266	3.2	4.1	65.4
10	x	11	15	.008	260	5.8	4.7	55.1
11	x	15	21	.012	187	17.4	7.2	25.9
12		13	12	.005	132	2.5	3.2	41.0
13	x	14	15	.005	292	4.6	3.7	156.3
14	x	15	18	.005	298	7.4	4.2	70.8
15	x	19	24	.010	242	31.0	7.8	31.0
16		17	12	.005	229	2.5	3.2	71.1
17		18	12	.015	156	4.4	5.6	28.0
18	x	19	21	.020	304	22.5	9.3	32.5
19	x	21	27	.012	384	34.0	8.5	44.9
20		21	10	.015	140	1.6	2.8	49.3
[illegible]	x	22	27	.009	161	29.4	7.4	21.8
[illegible]2	x	36	30	.005	390	29.1	5.9	65.9
23		24	12	.009	268	3.4	4.3	62.0
24		25	15	.010	300	10.5	6.0	50.3
25	x	27	18	.0068	301	8.7	4.9	61.3
26		27	10	.012	160	2.5	4.5	35.6
27	x	28	18	.012	224	11.5	6.5	34.3
28	x	30	18	.0156	292	13.2	7.4	39.2
29		30	10	.006	88	1.7	3.1	28.2
30	x	31	27	.0024	546	15.2	3.8	142.9
31	x	35	27	.002	194	13.9	3.5	55.6
32		33	12	.007	247	3.0	3.8	64.8
33		34	12	.020	172	5.1	6.4	26.7
34	x	35	12	.0236	238	5.5	7.0	34.0
35	x	36	27	.0042	280	20.1	5.1	55.3
36	x	outlet	33	.0086	176	49.2	8.3	21.3

4.0 CATCHMENT INSTRUMENTATION AND DATA ACQUISITION

4.1 Instrumentation

The precipitation and runoff flow were continuously monitored at a single point within the catchment boundaries. The location of the rainfall and runoff flow gauges is shown in Figure 1.

The precipitation was measured by one Leupold and Stevens Tipping Bucket Raingauge of capacity 0.01 inch (0.25 mm). The runoff flow rates were monitored by a calibrated rectangular weir located at the outfall of the sewer system. The rating curve for the rectangular weir is shown in Figure 3 after ref. 8).

The calibration of the raingauge revealed that for high rainfall intensities, say $i > 1.00$ in/hr, the recorded intensities were underestimated. Consequently, it was recommended to correct high recorded intensities by means of the following equation;

$$I_a = 1.167\, I_n - 0.168 \text{ (For } I_n > 1.00 \text{ in/hr)} \qquad (1)$$

where

I_a is the actual rainfall intensity (in/hr)
I_n is the recorded rainfall intensity (in/hr)

In total, seven storm hyetographs (Nos. 16, 18, 20, 30, 31, 37, and 42) were corrected using Eq. (2). The resulting corrections of the total rainfall depths, expressed as rainwater volume reaching the Malvern catchment, were given in Table 5.

4.2 Field Rainfall/Runoff Data

The 1976 rainfall and runoff records from the Malvern catchment were digitized using the HP 9107A Digitizer with the resolution of 40 points/cm (100 points/in). Digitized rainfall and runoff records were stored on a magnetic tape and processed by a computer. Finally, hyetographs and runoff hydrographs were produced for individual storms.

Since both the rainfall and runoff were recorded using the recorder chart speed of 2.4 in/hr and the digitizer resolution was 100 points/in, the records could be digitized with a time resolution of 0.25 minute.

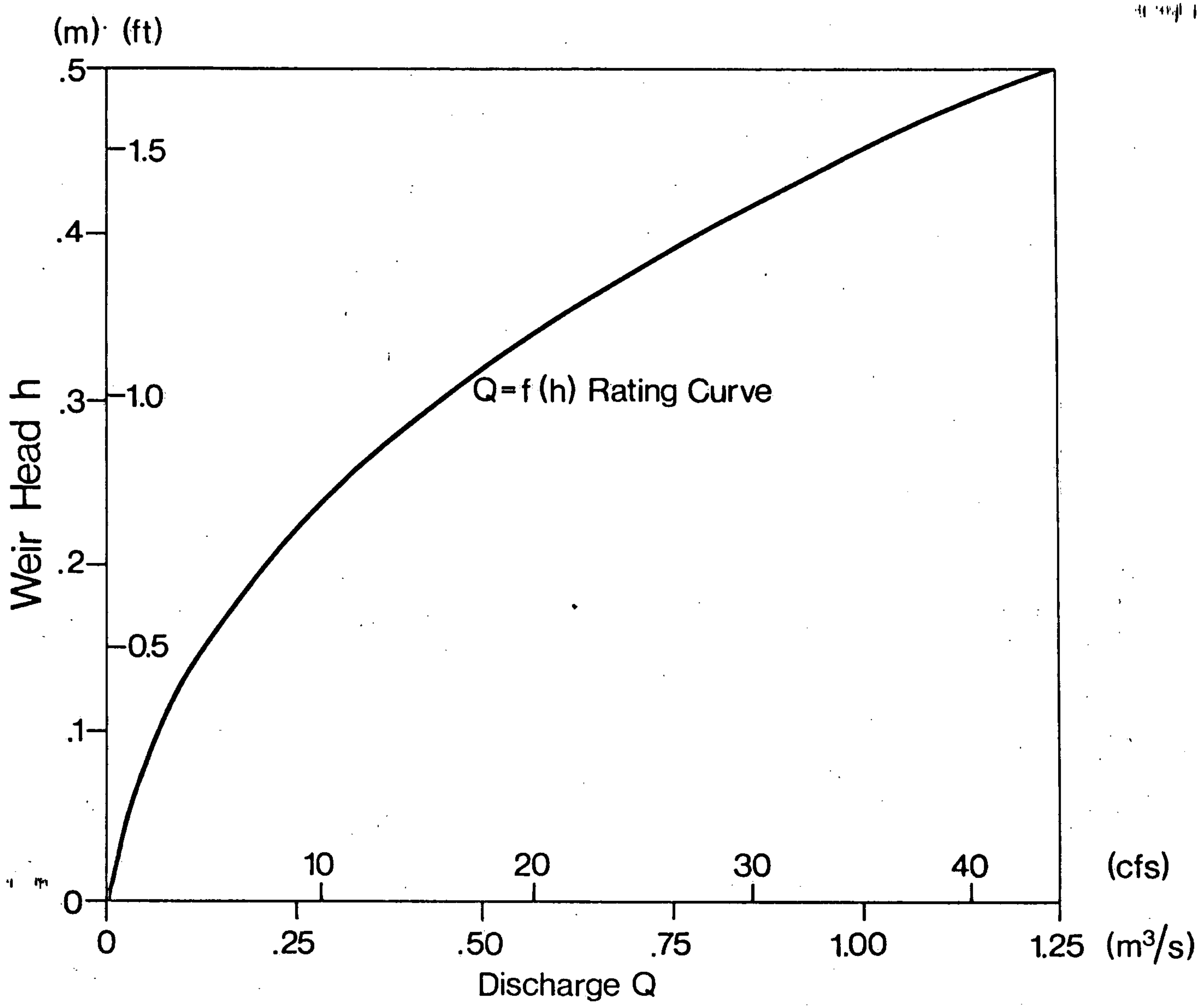


Figure 3. Measuring Weir - Rating Curve

Fourteen storms were selected from reference (6) for this study.

Values of the precipitation volume (V), runoff volume (R_o), ratio of R_o/V, and storm duration were listed for individual storms in Table 5.

The average value of the runoff/rainfall ratios (R_o/V) listed in Table 5 was expressed as

$$R_o = 0.338\ V \tag{2}$$

It is of interest to note that the average value of the R_o/V ratio is approximately equal to the imperviousness of the test catchment (i=0.31-0.34). It would appear, therefore, that practically all the monitored runoff originated on the impervious areas of the catchment and the pervious areas contributed only insignificantly to the total runoff.

TABLE 5

RAINFALL INPUT DATA

(1)		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)		(11)	(12)
No.	Storm Date	Rainfall Depth (mm)	Duration (hr)	Maximum Intensity (mm/hr)	Minimum Intensity (mm/hr)	Time Interval (min)	Total Rainfall Steps	Number of Time Steps	Integration Period (min)	Rainfall Volumes (m^3) Nominal	Actual (Calibrated)	Runoff Volume (m^3)	Ratio ($\frac{11}{10}$)
2	06/05/76	18.3	13.92	6.1	3.1	5	180	185	5	4267		1419	0.333
3	06/05/76	20.3	9.00	6.1	3.1	5	120	125	5	4741		1593	0.336
6	11/05/76	3.8	0.45	30.5	15.2	1	45	90	1	886		354	0.399
15	19/06/76	3.3	0.25	30.5	15.2	1	45	60	1	770		278	0.361
16	24/06/76	22.1	4.28	27.4	15.2	5	96	100	5	5154	5161	1745	0.338
17	26/06/76	5.1	1.87	61.0	15.2	1	135	150	1	1189		344	0.289
18	26/06/76	14.2	2.38	106.7	15.2	1	165	180	1	3312	3520	1168	0.332
19	28-29/05/76	6.4	4.53	30.5	15.2	2	136	150	2	1541		477	0.309
20	30/06/76	9.9	3.57	38.1	7.6	2	132	150	2	2309	2327	695	0.299
28	29/07/76	6.1	2.18	30.5	15.2	1	90	120	1	1423		520	0.365
30	31/07/76	11.9	1.67	45.7	15.2	1	105	150	1	2775	2861	1048	0.366
31	31/07/76	10.2	0.82	76.2	15.2	1	75	100	1	2379	2487	716	0.288
37	28/08/76	7.6	0.95	45.7	15.2	1	90	125	1	1773	1820	608	0.334
42	17-18/09/76	55.9	9.88	71.1	5.1	3	168	180	3	13,037	13,332	5037	0.378
	Average	13.94	3.98	43.29	12.21	2.14	113	133	2.14	3254	3309	1143	0.338

5.0 CALIBRATION OF THE SWMM RUNOFF BLOCK

5.1 Background

The calibration of a runoff model is a procedure in which model parameters are manipulated to reproduce the response of the catchment under study within some range of accuracy. Calibration is not a problem unique to hydrologic simulation. Any hydrologic procedure will yield better results if tested against observed data and any parameters are appropriately fixed by data from the area studied.

Main advantages of calibration are as follows:

(a) Calibration produces estimates of input parameters that are difficult to measure directly (e.g. infiltration rates, pollutant loadings)

(b) Calibration compensates, to some extent, for imperfections or omissions in the model structure

(c) Calibration together with verification lend reliability to the model predictions.

