RAINFALL-RUNOFF RELATIONSHIPS

OF THE HOP BROOK BASIN,

MANCHESTER, CONNECTICUT

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U.S. GEOLOGICAL SURVEY

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FOR THE CONVENIENCE OF READERS WHO MAY PREFER TO USE METRIC (INTERNATIONAL SYSTEM) UNITS RATHER THAN THE INCH-POUND UNITS USED IN THIS REPORT, VALUES MAY BE CONVERTED BY USING THE FOLLOWING FACTORS:

Multiply inch-pound units	By	To obtain metric units
inch	0.02540 25.40	meter (m) millimeter (mm)
foot (ft)	0.3048	meter (m)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
square mile (mi^2)	2.590	square kilometer (km^2)
mile (mi)	1.609	kilometer (km)

ABSTRACT

A rainfall-runoff relation was established for the Hop Brook drainage basin at Manchester, Connecticut by the unit-hydrograph technique. Eight storms were evaluated for infiltration and direct runoff in order to establish, by graphical methods, the relation between rainfall duration and infiltration. The storms of January 24-26, 1979, and June 4-7, 1982, were used to verify the techniques. The rainfall of August 18-19, 1955, as recorded at Bradley International Airport in Windsor Locks, Connecticut was superimposed on the basin, and simulated a peak flow of 3,500 cubic feet per second, a flow estimated to have a recurrence interval greater than 100 years.

INTRODUCTION

The Town of Manchester, Connecticut is located some 12 miles east of Hartford, Connecticut . Its 50,000 residents live within the 27.2 square mile corporate limits (fig. 1) and, there are pressures to develop the remaining open spaces, especially in the Hop Brook Basin. In 1975 the U.S. Geological Survey (USGS) began a cooperative surface-water investigation with the Town to monitor the flow and quality of Porter Brook, and to use these data for educational as well as engineering needs. This program was soon followed by several flood insurance studies in the Town of Manchester that were conducted by the USGS for the Federal Energy Management Agency, Federal Insurance Administration. As an outgrowth of these studies, the Town of Manchester and the USGS in July 1977 began a cooperative study of the rainfall-runoff characteristics of the Hop Brook basin. A stream-gaging station was installed at Olcott Street, and a weighing-type rain gage was installed at the Cooper Hill water-treatment facility (fig. 1). For the next five years streamflow and rainfall data were collected for selected storms.

As the Hop Brook Basin is increasingly developed, it will be necessary to design storm-drainage facilities. During the design it will be necessary to consider the probability of the occurrence of runoff events in order to achieve an economic balance between the cost of structures and the direct and indirect cost of possible property damage and inconvenience to the public during the life of the structure. Therefore, as a preliminary to the design of these drainage structures, the engineering department must compute storm discharges corresponding to various probabilities.

The purpose of this report is to present a technique that can be used by the Town of Manchester to estimate peak runoff magnitudes and volumes from precipitation data. The results contained in this report include estimates of the magnitudes of peak flows that would result from various rainfall distributions, based on curves computed by the unit-hydrograph technique. In addition, a flood-frequency analysis is presented so that the probability of the flood event can be ascertained.

The surface-water data on which this report is based were collected and Analyzed by employees of the USGS. The rain-gage data were collected by the Engineering Department of the Town of Manchester under the direction of Walter J. Senkow, the Town Engineer, and George A. Kandra, Director of Public Works.

BASIN GEOMETRY, GEOLOGY, AND URBANIZATION

The Hop Brook basin is located in central Connecticut east of Hartford and the Connecticut River. Hop Brook drains the southern part of the Town of Manchester (fig. 1) and flows into the Hockanum River, 0.7 miles (mi) downstream from the stream-gaging station on Hop Brook at Olcott Street. The drainage area of the basin at the gage is 11.6 square miles (mi^2) and includes the Howard, Porter, and Globe Hollow water-supply reservoirs, whose drainage areas total 4.2 mi^2 or about 36 percent of the total area drained by Hop Brook. The main channel length of Hop Brook is 7.7 mi and the mean channel slope is 66.5 ft/mi.

Six mi^2 or 52 percent of the basin area is underlain by coarse-grained, stratified drift, which is highly permeable and, therefore, has a high potential for infiltration. The remaining 5.6 mi^2 is underlain by glacial till, which has very low permeability and a low potential for infiltration. Natural infiltration in urbanized areas is reduced by the influences of impervious surface cover and storm sewering. As impervious areas within the basin increase due to urbanization, the changes in peak flow magnitude and timing will be more pronounced in areas underlain by coarse-grained stratified drift than in areas underlain by less permeable till. Of the 11.6 mi^2 drainage area of Hop Brook basin, 4.4 mi^2, or 38 percent, is sewered, and 2.9 mi^2 of this sewered area overlies 48 percent of the stratified-drift area of 6.0 mi^2. Thus, the high potential for infiltration on stratified drift is present only on about 27 percent of the total drainage area. Peak flows recorded at the gage are affected in large part by the high degree of urbanization in the lower part of the basin (fig. 1).

RAINFALL-RUNOFF MODEL

UNIT-HYDROGRAPH ANALYSIS

The unit-hydrograph method has been described in detail by Chow (1964). The unit hydrograph of a drainage basin is defined as a hydrograph of direct runoff resulting from one inch of effective rainfall generated uniformly over the basin area at a uniform rate during a specified period of time or duration. The critical characteristic of this method is that, if rainfall distribution in storms is similar with respect to time and area, then the ordinates of each direct runoff hydrograph are directly proportional to its volume of runoff.

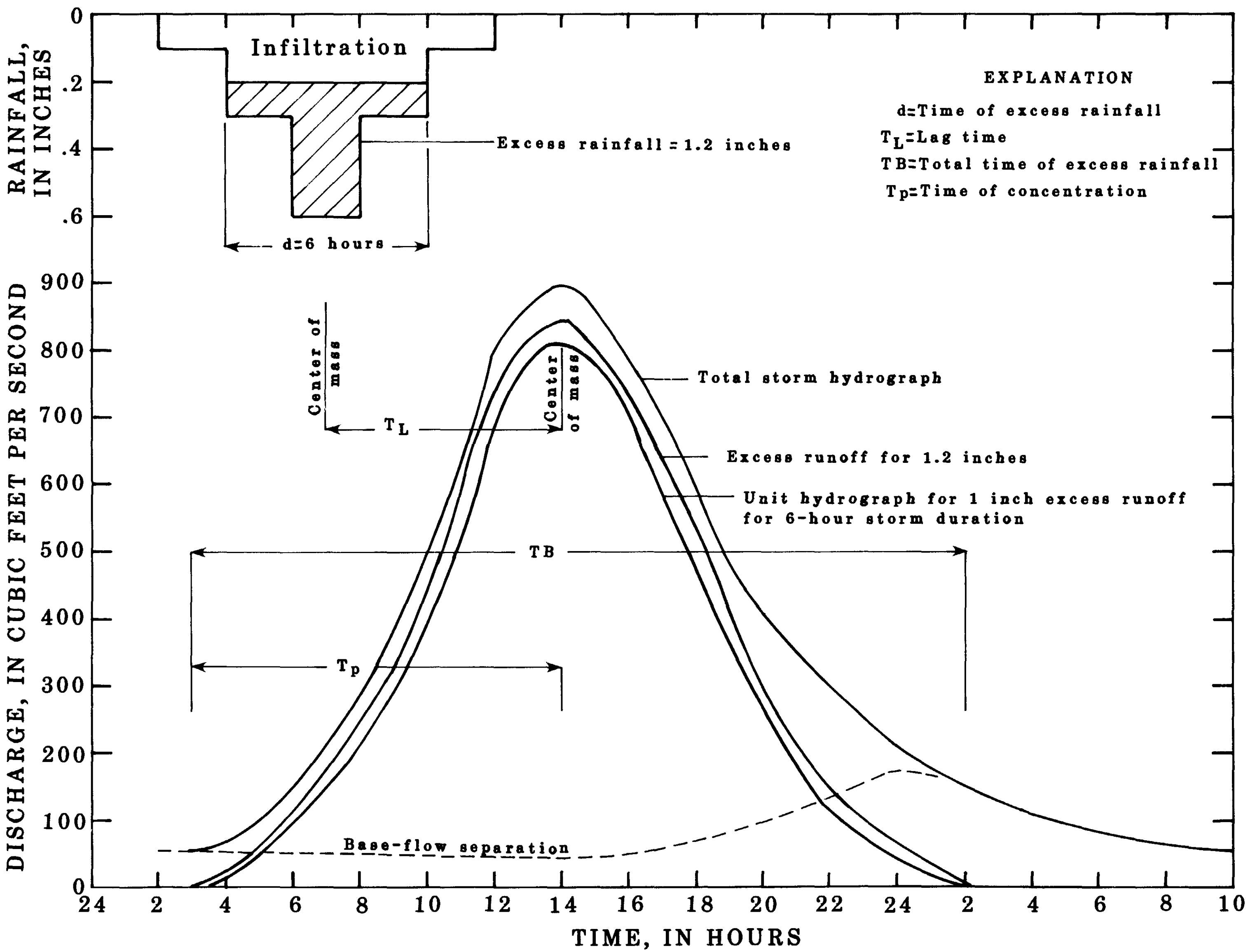

Figure 2.--Schematic derivation of the unit hydrograph from a storm.

