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A Hydrometeorological Study Related to the Distribution of Precipitation and Runoff over Small Drainage Basins—Urban Versus Rural Areas

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A HYDROMETEOROLOGICAL STUDY RELATED TO THE DISTRIBUTION OF PRECIPITATION AND RUNOFF OVER SMALL DRAINAGE BASINS - URBAN VERSUS RURAL AREAS

Principal Investigators

R. G. Feddes, R. A. Clark, and
R. C. Runnels

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ABSTRACT

The effects of urbanization on streamflow are investigated for two adjacent similar watersheds located in and near Bryan, Texas. The Burton Creek watershed is 84 per cent urbanized and the Hudson Creek watershed is completely rural. Storms observed within each basin are used for comparison of pertinent hydrograph parameters. Simultaneous events are compared between the watersheds and the urbanization effect noted. A synthetic precedure for predicting hydrographs on both watersheds is developed. Reproduction of actual events indicates better results in the rural watershed. There is conclusive evidence that the urbanization of a watershed decreases time-to-peak and increases the peak discharge.

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Much of the work was accomplished by Captain Robert G. Feddes, a graduate student in meteorology, while on a fellowship from the Institute of Technology, United States Air Force.

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LIST OF SYMBOLS

A	area (mi^2 or acres)
API	antecedent precipitation index (in.)
b_t	a constant less than unity
C	a coefficient that expresses the portion of the rainfall which runs off and also includes the effects of the overland flow
C_p	a coefficient which represents the effects of such factors as channel storage on the flood wave
C_t	a coefficient which represents differences in slope and channel storage between drainage basins
D	duration of rainfall excess (min)
I	rainfall intensity (in./hr)
L	length of the main stream (mi)
L_{ca}	length from center of basin on the main stream to outlet (mi)
L_g	lag time (min)
P_t	the amount of precipitation that occurred t days ago (in.)
Q	discharge (cfs)
Q_p	peak discharge of the unit hydrograph in Snyder's technique (cfs), or peak discharge of the hydrograph in the rational formula (cfs)
S	slope of the basin measured from the most distant point to the outlet (ft/ft)
t	time (days)
T_p	time-to-peak (min)

CHAPTER I

INTRODUCTION

Need for the Study

The need for more basic studies on the effects of urbanization on streamflow is urgent. This need was discussed by Smith et al. (1969) in a progress report by a task force on the effects of urban development on flood discharges. In that report the investigators indicated that studies should be made of runoff from adjacent similar watersheds, one of which is rural and the other urbanized. The importance of these studies to this region was brought to light in April of 1969 when a flash flood occurred on Burton Creek in Bryan, Texas, that caused enough property damage to move the City of Bryan to review critically the adequacy of drainage within the city.

The problem cited above is affecting virtually every growing city in the world. For the United States, Landsberg et al. (1963) discussed the pattern of growth from 1960-2000. These authors predict that by 1980 an urban population of 193×10^6 would represent three-quarters of the inhabitants in the United States and occupy only 50,000 mi^2. By the year 2000 the urban population should be 279×10^6, or four-fifths of the total, and occupy only 70,000 mi^2, which is 2.4 per cent of the conterminous land mass. If the above predictions are assumed to be accurate, the problem of flood discharge from urban areas will be very localized in an areal sense. The concentration of population also will mean congestion of a major part of our economic wealth, which makes crucial the solution of the urban flood problem.

The first study in this area was accomplished over 30 yr ago by Horner and Flynts (1936). They studied the relationship between rainfall and runoff over small impervious areas in St. Louis, Missouri. Since that time, and especially within the last 10 yr, numerous studies of various types have been prepared. These studies can be divided into two major areas:

1. investigation of a single urban watershed, e. g., Chow (1952), and
2. investigation of a group of urban and rural watersheds of various sizes within the same geographical area, e.g., Van Sickle (1962).

The single watershed investigations follow the watershed as urbanization develops. Many of the studies are of a continous type which examines variations in hydrograph characteristics with increasing urbanization (Watkins, 1956). Other studies involving single watersheds examine a short period of record and then develop equations which predict variations in hydrograph shape. These studies have revealed that the following modifications occur:

1. a decrease in Time-to-Peak;
2. an increase in Peak Discharge;
3. a shorter Lag Time;
4. a shorter Time-of-Concentration; and
5. an increased effect of Rainfall Intensity.

Unfortunately, the availability of adequate data for purposes of direct comparison presents a major obstacle to research. An ever-increasing supply of data, however, is becoming available; unfortunately, the lengths of record are very short so that synthetic procedures still are required generally (Gray, 1961; Espey et al., 1965: Willeke, 1966). A review of the literature indicates that many investigators have found workable solutions to the determination of storm runoff. However, this review indicates also a need for basic studies which reveal the actual variation between similar urban and rural watersheds. Studies of this type have been prepared by Sawyer (1961) and Waananen (1961) for fairly large watersheds (10 to 90 mi^2).

In this study, the effects of urbanization on runoff were investigated by utilizing data from two small watersheds in the same geographical area, one urban and the other rural.

The objectives of this study were:

1. to increase the basic knowledge of the effects of urbanization on streamflow;
2. to examine the effects of urbanization on hydrograph variables;
3. to examine the effects of rainfall intensity on hydrograph variables;
4. to compare the results of this study with other investigations; and
5. to derive an objective procedure for prediction of the

various parameters affecting hydrograph shape. These results will be verified as the length of record increases.

The results of this and similar studies will have an economic impact upon future design requirements for urbanized areas. They will dictate the design of drainage and channel improvements required to reduce flood damages to a minimum.

Description of Basins

The two basins investigated were the Burton Creek basin located within the City of Bryan, Texas, and the Hudson Creek basin located in a rural area approximately 3 mi east of the Burton Creek basin. The physical and areal properties of each watershed are listed in Table 1. Figures 1 and 2 present the pertinent features of the watersheds.

The soil in both basins is Lufkin-Tabor fine sandy loam, which is the most common soil in the area (Soil Conservation Service, 1958). This soil group, as characterized by the Soil Conservation Service (see Chow, 1964, p. 12-26), has:

1. a high runoff potential;
2. a low infiltration rate when thoroughly wetted;
3. a high percentage of clay with high swelling potential;
4. near or at the surface a clay pan, or clay layer that is very shallow, overlain by nearly impervious material; and
5. a very slow rate of water transmission.

Table 1. Description of basins used in this study.

	Burton	Hudson
Area (acres)	890	1230
(mi^2)	1.39	1.98
Impervious Area (acres)	210	None
(per cent)	23.6	None
Length of main stream (mi)	2.41	2.18
Length from centroid of basin to outlet (mi)	1.17	1.15
Slope of main stream (ft/ft)	0.0059	0.0065

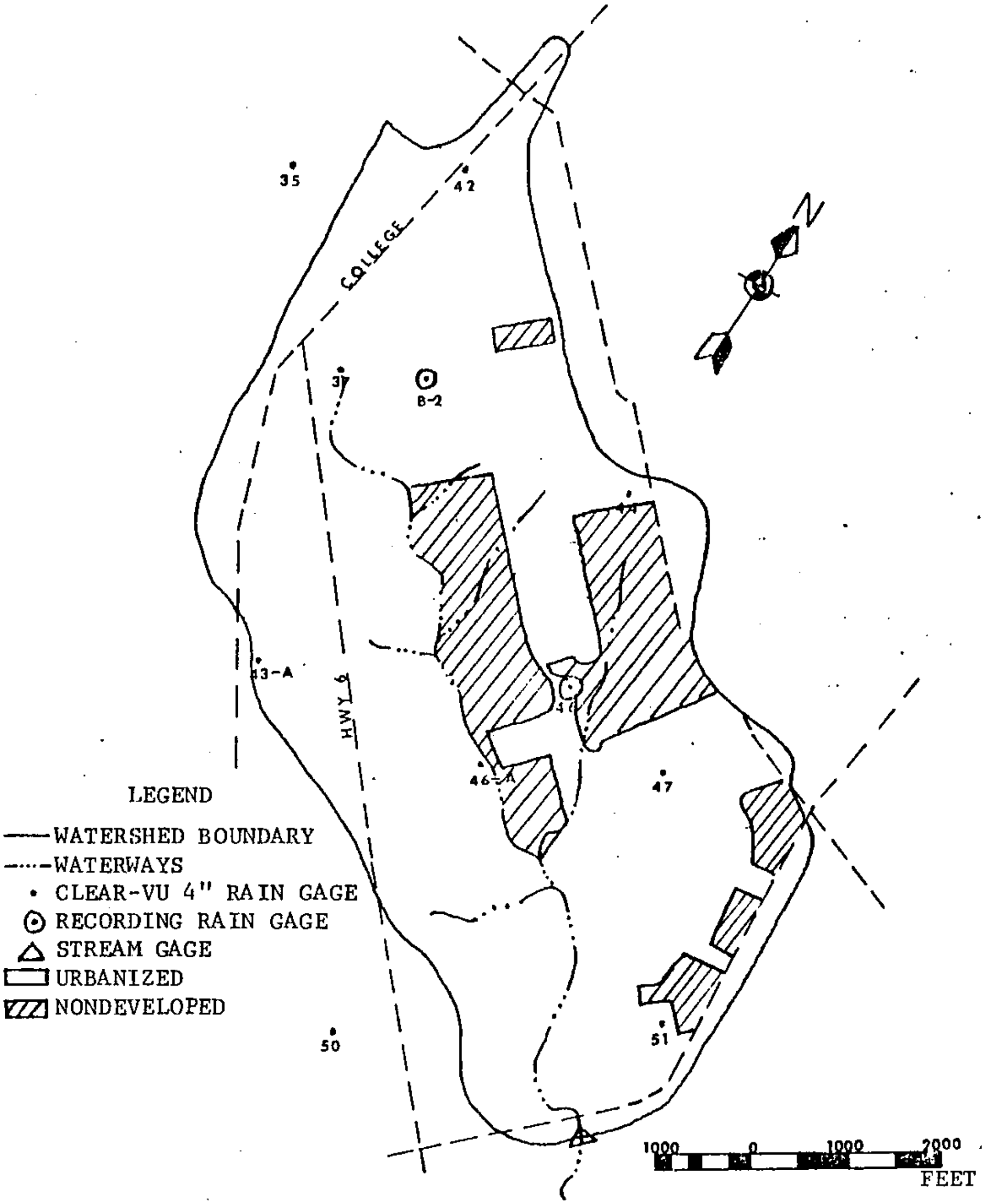

Figure 1. Burton Creek Watershed, Bryan, Texas.

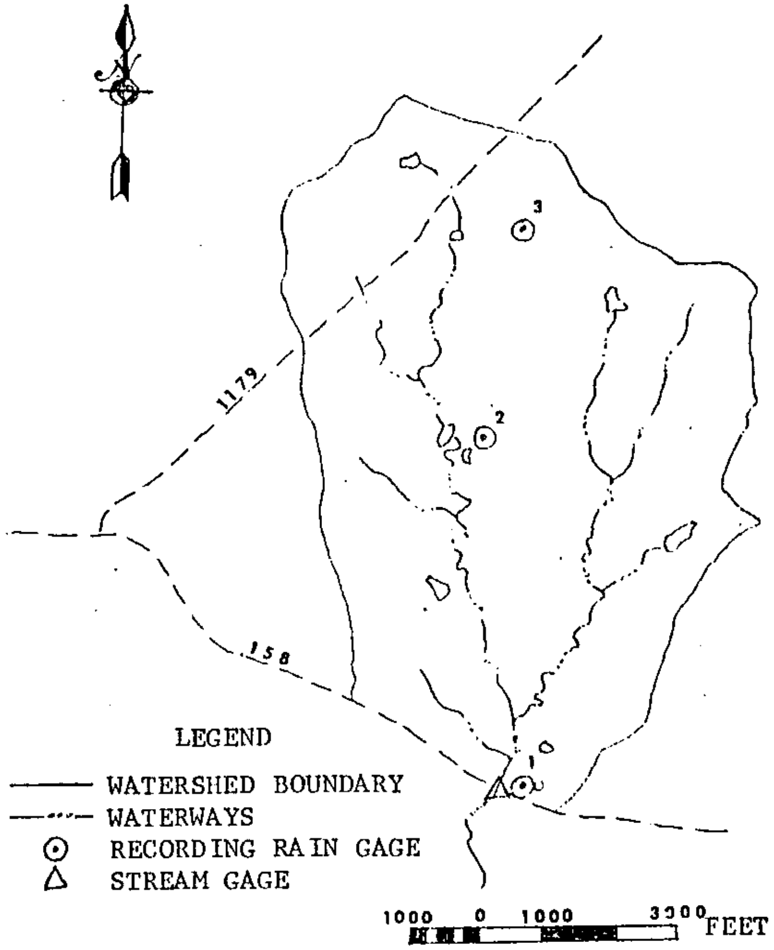

Figure 2. Hudson Creek Watershed, Bryan, Texas.

CHAPTER II

DEVELOPMENT AND PROCEDURE

Source, Selection, and Analyses of Data

The instrumentation used in this study became partially operational in May 1968 through a cooperative program between the United States Geological Survey (USGS) and Texas A&M University. The entire system was completed in August of the same year.

Burton Creek contains a network of eight non-recording rain gages and two recording rain gages above the stream gaging station. Installed at the outlet is a type A-35, water-stage recorder. The recording rain gages are located near the center (Station 46) and in the headwaters (Station B-2) of the basin (Fig. 1). There are two recording gages at Station 46 that have 6-hr and 24-hr recording periods. Station B-2 has a gage with 24-hr recording period.

Hudson Creek also is instrumented with a type A-35, water-stage recorder. In addition, there is a recording rain gage at the same location. This basin contains two additional 24-hr recording gages which are located near the center and in the upper reaches of the watershed.

The selection of the data was dictated by the occurrence of simultaneous flood events. Due to the relatively short period of record, only 19 suitable events were chosen (Table 2). Each flood event has been identified by a number and a suffix of either a B (Burton) or an H (Hudson). Thus, the storm of March 15, 1969, on

Table 2. Selected flood events with simultaneous occurrence over both the Burton Creek and Hudson Creek watersheds.

Storm Number	Date
01	May 10, 1968
02	May 11, 1968
*03	May 17, 1968
04	May 26, 1968
05	June 1, 1968
06	June 5, 1968
*07	June 23, 1968
*08	July 9, 1968
09	October 9, 1968
** *10	November 26, 1968
*11	November 30, 1968
*12	February 14, 1969
*13	February 21, 1969
14	March 7, 1969
** *15	March 15, 1969
16	April 4, 1969
17	April 9, 1969
** *18	April 12, 1969
*19	May 1, 1969

* Denotes multi-peaked hydrograph on Burton Creek.

** Denotes multi-peaked hydrograph on Hudson Creek.

Burton Creek is 15 B. The same storm on the Hudson watershed is 15 H.

Preliminary analyses of the data included the following steps (storm 15 B is used for illustration):

1. A computer program was written to convert stage readings in feet to discharge in cubic feet per second using a rating table developed by the USGS.
2. Each individual hydrograph was plotted on semilog paper (Fig. 3).
3. An hourly recession was computed for each storm.
4. Complex hydrographs were separated into individual hydrographs (Fig. 4).