Before proceeding with the actual calibration, goodness of fit and accuracy criteria need to be established. A wide variety of such criteria are described in reference (11). In urban drainage, criteria for peak flow rates, runoff volumes and times to peak flow are usually sufficient.

Once an acceptable goodness of fit is achieved by calibration, the model is then verified by comparing other measured samples with the computed output.

5.2 Runoff Quantity Calibration of the SWMM Model

Parameters to be adjusted in calibration of the RUNOFF Block of the SWMM Model were adopted from ref. (12) and listed below. The following seven parameters serve for calibration of the model output:

1. Resistance factor for impervious areas
2. Resistance factor for pervious areas
3. Surface storage on impervious areas
4. Surface storage on pervious areas
5. Maximum rate of infiltration
6. Minimum rate of infiltration
7. Decay rate of infiltration

The user has flexibility to adjust each of the above seven parameters.

The first two parameters are likely to affect the timing of the hydrographs. The last five parameters are primarily affected by both runoff values and timing.

The SWMM Runoff Block has been calibrated for the Malvern catchment by Marsalek (8). The calibrated parameters produced in ref. (8) which were valid for storms with minor contributions of runoff from pervious areas were adopted in this study (see Table 2). It should be noted that with the exception of the surface storage on impervious areas (reduced to 0.5 mm, or 0.02"), the SWMM default values were found acceptable for runoff simulations in the Malvern catchment (8).

6.0 RUNOFF SIMULATIONS WITH THE CALIBRATED RUNOFF BLOCK

6.1 Computer System

The RUNOFF Block of the SWMM model has been converted to adapt to the National Water Research Institute in-house computer CDC (3170) system. The CDC (3170) system has a maximum core storage of 96 K words. Individual jobs can use up to 64 K words and the remaining 32 K word memory can be used through a numbered COMMON STATEMENT. To include other Blocks of the SWMM model with the RUNOFF Block runs would require program OVERLAY procedures. The average computation time was three minutes per event simulation. The computation time depended on the input data specified externally.

6.2 Rainfall Input Data

The storm events selected for verification of the RUNOFF Block are given in Table 5.

The rainfall intensities of these storms ranged from 3.1 mm/hr to 106.7 mm/hr and the durations of these storms ranged from 15 minutes to 14 hours.

The data listed in Table 5 include the storm duration, the depth of rainfall, maximum and minimum rainfall intensities, the discretization interval of input hyetographs, the computational time step, and the total number of time steps.

6.3 Simulation Procedures

For most storms, the rainfall interval and the computational time step were equal to one minute. For storm nos. 2, 3, 16, 19, 20 and 42, rainfall intervals and time steps ranged from two to five minutes. The use of longer time steps and rainfall intervals for these storms was necessary because of the limited core space of the 3170 computer system. The longer rainfall intervals were found adequate for low-intensity and long-duration storms, but for short-duration and high-intensity storms, the longer precipitation intervals resulted in underestimated peak flow rates, as shown for storm number 16 in Table 6. By increasing the rainfall input interval from one to five minutes, the runoff peak flow rate was reduced by 19%.

6.4 Simulation Results

Runoff simulations were performed for the selected 14 events with the RUNOFF Block of the SWMM Model. The results of these simulations are summarized in Table 6. In particular, Table 6 contains the following information:

Runoff volumes for observed and simulated hydrographs,
Observed and simulated peak flow rates,
Observed and simulated times to peak,
Ratios of observed to simulated values for the above three parameters of the runoff hydrographs, and
The error in continuity for the simulated events.

The error in continuity ϵ is defined in the RUNOFF Block as

$$\epsilon = P - I - Q - D$$

where P is the precipitation volume
I is the infiltration volume
Q is the runoff volume, and
D is the surface storage volume.

The error in continuity of simulation had a negative sign for all events. For longer storms with larger rainfalls, the continuity errors became smaller. It is speculated here that the errors in continuity were primarily caused by an overestimation of loss functions (infiltration and surface storage).

There was no occurrence of sewer surcharging for the 14 storms studied.

The mean value of the observed to simulated runoff volume ratio was 0.98 with the standard deviation of 0.12. For the runoff peak flows, the mean value of the ratio of observed to simulated peaks was 1.12 with the standard deviation of 0.18. Finally, the mean value of the ratio of observed to simulated times to peak was 0.99 with the standard deviation of 0.15.

On the average, the volume of the simulated runoff from the Malvern catchment represented about 35% of the rainfall volume. This percentage approximated closely the value calculated for observed events (34%).

For storm numbers 16, 18, 20, 30, 31, 37, and 42, runoff simulations were done for both calibrated and noncalibrated rainfall records. The calibrated

The values of ratios of measured/simulated volumes, measured/simulated peak flow rates and measured/simulated times to peak were plotted against the measured rainfall, and measured runoff volumes in Figure 4. The upper and lower envelopes shown in these graphs tend to approach the line of perfect fit volumes.

The simulated and observed hydrographs were presented pictorially in Figures 5 to 18. The plots of the simulated hydrographs were shifted along the time axis to achieve a better visual agreement with the measured hydrographs. The magnitudes of these time shifts were also indicated in the figures.

Volumes of simulated infiltration and surface storage are shown in Table 7 together with the ratios of the infiltration to rainfall, measured runoff to infiltration, and surface storage to rainfall volumes.

TABLE 6

CHARACTERISTICS OF OBSERVED [illegible] SIMULATED RUNOFF HYDROGRAPHS FOR THE MALVERN CATCHMENT

Storm No.	(1) Runoff Volume (m^3)			(2) Ratio		(3) Peak Flow Rates (m^3/sec)			(4) Ratio		(5) Time to Peak (hour)			(6) Ratio		(7) Error in Continuity (%)		(8) Ratio	
	R_o	R_s	R_{sA}+	$\frac{R_o}{R_s}$	$\frac{R_o}{R_{sA}}$	P_o	P_s	P_{sA}	$\frac{P_o}{P_s}$	$\frac{P_o}{P_{sA}}$	T_o	T_s	T_{sA}+	$\frac{T_o}{T_s}$	$\frac{T_o}{T_{sA}}$	ε_N	ε_A	$\frac{R_s}{V}$	$\frac{R_s}{V_A}$+
2	1419	1584		0.896		0.080	0.079		1.025		6.65	6.83		0.974		-7.332		0.371	
3	1593	1650		0.966		0.096	0.100		0.960		8.61	8.75		0.984		-4.603		0.348	
6	354	295		1.200		0.578	0.380		1.521		0.33	0.43		0.767		-5.661		0.333	
15	278	252		1.103		0.375	0.307		1.222		0.23	0.28		0.821		-5.686		0.327	
16	1745	1720	1724	1.015	1.012	0.609	0.544* 0.439	0.562* 0.441	1.120 1.387	1.084 1.381	4.53	4.42	4.92	1.025	0.921	-3.163	-3.160	0.334	0.334
17	344	394		0.873		0.442	0.357		1.238		1.68	1.77		0.949		-5.075		0.331	
18	1168	1115	1160	1.048	1.007	0.901	0.973	1.070	0.926	0.842	0.20	0.15	0.15	1.333	1.333	-3.621	-2.905	0.337	0.330
19	477	578		0.825			0.212		1.236		0.67	0.80		0.838		-8.901		0.402	
20	695	883	890	0.787	0.781	0.518	0.498	0.512	1.129	1.098	3.20	3.16	3.20	1.013	1.000	-8.829	-8.851	0.382	0.382
28	520	543		0.958		0.296	0.334		0.886		1.20	1.05		1.143		-9.392		0.382	
30	1048	1004	1034	1.044	1.014	0.712	0.609	0.607	1.169	1.173	0.92	0.95	0.95	0.968	0.968	-6.191	-6.271	0.362	0.361
31	716	844	882	0.848	0.812	0.723	0.737	0.813	0.981	0.889	0.80	0.82	0.82	0.976	0.976	-5.907	-5.678	0.355	0.355
37	608	682	690	0.992	0.881	0.701	0.646	0.655	1.085	1.070	0.77	0.67	0.65	1.149	1.185	-8.557	-8.613	0.385	0.379
42	5037	4479	4877	1.125	1.033	1.112	1.165	1.298	0.955	0.857	1.22	1.25	1.25	0.976	0.976	-2.017	-2.011	0.344	0.366
Avg.	1143	1145	1182	0.977	0.954	0.529	0.488	0.512	1.123	1.100	2.22	2.24	2.28	0.994	0.988	-6.071	-6.014	0.357	0.357
Standard Deviation (% of Mean)				0.12	0.12				0.18	0.21				.15	.15				

+ Subscript A denotes calibrated rainfall input

* One-minute precipitation interval

7.0 DISCUSSION OF RESULTS

The verification results for the RUNOFF Block of SWMM indicated that, on the average, there was a close agreement between the observed and simulated runoff hydrographs. Larger discrepancies were found for some verification events. It should be realized that these discrepancies result not only from the model imperfections, but also from the errors in the input data and errors in the observed data.

A detailed discussion of verification results for runoff volumes, runoff peaks, and times to peak follows.

7.1 Runoff Volumes

The average values of the measured runoff to simulated runoff volumes were 0.98 and 0.95 for noncalibrated and calibrated rainfall input data respectively. The standard deviation about the mean for both ratios was 0.12 (see Table 6). No significant bias between the noncalibrated and calibrated rainfall data was found and the need for using the calibrated data in this study could be questioned.

The agreement between the observed and simulated runoff volumes found in this study was slightly worse than that reported in a previous progress report (8). The earlier study dealt with a relatively narrow range of rainfall volumes from 1837 m^3 to 8773 m^3 (the mean=4300 m^3). In the study reported here, the rainfall volumes ranged from 770 m^3 to 13,040 m^3 (the mean=3254 m^3). Considering the tendencies shown in Fig. 4, it is plausible to expect that the set of verification data with a larger range of rainfall volumes and a smaller mean volume will yield a lower goodness of fit.

For practical purposes, the accuracy of runoff volume simulations reported here appeared to be acceptable.

The volumetric runoff coefficient for the observed and simulated hydrographs was 0.338 and 0.357 respectively. Note that these values closely approximate the catchment imperviousness (0.31-0.34).

7.2 Peak Flow Rates

The agreement between the observed and simulated runoff peaks reported here was about the same as reported in the previous progress report (8). Compared to the other two hydrograph parameters the runoff peaks were simulated least accurately. This reduced accuracy was reflected by the mean value of the ratio of observed to simulated peaks (1.10) as well as by the increased standard deviation about the mean (0.18).