Table 1.-- Computation of the unit-and S-hydrographs for Hop Brook at Manchester, Connecticut
(All valves except hours are in cubic feet per second)

Storm of March 21, 1980			Storm of April 9, 1980										
Hour	4-hour excess runoff for 0.29 inches of excess rainfall	4-hour unit runoff	Hour	2-hour excess runoff for 0.31 inches of excess rainfall	2-hour unit runoff	Lag of 2 hour	4-hour unit runoff 1/	Average 4-hour unit runoff	S-hydro-graph additions	0.25 inch per hour S-hydro-graph	0.25 inch per hour S-hydro-graph from plot	2-hour lag of S-hydro-graph	2-hour unit hydro-graph 2/
1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	0	0	0	0	0		0	0		0	0		0
2	10	35	2	3	10	0	5	20		20	20	0	40
4	27	93	4	46	148	10	79	86	0	86	86	20	132
6	75	259	6	122	394	148	271	265	20	285	285	86	398
8	141	486	8	366	1052	394	723	604	86	690	700	285	830
10	196	676	10	246	794	1052	923	800	285	1085	1060	700	720
12	122	421	12	160	516	794	655	538	690	1228	1255	1060	390
14	70	241	14	92	297	516	406	324	1085	1409	1385	1255	260
16	62	214	16	52	168	297	232	223	1228	1451	1480	1385	190
18	54	186	18	30	97	168	132	159	1409	1568	1550	1480	140
20	43	148	20	21	68	97	82	115	1451	1566	1595	1550	90
22	32	110	22	15	48	68	58	84	1568	1652	1625	1595	60
24	22	76	24	11	35	48	42	59	1566	1625	1650	1625	50
26	16	55	26	5	16	35	26	40	1652	1692	1665	1650	30
28	14	48	28	2	6	16	11	30	1625	1655	1675	1665	20
30	8	28	30	0	0	6	3	16	1692	1706	1680	1675	10
32	0	0	32			0	0	0	1655	1655	1680	1680	0

Notes: 1/ Add 2-hour unit runoff and 2-hour lag of unit runoff, then divide by 2.

2/ Subtract the 2-hour lag of the S-hydrograph from the S-hydrograph and then multiply by 2.

Rainfall amounts were recorded on a weighing-type rain gage at the Cooper Hill water-treatment facility in the northern and most urbanized area of the town. Surface-water gage heights (stages) were recorded on a digital recorder and were transformed into discharges by a stage-discharge rating curve. The rating curve was developed from gage heights and concurrent measurements of streamflow. Using the recorded gage heights and the stage-discharge relation, flood hydrographs for 8 storms were drawn. The base flow was subtracted (fig. 2), and the rainfall excess (total rainfall minus infiltration) made equal to the excess runoff. The interval of time between the centroids of excess rainfall and runoff is called lag time. The average lag time for the Hop Brook basin, based on the eight storms between September 1977 and March 1980, is 9.2 hours.

The unit hydrograph is best derived from the hydrograph of a storm of reasonably uniform intensity, duration of a desired length, and a runoff volume near or greater than 1.0 in. The first step (fig. 2) is to separate the base flow and direct runoff components. The volume of direct runoff is then determined and the ordinates of the direct-runoff hydrograph are divided by the observed runoff depth. The adjusted ordinates form a unit hydrograph.

A unit hydrograph derived from a single storm may not be representative, and it is usually more beneficial to average unit hydrographs from several storms of about the same duration. This should not be an arithmetic average of concurrent coordinates since if peaks do not occur at the same time, the average peak will be lower than the individual peaks. It is preferable to compute average peak flow and time to peak, and then sketch the unit hydrograph to the shape of the other graphs, passing through the computed average peak, and having a unit volume of 1 in. The results of analyzing two storms for a 4-hour unit hydrograph are shown in table 1, column 9 and the resulting 4-hour unit hydrograph is shown in figure 3.

Figure 4 is a plot of the cumulative excess runoff produced by an infinite number of 4-hour unit graphs occurring consecutively and is referred to as an "S-shaped hydrograph" (Linsley and others, 1949). The S-hydrograph is a convenient technique for conversion to either a shorter or longer duration unit graph. An S-hydrograph is the hydrograph of flow from an infinite series of consecutive units of duration, each having 1 inch of runoff. In figure 4 the 4-hour, S-curve is derived by adding the ordinates of a series of 4-hour unit graphs with their beginning points spaced 4 hours apart (table 1). The maximum ordinate of the S-curve will equal the flow required to discharge 1 inch of runoff in 4 hours. A two-hour unit graph may then be constructed as shown in table 1 by subtracting two S-curves with their initial points separated by 2 hours and multiplying the resulting differences by 2.

Linsley and others (1949, p 453) states that "The accuracy of the S-curve method is dependent on the accuracy of the estimated effective duration of the unit hydrograph from which the S curve is derived. If the assumed duration is too long, the S-curve may fluctuate considerably instead of increasing steadily to a constant value. If the assumed duration is too short there may be no indication in the shape of the S-curve, but the resulting derived unit hydrographs will, of course, be in error."

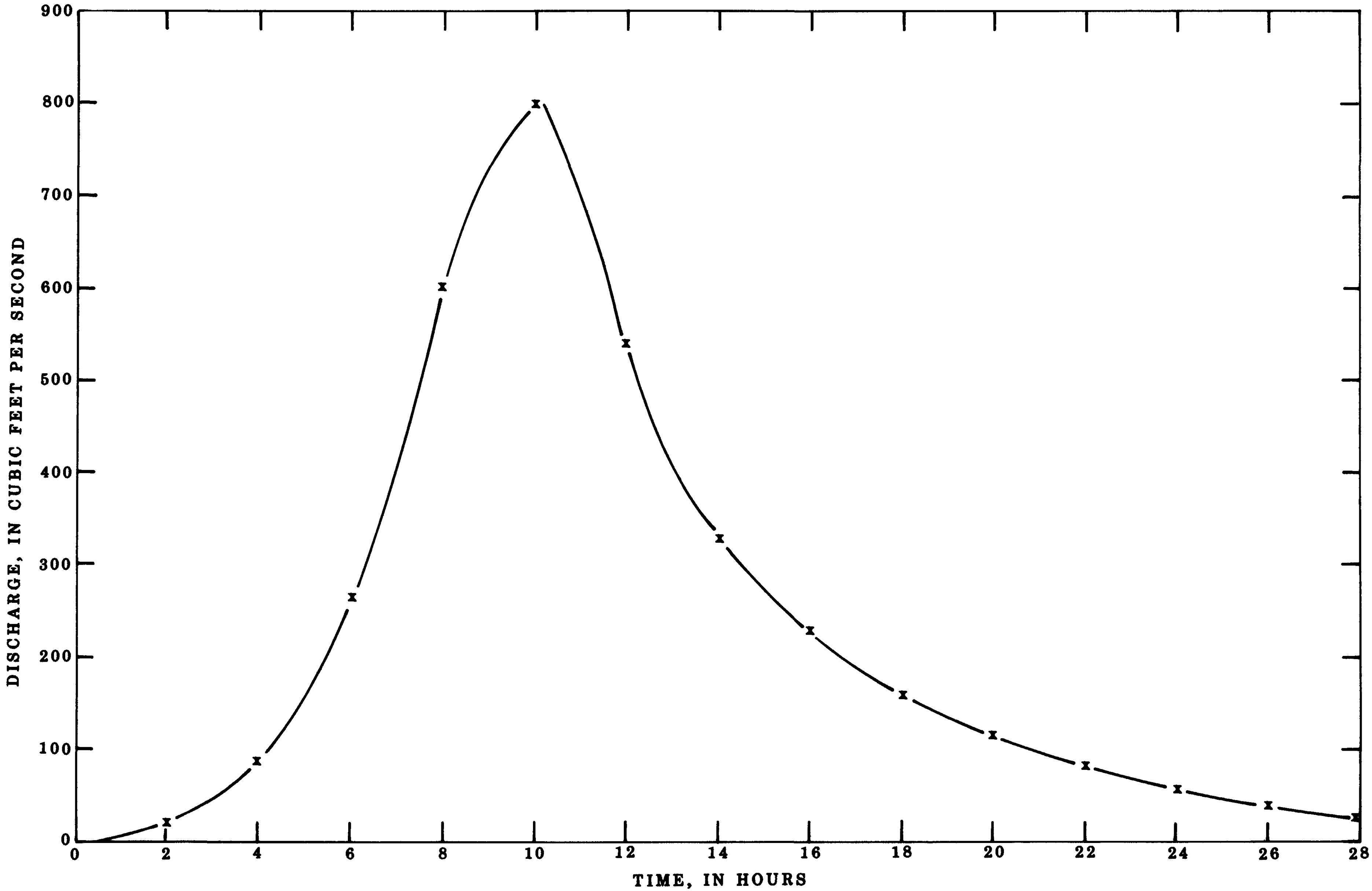

Figure 3.--Four-hour unit hydrograph for Hop Brook at Manchester, Connecticut.