Antecedent Precipitation Index

The amount of moisture in the soil is of prime importance when computing or predicting infiltration, discharge, and hydrograph shape. Several methods are used for evaluation of this property. One method is to use pan-evaporation data to arrive at a soil moisture index (Linsley et al., 1958, p. 170). A second method utilizes the period of time since the last rainfall. This method is inaccurate because soil moisture and time do not seem to be related linearly. In this study, a third method has been employed that has been termed an Antecedent Precipitation Index (API) (Linsley et al., 1958). The API for any given day is defined by

$$\mathrm{API} = \sum_{t=1}^{n} b_t P_t , \qquad (1)$$

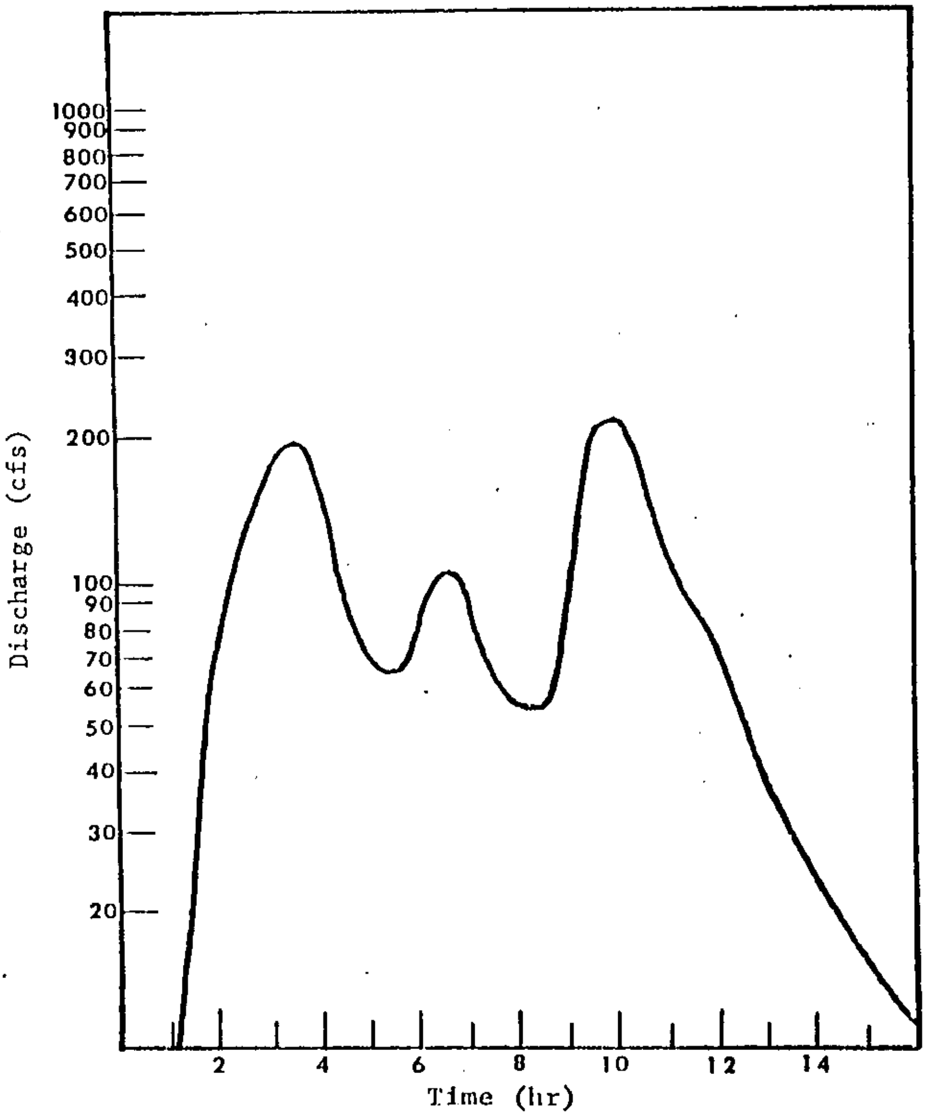

Figure 3. Complex hydrograph of storm number 15 on Burton Creek.

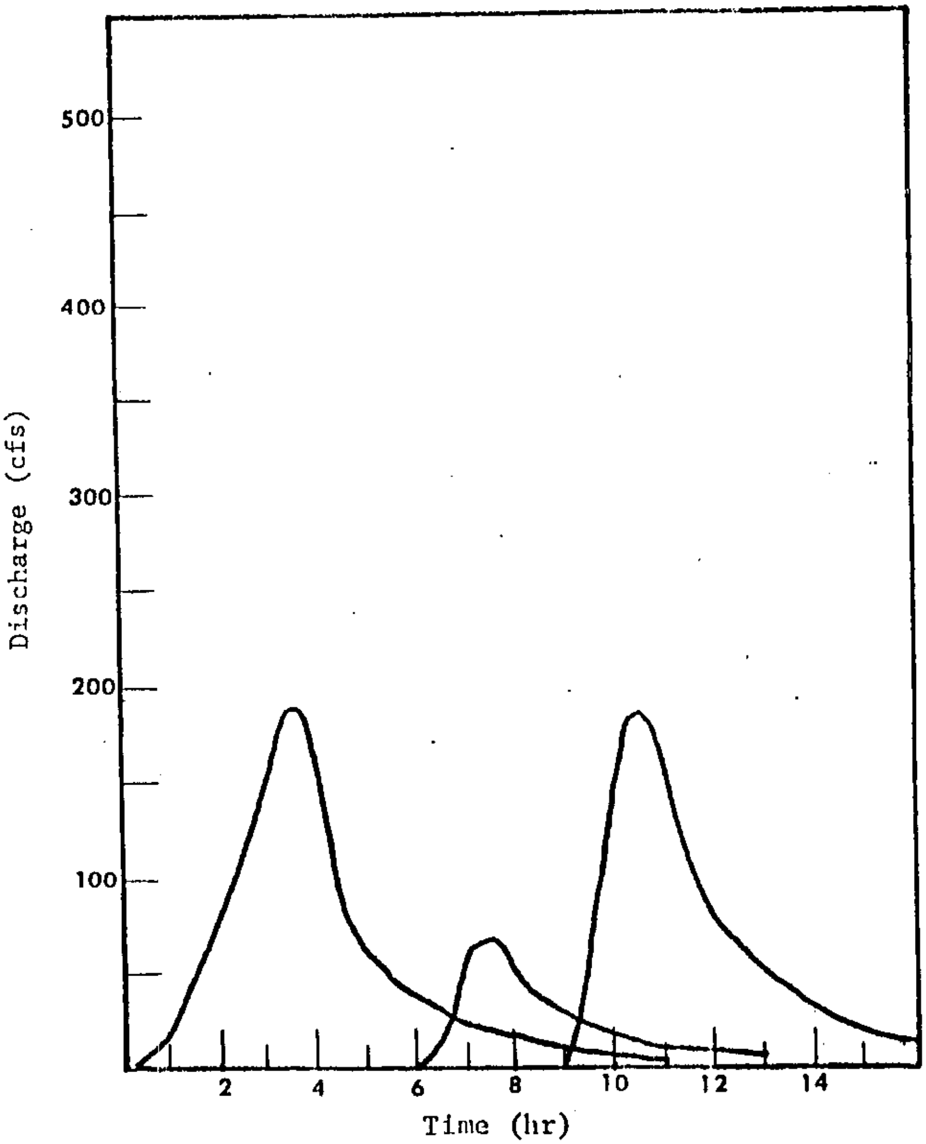

Figure 4. Separation of the complex hydrograph shown in Fig. 3.

where b_t is a constant less than unity, P_t is the amount of precipitation that occurred t days ago, and n is an arbitrarily selected number of days. b_t commonly is assumed to be a function of t (time), i.e., $b_t = b^t$, where b = a constant (in this study 0.90 was used). Daily values of API were calculated using the rainfall record obtained from the non-recording rain gage at Station 46 in the Burton Creek watershed. The same API was used for the Hudson basin since the basins are only 3 mi apart. Any error introduced through use of the same API for both basins probably would be smaller than errors in the index itself.

The values of API calculated for each storm are listed in Tables 3 and 4 which include also a list of additional variables that were calculated. Values from complex events were not included in these tables. Examples of each calculation and the assumptions made with each one are included below.

Hydrograph Analyses

Volume. The volume of each hydrograph was calculated by summing the 30-min ordinates. This sum when multiplied by the time increment of 30-min gives the volume of runoff in cubic feet. The basic assumption used in this summation was that the hydrograph was linear during the 30-min interval centered at the time of reading.

Table 3. Calculated parameters of Burton Creek used for intracorrelation within the watershed.

Storm No.	Volume ft^3x10^6	Rainfall in.	Time to Center of Volume min	Time-to-Peak min	Lag Time min	Total Period of Rainfall min
01 B	5.59	3.81	220	210	70	315
02 B	1.33	0.66	222	240	110	270
04 B	1.39	1.55	54	60	46	45
05 B	2.92	2.08	130	150	78	135
06 B	3.01	1.95	92	90	80	150
09 B	1.18	1.86	137	105	147	105
10 B	2.54	3.40	187	158	135	450
14 B	1.14	0.68	82	60	67	60
16 B	2.88	2.25	105	105	67	120
17 B	2.13	1.55	90	90	68	120
18 B	0.94	0.49	83	60	53	75

Table 3. (continued)

Storm No.	Duration of Rainfall Excess min	API in.	Mass Infiltration in.	Infiltration per cent	Dimensionless Peak
01 B	300	0.56	2.16	57	1.04
02 B	225	3.93	0.21	32	1.14
04 B	15	1.43	1.12	72	0.63
05 B	105	1.75	1.14	55	0.93
06 B	25	3.75	1.04	53	0.70
09 B	<15	0.16	1.49	80	1.57
10 B	105	0.52	2.61	77	0.83
14 B	30	1.21	0.33	48	0.71
16 B	75	0.68	1.36	60	0.85
17 B	45	1.86	0.88	57	0.76
18 B	60	3.19	0.20	41	0.65

Table 3. (continued)

Storm No.	Peak Discharge cfs	Discharge Peak/Area cfs/mi^2	Unit Hydrograph Peak cfs	Unit Hydrograph Peak/Area cfs/mi^2
01 B	439	316	487	350
02 B	114	82	396	285
04 B	272	196	373	268
05 B	347	250	407	293
06 B	383	276	301	217
09 B	226	163	464	334
10 B	187	135	248	178
14 B	164	118	341	245
16 B	389	280	408	294
17 B	301	217	362	260
18 B	122	88	357	257

Table 3. (continued)

Storm No.	Rainfall Intensity in./hr	Mean Infiltration in./hr	Recession	C_t	640 C_p	C	$C_t(L\,L_{ca})^{0.3}/A$
01 B	0.73	0.41	0.63	0.86	408	0.68	0.83
02 B	0.15	0.05	0.69	1.35	522	0.85	1.31
04 B	2.07	1.49	0.48	0.57	205	0.15	0.55
05 B	0.92	0.51	0.55	0.96	380	0.42	0.93
06 B	0.78	0.42	0.70	0.99	289	0.55	0.96
09 B	1.06	0.85	0.33	1.69	762	0.24	1.64
10 B	0.45	0.35	0.74	1.66	401	0.47	1.61
14 B	0.68	0.33	0.45	0.83	274	0.27	0.81
16 B	1.13	0.68	0.42	0.83	328	0.39	0.81
17 B	0.78	0.44	0.47	0.84	295	0.43	0.82
18 B	0.39	0.16	0.48	0.65	227	0.35	0.63

Table 4. Calculated parameters for Hudson Creek used for intracorrelation within the watershed.

Storm No.	Volume $ft^3 x 10^6$	Rainfall in.	Time to Center of Volume min	Time-to-Peak min	Lag Time min	Total Period of Rainfall min
07 H	13.46	3.60	528	525	251	355
08 H	14.75	6.61	246	210	126	420
09 H	0.68	2.67	185	150	185	135
11 H	4.71	1.80	435	435	240	660
12 H	2.86	1.24	345	315	240	300
13 H	3.59	1.21	277	225	165	300
14 H	1.67	0.82	233	135	233	75
16 H	3.78	2.06	195	165	188	135
17 H	4.77	1.94	184	165	169	120
19 H	1.69	1.15	276	240	186	225

Table 4. (continued)

Storm No.	Duration of Rainfall Excess min	API in.	Mass Infiltration in.	Infiltration per cent	Dimensionless Peak
07 H	585	4.69	0.67	19	1.35
08 H	240	2.07	3.40	51	0.83
09 H	<15	0.16	2.55	96	0.77
11 H	390	3.19	0.78	43	1.10
12 H	210	0.82	1.17	33	0.91
13 H	225	1.24	0.43	36	0.63
14 H	<15	1.21	0.46	56	0.58
16 H	15	0.68	1.24	60	0.67
17 H	30	1.86	0.90	46	0.39
19 H	180	2.08	0.78	68	0.63

Table 4. (continued)

Storm No.	Peak Discharge cfs	Discharge Peak/Area cfs/mi^2	Unit Hydrograph Peak cfs	Unit Hydrograph Peak/Area cfs/mi^2
07 H	555	280	300	152
08 H	829	419	289	146
09 H	47	24	212	107
11 H	198	100	252	127
12 H	126	64	209	105
13 H	136	69	186	94
14 H	81	41	159	80
16 H	225	114	182	92
17 H	383	193	259	131
19 H	64	32	172	37

Table 4. (continued)

Storm No.	Rainfall Intensity in./hr	Mean Infiltration in./hr	Recession	C_t	640 C_p	C	$C_t(L\,L_{ca})^{0.3}$
07 H	0.25	0.05	0.71	3.24	635	1.74	2.11
08 H	0.94	0.49	0.62	1.62	306	0.69	1.06
09 H	1.18	1.13	0.63	2.30	330	0.03	1.56
11 H	0.16	0.07	0.75	3.10	503	0.97	2.02
12 H	0.66	0.23	0.77	3.10	420	0.15	2.02
13 H	0.24	0.09	0.52	2.13	258	0.45	1.39
14 H	0.66	0.37	0.75	3.01	311	0.10	1.96
16 H	0.92	0.55	0.75	2.43	288	0.19	1.58
17 H	0.97	0.45	0.75	2.18	369	0.31	1.42
19 H	0.31	0.21	0.77	2.40	270	0.16	1.56

Rainfall. The rainfall for each basin was determined by using the depth in inches at the recording gages that are located near the center of the respective basins. Although the basins are extremely small in area, several isohyetal analyses were prepared for the Burton Creek basin which has a fairly dense rain-gage network. Fig. 5 is an example. The results of these analyses indicate some variability in areal distribution; however, the variability was not great generally. Thus, the rainfall at Station 46 was considered adequate to use as an average for the basin. The rainfall data recorded at Station 2 were used for the Hudson Creek basin.

Duration of Rainfall Excess. The duration of rainfall excess (D) is the total period of rainfall contributing to runoff after the hydrograph begins to rise. The length of this period was taken to be the total number of intervals after the beginning of rise when the rainfall intensity exceeded the mean infiltration rate. If periods of low intensity occurred after the last period contributing to the excess, these periods were excluded. This variable was used to calculate various relationships which are used and discussed in the following chapter.

Another parameter related to the period of rainfall excess can be determined by finding the time to center of rainfall mass. This parameter is related to hydrograph variables since it takes into account the distribution of rainfall intensity. This parameter is more difficult to determine and was not used in this study.

