UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
H. H. Bennett, Chief

HYDROLOGY OF RATES AND AMOUNTS OF SURFACE RUNOFF FROM SINGLE - AND MIXED - COVER WATERSHEDS

By Leonard Schiff, Hydraulic Engineer
Division of Drainage and Water Control
Soil Conservation Service - Research

SCS-TP-[redacted] 104
Washington, D. C.
March 1951

HYDROLOGY OF RATES AND AMOUNTS OF SURFACE RUNOFF FROM SINGLE- AND MIXED-COVER WATERSHEDS

By Leonard Schiff, hydraulic engineer, Division of Drainage and Water Control, Research, Soil Conservation Service

CONTENTS

	Page
Introduction	1
Purpose and objectives of study	2
Procedure	2
Results	12
Conclusions	25
Summary	25
Literature cited	26

INTRODUCTION

The hydrology of the development of rates and amounts of surface runoff on a watershed must be approached fundamentally. Subsequently, it may be possible to simplify methods of working out the hydrology of a watershed consistent with the degree of accuracy required by some objectives. Such simplification may best come from an understanding of the principles involved and the hydrologic laws operating on a watershed. These laws are based largely on:

(1) The precipitation pattern, that is, the intensities or rates of ground rainfall and the sequence of their occurrence;

(2) The infiltration rate curve for a specific land use on a particular soil at a definite soil-moisture content; and

(3) The depth and movement of detention storage (overland flow).

Information pertaining to factors (1) and (2) may be obtained in any locality based on the storms and hydrologic characteristics of the soil types. The development of detention storage depends upon these factors.

[1] Grateful acknowledgment is made to L. L. Harrold for a review of the paper, to Dan E. Hall for assistance in computations, and to Mrs. Mary A. Williams and Mrs. Mary K. Royer for the tabulation and plotting of data.

The movement of detention storage is the rate of surface runoff on a watershed. Its depth at any time for a given rate of surface flow at some measuring point is dependent upon the physiography and land use. This relationship can be developed for a watershed in any locality. The maximum rate of surface runoff for a storm usually occurs when every part of the watershed has maximum detention storage and is contributing to the flow at the measuring point simultaneously. The time required for this to occur has been called the ''time of concentration.'' The maximum ''excess rainfall,'' that is, differences between rainfall intensities and corresponding infiltration rates, lasting for a time equal to the time of concentration usually will produce this maximum rate of surface runoff. There are cases when the intensity of rainfall is so great for a period of time less than the time of concentration as to produce the maximum rate of surface runoff for a specific watershed. Methods of determining rates of surface runoff must be of such a type as to include such cases.

In this paper a comparison is made between computed and measured rates and amounts of surface runoff from single and mixed cover watersheds up to 75.6 acres. It also includes the computation of rates and amounts of surface runoff for a given precipitation pattern on a watershed with soil at different antecedent or initial soil-moisture contents. It further includes computation of rates and amounts of surface runoff for different precipitation patterns on a watershed with soil at the same initial soil-moisture content. The effect of changes in land use also is computed.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of this study was to develop methods of determining rates, the hydrograph, and amounts of surface runoff from a watershed using the major factors involved; namely, the precipitation pattern, infiltration rates, detention storage-rate of surface runoff relationships, and timing for that watershed. The method thus developed was to be such that the effect of changes in land use upon rates and amounts of surface runoff could be determined.

PROCEDURE

Terms and symbols used are listed below:

Precipitation--as measured, corrected for interception storage by plants if such interception is appreciable and if warranted by the accuracy required by the objective.

P--accumulated precipitation, inches.

i--rate or intensity of precipitation, inches per hour.

Infiltration--The passage of water through the surface of the soil into the soil mass.

f--Infiltration rate, inches per hour.

f_c--Infiltration capacity; that is, the rate at which infiltration would take place at any instant were the supply to equal or exceed this capacity, inches per hour.

f_p--Potential infiltration rate; that is, the rate at which infiltration would take place at a given soil-moisture content, at any instant, were the supply to equal or exceed this potential rate, inches per hour. INFILTRATION POTENTIAL, f_p, IS ONLY USED WHEN RATES OF RAINFALL ARE LESS THAN INFILTRATION CAPACITY, f_c.

Excess rainfall--The amount of rain in excess of infiltration, inches. This is the computed supply going to detention storage and surface runoff.

ΣE--Accumulated excess rainfall, inches.

E--Increment of excess rainfall for a specific time interval $T_2 - T_1$, inches.

Q_{sc}--Computed accumulated surface runoff, inches.

q_{sc}--Computed rate of surface runoff, inches per hour.

Q_{sm}--Measured accumulated surface runoff, inches.

q_{sm}--Measured rate of surface runoff, inches per hour.

Detention storage--The average depth of water on the watershed at any specific time, inches. It is the water which subsequently makes up the overland flow and the rate of surface runoff at a point. Over a period of time it represents accumulated surface runoff.

D_s--Average depth of detention storage at a specific time, inches.

Steps involved in the procedure are illustrated below by computing rates and amounts of surface runoff for the storm of June 16, 1946, occurring on Watershed 103, corn on Keene silt loam, and checking them against measured rates and amounts.

1. An infiltration curve was selected for the cover and soil and for the approximate antecedent or initial soil-moisture content of the topsoil, 0.32 inch of water per inch of soil. Infiltration curves for various covers, soil types, and different soil-moisture contents, have been developed by hydrograph analysis of single cover watersheds at Coshocton *(5)*.[1] (Information on infiltration has been developed in various localities by infiltrometer runs and permeability tests of cores. Information on permeability of cores may be converted into infiltration curves *(6)*.

   After rain has started, soil moisture will increase and the potential infiltration rate will drop. As this continues excess rainfall will begin at the time when the rate of rainfall exceeds the potential infiltration rate. It is necessary to find this time to locate on the rainfall-intensity bargraph the beginning of the infiltration curve for a given soil-moisture content. This point, where the f_c-curve intersects the intensity bargraph, is shown at 9:06 p. m. on *figure 1, page 5*. This point was obtained as follows. The total amount of rainfall up to 9:06 p. m. was 0.52 inch. This amount when divided by 7 inches, the depth of topsoil, is equal to approximately 0.07 inch of moisture gain per inch of soil. This amount when added to the initial soil-moisture content of 0.32 is 0.39. The capacity infiltration curve for this value is taken from the publication cited as reference *(5)*. This curve begins with a value of approximately 2.28 inches per hour, which is equal to the rate of rainfall. The curves shown in the reference are for 0.10, 0.20, 0.30, 0.40, and 0.45 inch of moisture per inch of soil and the curve for 0.39 is obtained by interpolation between the 0.30- and 0.40-curve. In other words, a selected amount of rainfall is divided by 7 (inches of topsoil). This selected amount is obtained by a simple trial and error procedure. It is tested by adding it to the initial soil-moisture content until the total soil-moisture content will support an infiltration rate just equal to or less than the rate

---

[1] Italic numbers in parentheses refer to Literature Cited.