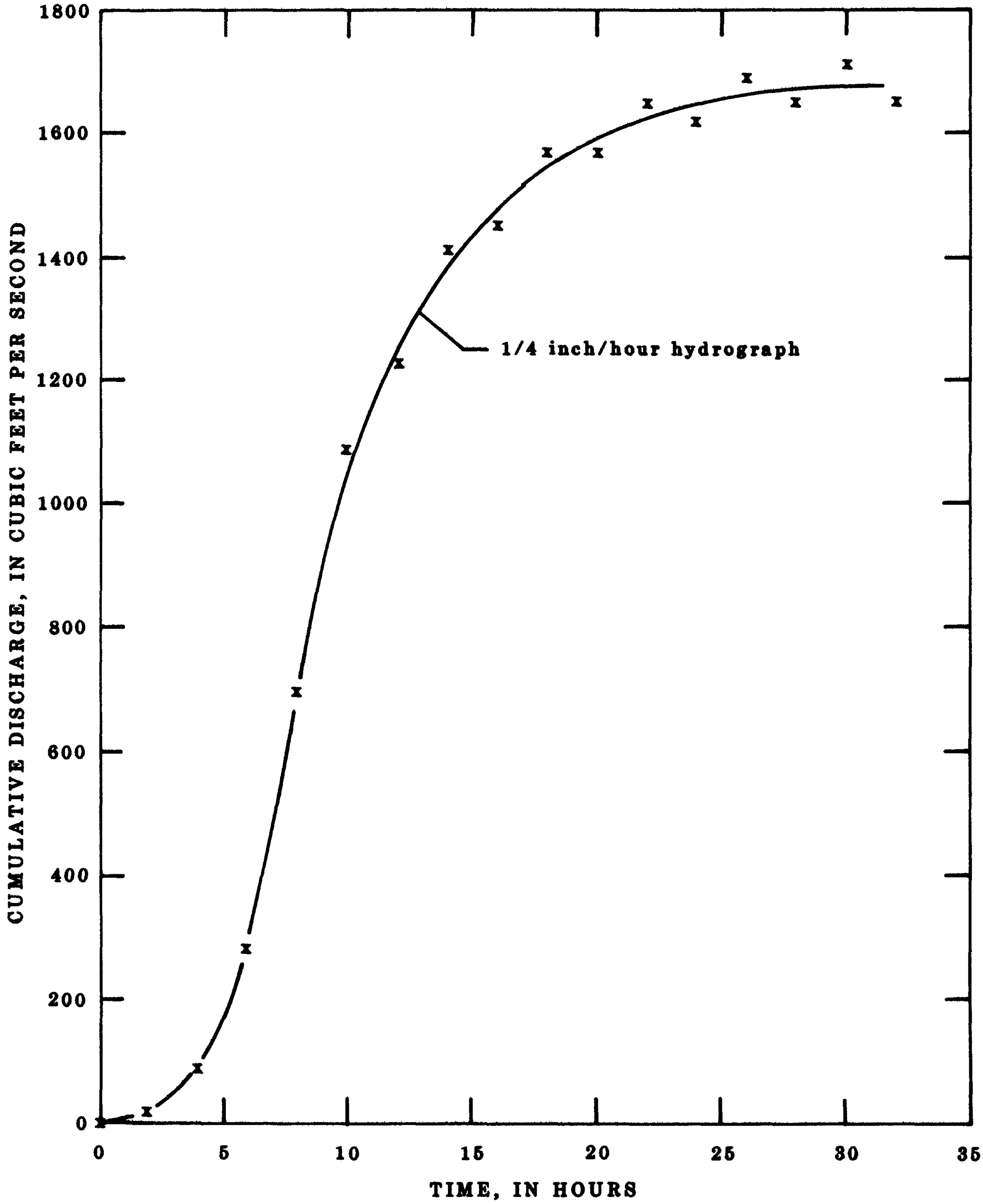

Figure 4.--S-hydrograph for Hop Brook at Manchester, Connecticut.

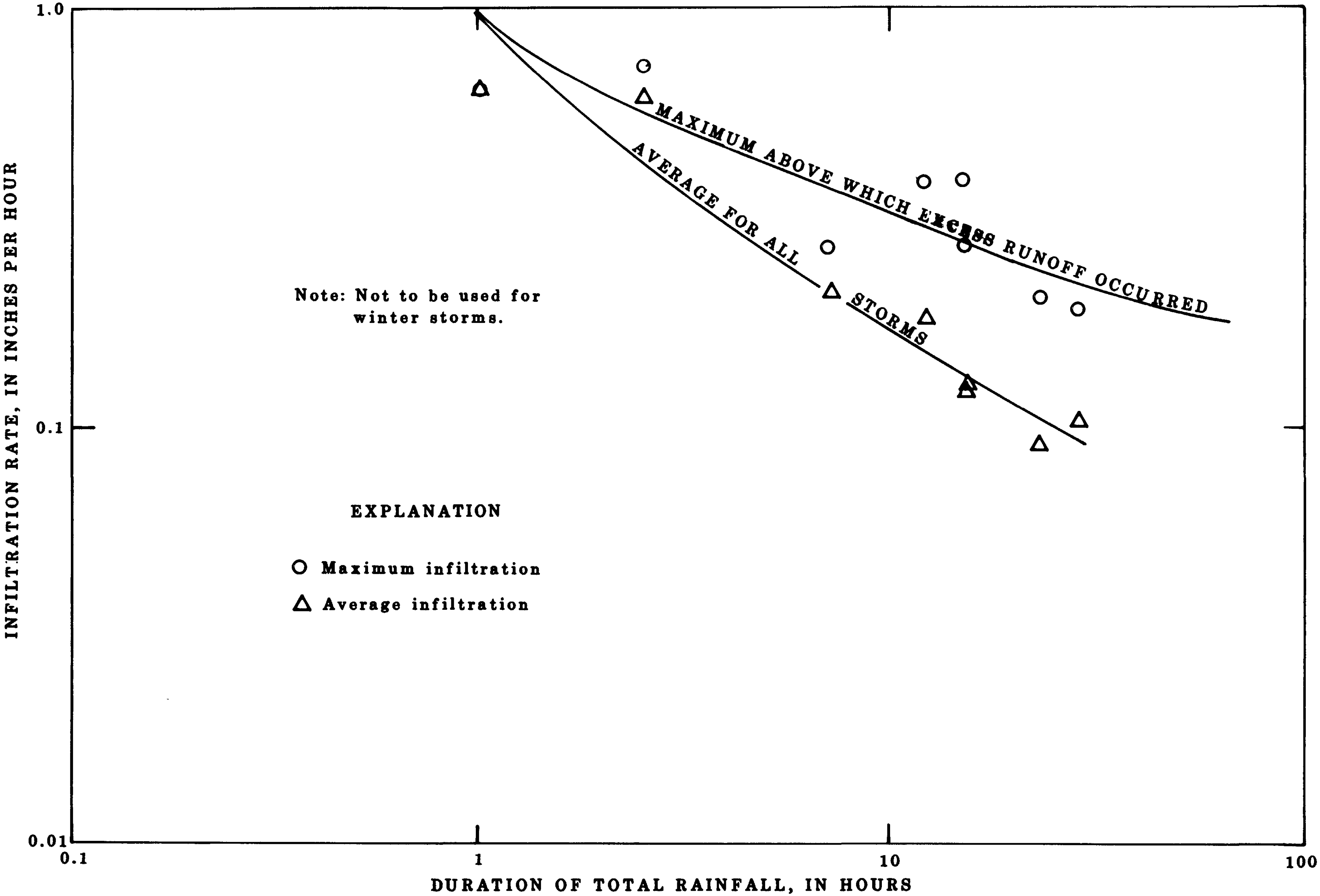

Figure 5.--Infiltration rates for Hop Brook, at Manchester, Connecticut.