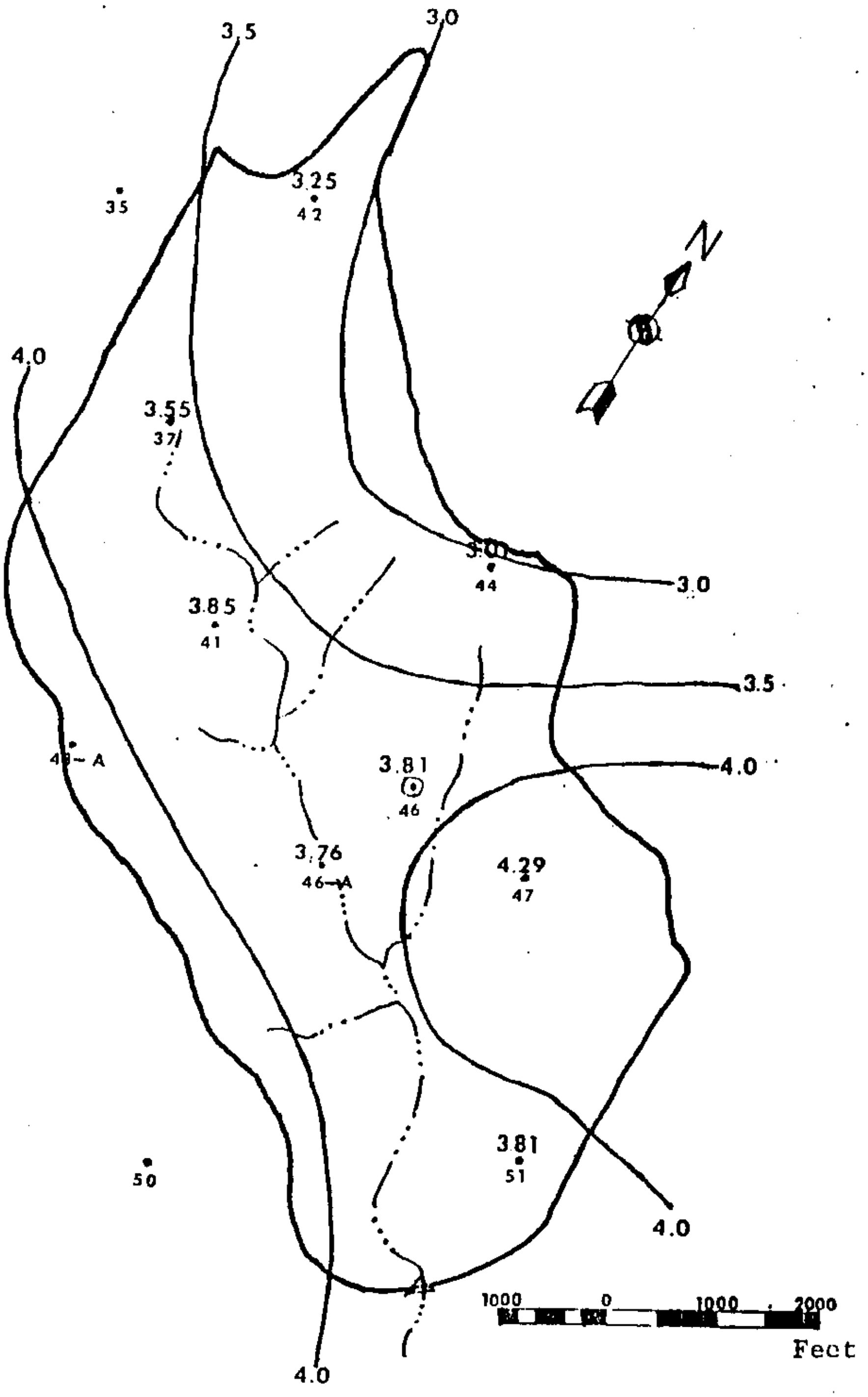

Figure 5. Rainfall analysis for May 10, 1968 on the Burton Creek watershed.

Time-to-Peak. Time-to-peak, T_p, is defined as the time from the beginning of the rise of the hydrograph to the occurrence of peak discharge. The extremely short time-to-peak, particularly in the urban basin, required that the estimate be very accurate. For this reason it was decided arbitrarily that when discharge became equal to or greater than 4 cfs, this time marked the beginning of time-to-peak.

Lag Time. Lag time, L_g, as used in this study, was defined as the period from the time when one-half the duration of rainfall excess has occurred to the time when one-half the volume of storm runoff is observed.

Infiltration. In this study, both mass infiltration and mean infiltration were used in the correlation procedures. Mass infiltration is defined as the total amount of rainfall that did not appear as runoff and was lost to surface flow. Mass infiltration was calculated and has been listed in Tables 3 and 4 both as a total amount and as a percentage loss.

Mean infiltration was calculated from the values determined for mass infiltration by dividing by the total number of hours in which rainfall occurred. The resulting averages appear in Tables 3 and 4 and in various graphical relationships in the following chapter. Because of the method used in determination of the mean infiltration the values computed will be less than obtained from, for example, the Φ index (see Linsley et al., 1958, p. 180). The infiltration values obtained will be actually less than the maximum rate at which water can enter the soil in this basin. The maximum rate is often called the infiltration capacity.

Dimensionless Hydrograph. Several different methods for construction of dimensionless hydrographs are available. Because of several advantages in analysis, the dimensionless hydrograph procedure developed by the Bureau of Reclamation (1947) was used in this study.

The abscissa of each hydrograph is expressed as a per cent of lag time plus one-half the duration (semi-duration) of rainfall excess $(L_g + D/2)$. The ordinate is discharge, Q, times $(L_g + D/2)$ divided by the total volume of runoff of the storm. This procedure produces a completely dimensionless hydrograph.

Snyder's Technique for Hydrograph Synthesis

One of the earliest techniques for synthesization of unit-hydrographs was developed by Synder (1938). Since both discharge and rainfall are available, it was possible to calculate the Snyder coefficients for both basins.

The basic equations developed by Snyder are:

$$T_p = C_t (L\ L_{ca})^{0.3} \qquad (2)$$

and

$$Q_p = 640\ C_p\ A/T_p, \qquad (3)$$

where

T_p = time-to-peak (hr), as defined previously,

L_{ca} = length from center of basin on the main stream to the outlet (mi),

L = length of the main stream (mi),

C_t = a coefficient which represents differences in slope and channel storage between drainage basins,

Q_p = peak of the unit hydrograph (cfs),

A = area of the watershed (mi^2), and

640 C_p = a coefficient which represents the effects of such factors as channel storage on the flood wave.

The two constants C_t and 640 C_p were calculated for each storm. These values have been plotted later for purposes of comparison with those presented by Hudlow (1966).

The Rational Formula

Among the most widely used equations in drainage design is the "so-called" rational formula. The rational formula is defined as:

$$Q_p = CIA, \qquad (4)$$

where

Q_p = peak discharge (cfs),

I = rainfall intensity (in./hr),

A = drainage area (acres), and

C = a coefficient that expresses the portion of the rainfall which runs off and also includes the effects of overland flow.

The equation states that the rate of runoff is related linearly to the rate of supply. This is dependent, of course, on whether the intensity of rainfall affects C. A range of values of the coefficient C was calculated from observed data. These computations revealed the effects of soil moisture and rainfall intensity.

CHAPTER III

PRESENTATION AND DISCUSSION OF RESULTS

The analyses of data were carried out as intracorrelation of hydrologic parameters within each watershed and cross correlation of similar parameters between the watersheds.

The quick response of the Burton Creek watershed to rainfall made the separation of complex hydrographs very arbitrary. As a result, only storms with single peaks were used. There was a total of 11 such events on Burton Creek. The basic data for the various parameters selected and used in the various correlations are listed in Table 3.

Sixteen of the 19 events on Hudson Creek were not complex. The first six events listed in Table 2 are not usable for most calculations because rainfall instrumentation had not been installed. The hydrologic data obtained for Hudson Creek, and used in the correlations, appear in Table 4.

Cross correlation between the watersheds was possible on only four events due to either complex hydrographs or lack of adequate rainfall data.

Intracorrelation

A plot of API vs dimensionless hydrograph peak was prepared to determine if there is any effect on this parameter due to the antecedent soil moisture. The plot for Burton Creek of these two variables shows only a slight tendency for the dimensionless hydrograph peak to decrease as API increases (Fig. 6). In addition, the plot for Hudson Creek of the same variables also indicates little, if any, relationship (Fig. 7). Storm numbers 1, 2, 4, 5, and 6 were included in Fig. 7 since rainfall data are not required to determine the peak of the dimensionless hydrograph. The dimensionless hydrograph peaks on Burton Creek have a maximum range of 0.94, from 0.63 to 1.57, while the range of peaks on Hudson Creek was 0.72, from 0.63 to 1.35. This effect may be due partially to the large impervious area in the urban watershed which affects infiltration. The rural basin apparently has a more uniform infiltration rate, in an areal sense, irrespective of the API. The impervious area and area in grass lawns in the urban watershed may cause large variations in infiltration throughout the Burton Creek basin which affect the volume of runoff. The volume, in turn, affects the peak of the dimensionless hydrograph.

Plots of lag time, L_g, vs time-to-peak, T_p, appear in Fig. 8 for Burton Creek and Fig. 9 for Hudson Creek. In the rural basin, T_p is approximately equal to L_g until T_p becomes greater than 200 min, when the difference between L_g and T_p increases markedly. This apparent effect may be due to rainfall duration and intensity. High intensities associated with a short period of rainfall excess have a L_g and T_p that are almost equal. Long periods of rainfall excess with generally low intensities show larger differences. The Burton Creek plot exhibits the same general trend, but to a lesser degree. Because of the shorter time-to-peak on the urban watershed, the resulting lag times have a wider range of variability, apparently

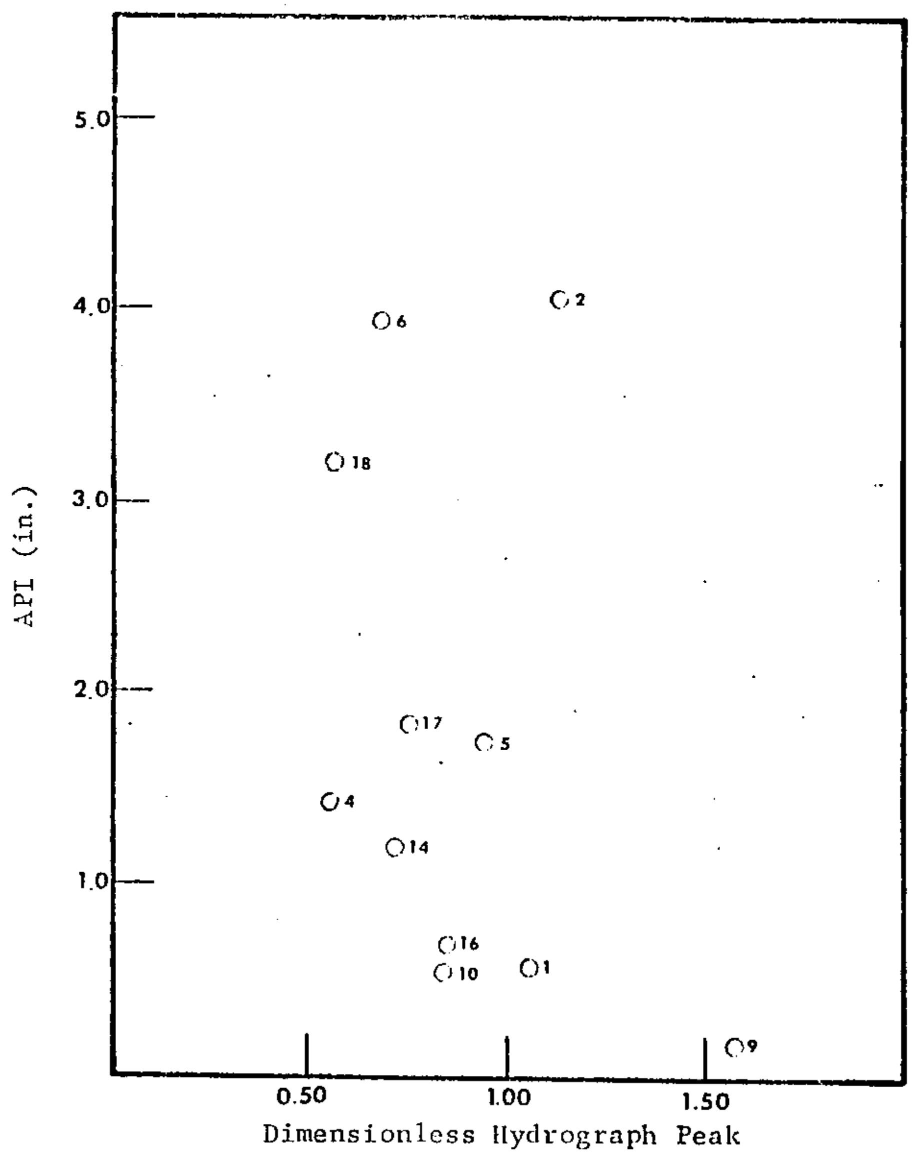

Figure 6. Antecedent precipitation index versus dimensionless hydrograph peak for Burton Creek.

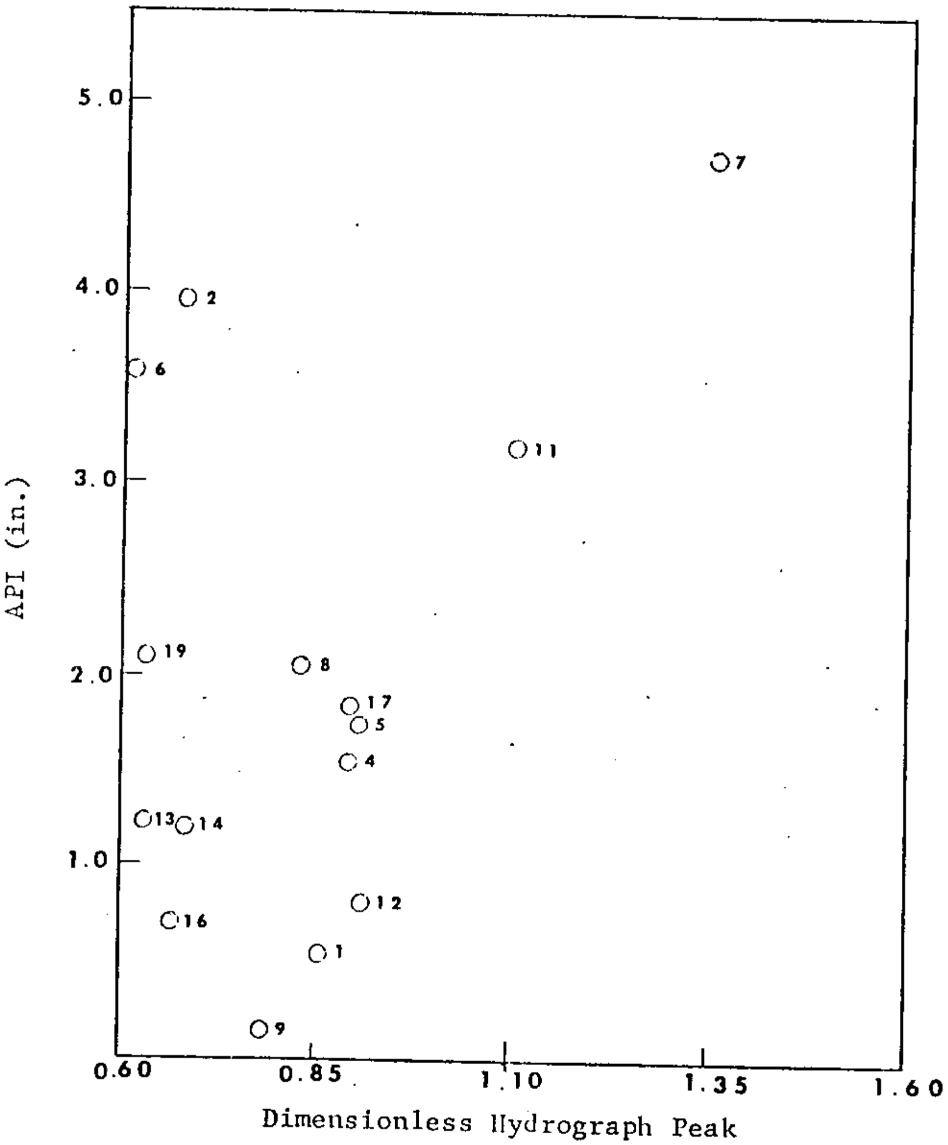

Figure 7. Antecedent precipitation index versus dimensionless hydrograph peak for Hudson Creek.