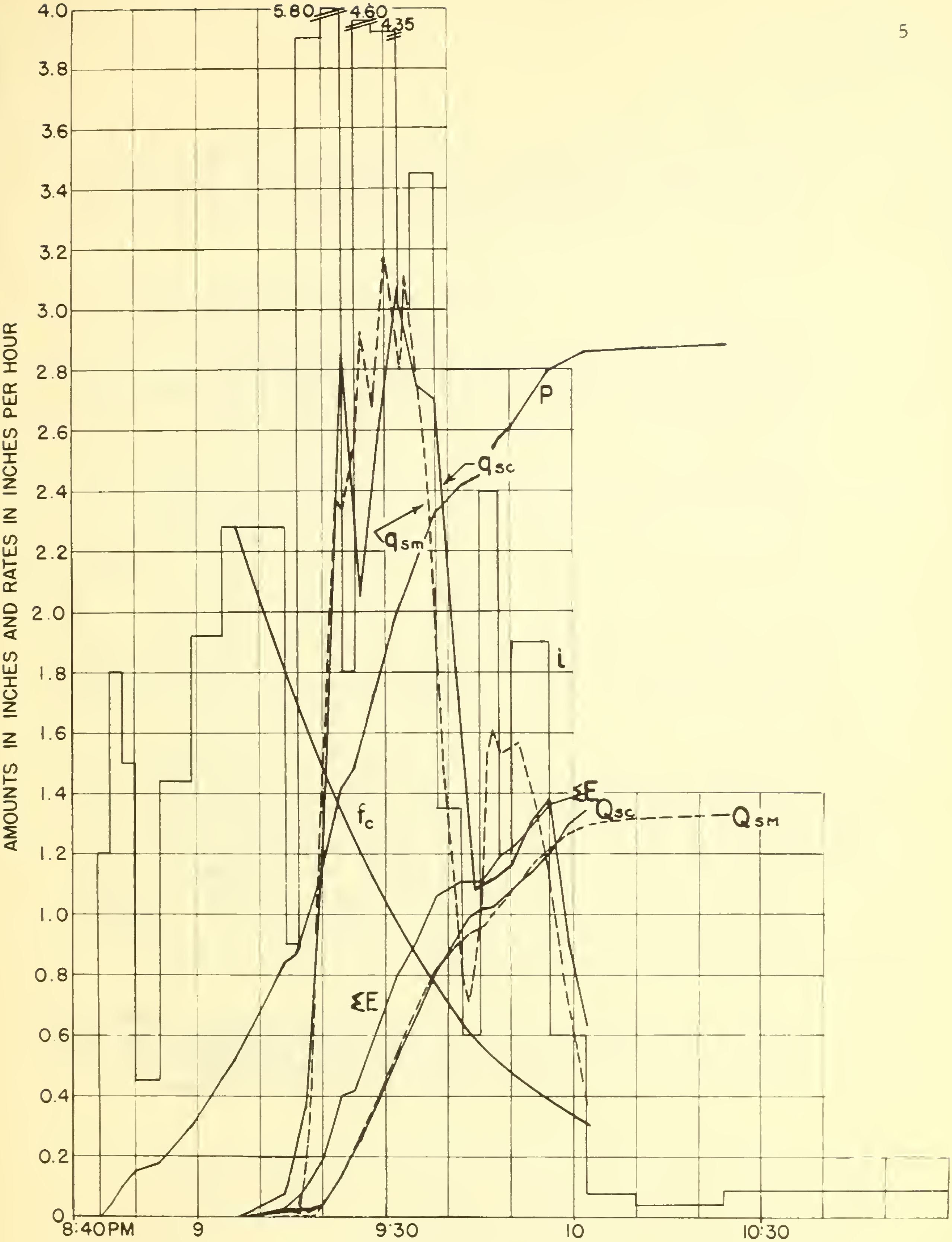

FIGURE 1.--Storm of June 16, 1946, on watershed 103, Keene Silt Loam. Computed and measured rates and amounts of surface runoff from corn. Initial soil-moisture content 0.32 inch of water per inch of soil.

of rainfall. The curves in the reference are infiltration-capacity curves. In the case of the storm of June 16, 1946, on Watershed 103, the curves in the reference cited may be used directly as it is evident that the intensities of rainfall will support a capacity curve.

The division of a selected amount of rainfall by the depth of topsoil, 7 inches, is based on the hydrologic characteristics of the soil. In both the well-drained Muskingum silt loam and the slowly permeable Keene silt loam, there is a rapid movement of water downward in the topsoil. That is, transmission rates are high in the topsoil of both soils and there is a rapid distribution of the water entering the topsoil. The initial infiltration rates are similar for these two soils. However, as water moves below the topsoil into the subsoil of either soil type the transmission rates are noticeably less. Those in the Keene silt loam subsoil are less than in the Muskingum silt loam, resulting in lower infiltration rates in the former. Further discussion on this subject may be found in another publication *(3)*.

2. The infiltration curve, f_c, obtained in the step above, is superimposed over the precipitation pattern under consideration, *figure 1, page 5*. This precipitation pattern is the sequence of rates of rainfall occurring during the storm of June 16, 1946.

3. The excess rainfall, E, is obtained for any time period from the ΣE-curve on *figure 1*. The ΣE-curve was obtained by accumulating the rainfall coming at rates in excess of infiltration rates. For example, for the period between 9:06 and 9:23 p. m.: $\Sigma E = (2.28 - 2.05)8/60 + (3.90 - 1.58)4/60 + (5.80 - 1.40)3/60 = 0.401$ inch. At any time, ΣE is equal to the detention storage and the accumulated surface runoff. It will generally be found satisfactory to subtract the f_c value at the middle of a period from the rainfall rate for that period to obtain the excess for the period.

4. Increments of excess rainfall are converted into the depth of detention storage and rate of surface runoff. For any time interval, say from T_1 to T_2, when the rainfall rate exceeds the infiltration rate, excess rainfall, E, is as follows:

$$E = \left[i - f_{av.}\right] \left[\frac{T_2 - T_1}{60}\right] = \left[Q_{sc-2} - Q_{sc-1}\right] + \left[D_{s-2} - D_{s-1}\right]$$

or, practically

$$E = \left[i - \frac{(f_1 + f_2)}{2}\right] \left[\frac{T_2 - T_1}{60}\right] = \left[\frac{q_{sc-1} + q_{sc-2}}{2}\right] \left[\frac{T_2 - T_1}{60}\right] + \left[D_{s-2} - D_{s-1}\right]$$

in which the subscripts 1 and 2 represent the values of the symbols used at the beginning and end of the time interval, T_1 to T_2, respectively.

At the beginning and end of surface runoff, D_s is zero and the total excess rainfall is equal to the total surface runoff. However, during the period of surface runoff the rate of surface runoff varies with the depth of detention storage. The increments of excess rainfall go to the increase or decrease of detention storage and corresponding increase or decrease of the rate of surface runoff. When the rain ends, a diminishing detention storage supplies a diminishing rate of surface runoff. When D_{s-2} is approximately equal to D_{s-1}, q_{sc-2} and q_{sc-1} are approximately equal, and the rate of surface runoff is simply the slope of the ΣE-curve over an appropriate period of time. Such conditions may prevail for the larger watersheds rather than for the smaller watersheds. For larger watersheds changes in q_{sc-2} and D_{s-2} are much more gradual.

To obtain the maximum rate of surface runoff, Holtan and Kirkpatrick *(1)* have used excess rainfall, E, in the equation:

$$E = \left[\frac{q_{sc-2}}{2}\right] \left[\frac{T_2 - T_1}{60}\right] + D_{s-2}$$

where q_{sc-1} is zero at the beginning of the period. Detention storage D_{s-1} corresponds to q_{sc-1} and is consequently zero at the beginning of the period. Such an equation is limited to the case when the rate of surface runoff and detention storage are zero at the beginning of a selected amount of excess rainfall.

The equation,

$$E = \left[\frac{q_{sc-1} + q_{sc-2}}{2}\right]\left[\frac{T_2 - T_1}{60}\right] + \left[D_{s-2} - D_{s-1}\right],$$

is a general equation. Starting at the beginning of excess rainfall it is a simple matter to balance this ''excess-detention-rate'' bookkeeping equation for a given or anticipated storm. The time period, $T_2 - T_1$, selected is the approximate time of concentration of the watershed in question, this may vary somewhat, with little effect on the results. Methods of estimating the time of concentration are well established in the literature. It is convenient to prepare the excess rainfall in advance for each time period and have one of the time periods end at the same time as the end of the high intensity likely to cause the maximum rate of surface runoff. For example, the time of concentration is approximately 3 minutes for Watershed 103 and the intensity period likely to cause the maximum rate of surface runoff ends at 9:32 p. m. *(fig. 1, page 5).* Time intervals selected for cornland Watershed 123 are illustrated in *table 1, page 9*. *Table 1* was prepared as a convenient form to balance the bookkeeping equation. It is to be noted that one of the time periods ends at 9:32 p. m. The initial period, 9:06 to 9:14, may be taken over a longer period since excess rainfall, *E*, is small.

At the beginning of excess rainfall $q_{sc-1} = 0$ and $D_{s-1} = 0$. To balance the bookeeping equation q_{sc-2} is assumed and the related D_{s-2} selected *(fig. 2, page 10)*. The detention storage-rate of surface runoff relationships reflect the effect of the physical characteristics of a watershed. This relationship for Watershed 103, along with that for Watersheds 123 and 177, is shown in *figure 2*. The detention storage-rate of surface runoff relationship of a watershed is represented by two curves, one for the rising side and one for the falling side of the hydrograph. Detention storage is greater for the rising side for a given rate of surface runoff. Two curves are shown for the falling sides of the relationships for watersheds 103 and 177. The upper curve is used for storms having the higher rate of surface runoff. Such relationships for a watershed may be established through hydrograph analysis. This would require data for a storm on such a watershed producing fairly high rates of surface runoff. It would also be possible to estimate such relationships from a reasonably similar watershed from which hydrologic data were available.