Average infiltration rates were determined from eight different storm durations and maximum rates were also determined from eight storm durations indirectly by: 1) equating excess rainfall and runoff; and 2) assuming the remaining rainfall to have infiltrated. The average and maximum infiltration rates versus total storm duration are shown in figure 5. The use of figures 3 and 5 in determining peak flow will be discussed later in the report.

VERIFICATION OF THE UNIT-HYDROGRAPH ANALYSIS

The storms of January 24-26, 1979, and June 5-7, 1982, were used to verify the use of the 4-hour unit graph and infiltration curves (figs. 3 and 5) in computing the peak flows for these storms. During the January 1979 storm 2.30 inches of rain fell in 12 hours; about 0.2 inches per hour (fig. 6). Analysis of a storm on January 22, 1979, indicated that during winter storms, an infiltration rate of 0.07 inches per hour is applicable. The excess rainfall, in inches per hour, and runoff, as computed from a 4-hour unit graph (table 1) are shown in figure 6. The excess rainfall and runoff began at 1600 hours on January 24, 1979, and the excess runoff ended at 0200 hours on January 26, 1979 (fig. 6). This 34-hour period was used to compute the excess runoff hydrograph (fig. 6).

The actual peak flow was 1,380 ft^3/s and the base flow was 70 ft^3/s. Thus, the excess runoff peak flow was 1,310 ft^3/s (fig. 6). The computed peak flow of 1,260 ft^3/s was only 3.8 percent less than the actual excess runoff peak flow. The timing of the computed peak was delayed by four hours. This is a result of the unit graph being developed by spring storms when all reservoirs in the upper part of the basin were spilling. When these reservoirs do not spill, as was the case for January 24-26, 1979, then the peak is caused mainly by the urbanized area in the lower part of the basin, which accelerates the time for peaking. However, since these are water-supply reservoirs they are operated to remain as close to full as possible so that it can be postulated that most floods will occur when the reservoirs are full. If however, the reservoirs are not full they will store water, with a resultant storm having an accelerated peaking time, and reduced volume of runoff. Advanced watershed simulation techniques and additional data would be needed to fully represent the effects of the reservoirs.

The storm of June 5-7, 1982, was nonuniform in its rainfall distribution and occurred in late spring when increased infiltration was critical to the computation of peak flow and the water-supply reservoirs were not spilling. The total rainfall for a period of 30 hours was 5.61 inches of which 1.13 inches contributed to excess runoff over a period of 30 hours (fig. 7). In the January 24-26, 1979 storm, 1.90 inches of excess rainfall occurred in a period of 12 consecutive hours, whereas in the June 5-7, 1982 flood, the 1.13 inches of excess rainfall occurred over a period of 8 hours and mostly at the end of the storm. The computed June 5-7, 1982 peak flow (931 ft^3/s) was 2.3 percent greater than the actual excess peak flow

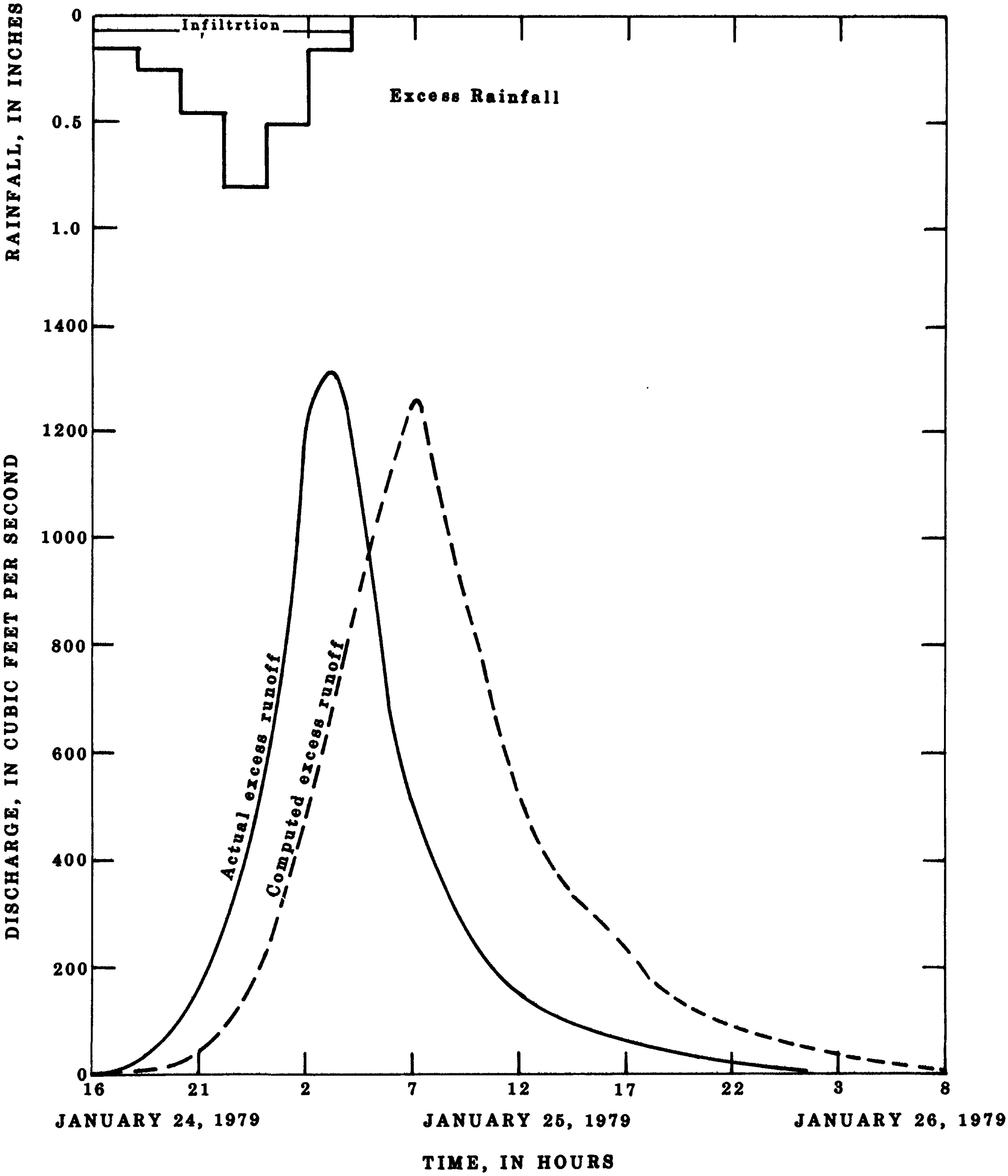

Figure 6.--Excess runoff hydrograph for storm of January 24-26, 1979, for Hop Brook at Manchester, Connecticut.