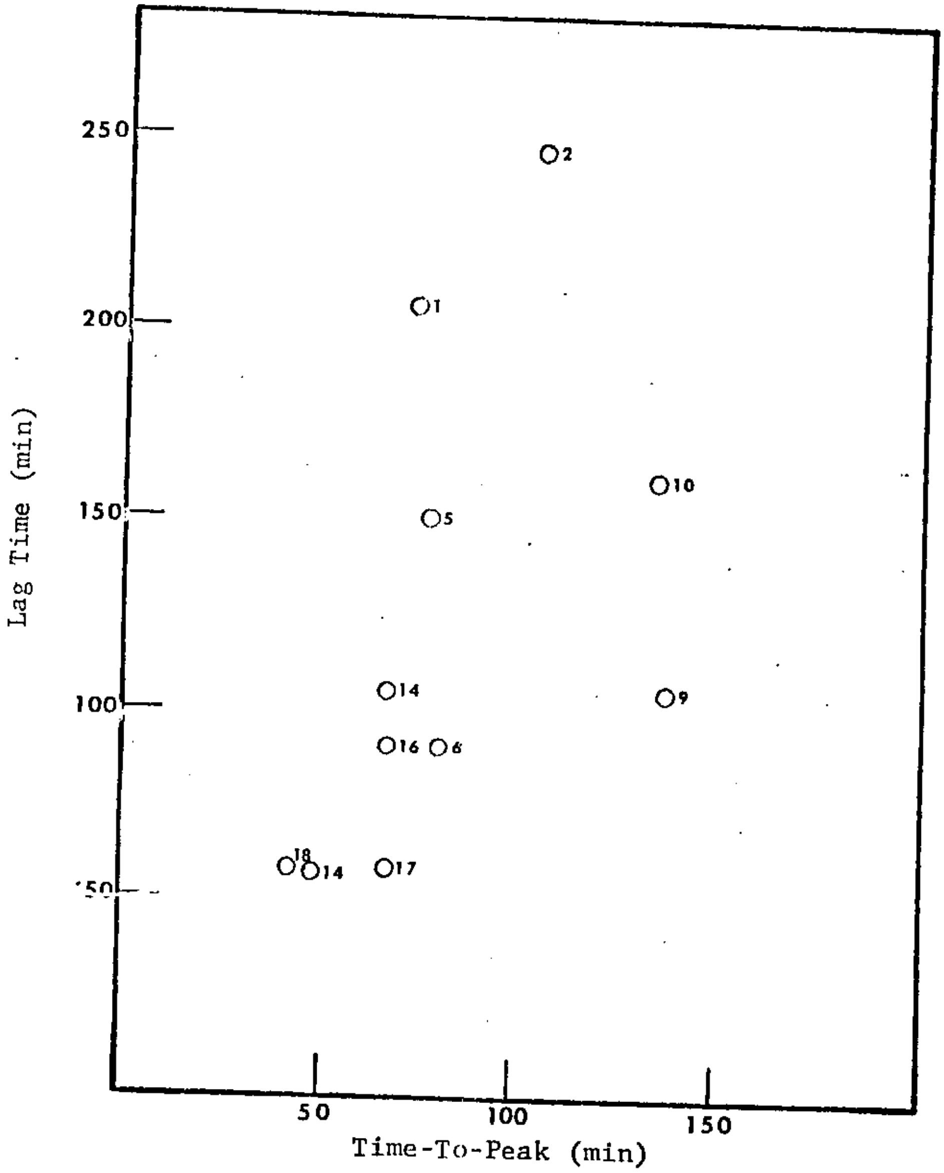

Figure 8. Lag time versus time-to-peak for Burton Creek.

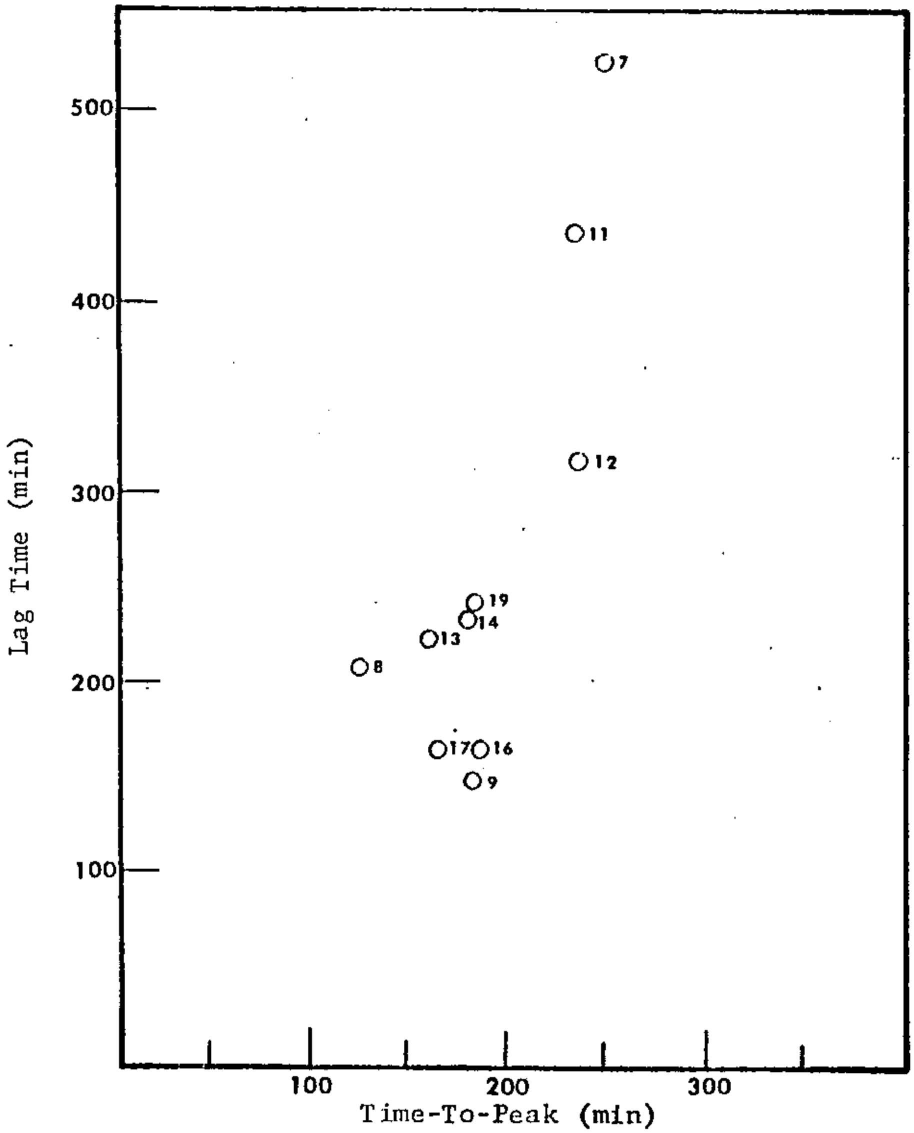

Figure 9. Lag time versus time-to-peak for Hudson Creek.

due to the effects of the impervious areas.

The relationship between mean rainfall intensity and mean infiltration shows a high degree of correlation on both Burton Creek (Fig. 10) and Hudson Creek (Fig. 11). This relationship agrees with that found by Scully and Bender (1969). Their results show that average rainfall equalled average infiltration for intensities less than 0.5 in./hr with the infiltration rate decreasing to 0.9 in./hr with a rainfall intensity of 1.5 in./hr. Their study was carried out on a small watershed in Iowa City, Iowa. The mean infiltration rate on Hudson Creek is 50 per cent of the rainfall intensity while on Burton Creek the mean infiltration is 56 per cent of mean intensity. Examination of the soil cover on both basins indicates that the pervious areas of Burton may have a higher water holding capacity than Hudson. For this reason the infiltration rate on the lawns in the urban watershed actually may be greater for the same rainfall intensities.

A plot of API vs mean infiltration produced the expected results, viz., as the API increases the infiltration rate decreases rapidly. The rural watershed shows the best relationship (Fig. 12). This plot indicates very low infiltration rates for API greater than 3.0. Unfortunately, the points are rather widely scattered about the line of best fit. Burton Creek (Fig. 13) also produced a similar relationship; however, the results are not as good. This variability may be explained by the surface detention caused by grass lawns in the pervious areas of the basin and by the rather large impervious area which produces runoff irrespective of the API.

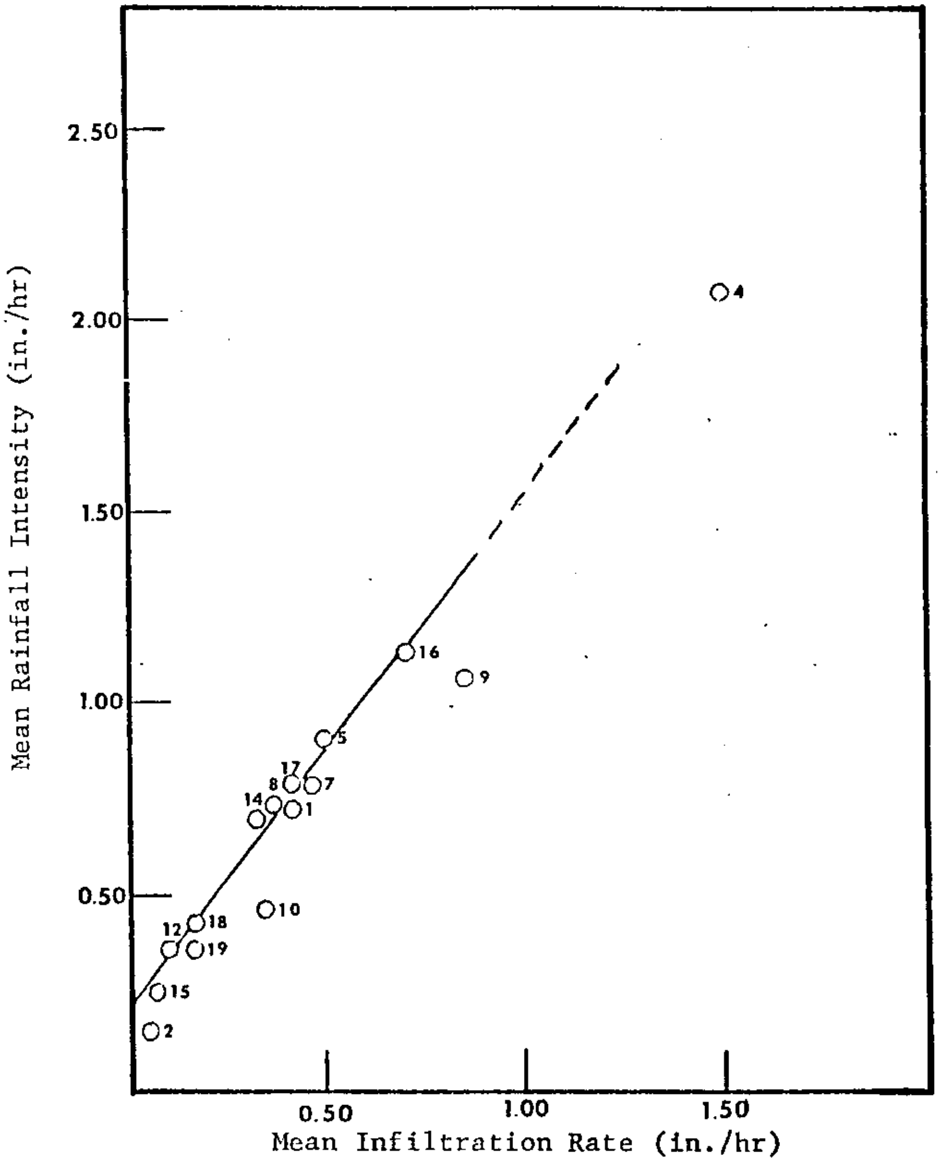

Figure 10. Mean rainfall intensity versus mean infiltration rate for Burton Creek.

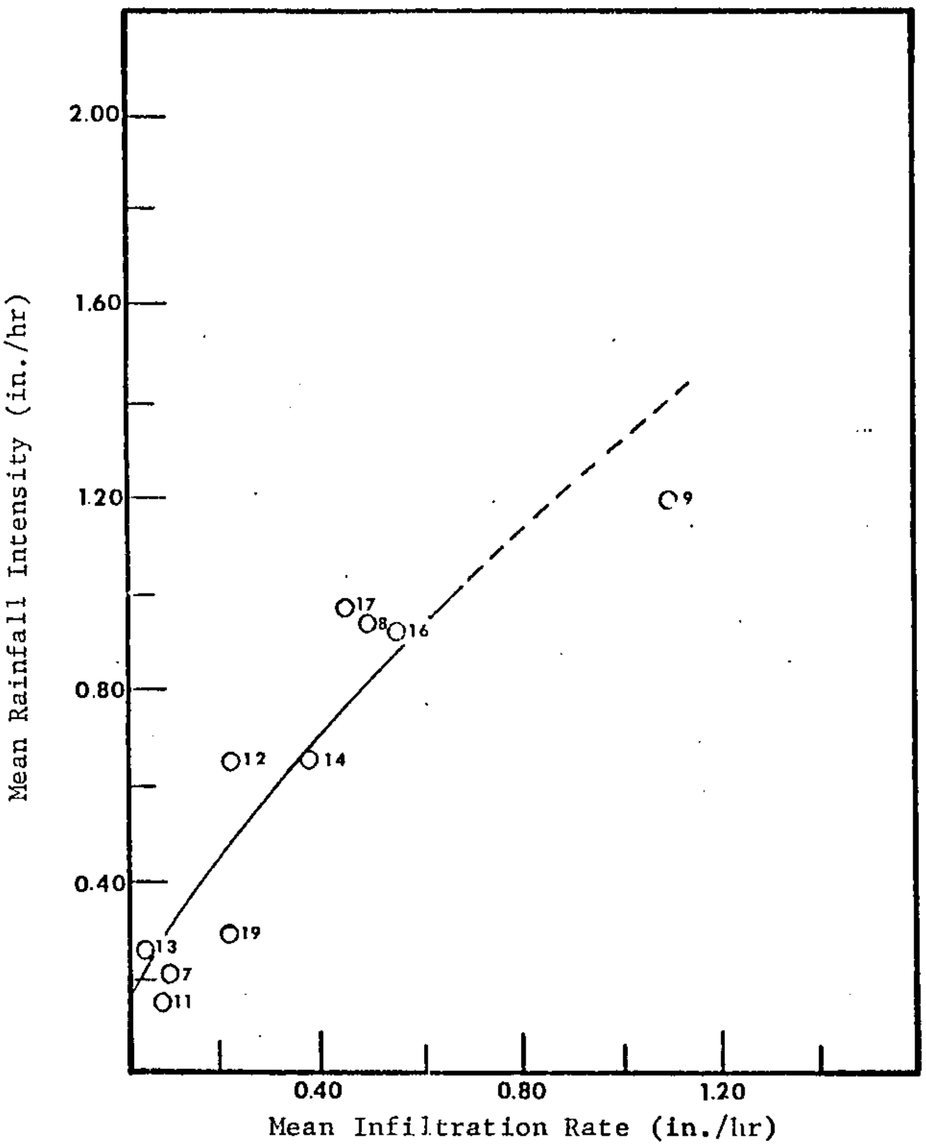

Figure 11. Mean rainfall intensity versus mean infiltration rate for Hudson Creek.