TABLE 1.--*Balancing* $E = \left[\frac{q_{sc-1} + q_{sc-2}}{2}\right] \left[\frac{T_2 - T_1}{60}\right] + \left[D_{s-2} - D_{s-1}\right]$ *for storm of June 16, 1946, on Watershed 103*

Time period	T_2-T_1	Balanced q_{sc-1}	Balanced D_{s-1}	Assumed q_{sc-2}	Related D_{s-2}	Balanced q_{sc-2}	Balanced D_{s-2}	*E* from "ΣE-curve"	Computed *E*	Balancing
	Min.	*In./hr.*	*Inches*	*In./hr.*	*Inches*	*In./hr.*	*Inches*	*Inches*	*Inches*	
9:06	0	0	0					0		
:14	8			0.09	0.0252			.030	0.0312	High
				.08	.0232				.0285	Low
				.085	.0242	0.085	0.0242		.0299	Balanced
:14		.085	.0242							
:17	3			.30	.0564			.050	.0418	Low
				.355	.0638	.355	.0638		.0506	Balanced
:17		.355	.0638							
:20	3			1.10	.137			.114	.1096	Low
				1.14	.140	1.14	.140		.1136	Balanced
:20		1.14	.140							
:23	3			2.70	.253			.207	.2090	High
				2.69	.252	2.69	.252		.2078	Balanced
:23		2.69	.252							
:26	3			2.10	.213	2.10	.213	.081	.0808	Balanced
:26		2.10	.213							
:29	3			2.70	.253			.153	.1617	High
				2.60	.247	2.60	.247		.1532	Balanced
:29		2.60	.247							
:32	3			2.90	.266			.169	.1565	Low
				3.10	.277				.1725	High
				3.05	.275	3.05	.275		.1692	Balanced
:32		3.05	.275							
:35	3			2.80	.246			.120	.1263	High
				2.75	.241	2.75	.241		.120	Balanced
:35		2.75	.241							
:38	3			2.70	.238	2.70	.238	.133	.1332	Balanced
:38		2.70	.238							
:41	3			1.85	.165			.037	.041	High
				1.82	.162	1.82	.162		.037	Balanced
:41		1.82	.162							
:44	3			1.05	.095			.008	.005	Low
				1.08	.098	1.08	.098		.0085	Balanced
:44		1.08	.098							
:47	3			1.15	.142			.057	.061	High
				1.12	.139	1.12	.139		.057	Balanced
:47		1.12	.139							
:50	3			1.15	.142	1.15	.142	.060	.0597	Balanced
:50		1.15	.142							
:53	3			1.20	.146			.073	.063	Low
				1.30	.153	1.30	.153		.0722	Balanced
:53		1.30	.153							
:56	3			1.35	.158			.075	.071	Low
				1.38	.160	1.38	.160		.074	Balanced
:56		1.38	.160							
:59	3			.90	.0825	.90	.0825	.014	.0145	Balanced
:59		.90	.0825							
10:02	3			.65	.060			.014	.016	High
				.63	.0582	.63	.0582		.014	Balanced

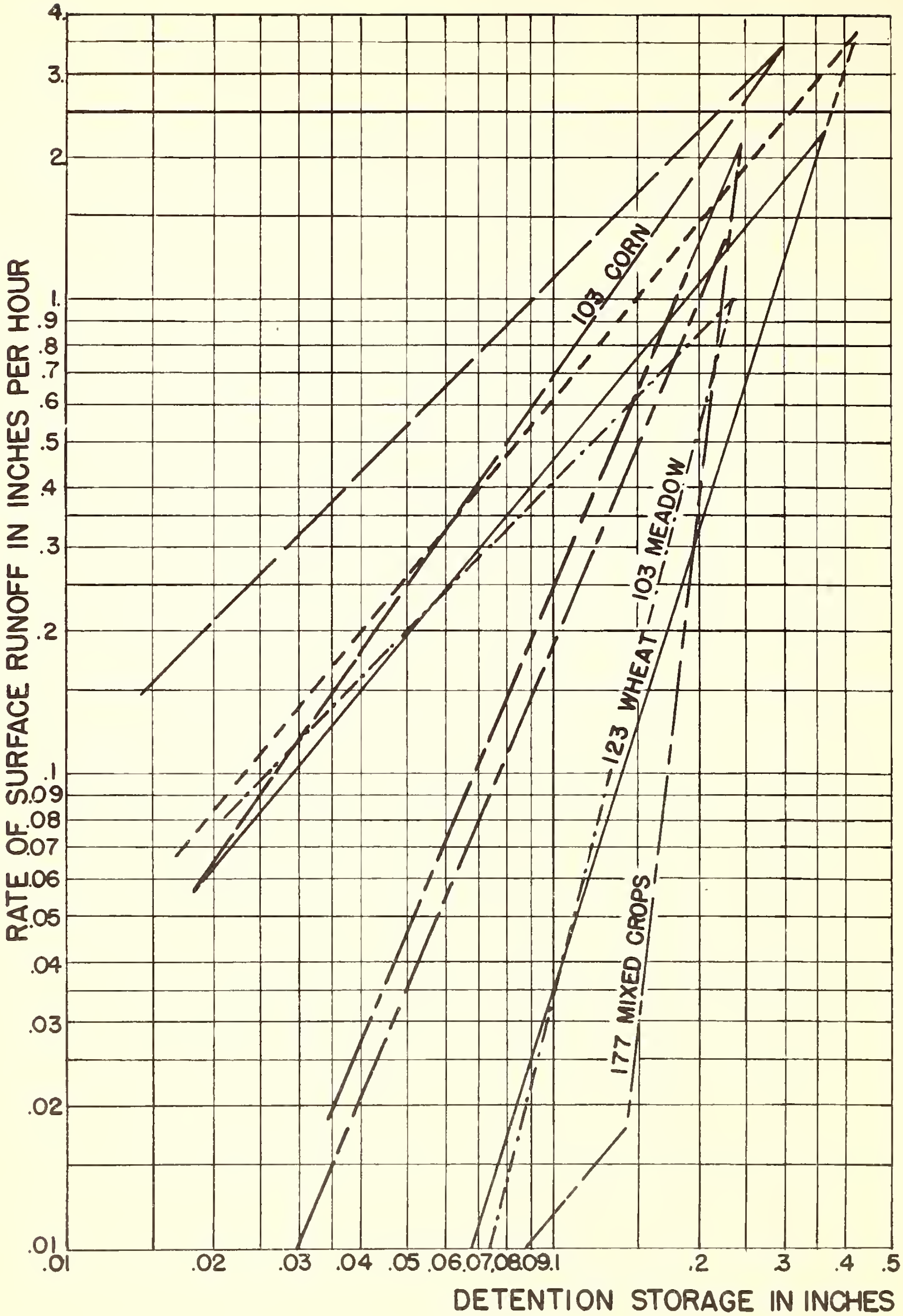

FIGURE 2.--Detention storage-rate of surface runoff relations for watersheds 103, 123, and 177.

The following illustrates the balancing of the equation:

Time period 9:06 to 9:14

$$E = 0.030 = \left[\frac{q_{sc-1} + q_{sc-2}}{2}\right]\left[\frac{T_2 - T_1}{60}\right] + \left[D_{s-2} - D_{s-1}\right]$$

$$= \left[\frac{0 + q_{sc-2}}{2}\right]\frac{8}{60} + \left[D_{s-2} - 0\right]$$

Assume $q_{sc-2} = 0.09$ and then $D_{s-2} = 0.0252$, as obtained from detention storage-rates of surface runoff relationships shown in *figure 2, page 10*. Then:

$$E = 0.030 = \left[\frac{0 + 0.09}{2}\right]\frac{8}{60} + (0.0252 - 0)$$

$E = 0.030 = 0.0060 + 0.0252 = 0.0312$ (High)

Assume $q_{sc-2} = 0.08$ then $D_{s-2} = 0.0232$

$E = 0.030 = 0.0053 + 0.0232 = 0.0285$ (Low)

Assume $q_{sc-2} = 0.085$ then $D_{s-2} = 0.0242$

$E = 0.030 = 0.0057 + 0.0242 = 0.0299$ (Balanced)

Time period 9:14 to 9:17

(q_{sc-2} and D_{s-2} at the end of the 9:06 to 9:14 period is the q_{sc-1} and D_{s-1} at the beginning of the 9:14 to 9:17 period)

Assume $q_{sc-2} = 0.30$ then $D_{s-2} = 0.0564$

$$E = 0.050 = \left[\frac{0.085 + 0.30}{2}\right]\frac{3}{60} + (0.0564 - 0.0242)$$

$$E = 0.050 = \left[\frac{0.085 + 0.30}{40}\right] + (0.0564 - 0.0242)$$

$$E = 0.050 = 0.0096 + 0.0322 = 0.0418 \quad \text{(Low)}$$

Assume $q_{sc-2} = 0.355$ then $D_{s-2} = 0.0638$

$$E = 0.050 = \left[\frac{0.085 + 0.355}{40}\right] + (0.0638 - 0.0242)$$

$$E = 0.050 = 0.0110 + 0.0396 = 0.0506 \quad \text{(Balanced)}$$

This procedure may be continued for the other periods throughout the storm. It is continued until 10:02 p. m. in *figure 1, page 5, and table 1, page 9.*

Values of D_{s-2} at the end of each time period are subtracted from the ΣE-curve on *figure 1, page 5.* Values so obtained are the Q_{sc}, computed accumulated surface runoff, since at any time ΣE is equal to $Q + D_{s-2}$. The measured accumulated surface runoff is shown as Q_{sm} in *figure 1.* The computed accumulated surface runoff at 10:02 p. m. is 1.35 as compared to a measured amount of 1.30 inches. Values of q_{sc-2} at the end of the time periods represent the rates of surface runoff and are plotted as the computed hydrograph q_{sc}. This is shown in *figure 1* as well as the measured rates of surface runoff q_{sm}. The accumulated surface runoff determined from the computed hydrograph is 1.33 inches. The computed maximum rate of surface runoff is 3.05 as compared to a measured rate of 3.17 inches per hour.