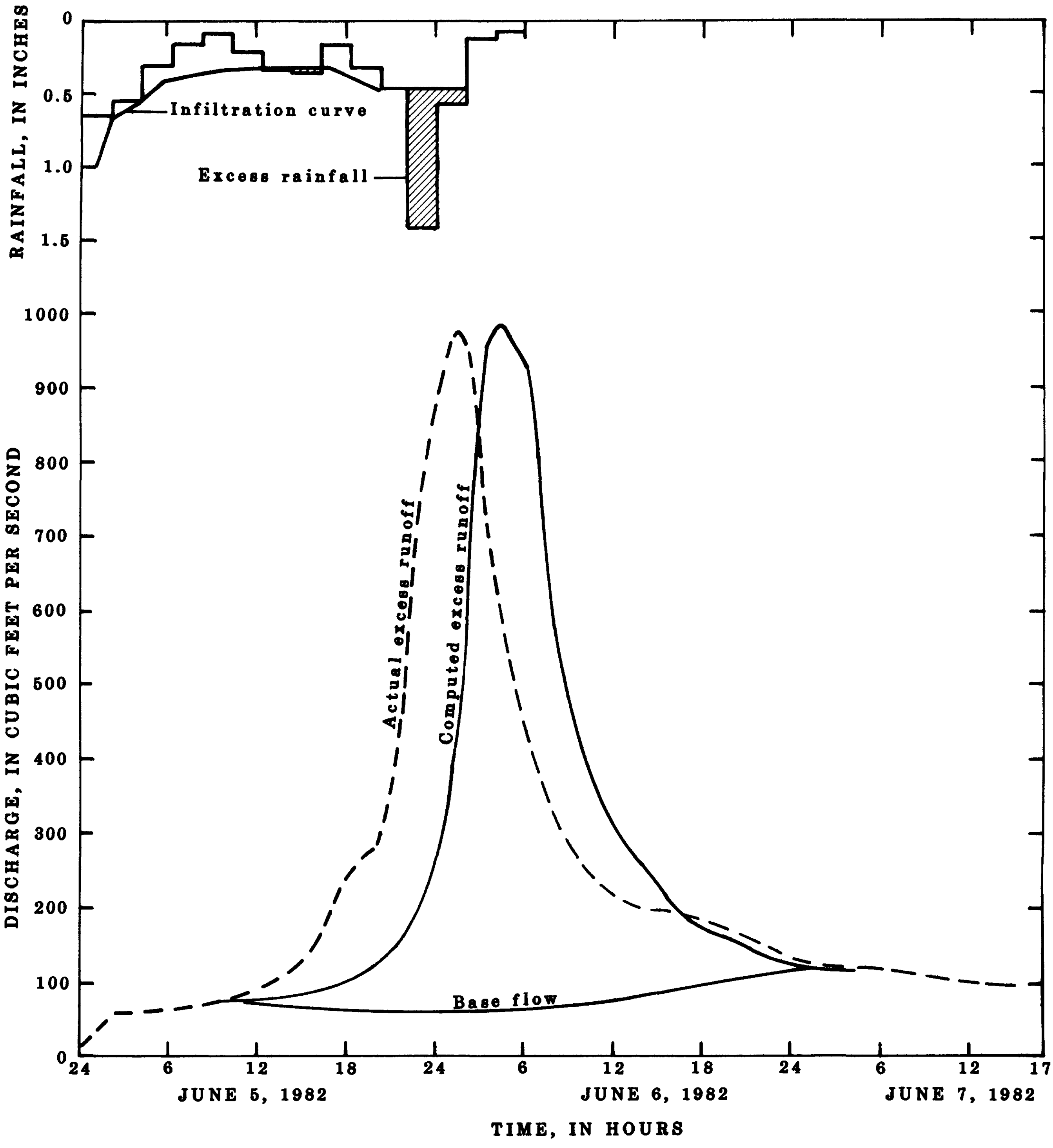

Figure 7.--Excess runoff hydrograph for storm of June 5-7, 1982, for Hop Brook at Manchester, Connecticut.

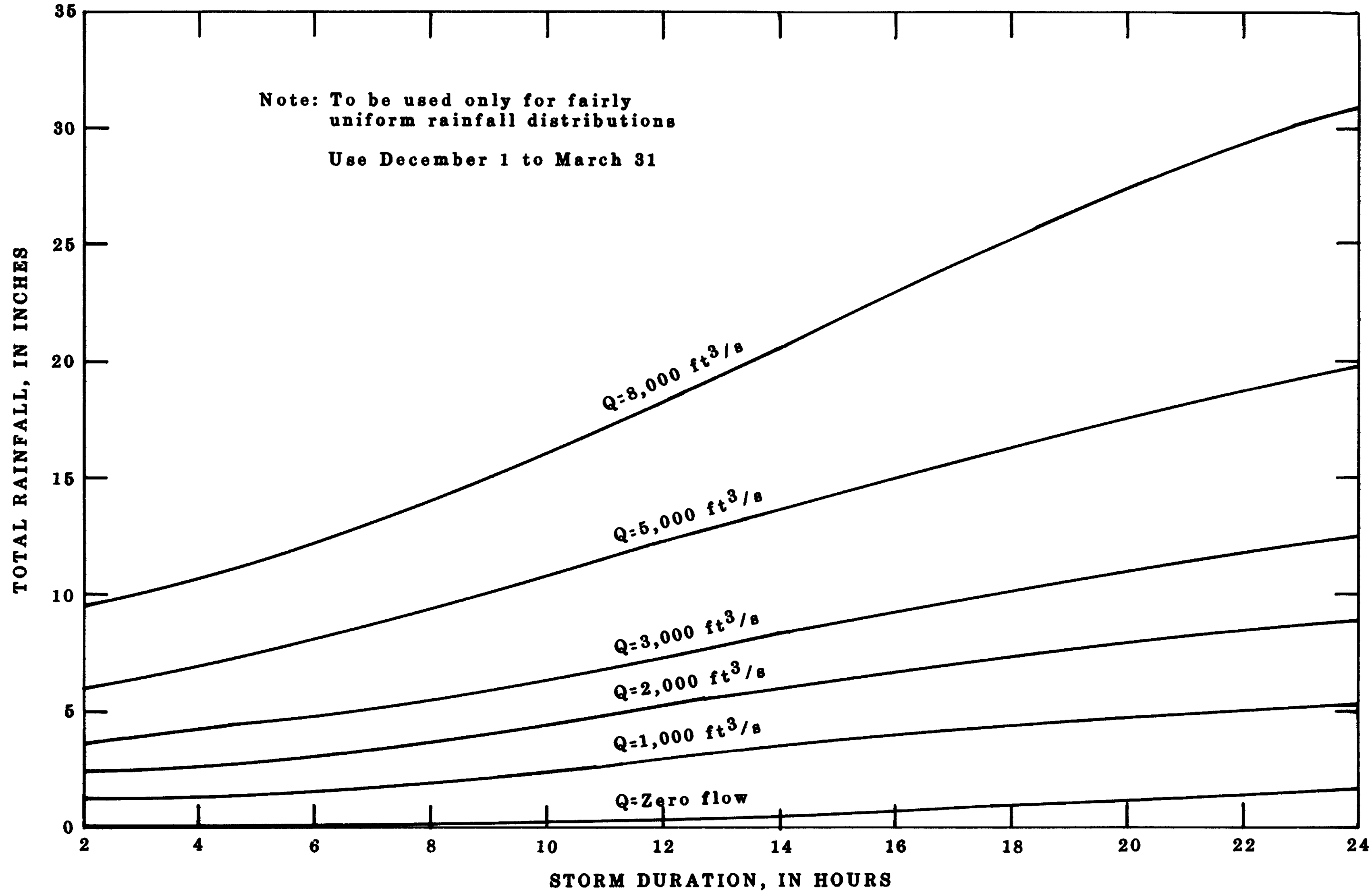

Figure 8.--Maximum discharges for winter storms for Hop Brook at Manchester, Connecticut.