For high intensity storms, the use of short rainfall input intervals and short time steps is required for accurate reproduction of observed peaks. This point was demonstrated for storm no. 16 in Table 6. By shortening the rainfall input interval and the time step from five to one minute, the simulated runoff peak increased from 72% to 89% of the observed value.

The largest deviation of the simulated peak flow rate from the observed one was found for storm no. 6. The simulated peak represented only 66% of the observed value. For the same storm, the simulated runoff volume was 83% of the observed one. A further examination of the field records for storm no. 6 revealed a possible malfunction of the stage recorder. Such a malfunction and the resulting error in the observed peak could have contributed to the apparent disagreement between the observed and simulated runoff peaks. Runoff hydrographs for storms with two or more peaks of magnitude greater than 0.14 m^3/s (5 cfs) were reproduced quite accurately (see Figs. 9, 11, 12, 16 and 18).

In general, the simulations of runoff peaks for the Malvern catchment were found to be satisfactory. Inherent limitations of the input data possibly contributed to the somewhat reduced goodness of fit found for simulated runoff peaks (as compared to the fit obtained for other hydrograph attributes). In particular, the simulated peaks seemed to be greatly affected by the magnitude and distribution of rainfall intensities. Among the quantities observed in the field, rainfall intensities are subject to the largest error.

7.3 Time to Peak

The observed times to peak were reproduced fairly well in runoff simulations for the Malvern catchment. On the average, the simulated times to peak were nearly identical to the observed ones.

The largest deviations of simulated times from the observed ones were noticed for storms no. 6 and 18. Since both these storms were extremely short (less than 0.5 hr), even a small absolute error in the hydrograph timing will result in an appreciable relative error.

It was further recognized that some errors in the timing of the simulated hydrographs were caused by the location of the raingauge in the southwest corner of the catchment, about 0.6 km from the centroid of the catchment area.

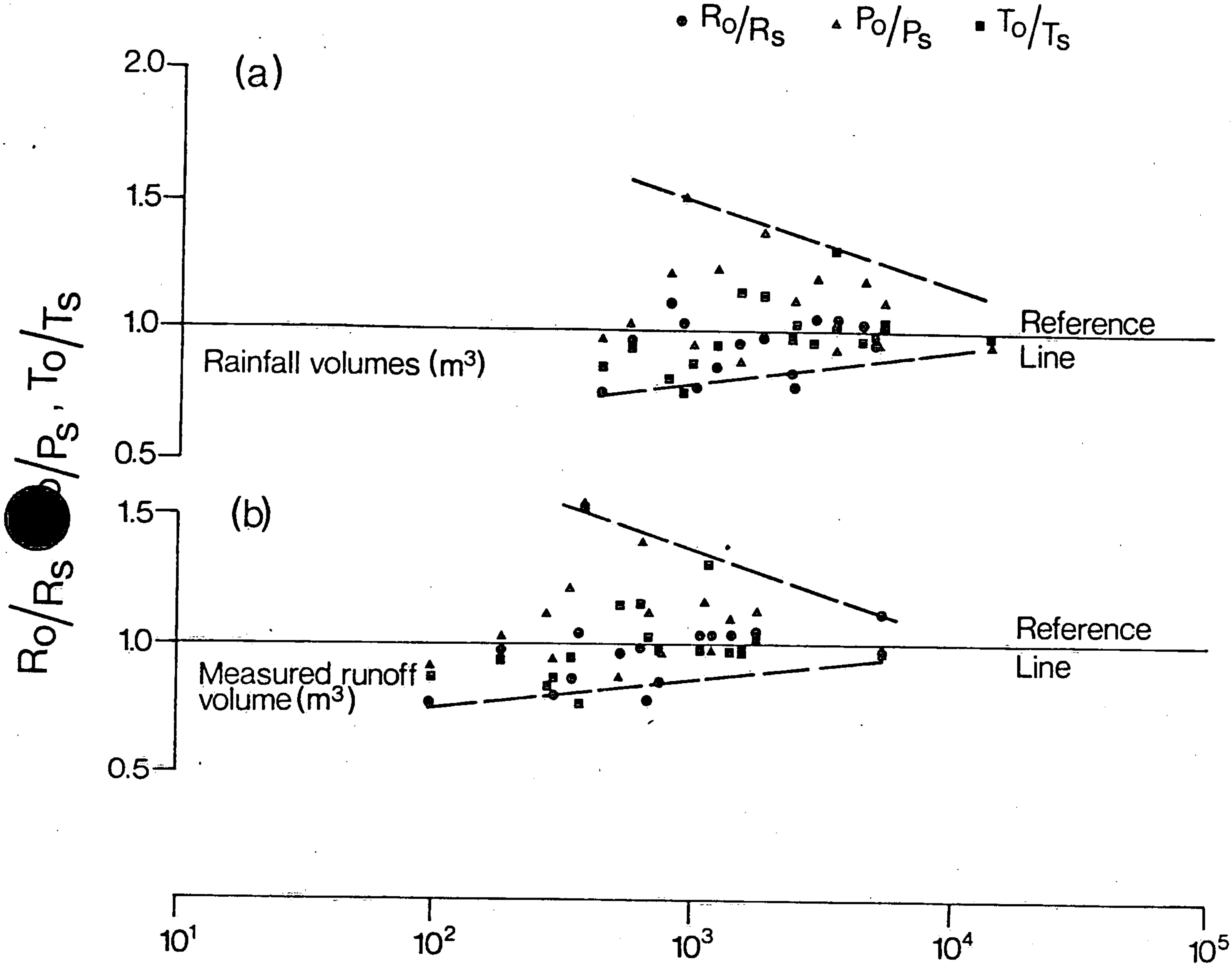
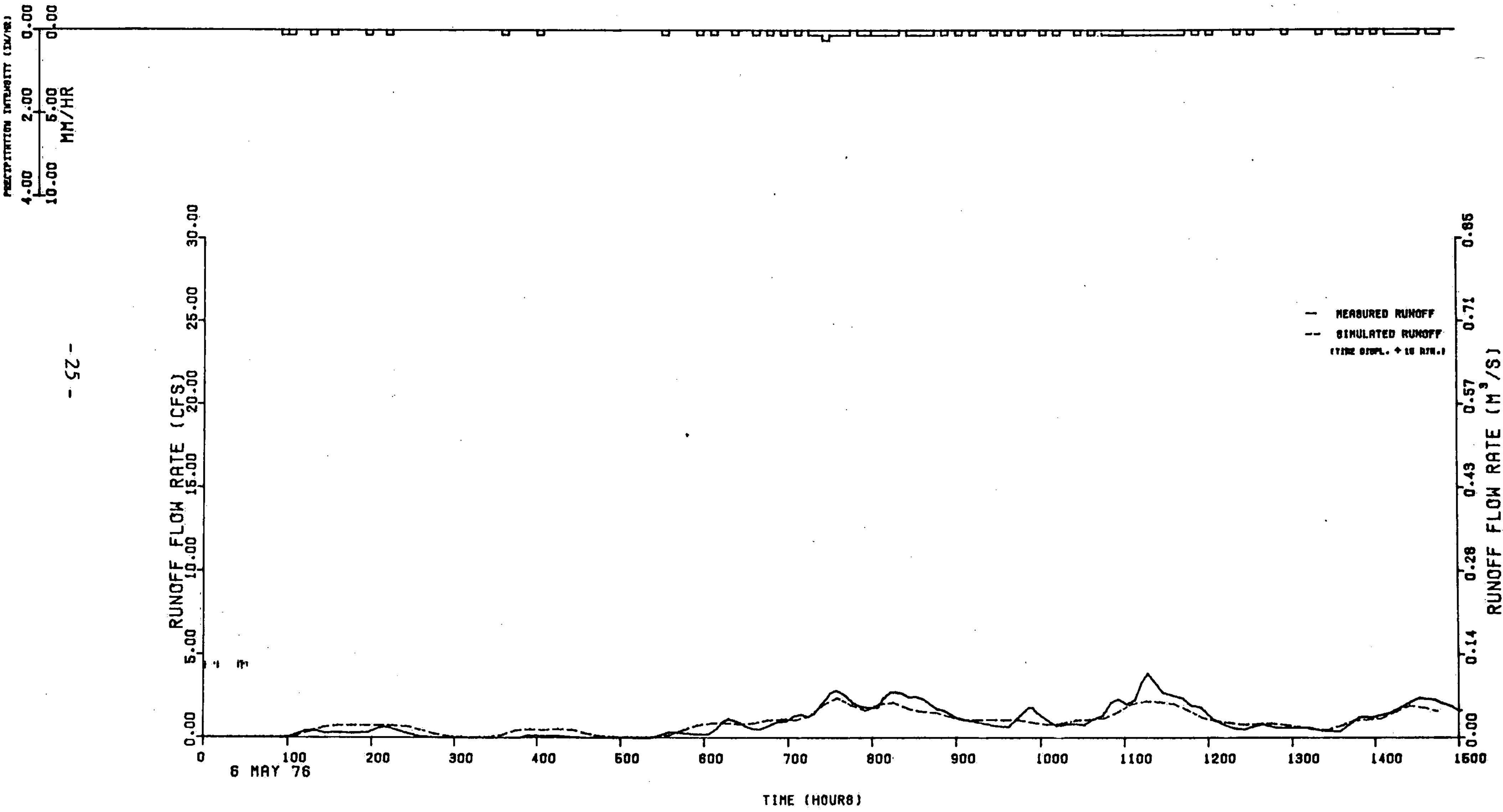


Figure 4. Goodness of fit criteria plotted against the volumes of rainfall and measured runoff



MALVERN CATCHMENT - STORM NO. 2
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

Figure 5.