RESULTS

Results of computed and measured rates and amounts of surface runoff have been shown in *figure 1, page 5,* for Watershed 103, contour corn on Keene silt loam when the initial soil-moisture content was 0.32 inch of water per inch of soil. The possible effect of corn in straight rows was computed for Watershed 103 by using the same storm and the same initial soil-moisture content as shown in *figure 1;* in other words, the same excess rainfall. The effect of the detention storage-rate of surface runoff relationship and related timing for straight-row corn on this excess rainfall was then computed. The maximum rate of surface runoff and accumulated surface runoff so obtained were 4.90 inches per hour and 1.37 inches, respectively, as compared to 3.05 and 1.35, respectively, for contour corn.

Due to slaking as well as sealing of the soil surface, rates and amounts of surface runoff from cornland are greater when the soil-moisture content is lower than 0.32 inch of water per inch of soil, (5). *Figure 3, page 14,* shows rates and amounts of surface runoff as computed for contour corn on Keene silt loam for Watershed 103, using the storm pattern of June 16, 1946, for an initial soil-moisture content of 0.15 inch of water per inch of soil. As a comparison, *figure 4, page 15,* shows rates and amounts of surface runoff as computed for meadow on Keene silt loam for Watershed 103, using the storm pattern of June 16, 1946, for an initial soil-moisture content of 0.15 inch of water per inch of soil. *Figure 5, page 16,* shows computed and measured rates and amounts of surface runoff for the storm of June 16, 1946, on Watershed 123, wheat on Keene silt loam, when the soil-moisture content was 0.29 inch of water per inch of soil. As a comparison, *figures 6 and 7, pages 17 and 18,* show rates and amounts of surface runoff as computed for wheat on Keene silt loam for Watershed 123, using the storm pattern of June 16, 1946, for an initial soil-moisture content of 0.10 and 0.40 inch of water per inch of soil. Infiltration rates during certain periods in *figures 3, 4, and 6, pages 14, 15, and 17,* are not capacity rates due to insufficient rainfall during these periods. For example, the potential infiltration rate at 9:43 p. m. in *figure 6* is based on the increase in soil moisture due to the precipitation that has occurred in the interval between 9:34 and 9:43 p. m., using a procedure similar to that shown under *Point 1 of Procedure, page 4.*

The method was applied to the storm of June 16, 1946, on Watershed 177, 75.6 acres of mixed crops on mixed soil types. *Figure 8, page 19,* shows the excess rainfall for each cover and soil type using infiltration curves obtained from reference (5) and following the procedure described previously. The ratio of the area occupied by a given cover to the total area of the watershed was obtained for each cover. The excess rainfall for each cover was then multiplied by its appropriate ratio. The results obtained for all covers were accumulated and represent the composite excess rainfall, ΣE, also shown in *figure 8.*

The bookkeeping equation was applied to the composite excess rainfall, and computed and measured rates and amounts of surface runoff are shown in *figure 9, page 20.* The portion of the measured rates and amounts of surface runoff shown by a dash and dot line were estimated. However, the measured maximum rate is accurate, although its location in reference to time was estimated. The computed maximum rate of surface runoff was 1.42

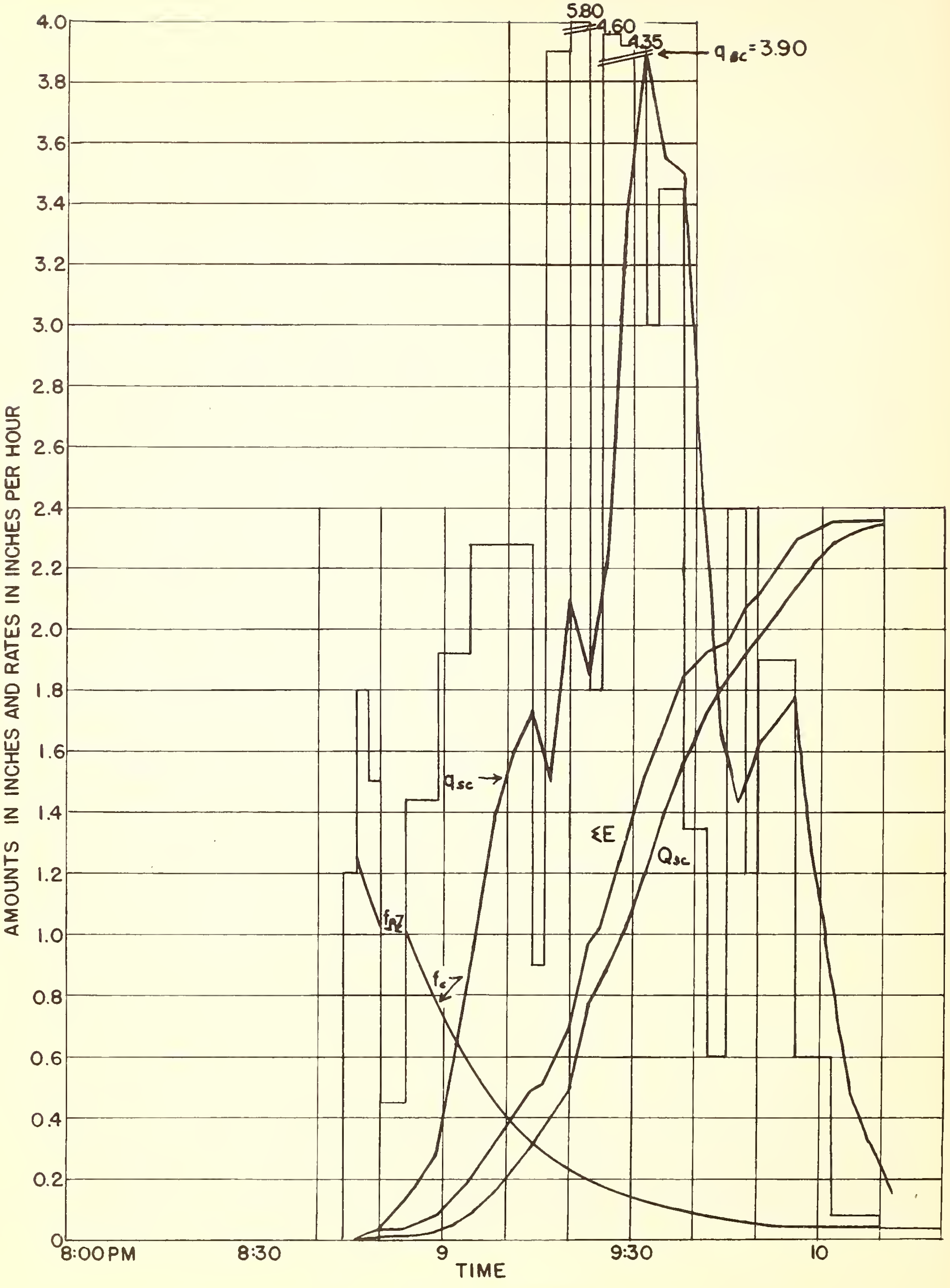

FIGURE 3.--Storm of June 16, 1946, on watershed 103, Keene Silt Loam. Computed rates and amounts of surface runoff from corn. Initial soil-moisture content 0.15 inch of water per inch of soil.