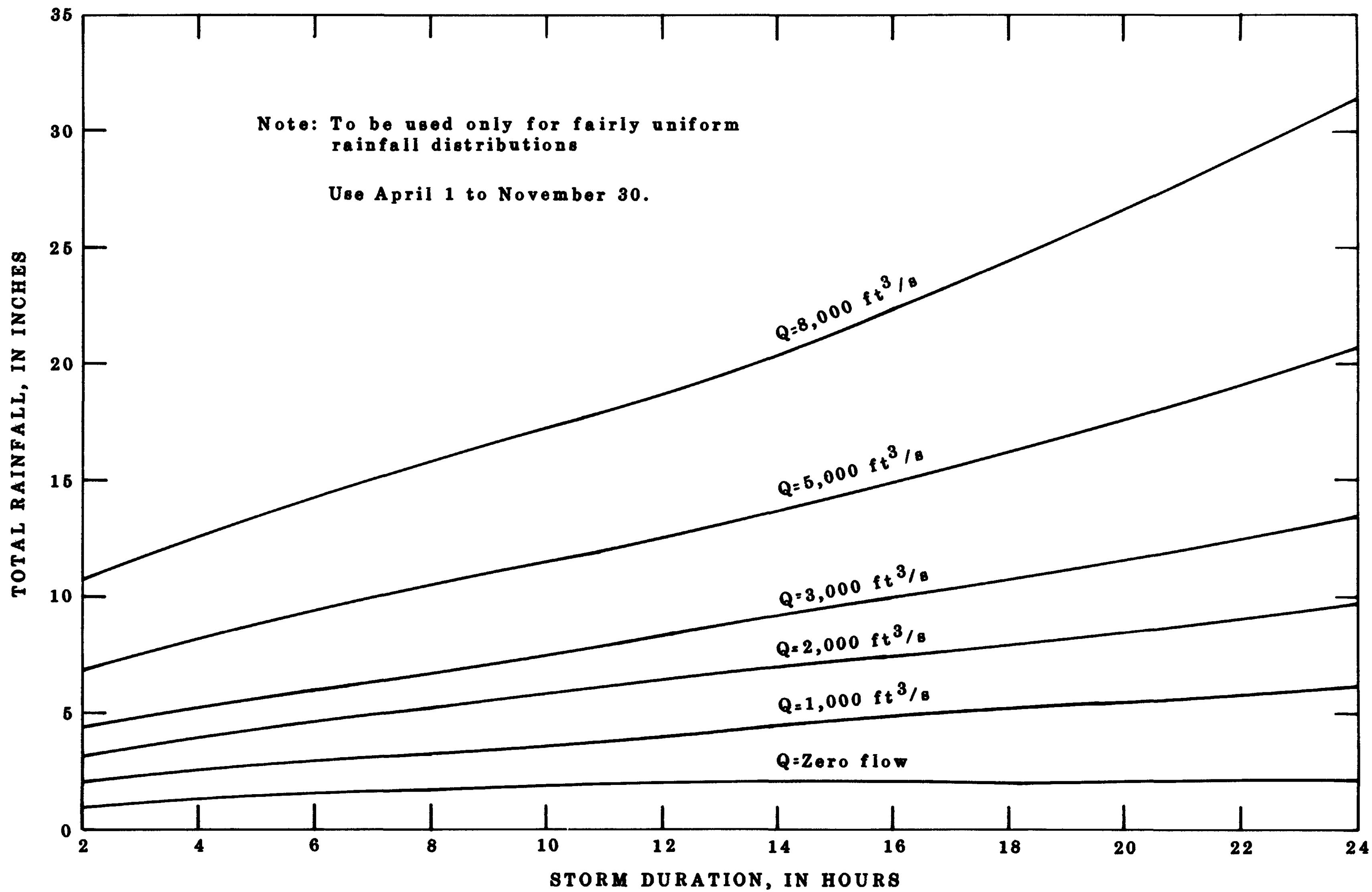

Figure 9.--Maximum discharges for fall, spring, and summer storms for Hop Brook at Manchester, Connecticut.

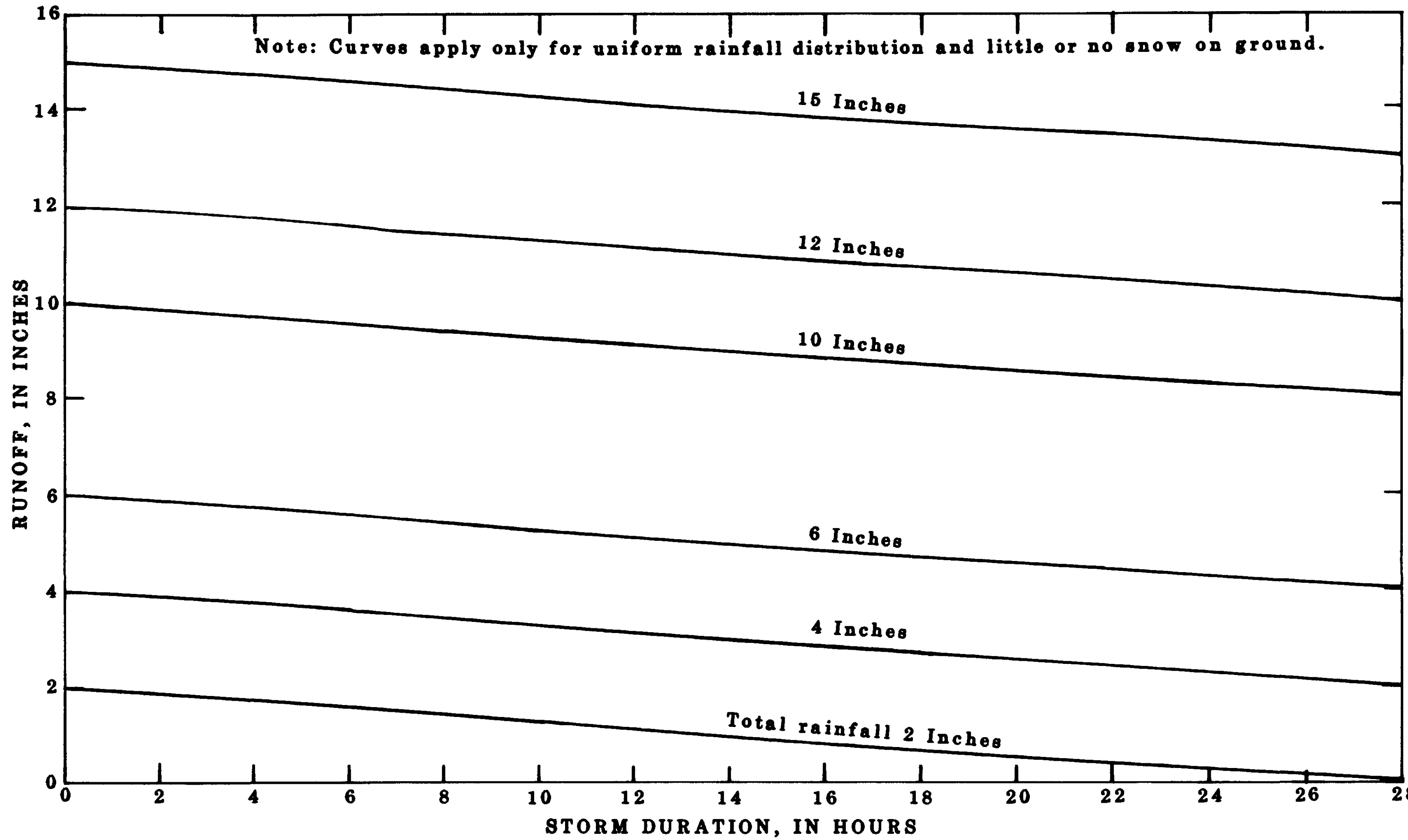

Figure 10.--Excess runoff for winter storms for Hop Brook at Manchester, Connecticut.

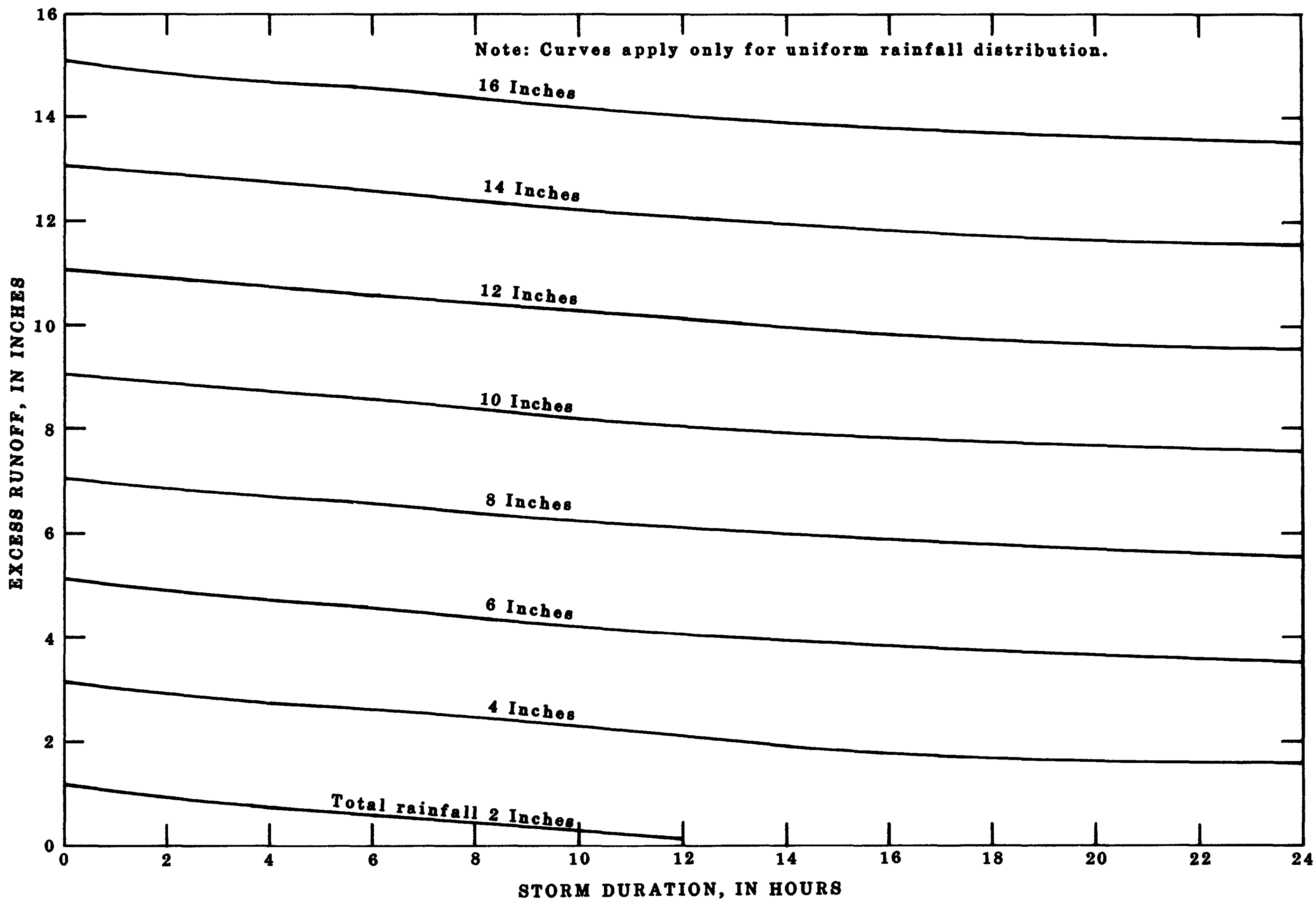

Figure 11.--Excess runoff for fall, spring, and summer storms for Hop Brook at Manchester, Connecticut.