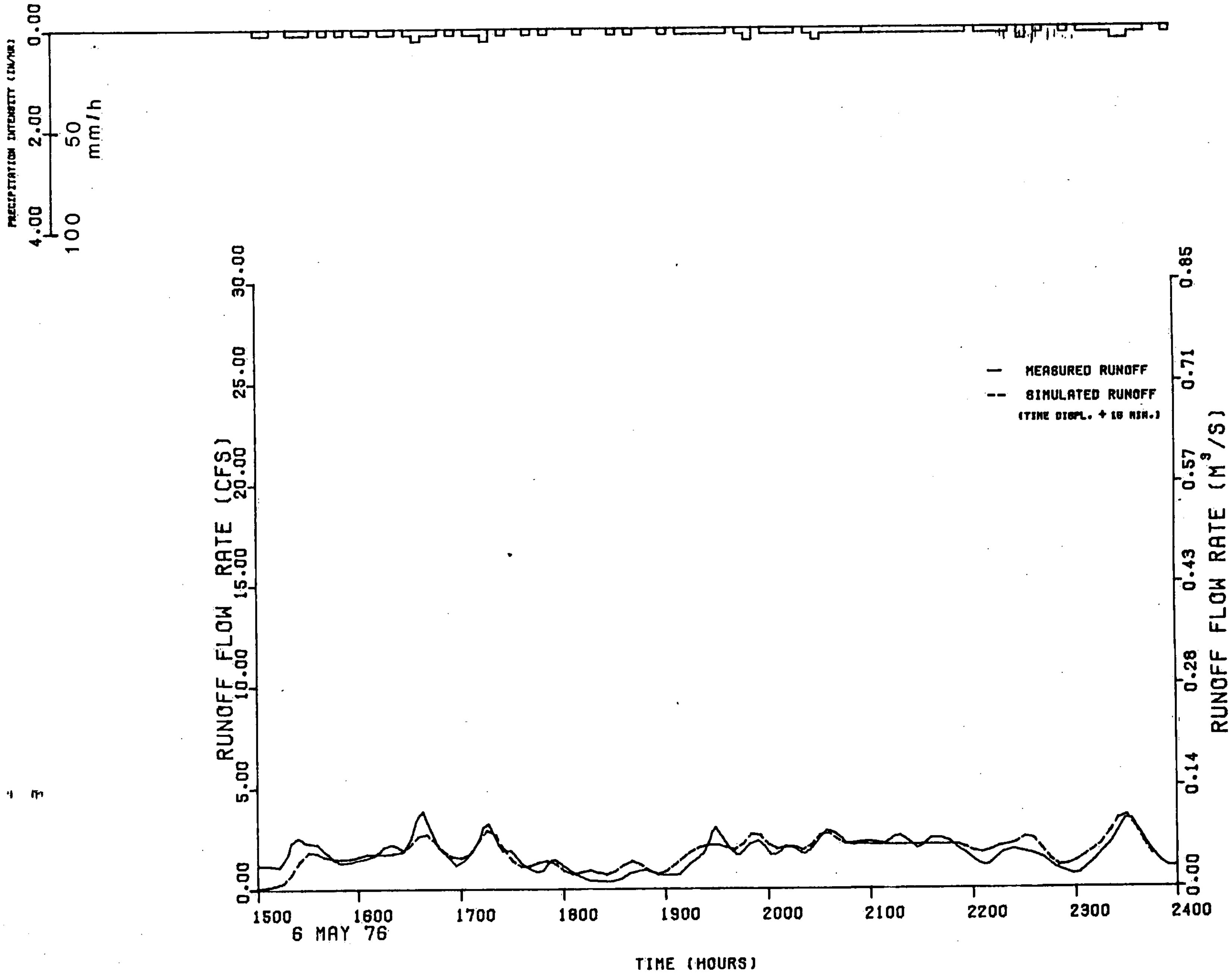


Figure 6. MALVERN CATCHMENT - STORM NO. 3
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

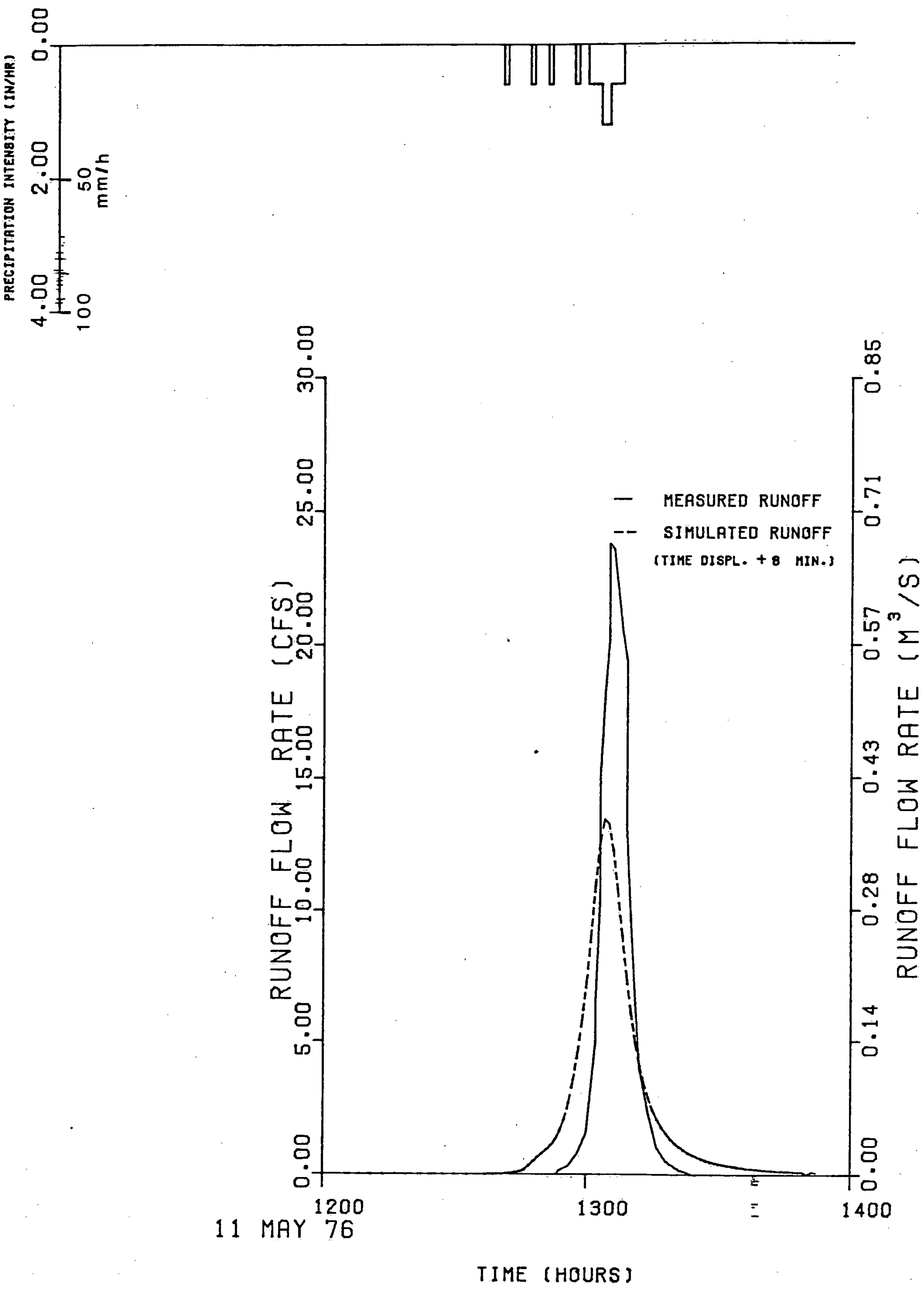


Figure 7. MALVERN CATCHMENT - STORM NO. 6
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

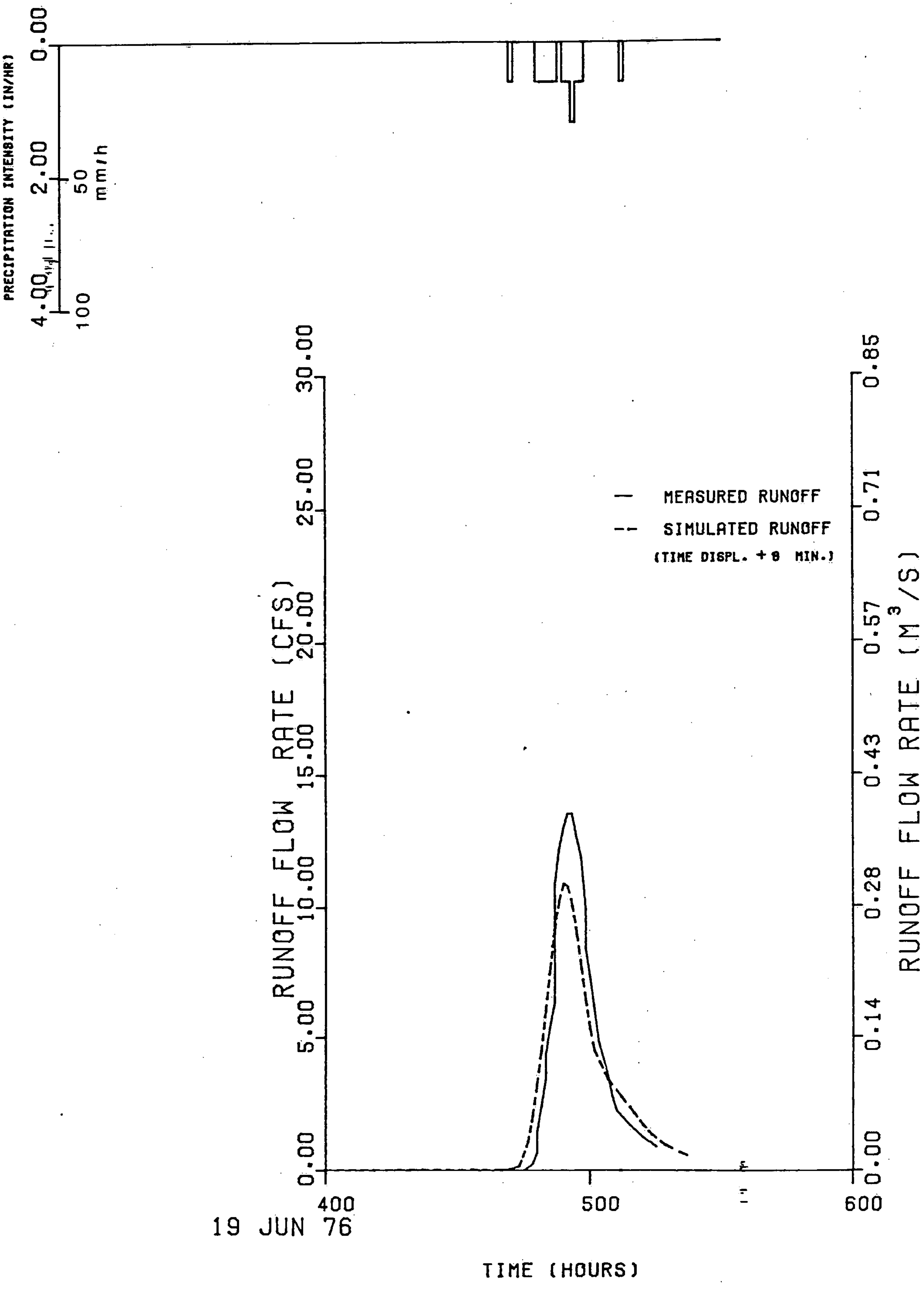


Figure 8. MALVERN CATCHMENT - STORM NO. 15
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