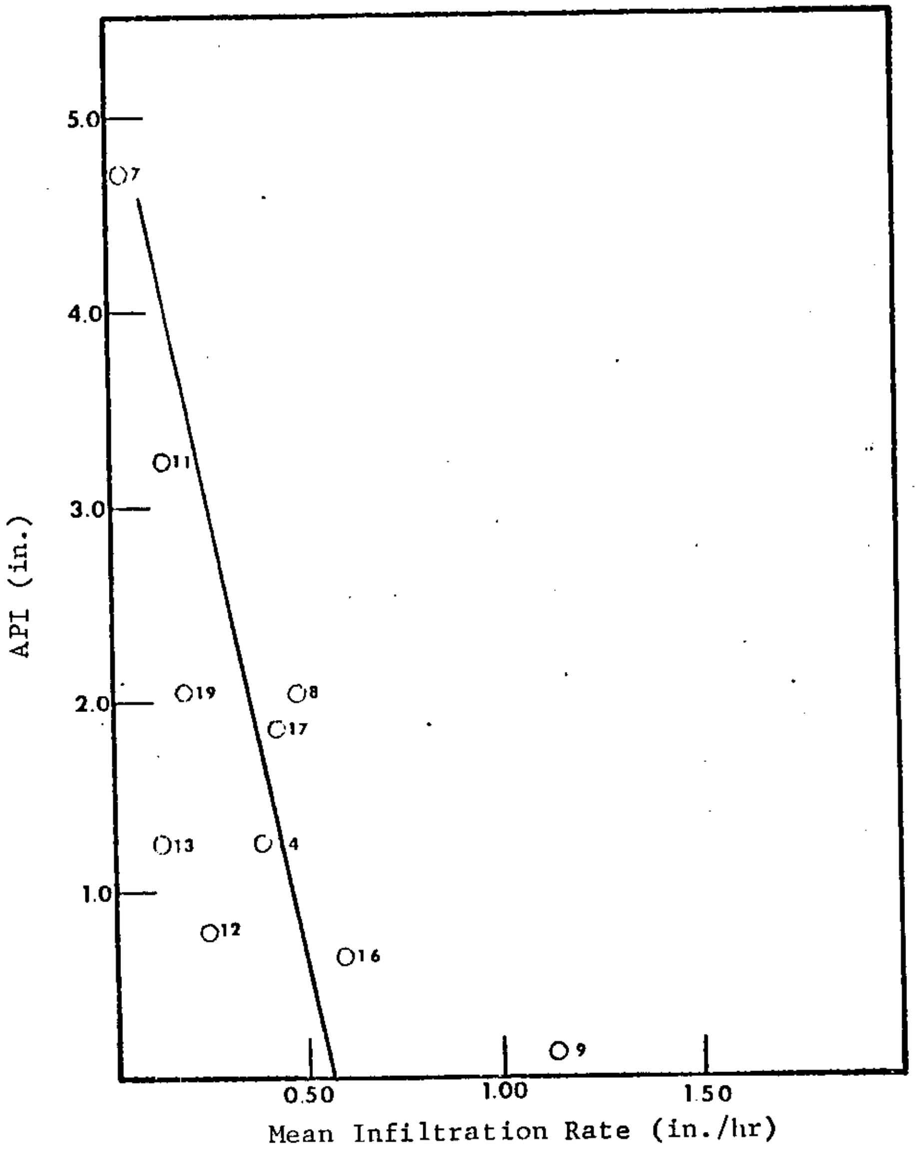

Figure 12. Antecedent precipitation index versus mean infiltration rate for Hudson Creek.

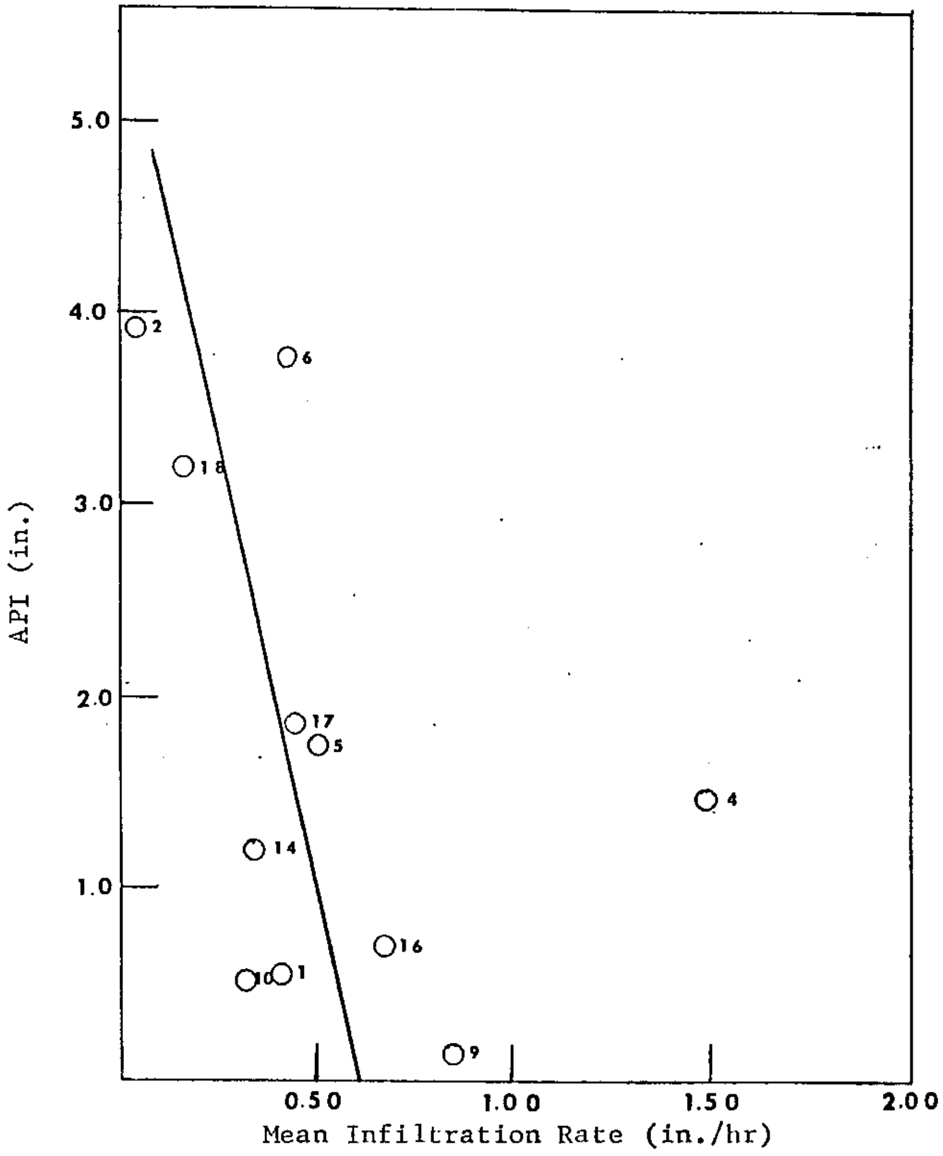

Figure 13. Antecedent precipitation index versus mean infiltration rate for Burton Creek.

A plot which related mean rainfall intensity to peak discharge per unit area proved reasonably successful for the urban basin (Fig. 14). However, this relationship was not evident in the rural basin (Fig. 15). The correlation of these variables again indicates the importance of the impervious area in the urban watershed. With an increase in the rainfall intensity on Burton Creek there is an increase in peak discharge per unit area. A major portion of this increase apparently comes from the impervious areas.

A plot of API vs the coefficient C in the rational formula indicates a high degree of correlation for the rural basin (Fig. 16). With low values of API, C also is small. Since C is a measure of the relationship between runoff peak produced by no infiltration and the actual peak, the soil moisture will be critical in its computation, particularly on the rural watershed. The urban watershed (Fig. 17) did not show this excellent relationship. This lack of correlation is again attributed to the impervious area and to the surface detention by the lawns in the urban watershed.

Values of the Snyder coefficient C_t were computed for each flood event. The range of values of the coefficient C_t was plotted versus the square root of the slope, $\sqrt{S}$, for each basin (Fig. 18) and compared with the work of Hudlow (1966). The rural basin has values of C_t varying from 0.67 to 3.10, which plot above the line of best fit obtained by Hudlow. The urban basin had values ranging from 0.24 to 1.75, which fall generally below the line of best fit. The plots indicate that there is considerable variability from basin to basin and also that the coefficient varies over a wide range from

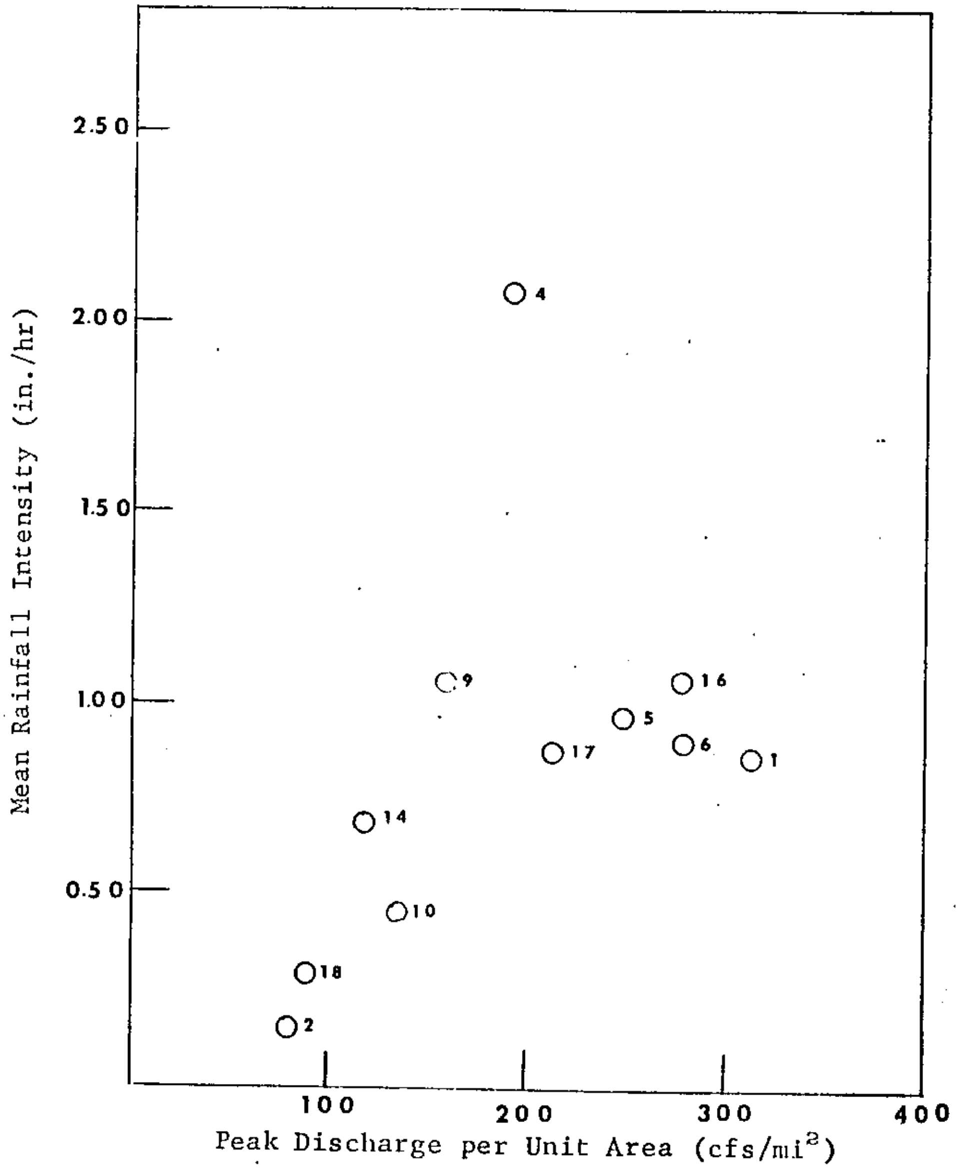

Figure 14. Mean rainfall intensity versus peak discharge per unit area for Burton Creek.

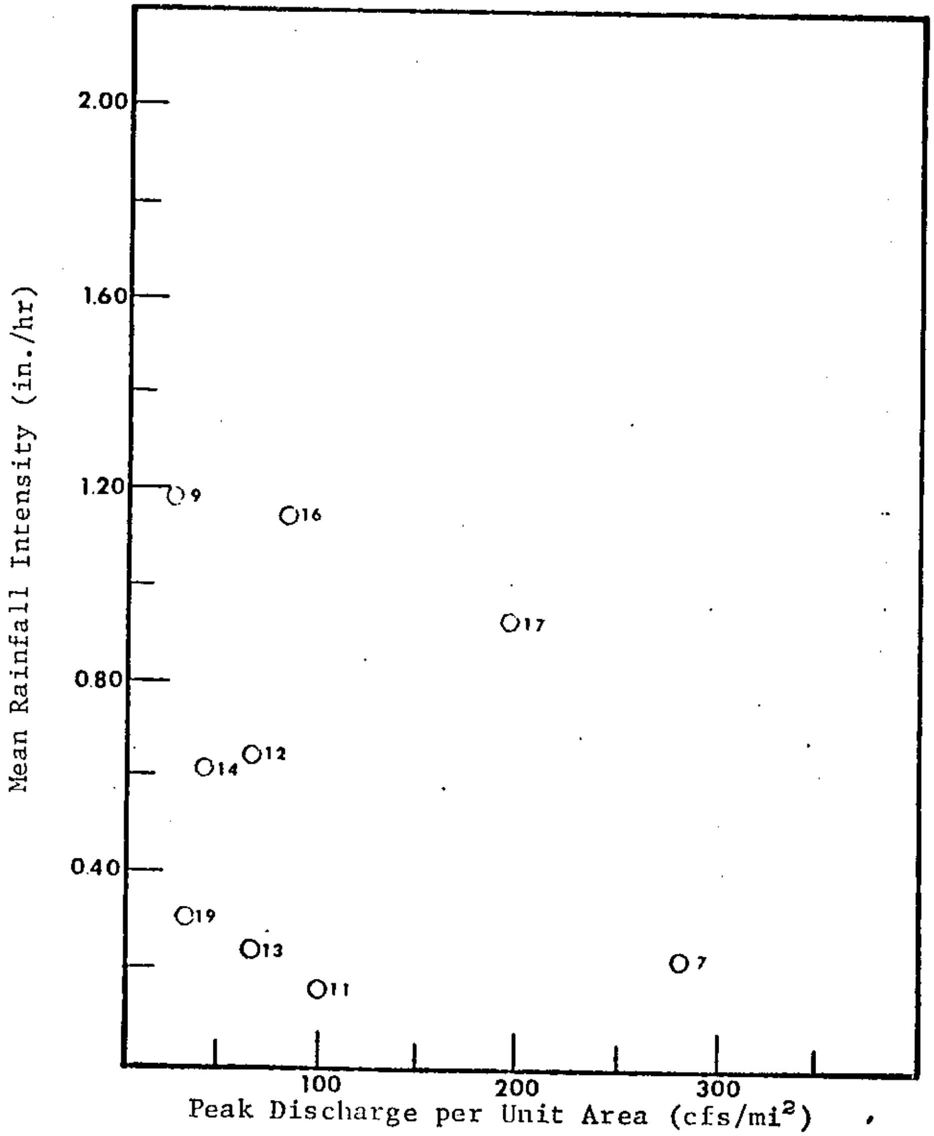

Figure 15. Mean rainfall intensity versus peak discharge per unit area for Hudson Creek.

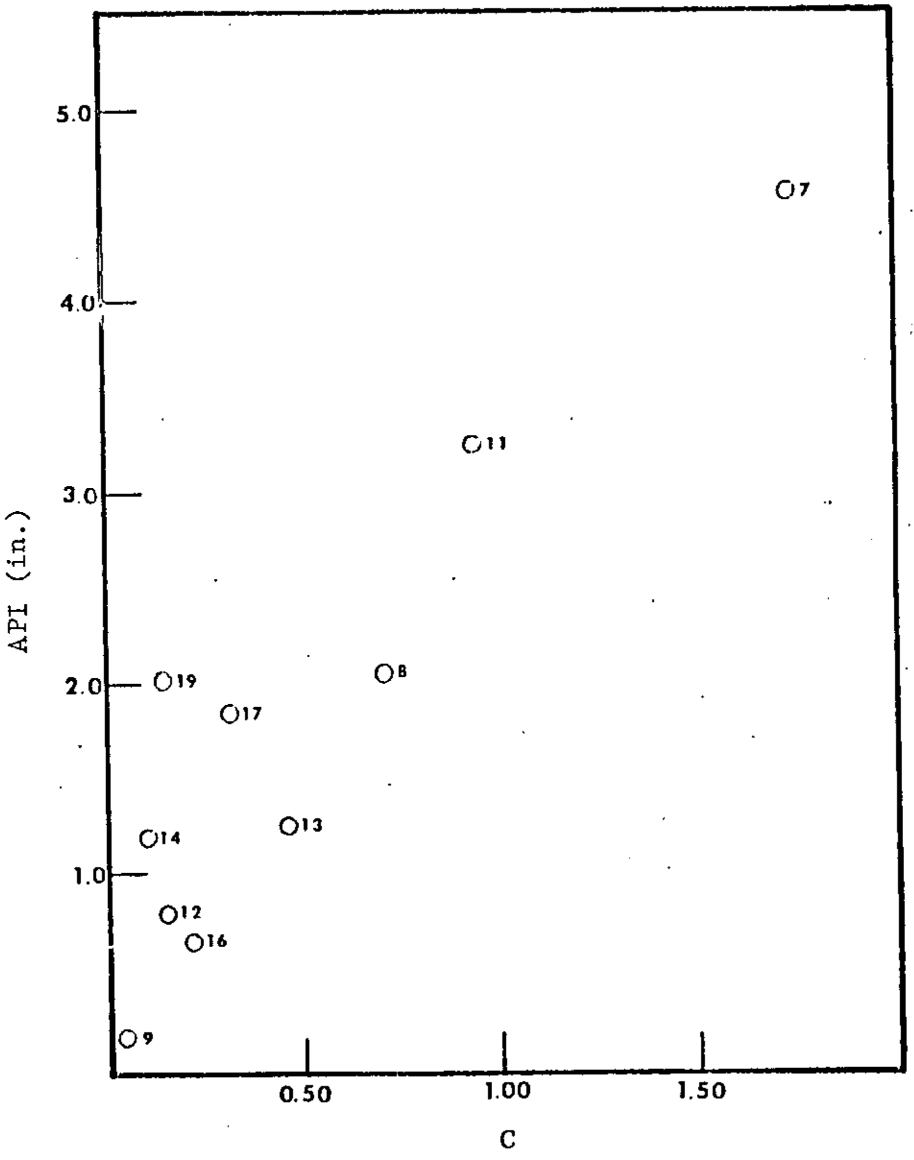

Figure 16. Antecedent precipitation index versus C, from Q_p = CIA, for Hudson Creek.