($910\ ft^3/s$). The January 24-26, 1979 excess rainfall was 68-percent greater than the June 1982 excess rainfall, owing to the greater intensity of the winter storm, and reduced soil infiltration.

If rainfall is fairly uniform, such as during the September 27, 1977, storm, the curves shown in figures 8-11 can be used to determine peak flow in cubic feet per second, or total runoff in inches, for storms in any season of the year. These four curves were developed from a 2-hour unit hydrograph for a uniformly time-distributed rainfall, and are based on the maximum infiltration-rate curve as shown in figure 5. The maximum rate is used because it is a better indicator of infiltration necessary to reach saturated soil conditions for different combinations of total rainfall and storm duration. The September 27,1977 storm lasted 2 hours, with a total rainfall of 1.70 inches. Application of these data to figure 9 and interpolating between the 0 and 1,000 ft^3/s curves indicate a peak flow of about 600 ft^3/s as compared to the actual excess flow of 640 ft^3/s.

The storm of June 5-7, 1982, was nonuniform in its rainfall distribution and occurred in late spring when increased infiltration was critical to the computation of peak flow and the water-supply reservoirs were not spilling. The total rainfall for a period of 30 hours was 5.61 inches of which 1.13 inches contributed to excess runoff over a period of 30 hours (fig. 7). In the January 24-26, 1979 storm, 1.90 inches of excess rainfall occurred in a period of 12 consecutive hours, whereas in the June 5-7, 1982 flood, the 1.13 inches of excess rainfall occurred over a period of 8 hours and mostly at the end of the storm. The computed June 5-7, 1982 peak flow ($931\ ft^3/s$) was 2.3 percent greater than the actual excess peak flow ($910\ ft^3/s$). The January 24-26, 1979 excess rainfall was 68-percent greater than the June 1982 excess rainfall, owing to the greater intensity of the winter storm, and reduced soil infiltration.

If rainfall is fairly uniform, such as during the September 27, 1977, storm, the curves shown in figures 8-11 can be used to determine peak flow in cubic feet per second, or total runoff in inches, for storms in any season of the year. These four curves were developed from a 2-hour unit hydrograph for a uniformly time-distributed rainfall, and are based on the maximum infiltration-rate curve as shown in figure 5. The maximum rate is used because it is a better indicator of infiltration necessary to reach saturated soil conditions for different combinations of total rainfall and storm duration. The September 27,1977 storm lasted 2 hours, with a total rainfall of 1.70 inches. Application of these data to figure 9 and interpolating between the 0 and 1,000 ft^3/s curves indicate a peak flow of about 600 ft^3/s as compared to the actual excess flow of 640 ft^3/s.

APPLICATION OF THE UNIT HYDROGRAPH TO THE AUGUST, 1955 FLOOD

Widespread flooding that resulted from Hurricane Diane on August 18-19, 1955 produced floods of magnitudes not previously experienced. Computation of the hydrograph of the August 18-19, 1955 flood in the Hop Brook basin is presented here to illustrate the use of the unit hydrograph presented in

Table 2.-- Computed excess runoff for the August 18-19, 1955 storm superimposed on Hop Brook at Manchester, Connecticut
(Discharge in cubic feet per second)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	2-hour unit graph	2-hour interval excess rainfall in inches											Instantaneous Discharge
Hour		0.22	1.58	0.70	0.08	0.62	1.07	1.46	0.34	2.33	0.58	0.40	
0	0	0											0
2	40	9											9
4	132	29	0										29
6	398	88	63										151
8	830	183	209	0									392
10	720	158	629	28	0								815
12	390	86	1311	92	3								1492
14	260	57	1138	279	11								1485
16	190	42	616	581	32	0							1271
18	140	31	411	504	66	25	0						1037
20	90	20	300	273	58	82	43	0					776
22	60	13	221	182	31	247	141	58	0				893
24	50	11	142	133	21	515	426	193	14	0			1455
26	30	7	95	98	15	446	888	581	45	93	0		2268
28	20	4	79	63	11	242	770	1212	135	308	23	0	2847
30	10	2	47	42	7	161	417	1051	282	927	77	16	3029
32	0	0	32	35	5	118	278	569	245	1934	231	53	3500
34			16	21	4	87	203	380	133	1678	481	159	3162
36			0	14	2	56	150	277	88	909	418	332	2246
38				7	2	37	96	204	65	606	226	288	1531
40				0	1	31	64	131	48	443	151	156	1025
42					0	19	54	88	31	326	110	104	732
44						12	32	73	20	210	81	76	504
46						6	21	44	17	140	52	56	336
48						0	11	29	10	116	35	36	237
50							0	15	7	70	29	24	138
52								0	3	47	17	20	87
54									0	23	12	12	47
56										0	6	8	14