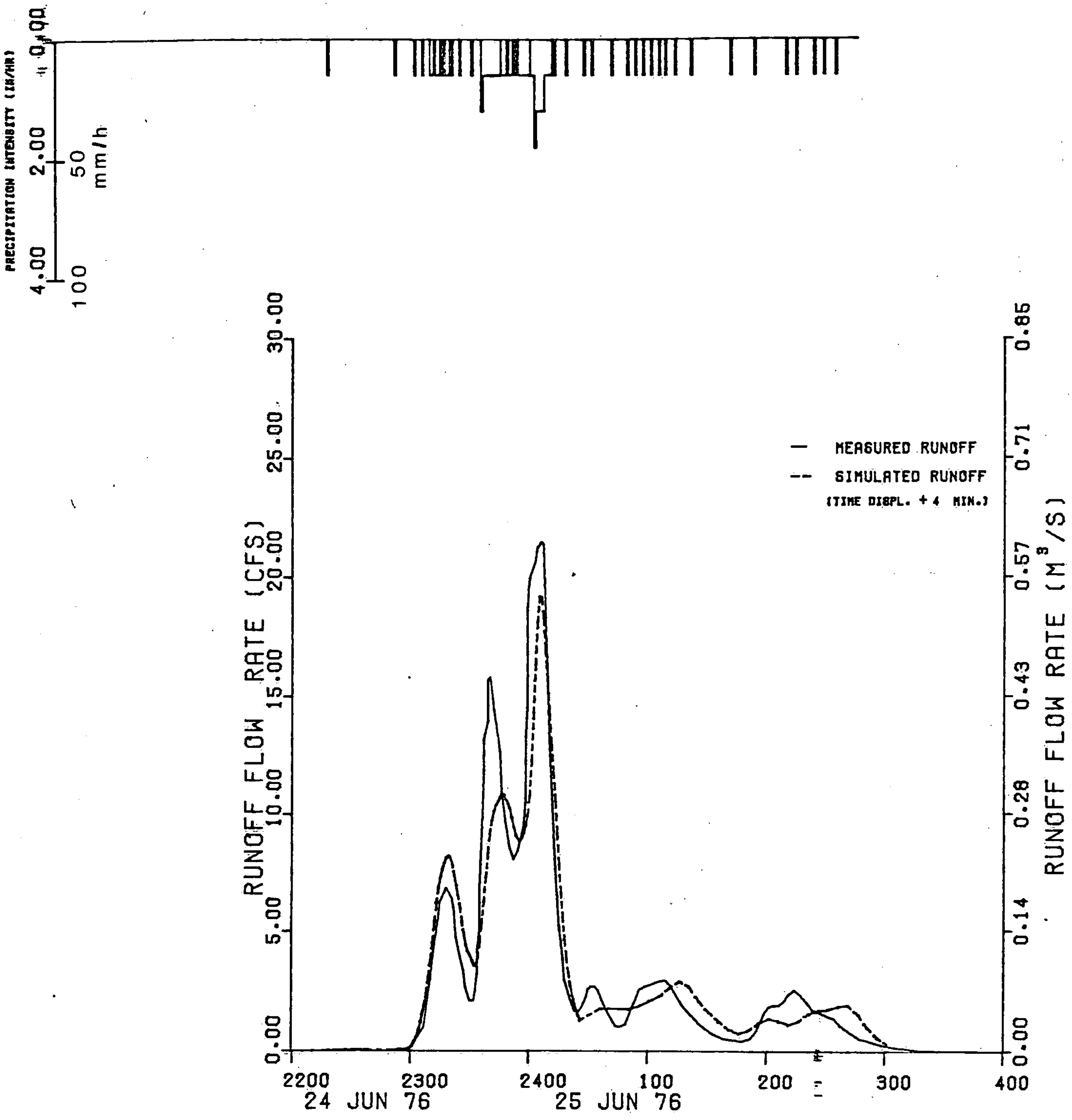


Figure 9.

MALVERN CATCHMENT - STORM NO. 16
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

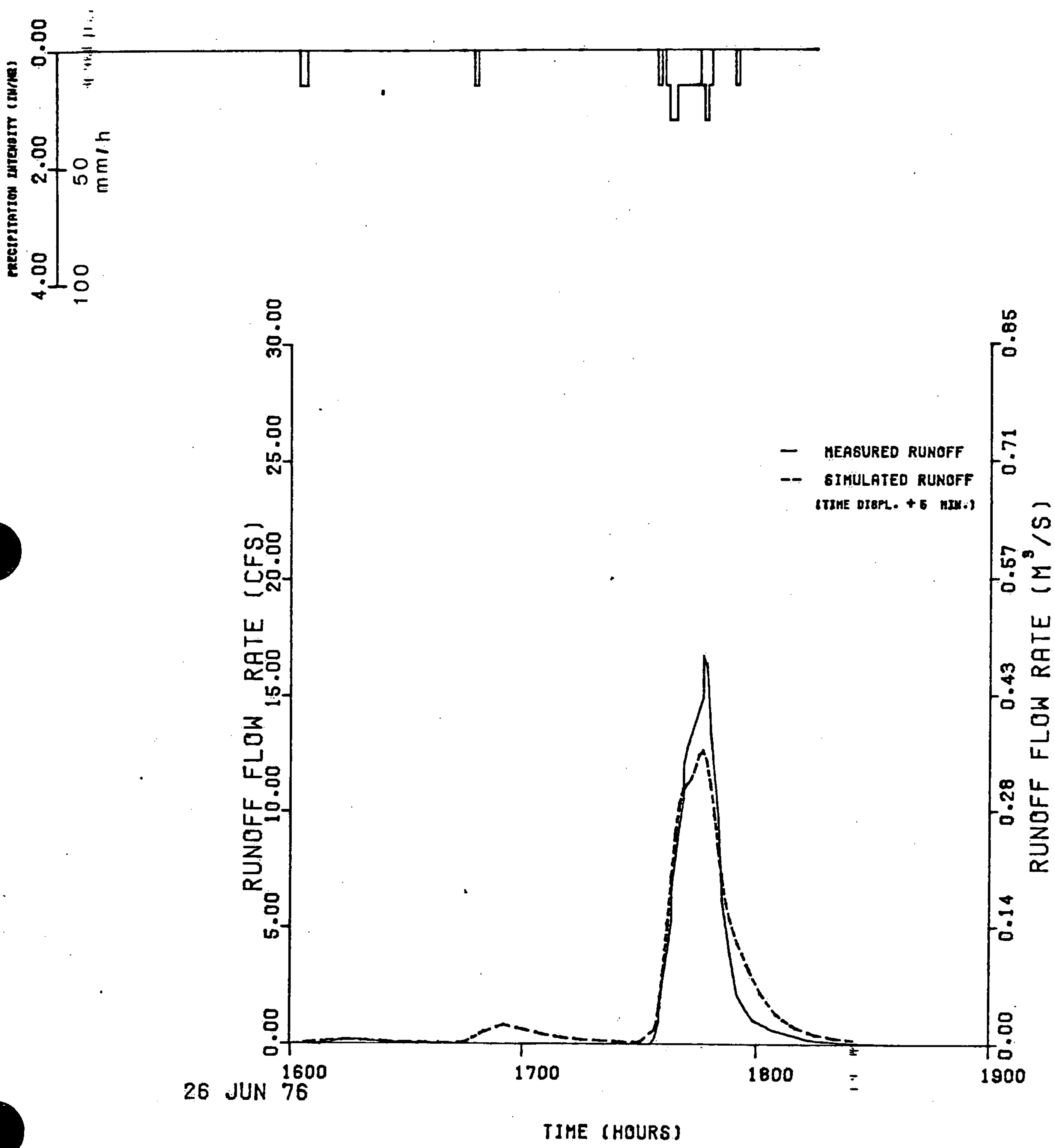


Figure 10. MALVERN CATCHMENT - STORM NO. 17
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

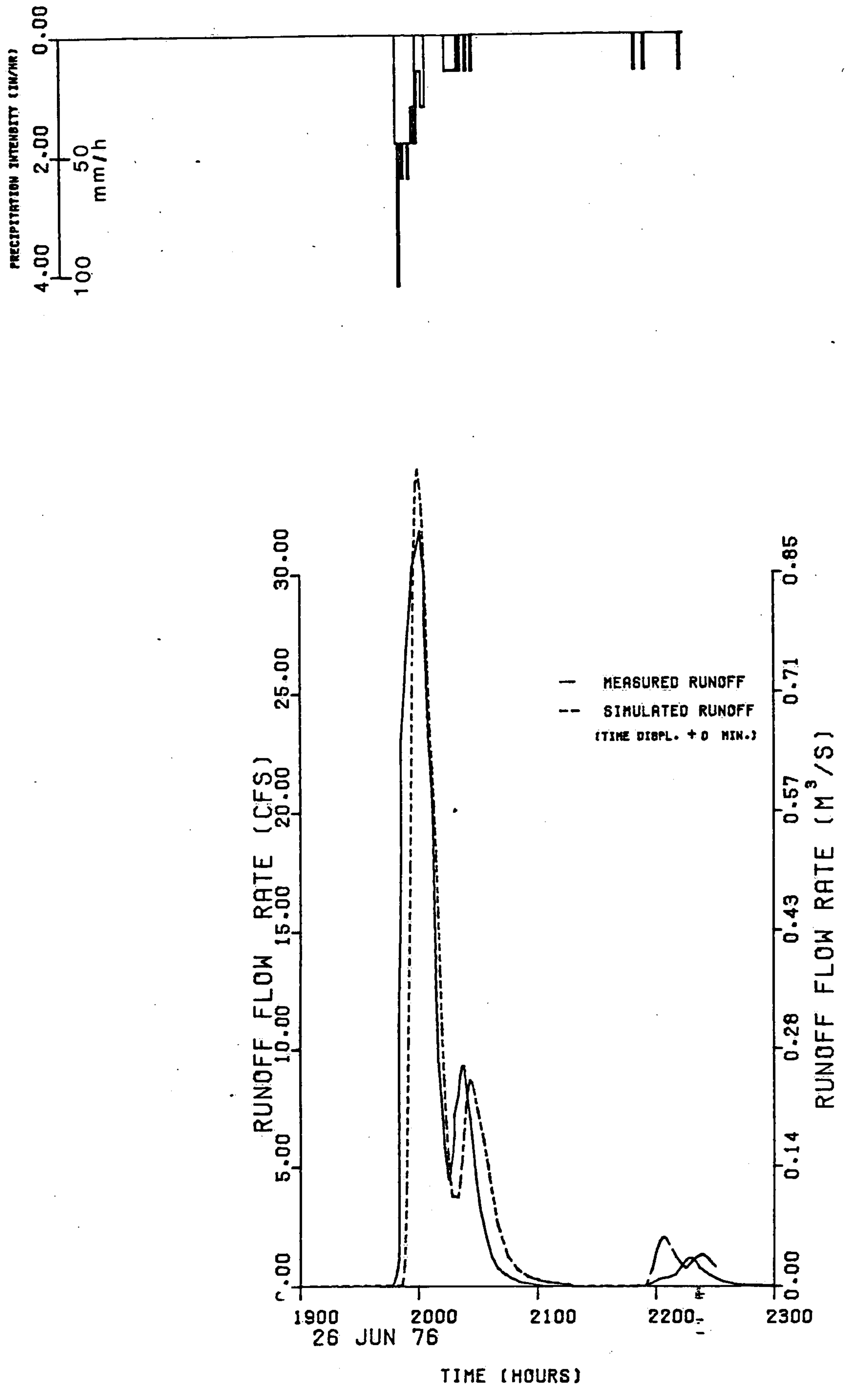


Figure 11. MALVERN CATCHMENT - STORM NO. 18
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