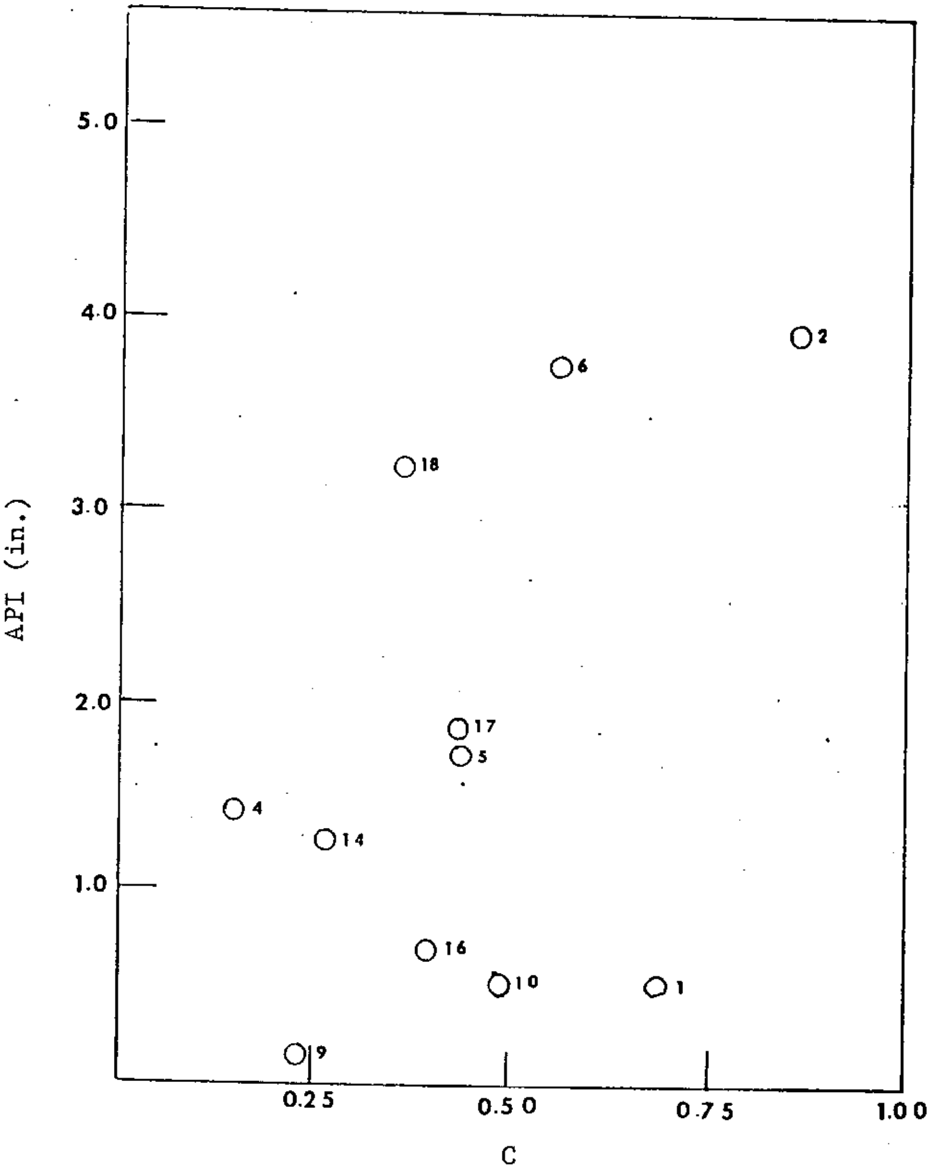

Figure 17. Antecedent precipitation index versus C, from Q_p = CIA, for Burton Creek.

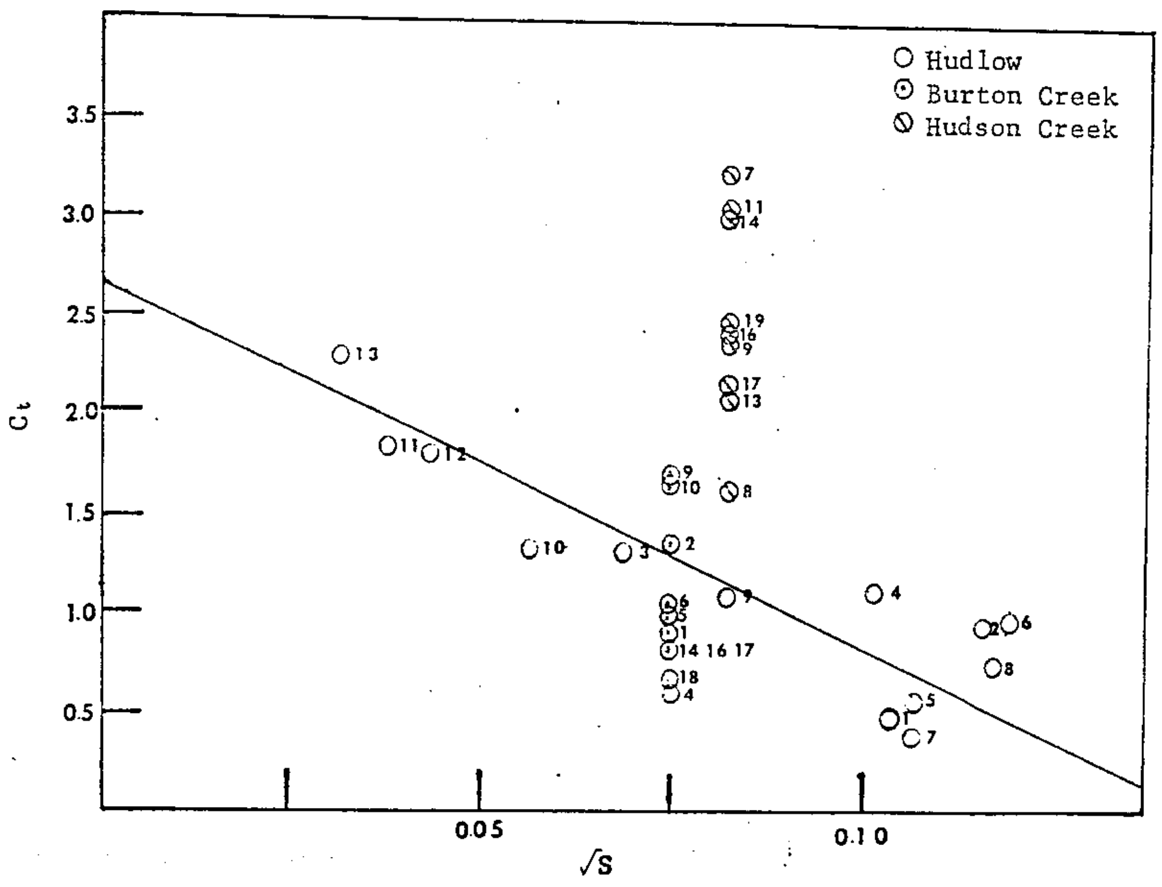

Figure 18. Relationship between Snyder's coefficient, C_t, and the watershed slope.

storm to storm within each basin.

The relationship of Snyder's Coefficient, C_p, and a parameter which is related to basin characteristics, $C_t (L L_{ca})^{0.3}/A$, is plotted in Fig. 19 and also compared with the work of Hudlow (1966). All but two cases for the urban watershed fell near or below the line of best fit in the comparison while all of the calculated points from the rural basin were above the line of best fit.

Cross Correlation

Cross correlations made of the four storms with single peaks immediately show the effects of the impervious area in the urban watershed (Table 5). A striking difference is evident in the rainfall variability between the two basins. In all but one of the storms used, the rainfall amount in the rural basin was greater than the urban basin to the west. This feature is due apparently to a biased selection of data which were used in the study. Climatology should show no significant statistical difference over a long period of record.

Comparison of the physical characteristics of the watersheds reveals that Burton Creek has an elongated, elliptically-shaped area while Hudson Creek is more circular. The change in elevation from the headwaters to the outlet in both basins is 75 ft with the main stream on Burton Creek 0.2 mi longer; however, it has a drainage area that is only 70 per cent of the area of Hudson Creek.

The most important effect of urbanization is the decrease in lag time. Carter (1961) found that for a watershed that was

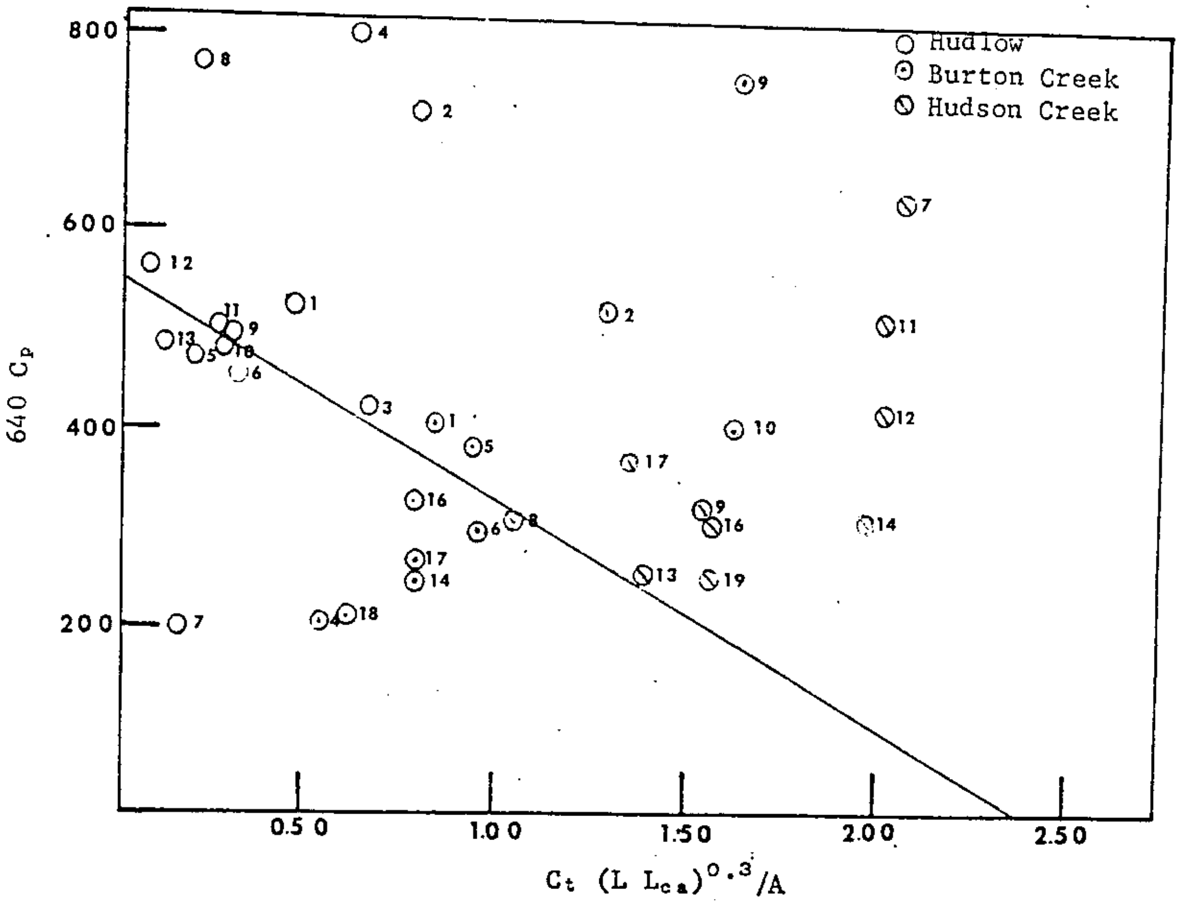

Figure 19. Relationship between Snyder's coefficient, C_p, and basin characteristics.

Table 5. Calculated parameters used for cross correlation between the two watersheds.

Storm No.	Volume $ft^3 x 10^6$	Rainfall in.	Time to Center of Volume min	Time-to-Peak min	Lag Time min	Period of Rainfall min
09 B	1.18	1.86	137	105	137	105
09 H	0.63	2.67	185	150	135	135
14 B	1.14	0.68	82	60	67	60
14 H	1.67	0.82	233	135	233	75
16 B	2.83	2.25	105	105	67	120
16 H	3.78	2.06	195	165	188	135
17 B	2.13	1.55	90	90	68	120
17 H	4.77	1.94	184	165	169	120

Table 5. (continued)

Storm No.	Rainfall Excess min	API in.	Mass Infiltration in.	Infiltration per cent	Dimensionless Peak
09 B	0	0.16	1.49	30	1.57
09 H	0	0.16	2.55	95	0.77
14 B	30	1.21	0.33	48	0.71
14 H	0	1.21	0.46	56	0.68
16 B	75	0.68	1.36	60	0.85
16 H	15	0.68	1.24	60	0.67
17 B	45	1.86	0.88	57	0.76
17 H	30	1.86	0.90	46	0.39

Table 5. (continued)

Storm No.	Peak Discharge cfs	Discharge Peak/Area cfs/mi^2	Unit Hydrograph Peak cfs	Unit Hydrograph Peak/Area cfs/mi^2
09 B	226	163	538	334
09 H	47	24	212	107
14 B	164	118	308	245
14 H	81	41	159	80
16 B	389	280	388	294
16 H	255	114	132	92
17 B	301	207	362	260
17 H	383	193	259	131

Table 5. (continued)

Storm No.	Rainfall Intensity in./hr	Mean Infiltration in./hr	Recession	C_t	640 C_p	C	$C_t (L\ L_{ca})^{0.3}$
09 B	1.06	0.85	0.33	1.69	362	0.24	1.64
09 H	1.18	1.13	0.63	2.39	425	0.03	1.56
14 B	0.68	0.33	0.45	0.83	274	0.27	0.81
14 H	0.66	0.37	0.75	3.01	403	0.10	1.96
16 B	1.13	0.68	0.42	0.33	328	0.39	0.81
16 H	0.92	0.55	0.75	2.43	391	0.19	1.58
17 B	0.78	0.44	0.47	0.34	295	0.43	0.82
17 H	0.97	0.45	0.75	2.18	510	0.31	1.42

partially sewered the lag time decreased 60 per cent while in a basin that was completely sewered the lag time decreased by 80 per cent. In the present study, the four events analyzed indicate a decrease of mean lag time of 43 per cent. During one of the events investigated the API was 0.16 in. and the lag time in the urban basin was 137 min. This was almost twice as long as the lag times for the other three events, which had higher API indexes. With this event eliminated, the decrease in lag time would be greater than the 60 per cent level found by Carter.

A recent study by Harris and Rantz (1964) on a small watershed in Clara County, California, indicated an increase in runoff yield due to urbanization. All of the storms examined show that the percentage infiltration in the rural basin is equal to or higher than the urban basin. This agrees in principle with the fact that an increase in urbanization increases the runoff yield of the basin.