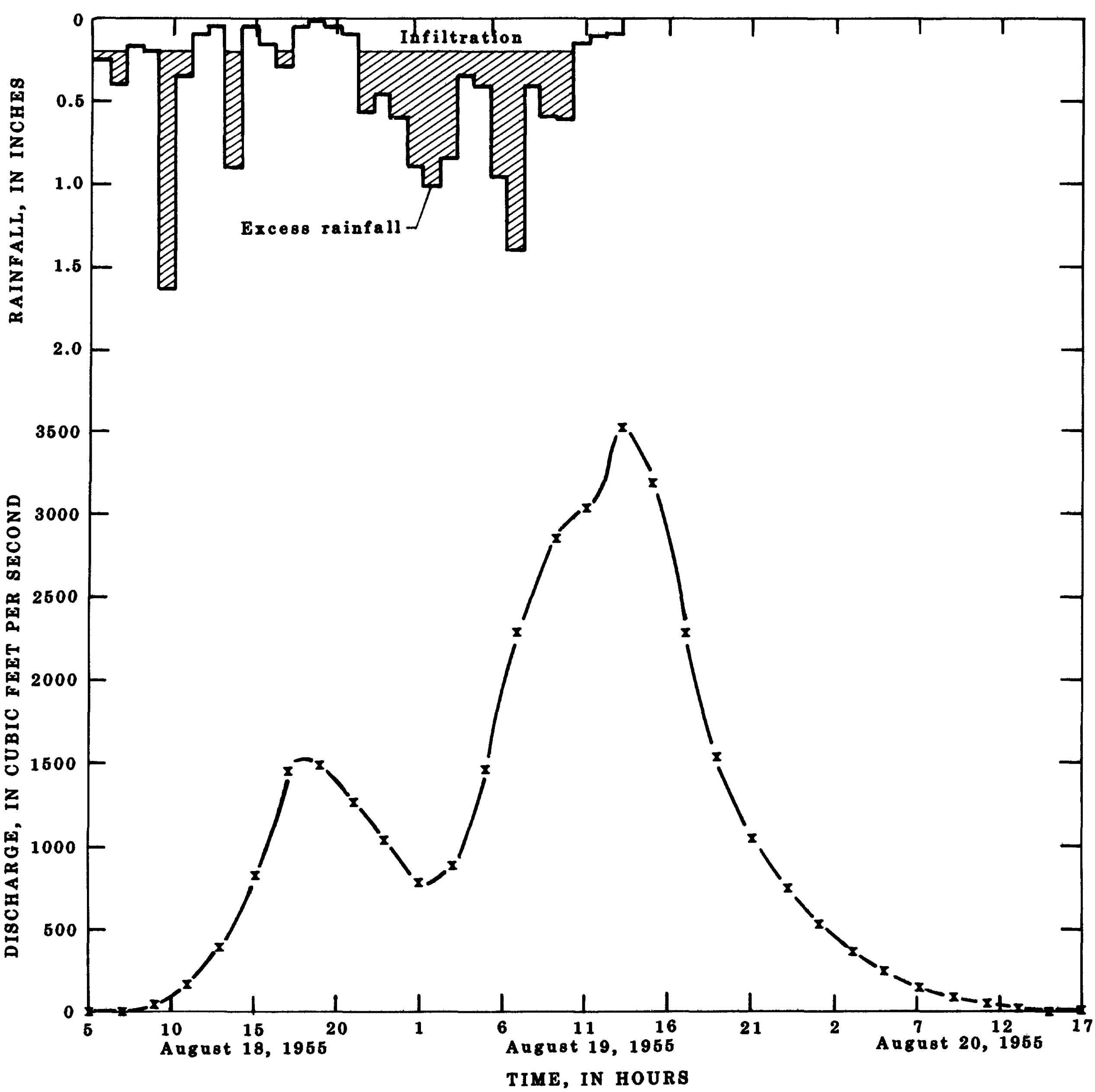

Figure 12.--Excess runoff hydrograph estimated by the unit-hydrograph method for the August 18-19, 1955, storm on Hop Brook at Manchester, Connecticut.

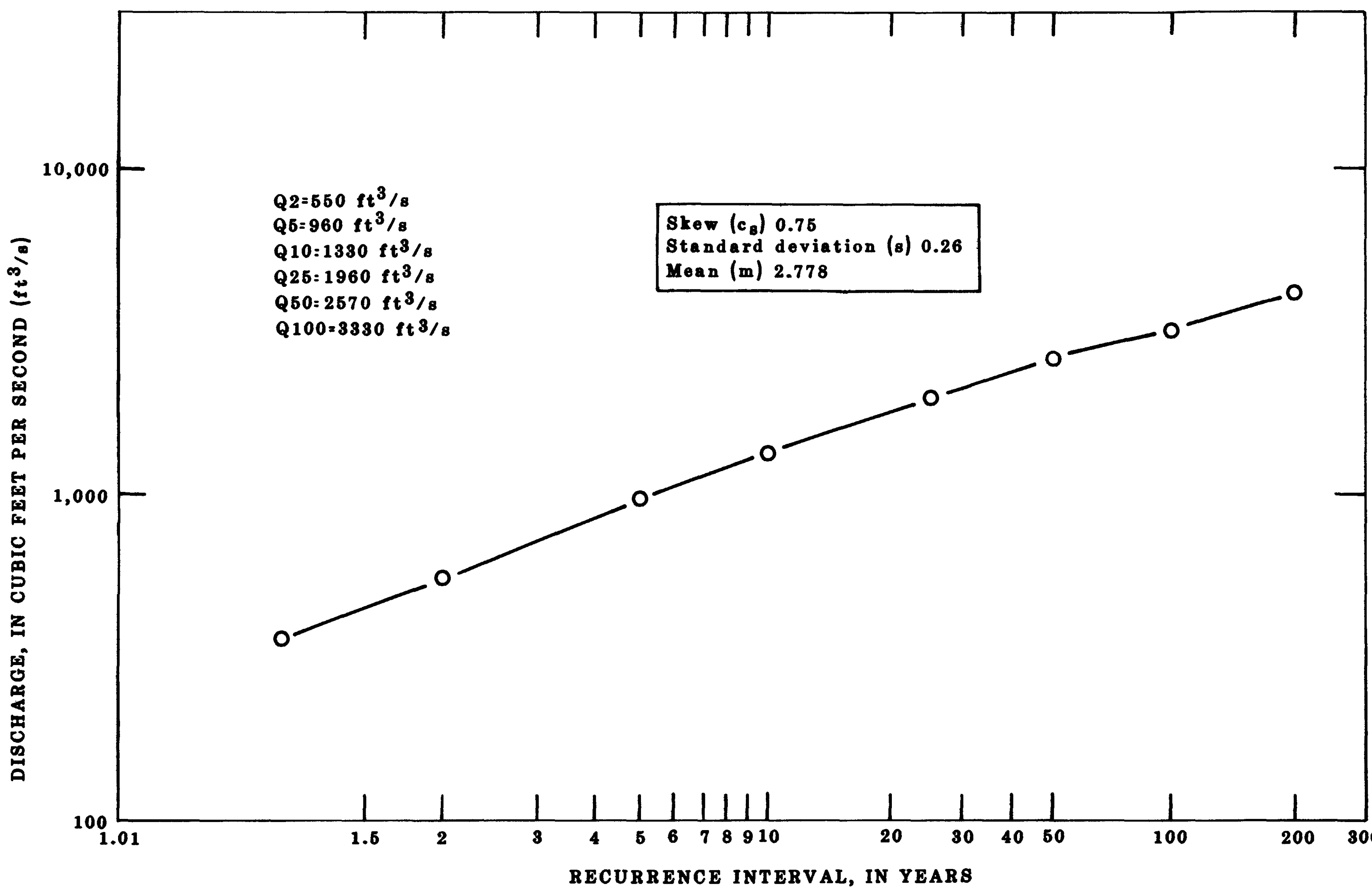

Figure 13.--Magnitude and frequency of annual maximum flows for Hop Brook at Manchester, Connecticut.

table 2. The National Weather Service at Bradley Field in Windsor Locks, Connecticut recorded 13.97 inches of rainfall over a period of 32 hours. Assuming that 13.97 inches of rain also fell on the Hop Brook basin in 32 hours, then the maximum infiltration curve in figure 5 yields an infiltration rate of about 0.2 in/hr. This infiltration rate results in 9.38 inches of excess runoff (67 percent of total rainfall) and a peak flow of 3,500 ft^3/s, as calculated in table 2 and shown in figure 12. The results in table 2 are computed by first subtracting 0.2 in/hr from each 2-hour rainfall to derive the 2-hour interval excess rainfall. (In this instance and for most storms in the Hop Brook basin, the 2-hour unit-hydrograph should be used.) Each 2-hour interval excess rainfall is multiplied by the 2-hour unit graph values (column 14,table 1) in column 2 of table 2. The storm interval is lagged to coincide with the beginning of each interval of rainfall excess. The values of discharge are summed horizontally to yield the instantaneous discharge for each 2-hour interval. The same procedure would be followed if the 4-hour unit hydrograph shown in column 8, table 1 were to be utilized in the analysis.

FLOOD FREQUENCY

As stated in the introduction to this report, the design engineer must compute storm discharges corresponding to various probabilities of occurrences. The foregoing sections of this report presented a method for determining the peak discharge and total volume of flow that would result from a particular set of hydrologic events. To complete the analysis it is necessary to equate the computed discharge to a specific probability of occurrence. The U.S Water Resources Council, (1981) has presented a flood frequency computation method used by Federal agencies. Utilizing the guidelines presented in the Water Resources Council report, and regression equations for Connecticut (Weiss, 1983), the magnitude and frequency of annual maximum flows for Hop Brook were developed, and are summarized in figure 13.

The computed peak discharge of 3,500 cfs for the August 19, 1955 flood exceeded that of a peak flow with a 100-year recurrence interval. A flood of this magnitude would have a chance of occurence of less than 1.0 percent in any year. The largest flood of record during the period 1977-83 was 1,380 ft^3/s, a discharge having approximately a 10-year recurrence interval.

SUMMARY

Two storms were used to develop a unit hydrograph and eight storms were used to develop a relation between rainfall and excess runoff in order to develop an infiltration curve for the Hop Brook drainage basin upstream from Olcott Street in Manchester, Connecticut. This report produces a series of curves to: 1) compute infiltration of rain during storms of various durations; 2) compute peak flows from storms having uniform distribution of rainfall; 3) compute total excess runoff from storms having uniform distribution of rainfall; and 4) created a unit graph to be used in computing peak flows from storms having nonuniform distributions of rainfall.

The storms of January 24-26, 1979 and June 5-7, 1982 were used to verify the model, and actual peak flows were simulated within a range of -3.8 to +2.3 percent, respectively. Transposing the August 18-19, 1955 rainfall distribution, as recorded at Bradley Field by the National Weather Service, to the Hop Brook basin produced a computed peak flow of 3,500 ft^3/s. A magnitude and frequency relation was developed for the Hop Brook basin, utilizing guidelines developed by the United States Water Council. The flow computed for the flood of August 18-19, 1955, would have a recurrence interval exceeding 100 years, based on this relation.

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