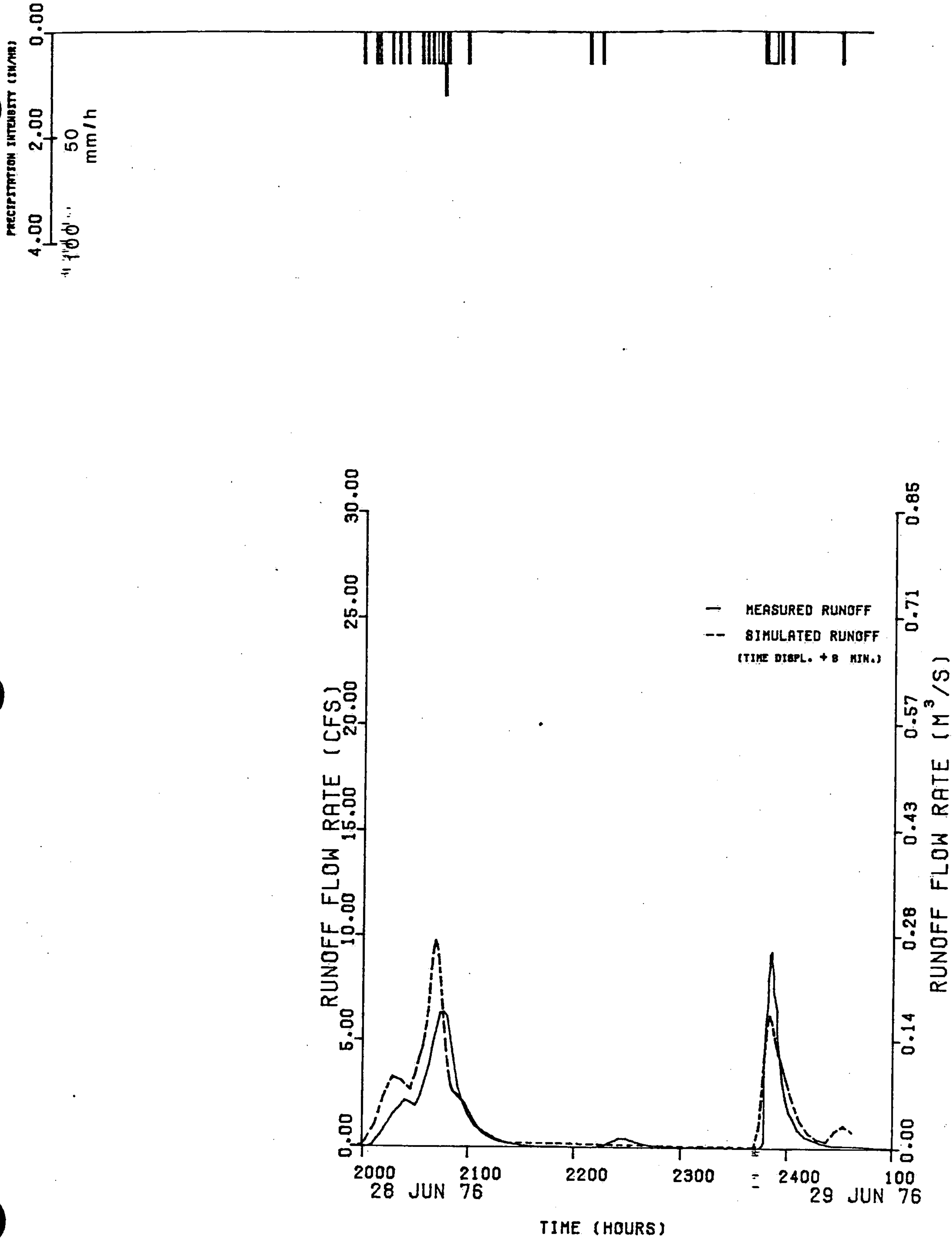


Figure 12.

MALVERN CATCHMENT - STORM NO. 19
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

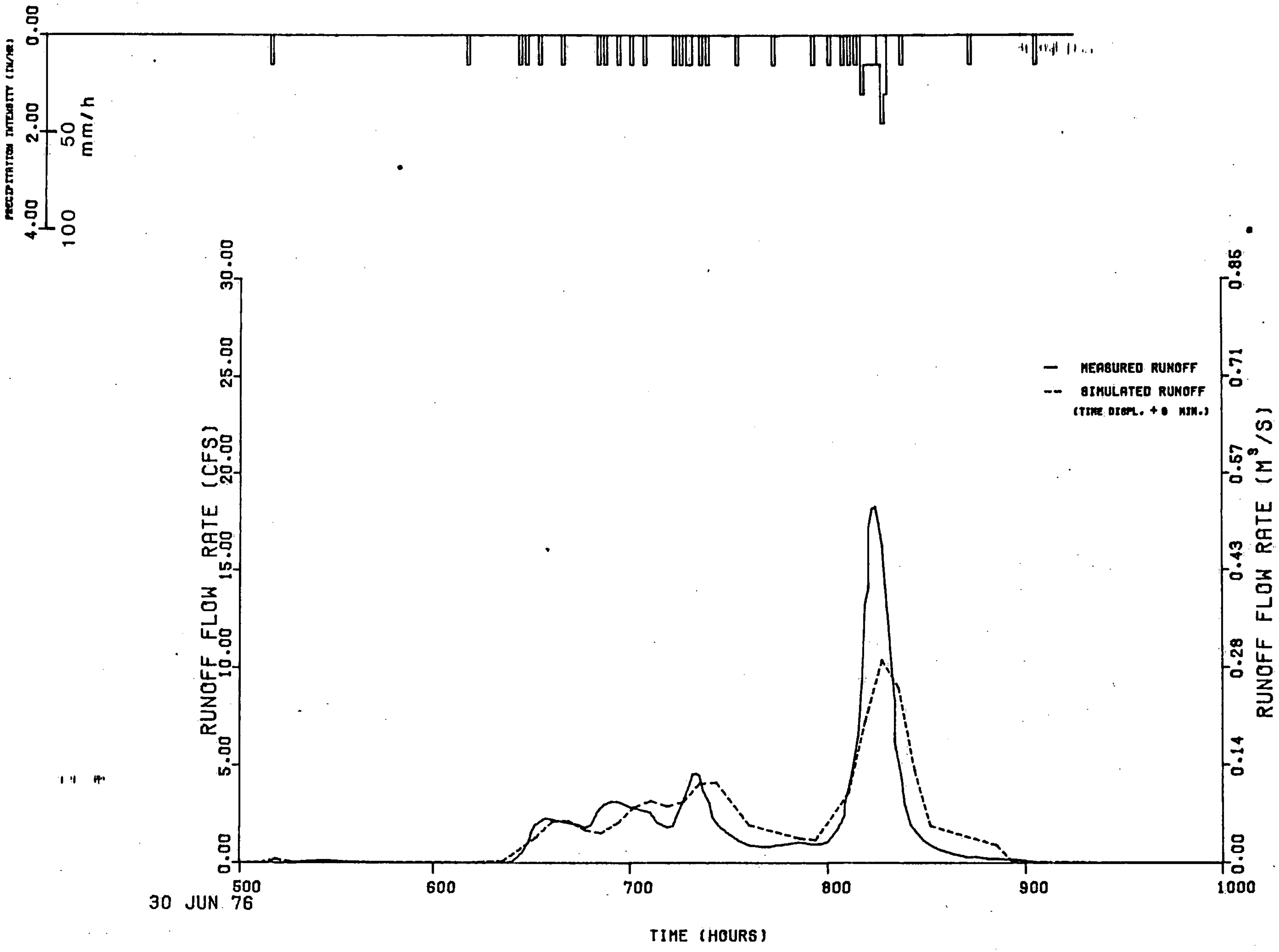


Figure 13. MALVERN CATCHMENT - STORM NO. 20
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