Constants of ground water recession computed for both basins show consistently higher values for the rural basin. This may be due partially to the fact that the ground water in the urban areas tends to remain high due to extensive watering of lawns during the summer months.

Application of An Averaged Unit Hydrograph to Actual Events

An averaged unit hydrograph was determined for each basin and used to reproduce actual storm events. The following steps were taken in their construction:

1. Dimensionless hydrographs obtained from each storm were averaged for each basin.
2. A 30-min unit hydrograph was constructed for each basin from the averaged dimensionless hydrographs using mean lag times of 198 min for Hudson Creek and 82 min for Burton Creek.

The average dimensionless hydrograph for Burton Creek (Fig. 20) has a peak of 0.80 centered at 100 per cent of (L_g + D/2). For Hudson Creek (Fig. 21) the peak was 0.92 centered at 95 per cent.

The 30-min unit hydrographs for each basin appear in Fig. 22, Burton Creek, and Fig. 23, Hudson Creek. The effects of urbanization are observed readily when one examines the magnitude of the peak discharge and the time to peak. Hudson Creek has a unit hydrograph peak of 325 cfs at 210 min while Burton Creek has a peak of 470 cfs at 85 min.

The adequacy of these hydrographs was tested by the reproduction of actual events. The following steps were followed:

1. 30-min rainfall intensities were determined for each storm.
2. With a known API, either Fig. 12 or Fig. 13 was used to find the appropriate mean infiltration rate.
3. This mean rate was subtracted from the various rainfall intensities and applied to the unit hydrograph.

The Burton Creek reproductions generally were very good (Figs. 24 and 25 are reproductions of two selected events). In general, the time-to-peak was very good; however, the hydrograph peaks on both reproductions were somewhat higher than the actual peak. The volumes under both the predicted and the actual curves were also

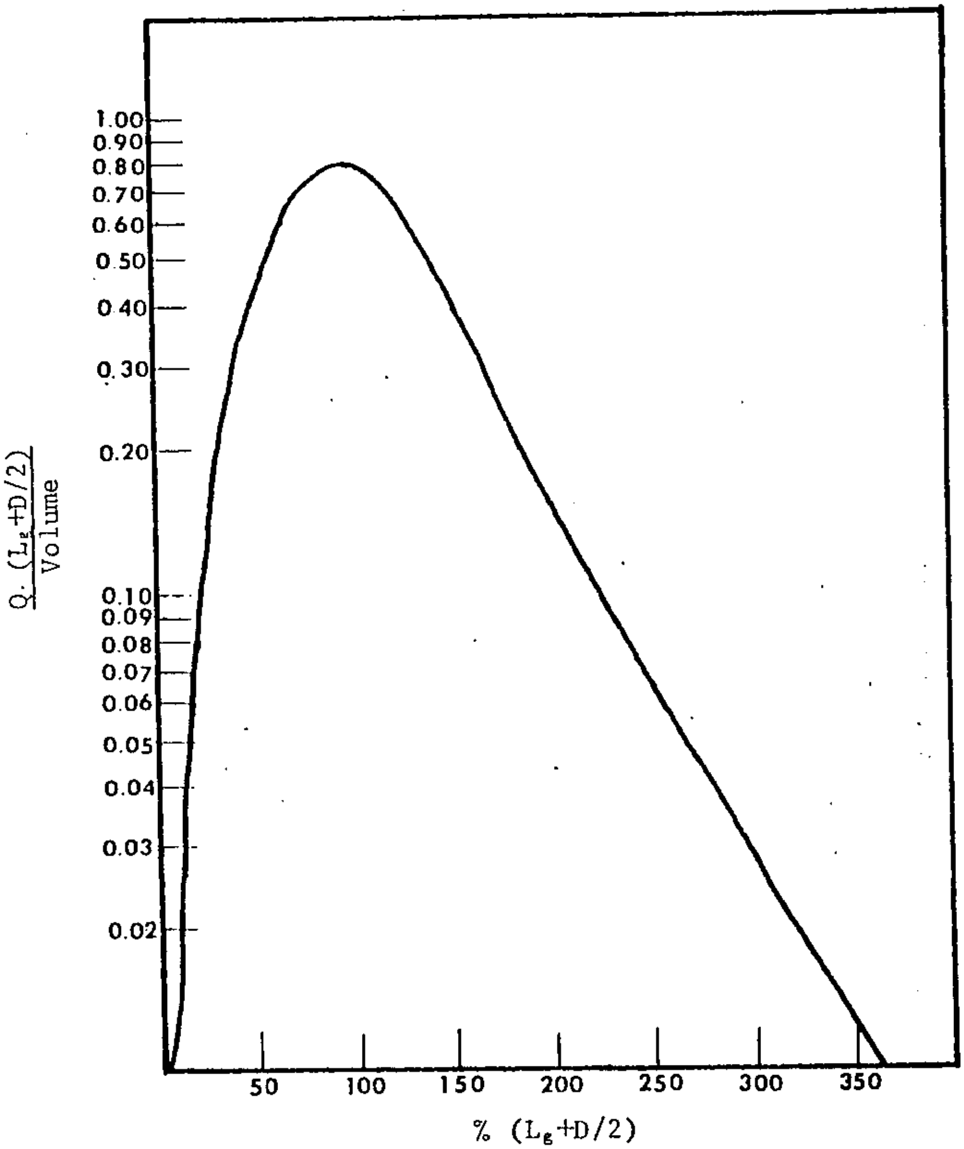

Figure 20. Average dimensionless hydrograph for Burton Creek.

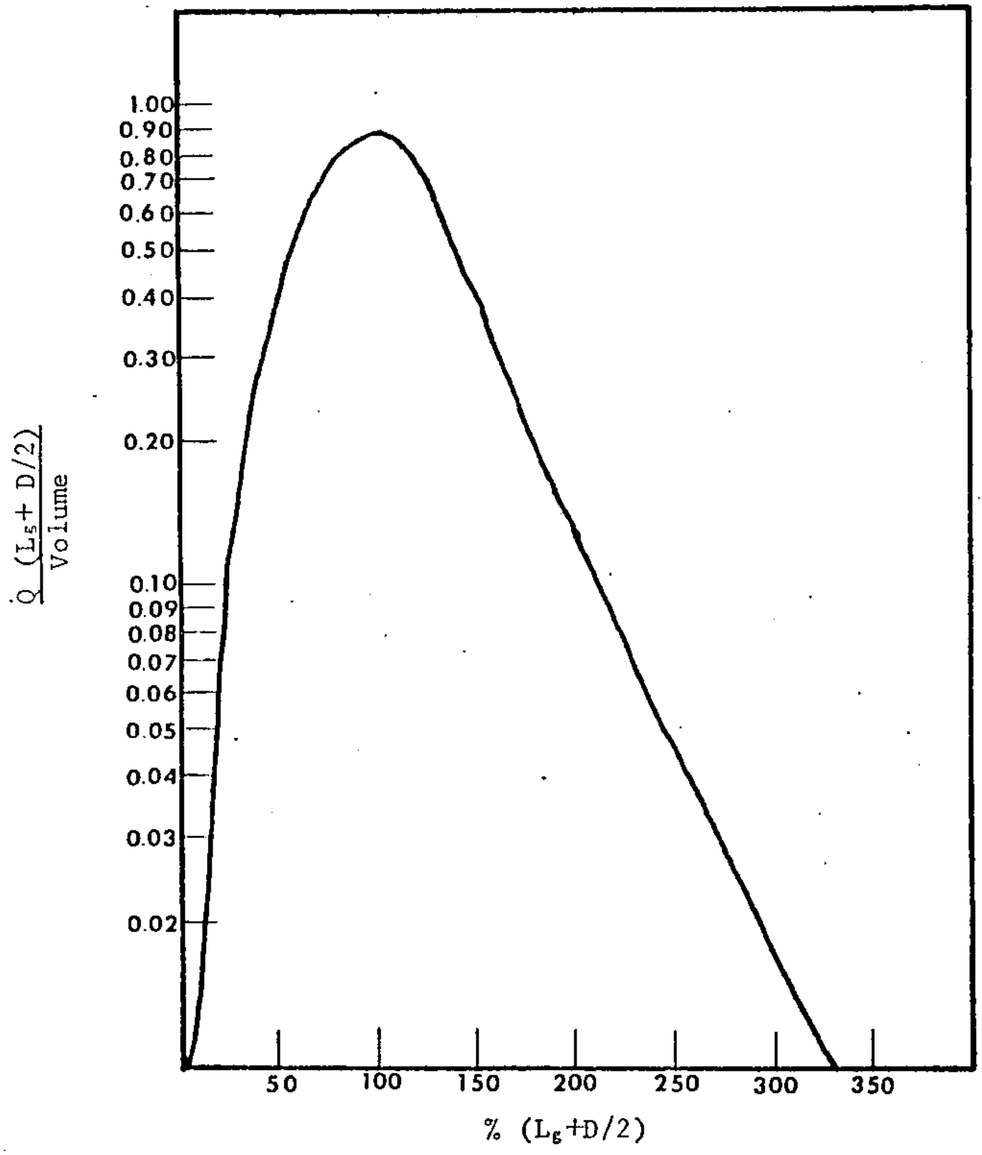

Figure 21. Average dimensionless hydrograph for Hudson Creek.

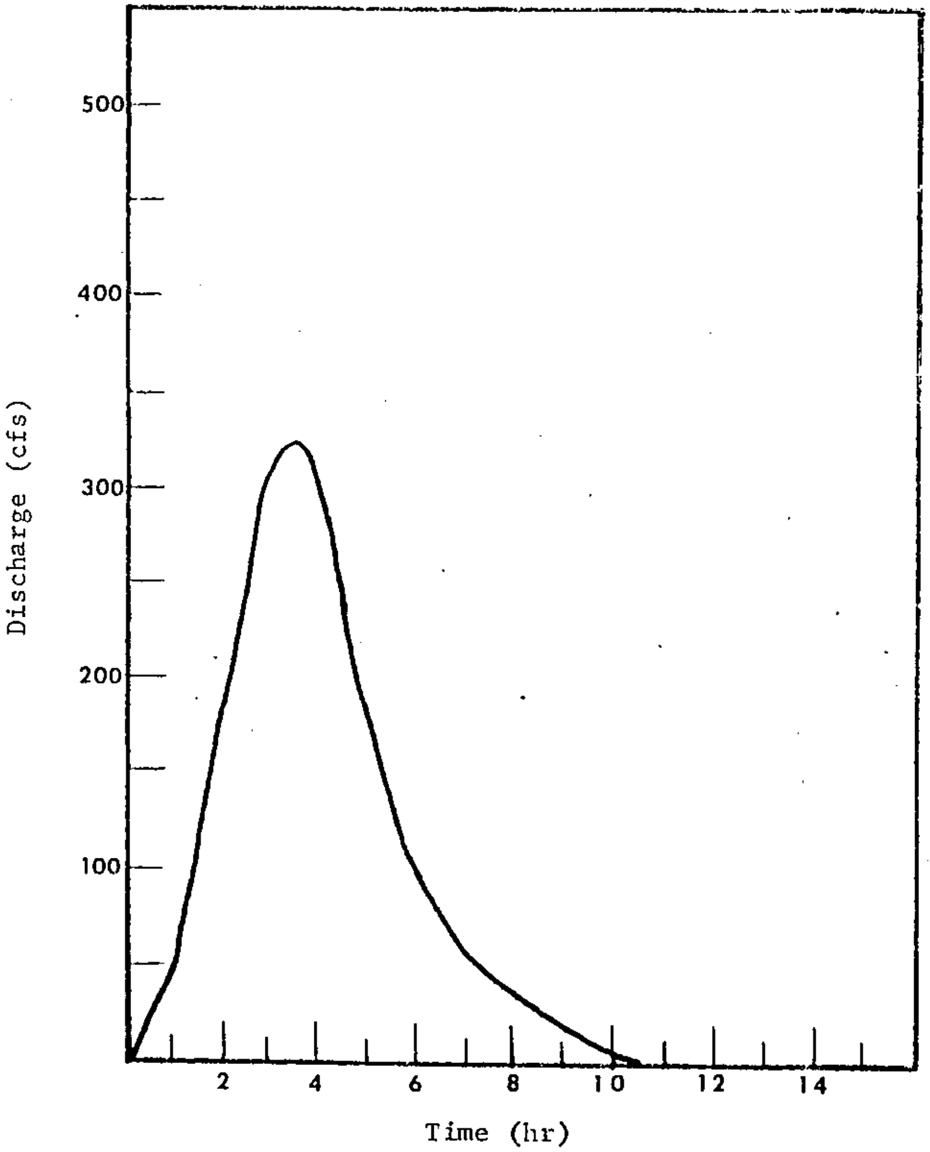

Figure 22. 30-min unit hydrograph for Hudson Creek.

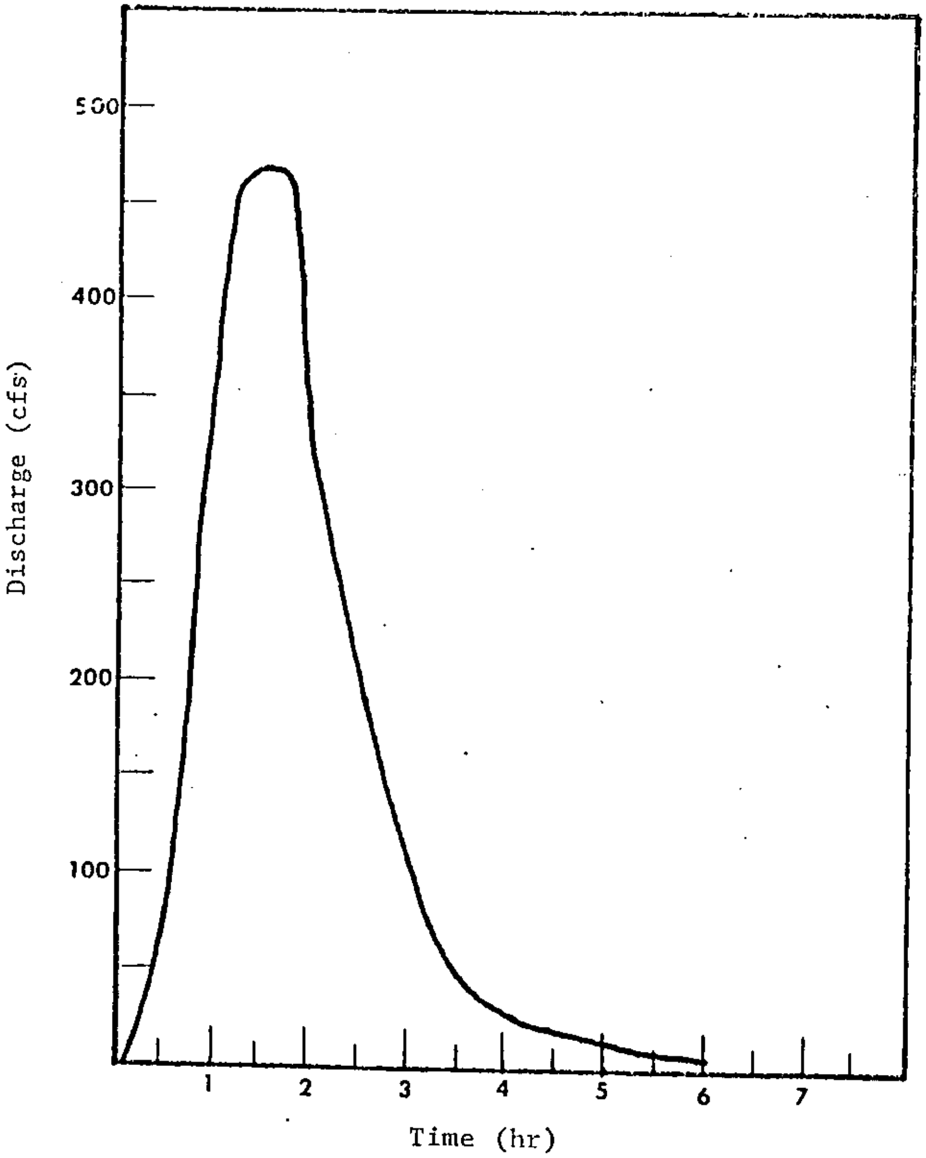

Figure 23. 30-min unit hydrograph for Burton Creek.