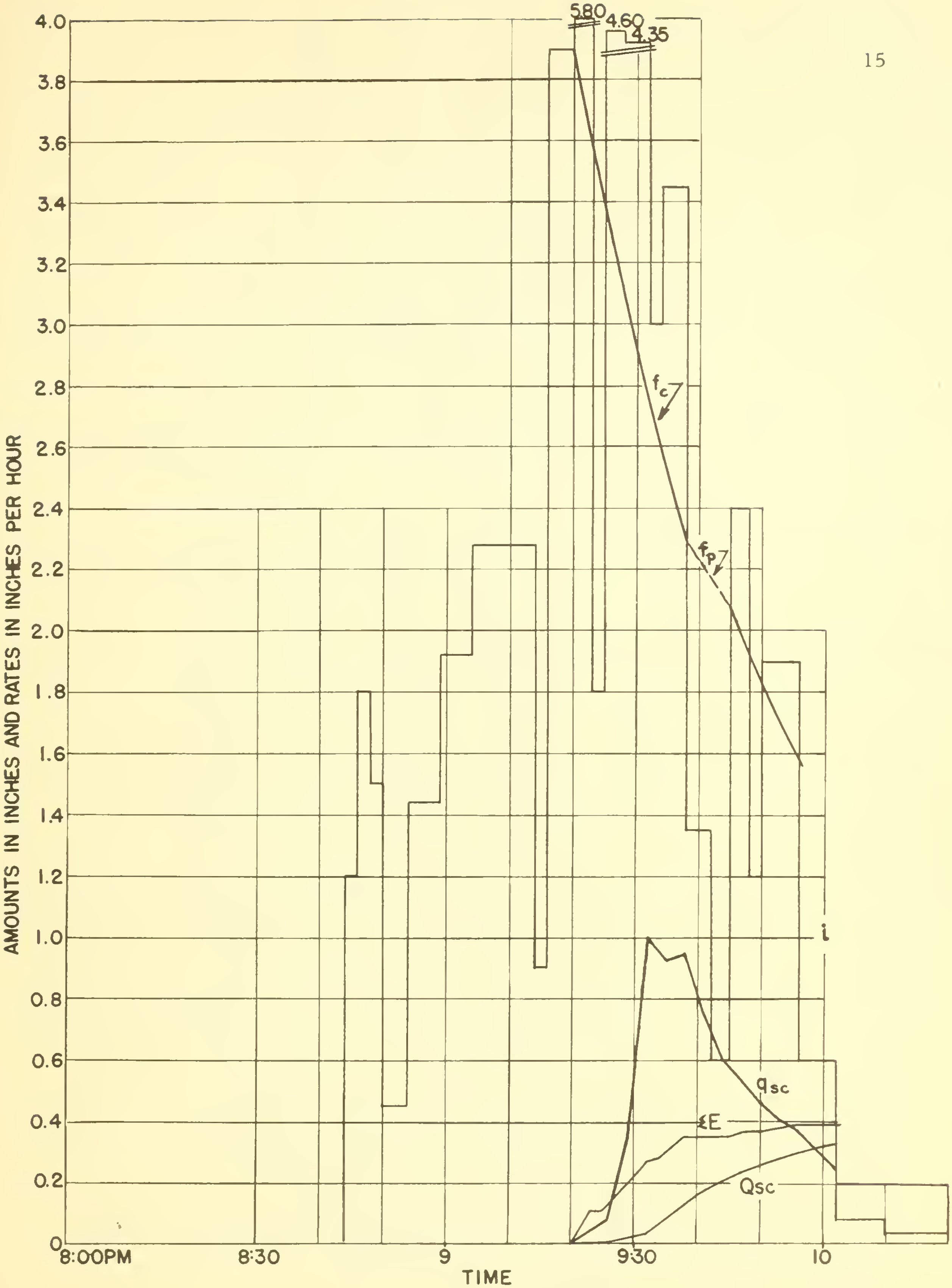

FIGURE 4.--Storm of June 16, 1946, on watershed 103, Keene Silt Loam. Computed rates and amounts of surface runoff from meadow. Initial soil-moisture content 0.15 inch of water per inch of soil.

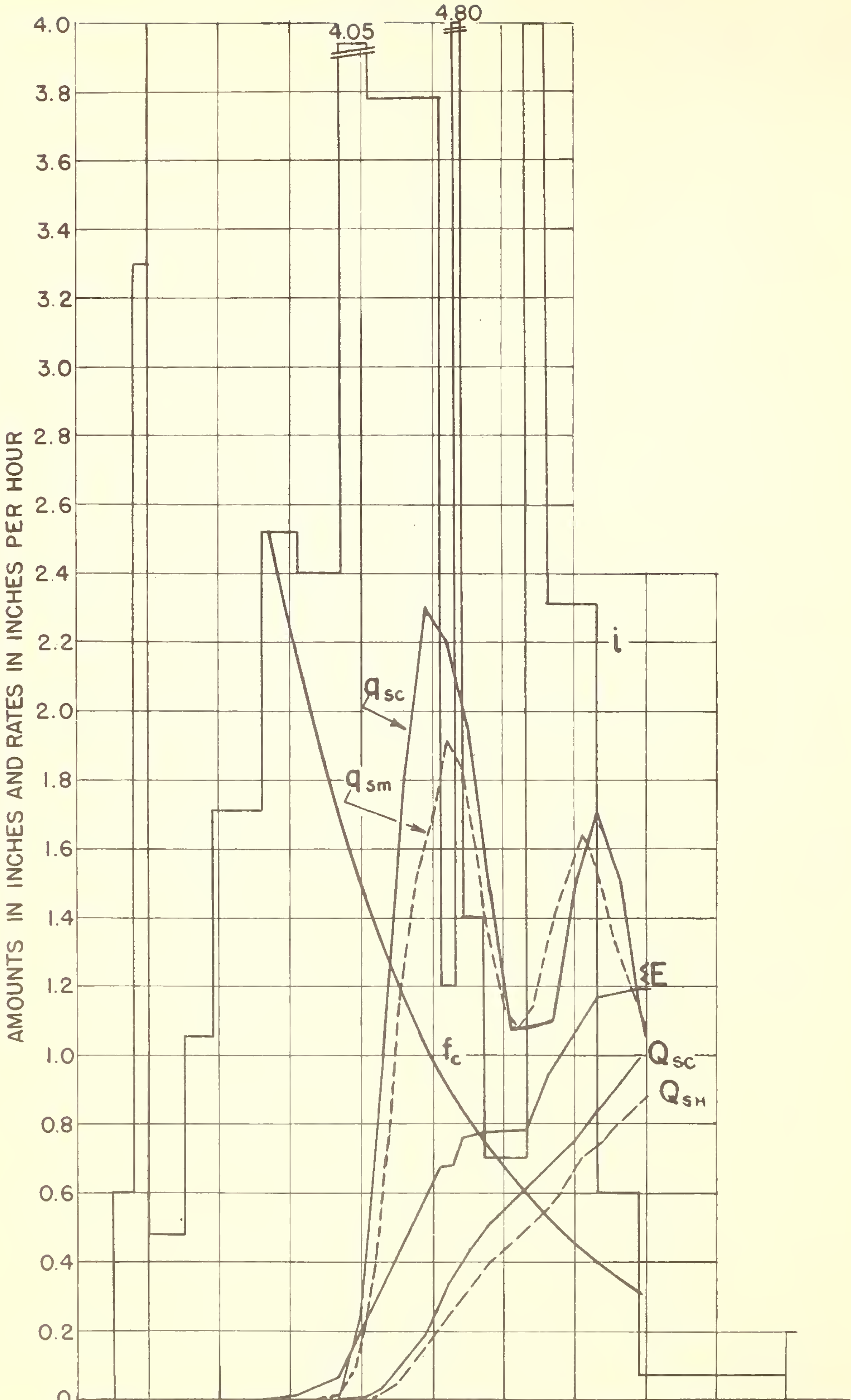

FIGURE 5.--Storm of June 16, 1946, on watershed 123, Keene Silt Loam. Computed and measured rates and amounts of surface runoff from wheat. Initial soil-moisture content 0.29 inch of water per inch of soil.

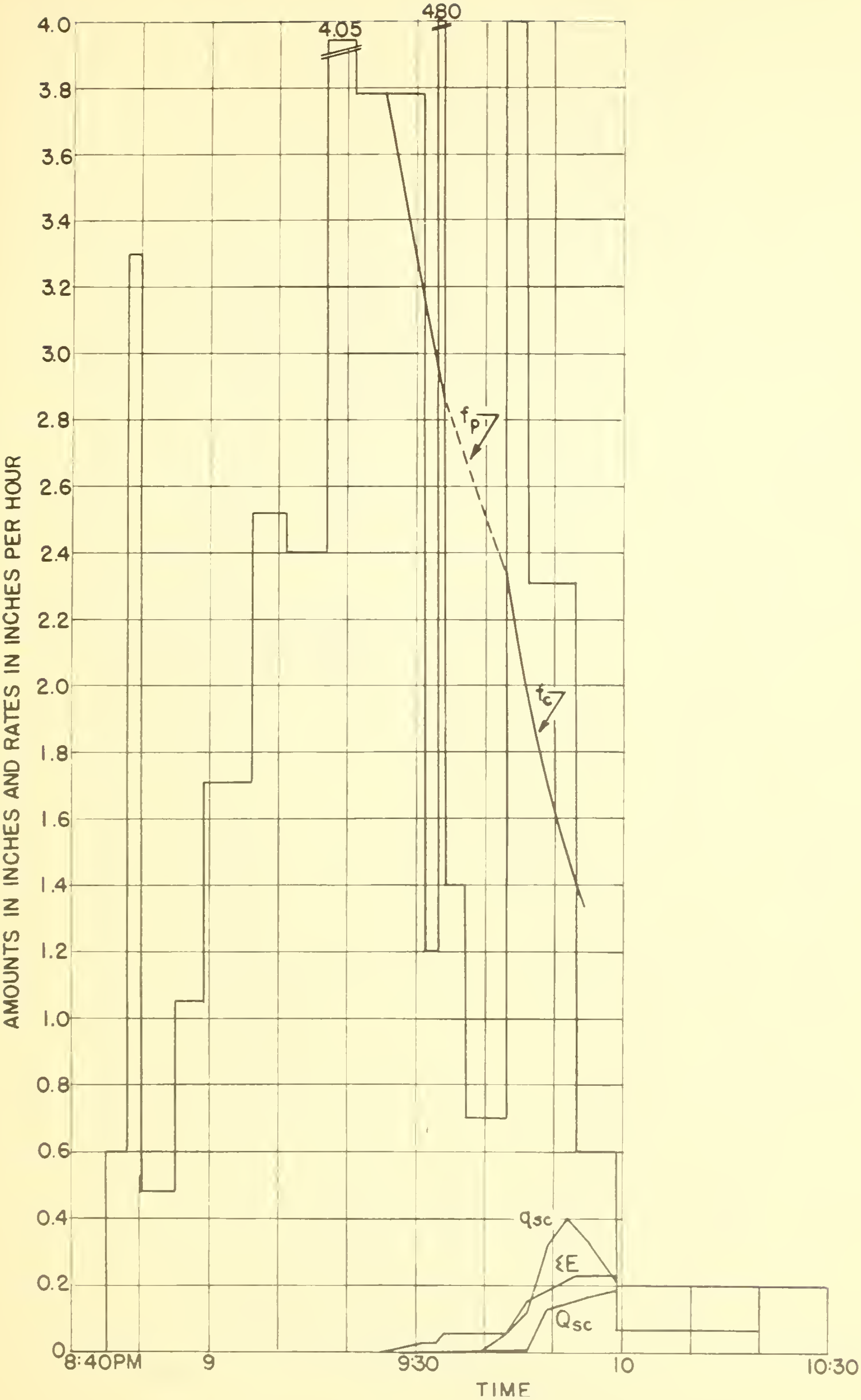

FIGURE 6.--Storm of June 16, 1946, on watershed 123, Keene Silt Loam. Computed rates and amounts of surface runoff from wheat. Initial soil-moisture content 0.10 inch of water per inch of soil.