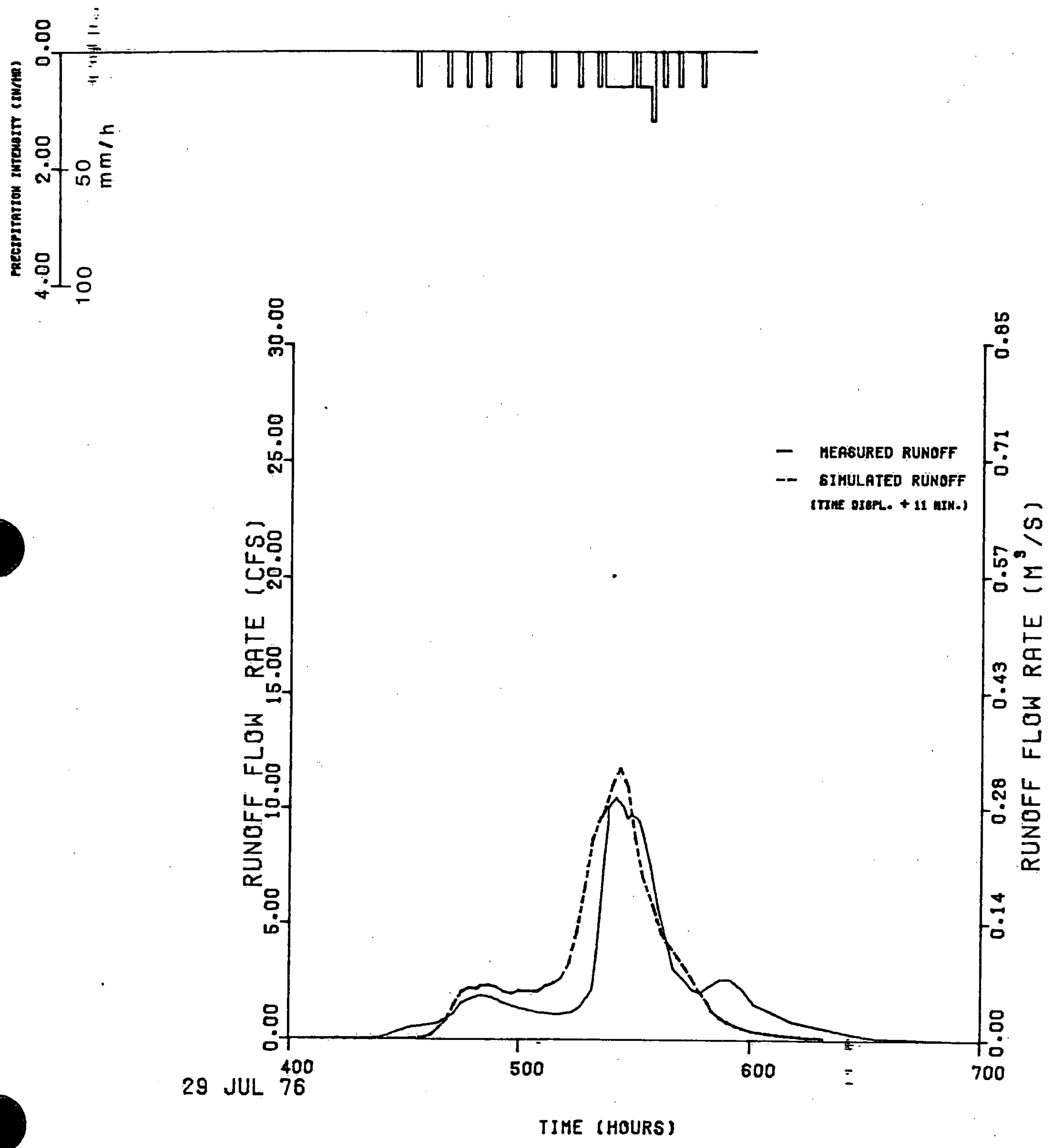


Figure 14. MALVERN CATCHMENT - STORM NO. 28
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

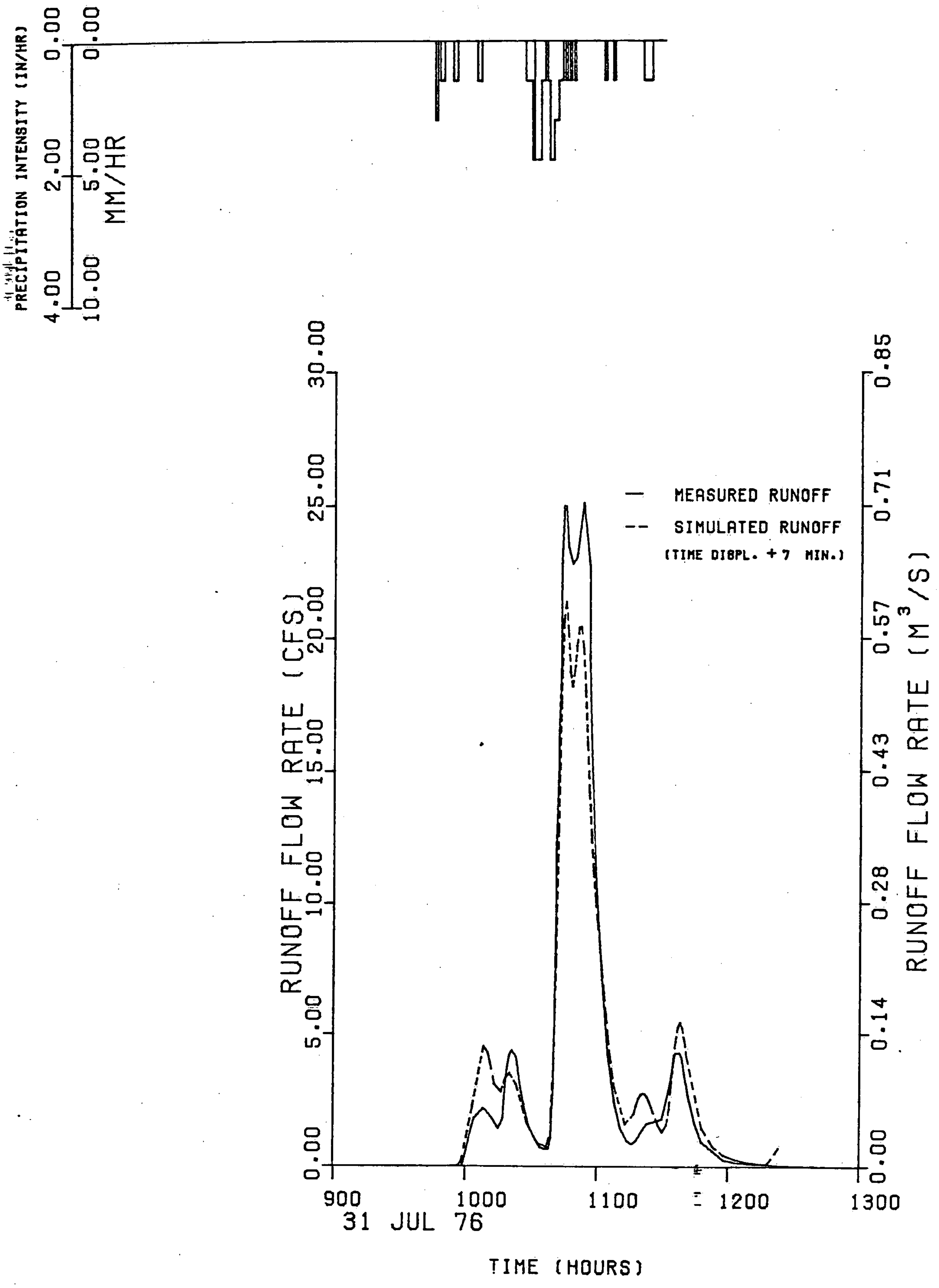


Figure 15.

MALVERN CATCHMENT - STORM NO. 30
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

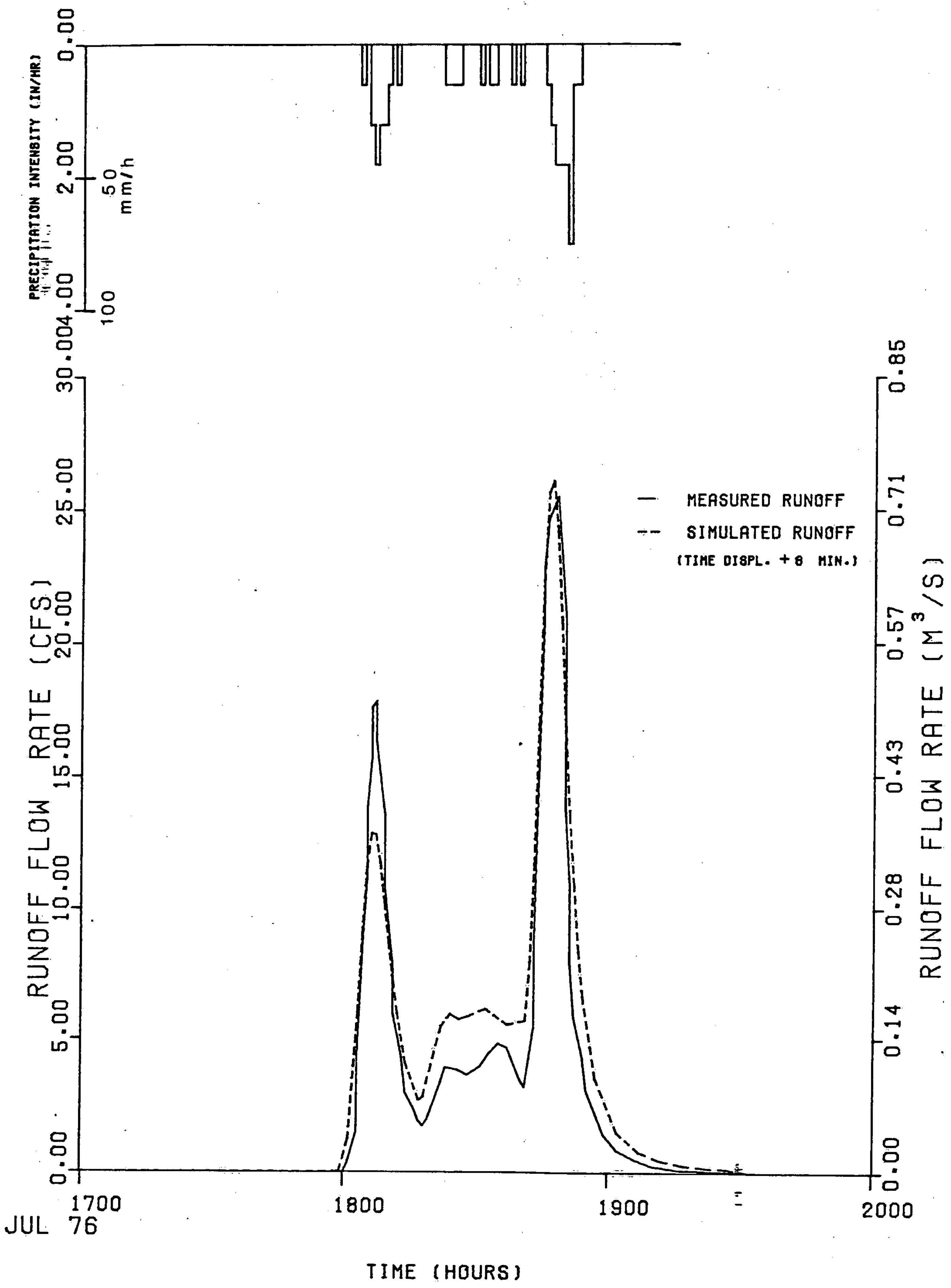


Figure 16. MALVERN CATCHMENT - STORM NO. 31
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