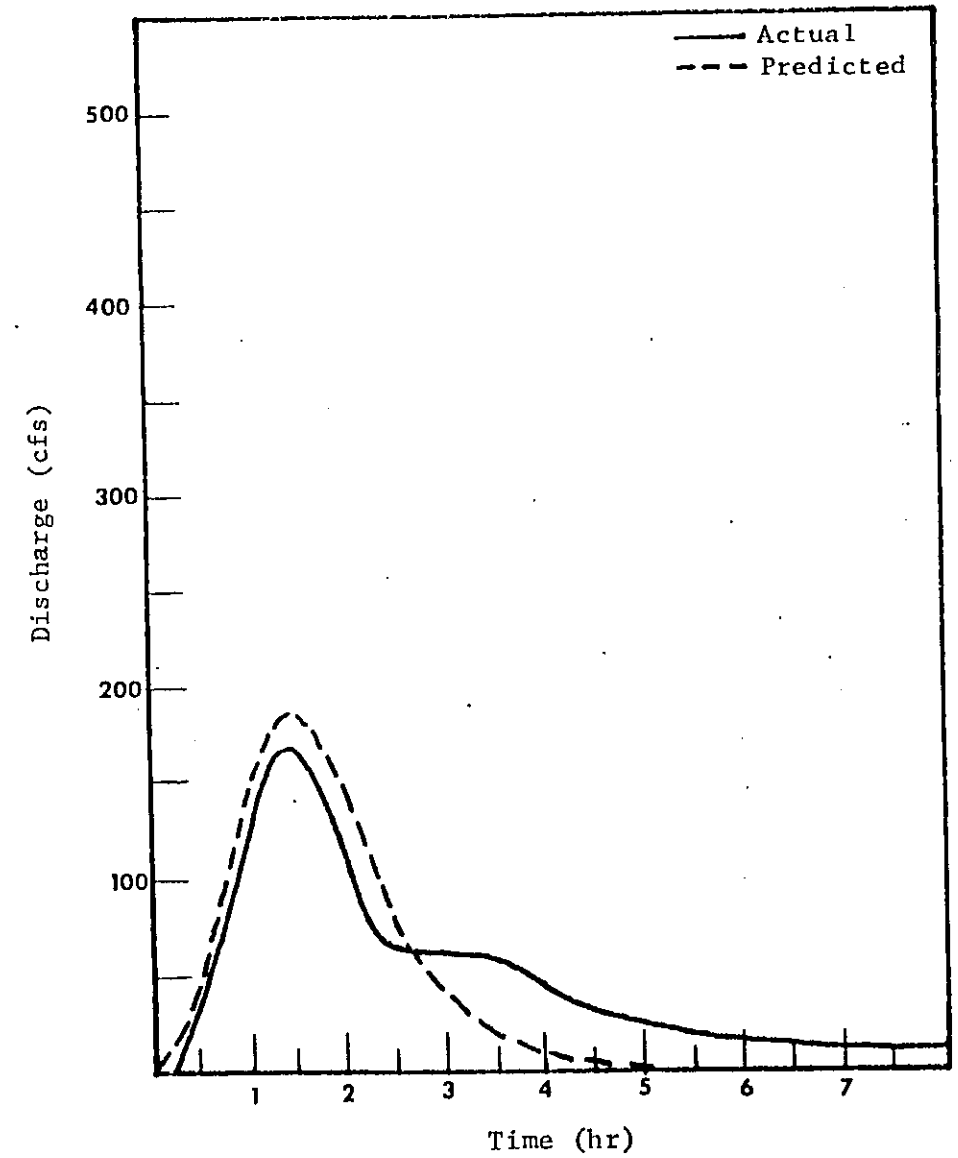

Figure 24. Actual and predicted hydrograph for April 27, 1969 on Burton Creek.

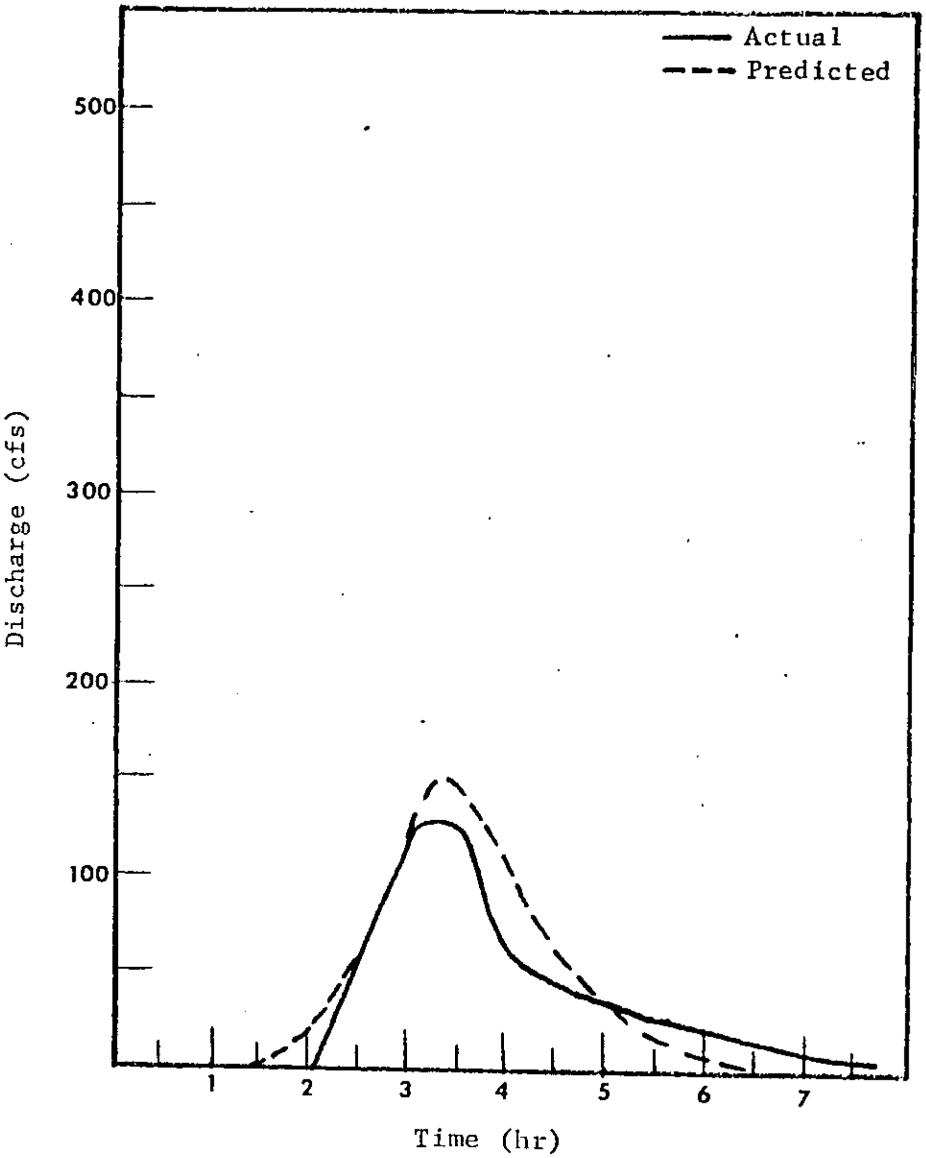

Figure 25. Actual and predicted hydrograph for May 5, 1969 on Burton Creek.

nearly equal.

The Hudson Creek reproductions, Fig. 26 and Fig. 27, also gave good results with both time-to-peak and peak discharge.

Both basin reproductions had the recession portion of the hydrograph slightly steeper than the actual hydrographs. When the dimensionless hydrographs were averaged, a constant recession was, of course, determined. Apparently this average recession was a bit steep to yield excellent reproductions for these spring and early summer events.

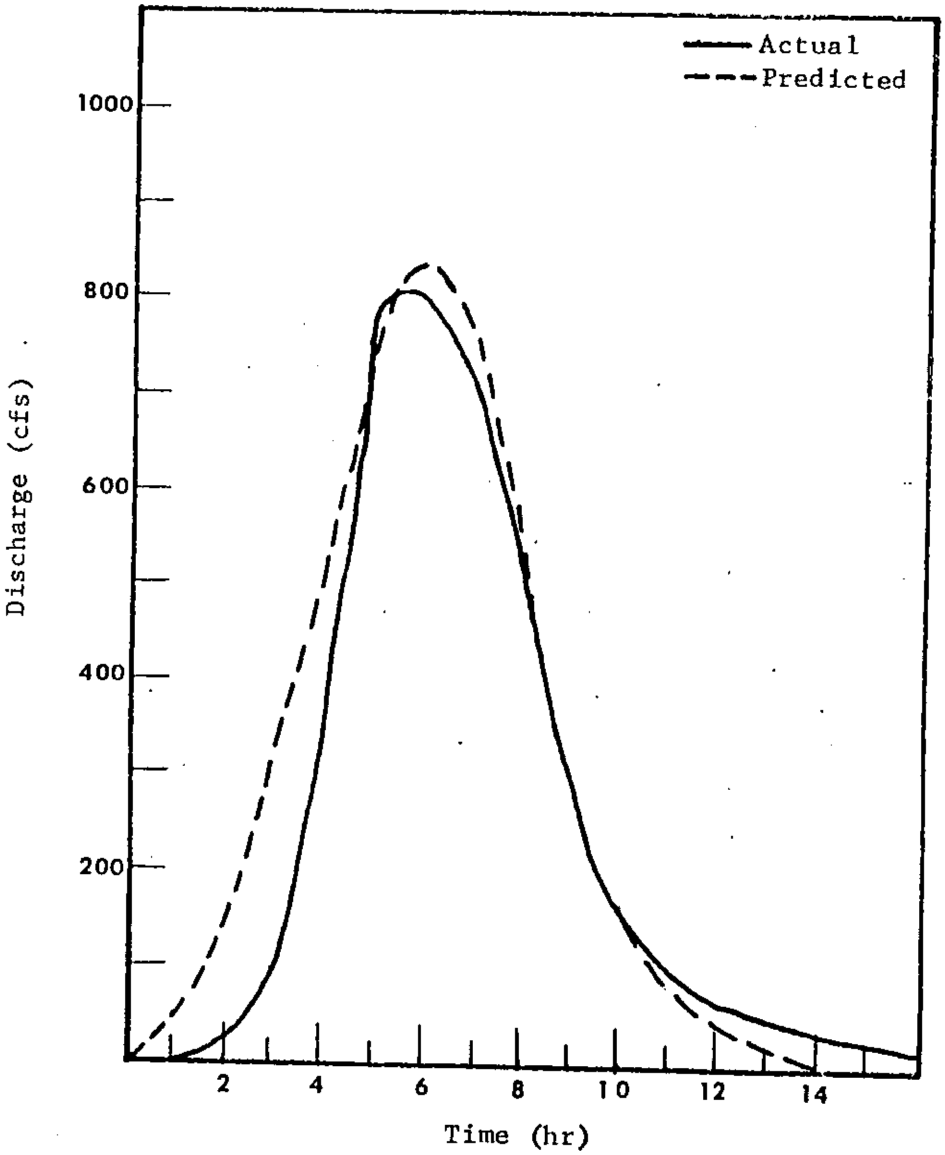

Figure 26. Actual and predicted hydrograph for July 9, 1968 on Hudson Creek.

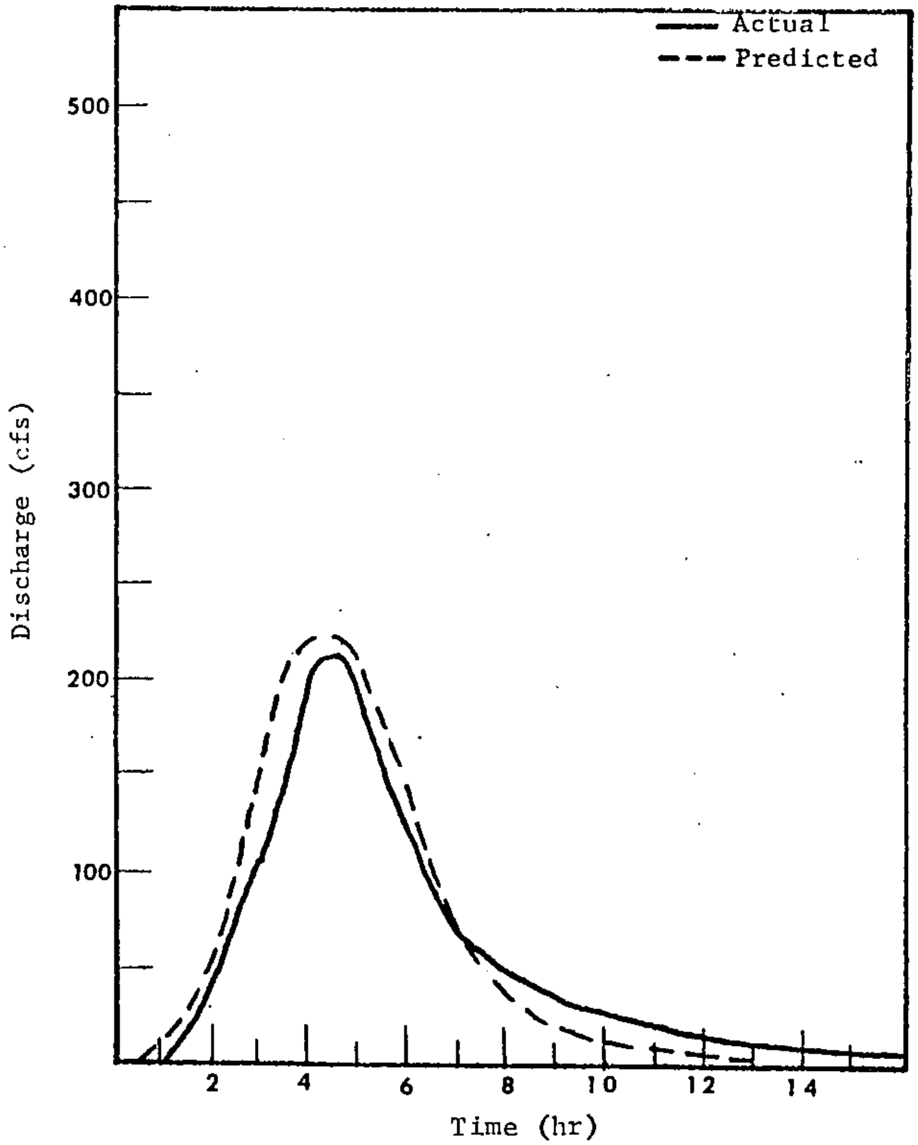

Figure 27. Actual and predicted hydrograph for April 4, 1969 on Hudson Creek.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions can be inferred from this study:

1. Urbanization decreases the lag time and time-to-peak.
2. The use of a single rain gage in basins smaller than 2 mi^2 apparently yields rainfall values that are adequate for hydrograph analysis in the central Texas area.
3. The basin constants determined from the various techniques of hydrograph analysis are as variable from storm to storm within a basin as between basins.
4. The dimensionless hydrograph technique appears to be a satisfactory method for hydrograph synthesis for both the small urban and rural basins.
5. Surface detention by lawns in the urban basin is apparently an important factor in the determination of the total runoff.
6. From the data analyzed, there was no seasonal effect detectable in the streamflow in either basin.
7. The unit hydrograph peak for the rural basin, expressed in cfs per square mi, was only 49 per cent of the urban peak which indicates the effects of the large impervious area.
8. The difficultities encountered in the use of the rational formula are revealed. In the rural area C is very dependent upon API. The urban basin did not exhibit this tendency.

Recommendations

Some areas, suggested by this study, for further research are:

1. Continuation of analyses of data of the type used in this study to improve the unit hydrographs and thus the prediction method.
2. Application of the derived unit hydrograph procedures to similar basins.
3. A study estimating the temporal distribution of infiltration capacity from rainfall-runoff data available on the two watersheds.

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