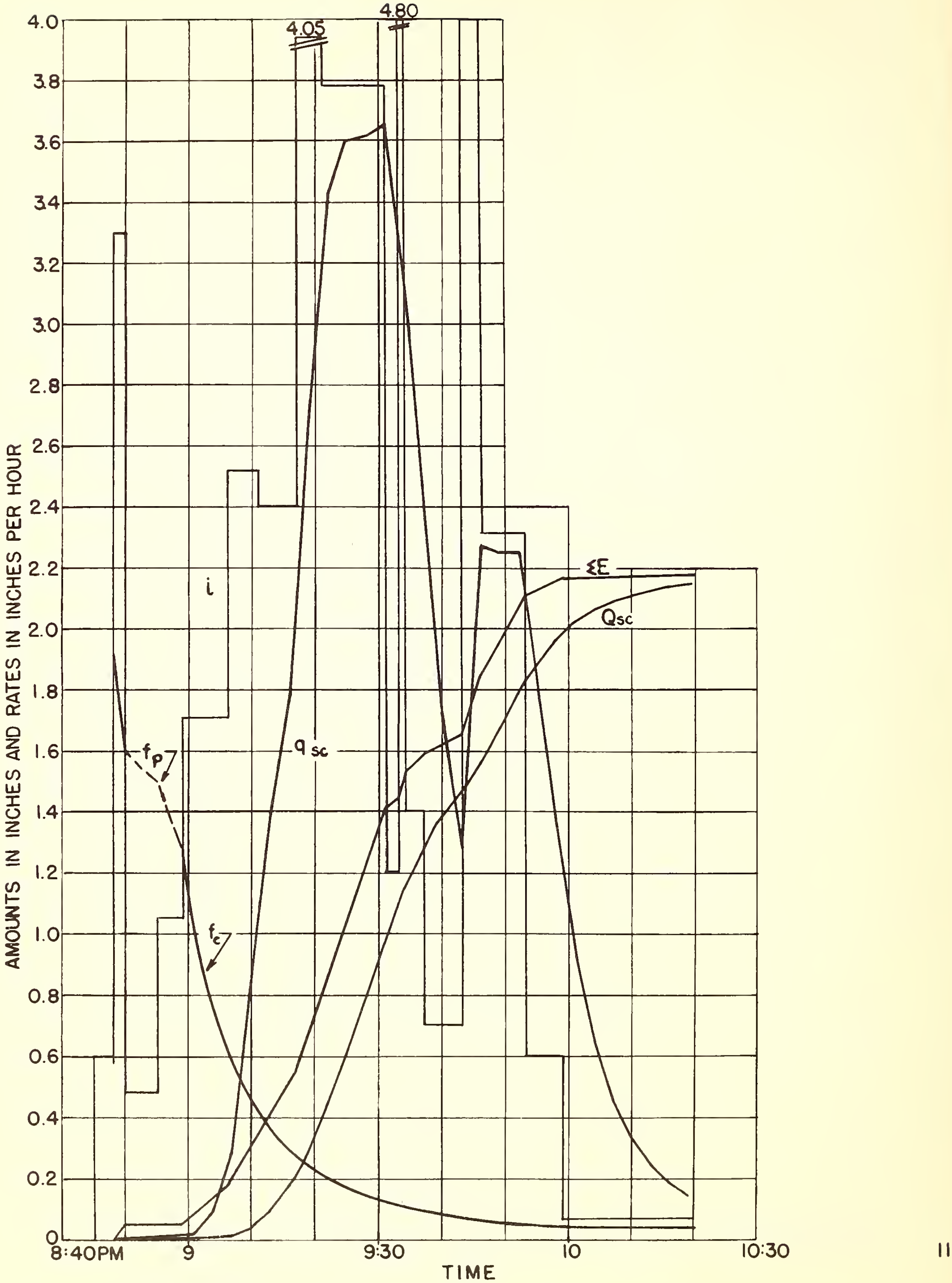

FIGURE 7.--Storm of June 16, 1946, on watershed 123, Keene Silt Loam. Computed rates and amounts of surface runoff from wheat. Initial soil-moisture content 0.40 inch of water per inch of soil.

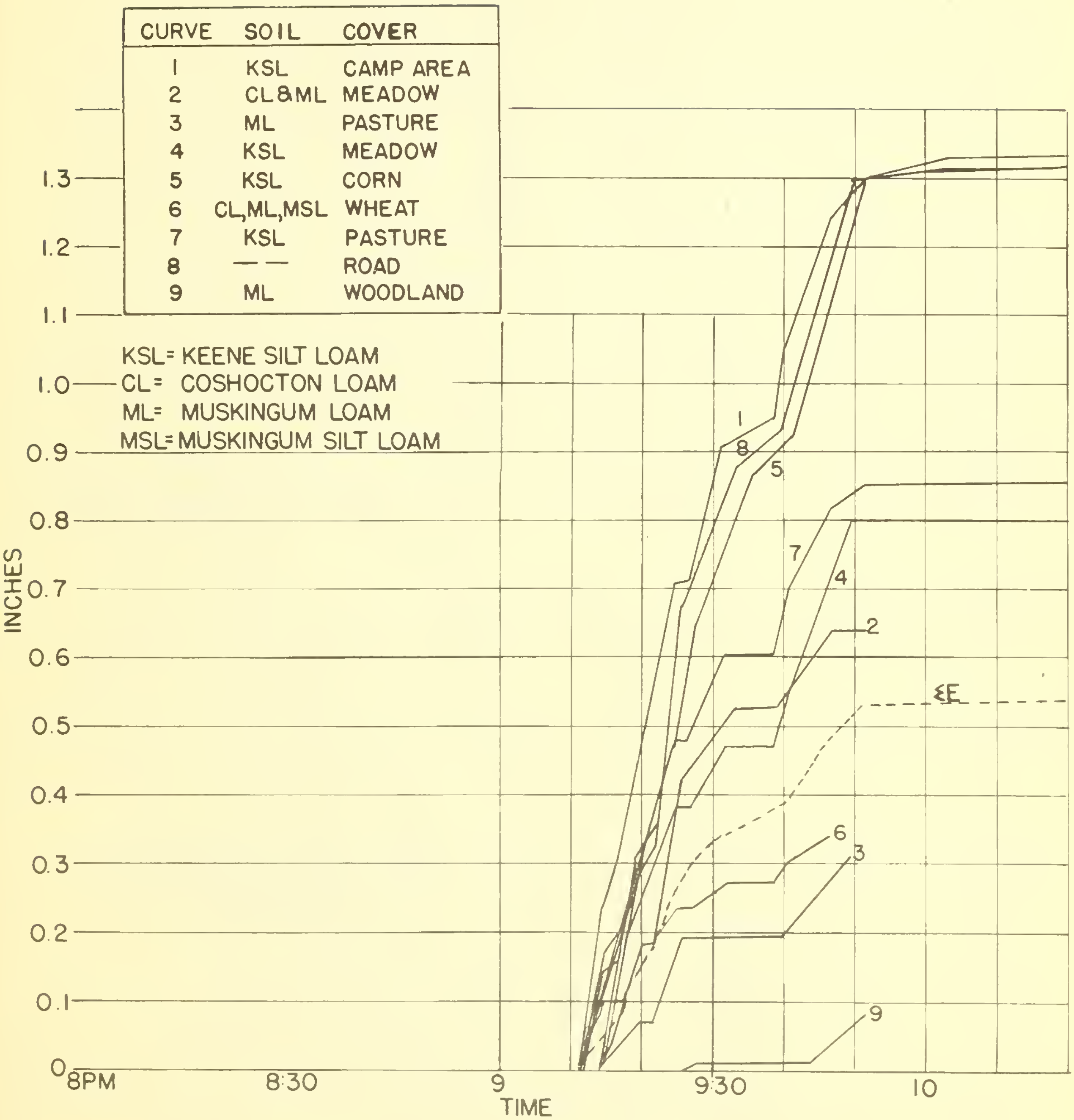

FIGURE 8.--Storm of June 16, 1946, on watershed 177, mixed soil types and cover. Computed excess rainfall for each cover type and soil and composite excess rainfall.