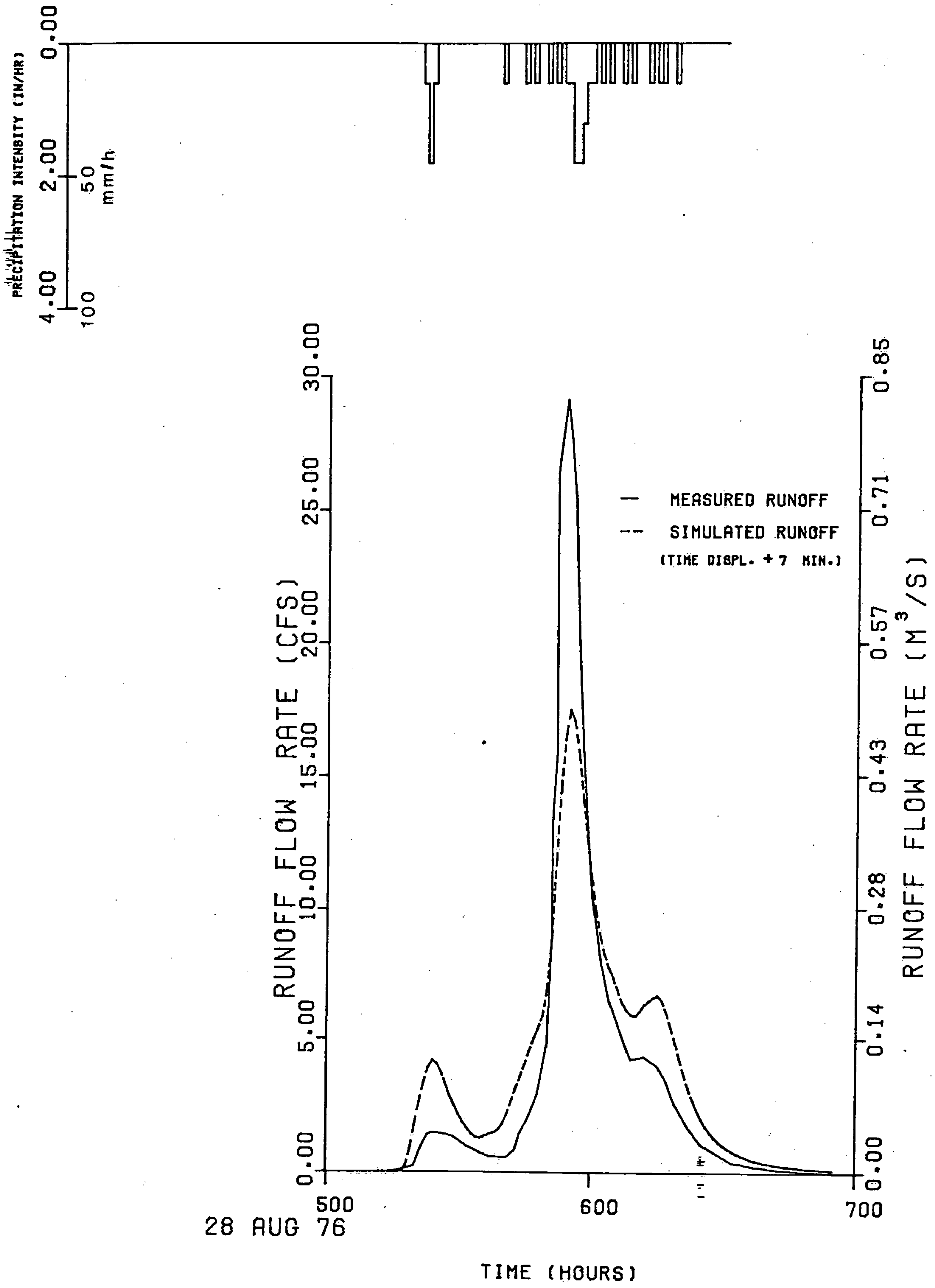


Figure 17. MALVERN CATCHMENT - STORM NO. 37
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

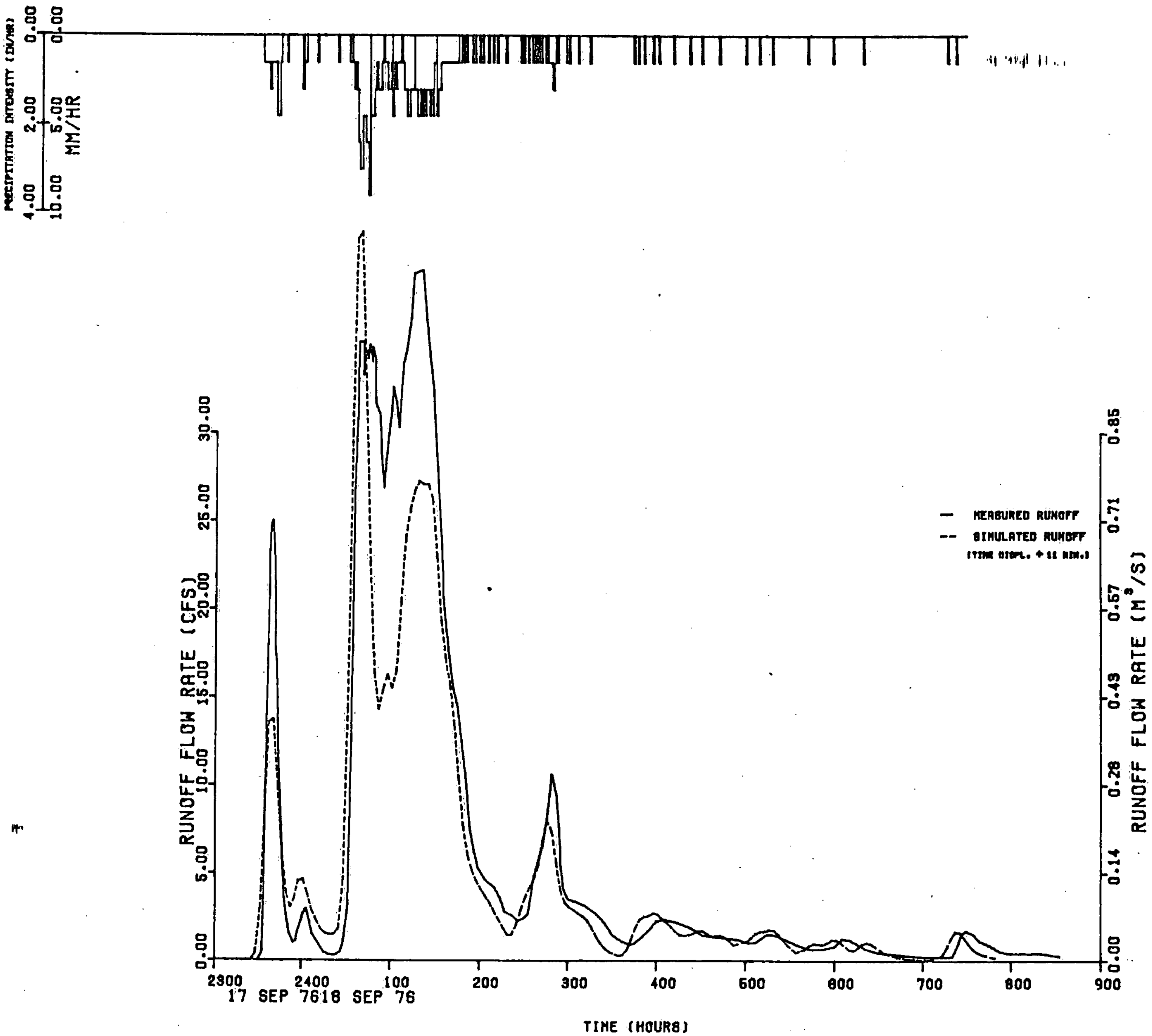


Figure 18. MALVERN CATCHMENT - STORM NO. 42
MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

In general, the timing of the simulated runoff hydrographs was found to be satisfactory.

7.4 Simulated Losses

The volumes of simulated infiltration and surface storage, at the end of the simulation period, were given in Table 7. Since in the studied events nearly all the runoff originated on the impervious areas, the infiltration volume should represent a constant fraction of the rainfall volume. This was confirmed by the data shown in Table 7.

The surface storage volume should be constant for all the storms (about 27.6 m^3). Minor deviations from this value shown in Table 7 resulted in various durations of the simulation period. If the simulation is terminated before all the surface runoff entered the inlet, increased surface storage volumes are encountered.

In runoff simulations with SWMM, a continuity check is made and the error in continuity evaluated for individual events. These continuity errors were described earlier and presented in Table 6 for individual events. On the average, this error was always negative and amounted to about 6% of the rainfall volume. In other words, the sum of infiltration, surface storage, and runoff volumes exceeded the rainfall volume by about 6%. Since the surface storage was fairly small, the error in continuity was caused by overestimation of infiltration and runoff. It appeared that the error in continuity could have affected the simulation of runoff volumes simulated earlier. Note that the simulated volumes were overestimated and the analysis of the continuity errors led to a similar conclusion.

TABLE 7 VOLUMES OF SIMULATED INFILTRATION (I) AND SURFACE DEPRESSION STORAGE (D)

Storm No.	I (m^3)		D (m^3)		I/V	I/VA	Ratio R_o/I	Ratio D/V
	Nominal NC	Actual C	Nominal NC	Actual C				
2	2968		28		0.695		0.478	0.007
3	3287		28		0.693		0.485	0.006
6	616		28		0.695		0.575	0.032
15	533		29		0.692		0.522	0.038
16	3569	3572	28	28	0.693	0.692	0.489	0.005
17	823		28		0.692		0.418	0.024
18	2294	2433	30	29	0.693	0.691	0.509	0.009
19	1074		28		0.697		0.444	0.019
20	1604	1615	28	28	0.695	0.694	0.433	0.012
28	985		28		0.692		0.528	0.020
30	1926	1978	28	28	0.694	0.691	0.544	0.010
31	1638	1718	28	28	0.689	0.690	0.437	0.012
37	1230	1259	28	28	0.694	0.692	0.494	0.016
42	8630	8694	28	28	0.662	0.652	0.584	0.002
Average	2277	2254	28	28	0.690	0.690	0.496	0.015

NC - for noncalibrated rainfall data

C - for calibrated rainfall data

8.0 CONCLUSIONS

1. Fourteen storms monitored in the Malvern catchment during 1976 represented a good set of data for verification of the RUNOFF Block of the SWMM Model. The runoff volumes produced by these storms ranged from 252 m^3 to 4479 m^3, the observed peak flows ranged from 0.080 m^3/s to 1.112 m^3/s, and the storm durations ranged from 0.25 hrs to 13.92 hrs.

2. Using a partially calibrated RUNOFF Block, the monitored runoff events were reproduced with the following accuracy:

	Mean	Standard Deviation
Measured/simulated runoff volume	0.98	0.12
Measured/simulated peak flow rate	1.10	0.18
Measured/simulated times to peak	0.99	0.15

   The above verification results are fully comparable to those reported in a previous progress report (8).

3. The correction of rainfall records resulting from the calibration of the tipping-bucket raingauge did not significantly improve the agreement between the observed and simulated runoff hydrographs.

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