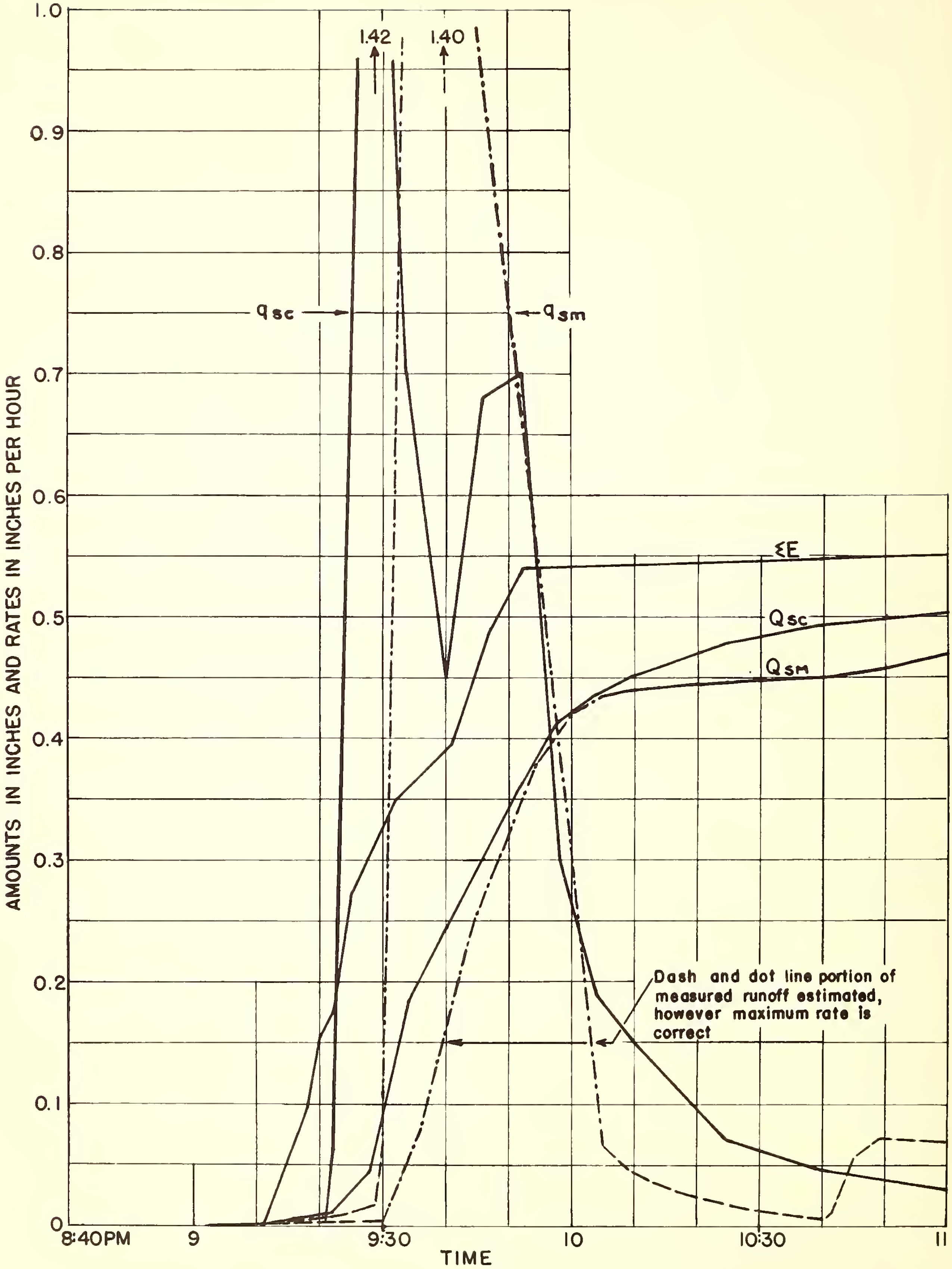

FIGURE 9.--Storm of June 16, 1946, on watershed 177, mixed soil types and cover. Computed and measured rates and amounts of surface runoff.

as compared to a measured rate of 1.40 inches per hour. At the time of the maximum rate there was little subsurface flow.

The storm of June 16, 1946, may be described as an ''advance pattern'' rainfall. High intensities occurred at the beginning of the storm, followed by low intensities during the latter part of the storm. Of interest is the effect on surface runoff of the same storm reversed; that is, the low intensities occurring at the beginning of the storm followed by high intensities during the latter part of the storm, ''delayed pattern.'' *Figure 10, page 22,* shows the computed effect on rates and amounts of surface runoff of the storm of June 16, 1946, reversed, delayed pattern. During the storm of June 16, high intensities were followed by low intensities of rain on June 17. When the storm is reversed the high intensities occur on June 17. The composite excess ΣE is shown in *figure 10* and was determined as described previously. In the delayed pattern the early low intensities of rainfall increase the soil-moisture content and the high intensities occurring later create a greater excess rainfall. This is due to lower infiltration rates associated with higher soil-moisture contents. The maximum rate of surface runoff for the advance pattern storm on Watershed 177 was 1.42 as compared to 2.15 inches per hour for the delayed pattern storm. Results are summarized in *table 2, page 23.* If comparisons are made between Watersheds 103 and 123, note that somewhat higher intensities occurred on Watershed 103.

It is important to note that relationships exist between detention storage, rate of surface runoff, land use, and erosion *(4)*. Work of the type contained herein should also be helpful in the determination of the effect of land use on erosion.

Some ideas dealing with simplification and accuracy of the procedure described, based on results obtained, are as follows:

1. An infiltration curve of approximate accuracy will be sufficient for most cases. When considering small watersheds, high intensities of rainfall associated with short times of concentration considerably exceed the rates of infiltration for many soils and covers. Minor differences in infiltration rates have little effect. For larger watersheds, lower intensities of rainfall over a long period of time are generally associated with the maximum rates of runoff. In such cases infiltration rates are low for many soils, and must be reasonably accurate as they may not differ too greatly from the intensity of rainfall. Small differences in excess rainfall over a long period of time would result in

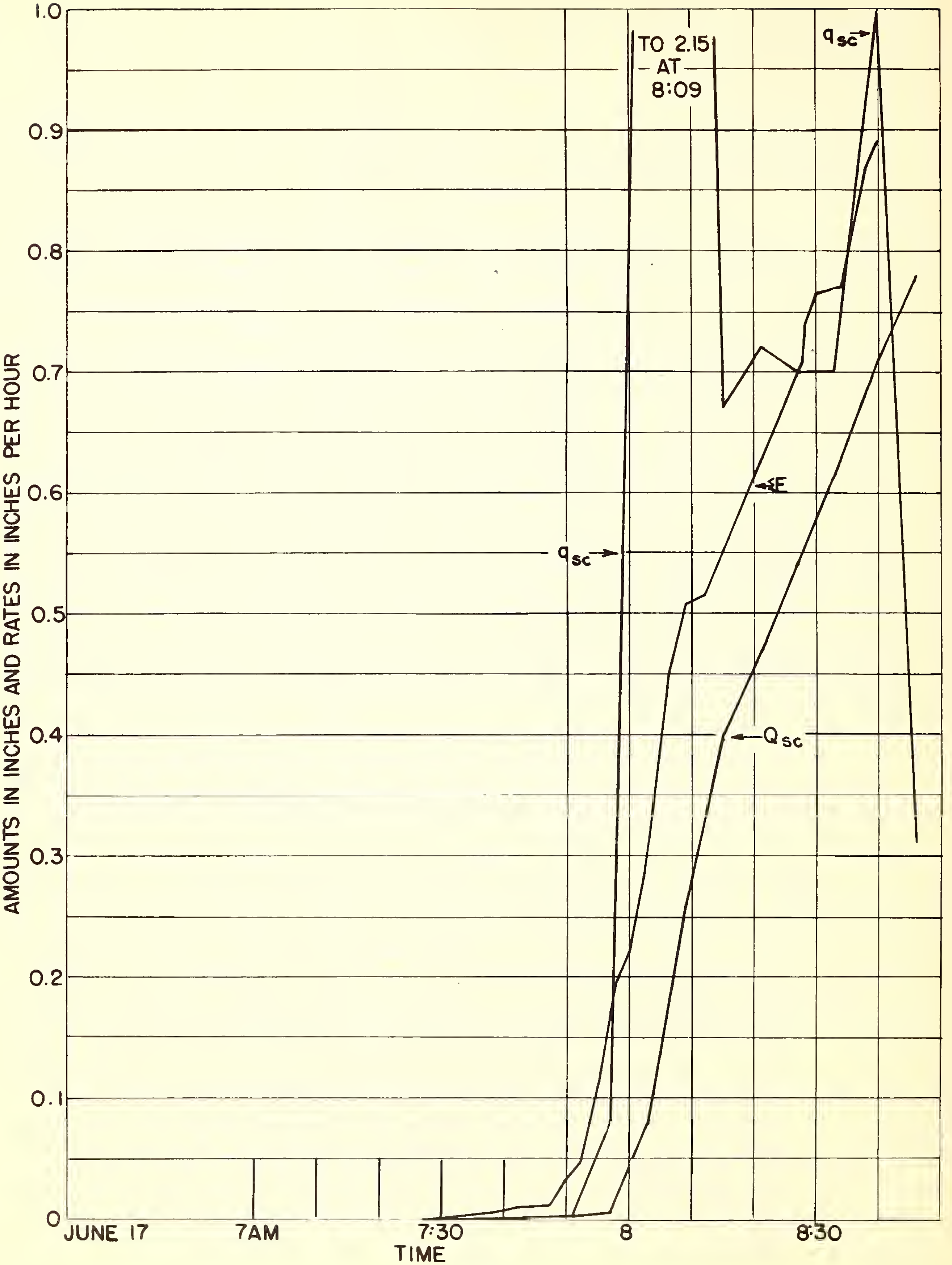

FIGURE 10.--Reversed (delayed pattern) storm of June 16, 1946, on watershed 177, mixed soil types and cover. Computed composite excess rainfall and computed rates and amounts of surface runoff.

TABLE 2.--*Measured and computed rates and amounts of surface runoff for storm pattern of June 16, 1946*

Watershed				Cover		Antecedent soil moisture		Surface runoff				Reference
								Measured		Computed		
No.	Area	Soil	Slope	Actual	Assumed	Actual	Assumed	Max. rate	Total amount	Max. rate	Total amount	Figure
	Acres		*Percent*			*In./in.*	*In./in.*	*In./hr.*	*Inches*	*In./hr.*	*Inches*	
103	0.65	[1]KSL	11.3	Corn (contour)	--	0.32	--	3.17	1.30	3.05	1.35	1
103	.65	KSL	11.3	--	Corn (straight row)	--	0.32	--	--	4.90	1.37	--
103	.65	KSL	11.3	--	Corn (contour)	--	.15	--	--	3.90	2.34	3
103	.65	KSL	11.3	--	Meadow	--	.15	--	--	1.00	.33	4
123	1.37	KSL	5.8	Wheat	--	.29	--	1.91	.88	2.30	.99	5
123	1.37	KSL	5.8	--	Wheat	--	.10	--	--	.40	.18	6
123	1.37	KSL	5.8	--	Wheat	--	.40	--	--	3.65	2.14	7
177	75.6	Mixed	15.7	Mixed	--	(2)	--	1.40	.47	1.42	.51	9
177[3]	75.6	Mixed	15.7	Mixed	--	(2)	--	--	--	2.15	.71	10

[1] KSL, Keene silt loam.
[2] Soil moisture for each specific soil and crop was used.
[3] For storm of June 16, 1946, reversed (delayed pattern).

errors of considerable magnitude for flood-flow determinations for large areas. However, data on minimum infiltration rates may be more readily obtained.

2. A composite infiltration curve may be reasonably representative of a number of soils and covers and reduce the work involved in obtaining excess rainfall. For example, *figure 8, page 19*, shows the excess rainfall obtained for each cover on Watershed 177. Nine infiltration curves were used, whereas four would have been sufficiently accurate; viz., one to represent areas 1, 5, and 8; one to represent areas 2, 4, and 7; one to represent areas 3 and 6; and one to represent area 9.

3. As areas of watersheds increase, the hydrographs tend to become flatter at the peaks. That is, the rate of change of the rate of surface runoff with time decreases with increases in the size of the drainage area. This is even more true of the depth of detention storage. Where only minor changes occur in detention storage near the peak, $D_{s-2} - D_{s-1}$, is small, then,

$$E = \left[\frac{q_{sc-1} + q_{sc-2}}{2}\right]\left[\frac{T_2 - T_1}{60}\right]$$

From a study of a few hydrographs the ratio between q_{sc-1} and q_{sc-2} may be estimated for a time period approximately equal to the time of concentration.

For example, say $q_{sc-1} = 0.9\ q_{sc-2}$, then,

$$0.85\ q_{sc-2} = \left[\frac{60}{T_2 - T_1}\right] E$$

which simply means that the maximum rate of surface runoff may be obtained from the amount of excess rainfall for the time period T_2-T_1, this time period being approximately equal to the time of concentration. For large watersheds, if there is little difference between q_{sc-1} and q_{sc-2} for the time of concentration up to the peak,

$$q_{sc-2} = E\left[\frac{60}{T_2 - T_1}\right]$$

and since $E\left[\frac{60}{T_2 - T_1}\right]$ is the slope or rate of excess rainfall, the maximum rate of surface runoff is simply the maximum slope of the ΣE-curve for the conditions mentioned.

CONCLUSIONS

The method discussed in this paper makes it possible to determine the effect of different combinations of land use, soil moisture, and precipitation patterns on rates and amounts of surface runoff from watersheds. Infiltration curves could be developed for soils, grouped hydrologically, and for precipitation patterns determined for the climatic provinces of the country. The effect of physiography or changes in physiography due to conservation practices could be evaluated through detention storage and rate of surface runoff relationships and timing. With such information this method should become a powerful tool in the evaluation of the effect of land use on surface runoff as well as the evaluation of other hydrologic objectives.

In reference to frequency problems the soil-moisture content at any time may be estimated from the storms over an antecedent period. Some work has been done in this connection. For a storm in question the estimated soil-moisture content and the precipitation pattern are used to compute the hydrograph as herein described. From such computations for major storms covering a number of years, frequency determinations may be made. However, if the frequency of certain rates of surface runoff have been established for a specific land use the effect of another land use may be computed.

SUMMARY

The method of determining rates and amounts of surface runoff described in this paper may be applied to any soil-moisture condition, precipitation pattern, and cover on soil types for which infiltration curves have been developed. Types of precipitation patterns for Coshocton have been illustrated in a previous publication *(2)*. The effect of physiography was evaluated through detention storage-rate of surface runoff relationships and timing. Only a few hydrographs may be necessary for this purpose. Where necessary such relationships and timing may be estimated from watersheds, similar to the one in question, from which data are available. Where conservation practices change the physiography, such relationships and timing may change and may thus be evaluated. It is important enough to repeat that this method develops the entire surface-runoff hydrograph as well as the maximum rate.

This method involves excess rainfall, detention storage, rate of surface-runoff relationships. The excess rainfall is dependent upon the land use and soil properties. Therefore, this method evaluates the effect of land use. The effect of the June 16, 1946, storm pattern on contour corn on Watershed 103 was measured and computed. The possible effect of straight-row corn on Watershed 103 was computed by using detention storage-rate of surface-runoff relationships for such conditions and related timing. The possible effect of sealing and slaking on cornland in producing the maximum rates of surface runoff from a soil of low soil-moisture content was also determined (Watershed 103). The possible effect of meadow, rather than corn, on rates and amounts of surface runoff from Watershed 103 for the same storm and soil-moisture conditions was evaluated with this method. The appreciable possible effect of different soil-moisture contents, 0.10 and 0.40 inch of water per inch of soil, with identical storm patterns was also determined (Watershed 123).

The method was also applied to mixed-cover Watershed 177, 75.6 acres. The computed and measured rates and amounts of surface runoff are very close. This seems to bear out the point that larger watersheds are composed of smaller units, acting like small watersheds, and the hydrologic laws operate on these units as they do on small watersheds. This statement applies to surface runoff. When subsurface flow is appreciable the subsurface-flow hydrograph must be combined with the surface-runoff hydrograph. Subsurface flow is used in the preceding statement as including all types of flow beneath the soil surface which reappears above the point in question.

The effect on rates and amounts of surface runoff of reversing an advanced pattern to a delayed pattern of precipitation was also determined (Watershed 177).

LITERATURE CITED

(1) Holtan, H. N., and Kirkpatrick, jr., M. H.
1950. Some broad phases of the hydrology of runoff. (Unpublished.)

(2) SCHIFF, L.
1943. CLASSES AND PATTERNS OF RAINFALL WITH REFERENCE TO SURFACE RUNOFF. Amer. Geophys. Union Trans. Part 2: 438-452.

(3) ________
1949. SURFACE RUNOFF SUPPLY ESTIMATES BASED ON SOIL-WATER MOVEMENTS AND PRECIPITATION PATTERNS. U. S. Dept. Agr. Soil Conserv. Serv. Tech. Pub. 86, 18 pp., illus.

(4) ________
1950. SURFACE DETENTION, RATE OF RUNOFF, LAND USE, AND EROSION RELATIONSHIPS ON SMALL WATERSHEDS. (Paper presented at Amer. Geophys. Union meeting, Washington, D. C., May 1950. Submitted for publication.)

(5) ________
1951. HYDROLOGY OF SURFACE SUPPLIES TO RUNOFF. U. S. Dept. Agri. Soil Conserv. Serv. Tech. Pub. 90, 25 pp., illus.

(6) ________, and DREIBELBIS, F. R.
1949. PRELIMINARY STUDIES ON SOIL PERMEABILITY AND ITS APPLICATION. Amer. Geophys. Union Trans. 30 (5): 759-766.