EFFECTS OF URBANIZATION ON RUNOFF VOLUME

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SUMMARY

The purpose of this study was to investigate the effect of urbanization on the volumes of runoff entering urban streams. Specific emphasis was on determining the magnitude of the changes in the volumes of baseflow and direct runoff from urbanizing watersheds and the relationship of these changes to the amount of urban growth in the watersheds. Eleven urbanizing watersheds selected for use in this study are located in five geographic areas. A natural (control) watershed was selected near each urban watershed. Drainage areas ranged from 10 square miles to 88.4 square miles.

The first step in data analysis was to determine the amount of urban development, defined as the change in urban land indicate on USGS 7 1/2 minute quadrangel maps, in each urban watershed and the change in urban land and impervious cover over selected periods of time. The amount of urban land in the 11 urban watersheds (each with a typical mixture of land uses) ranged from 5 percent to 91 percent, with changes of from 3 to 40 percent during the urbanization period studied. Estimated impervious areas in the various watersheds ranged from 2 to 35 percent. A relationship between urban land and impervious cover showed that for a watershed with zero urban land the average impervious area was about 4 percent of the total watershed area and with 100 percent urban land, the impervious area was about 35 percent.

The second step was to analyze the streamflow record for each watershed. Standard procedures were used to separate direct runoff from base flow on each annual hydrograph. A double mass curve was prepared for each watershed by plotting streamflow from the urban watershed versus streamflow from the associated control watershed. These double mass curves were used to detect changes in runoff due to urbanization. An increase in the annual volume of direct runoff was observed for all watersheds undergoing urbanization. These increases ranged from 10 to more than 60 percent of the direct runoff measured during the base period. In some cases increases in direct runoff were greatest during dry months and smallest during wet months. However, no consistent relationship between changes in land use and seasonal increases in direct runoff was found. Analyses showed that the percentage increase in annual direct runoff was about 1.8 times the percentage increase in urban land. No relationship between changes in baseflow and changes in urban land was found, probably because changes in annual volumes of baseflow were influenced by drainage practices, infiltration capacities, and groundwater management practices.

CHAPTER I

INTRODUCTION

Purpose, Scope and Objectives

Urbanization is the sequence of land use changes that convert land from fields and forests to areas more intensely used for the purposes of man's activities. Principally urbanization is the process of constructing roads, houses and buildings, commercial and industrial areas and all the appurtenent structures on land that was once open.

The purpose of this study is to investigate the effects of urbanization on the volumes of runoff entering urban streams with specific emphasis on determining the magnitude of the changes in the volumes of baseflow and direct runoff from urbanizing watersheds and the relationship of these changes to the amount of urban growth in the watersheds. Subtle and long term water losses from a watershed undergoing urban development can have important implications for the management of the water resources of the area. Results of this study will provide the water manager with information to better assess the impact of urban growth on the water resources of his area, and to plan for water conservation measures and improved drainage facilities where necessary.

The original scope of the study was to include urban watersheds located throughout the United States, avoiding regions where snow significantly affected runoff patterns. A search for watersheds that met the following criteria was conducted:

1. Watersheds that have undergone urbanization;

2. Watersheds that have a continuous record of streamflow over at least part of the period of urbanization;

3. Watersheds where snowmelt is a negligible part of the streamflow record;

4. Watersheds that have a nearby watershed that has not undergone urbanization and has a corresponding period of continuous streamflow record;

5. Watersheds that have existing and readily available data on urban development, such as changes in urban land and impervious area.

The number of watersheds ultimately found that met this criteria limited the scope of the study to four geographic areas. Eleven urban watersheds were located in these four areas: two on Long Island, New York, three in the Piedmont Plateau of North Carolina, and near Atlanta, Georgia, five near Houston, Texas, and one near Sacramento, California. The general location of these areas are shown in Figure 1. Two of these watersheds--Little Sugar Creek near Charlotte, North Carolina and Morrison Creek near Sacramento, California, do not have comparable nearby non-urbanized watersheds for comparison and therefore were not used in the streamflow analysis of this study.

The steps taken to accomplish this purpose were to:

1. Determine the change in land use due to urbanization of selected watersheds over a period of years;

2. Determine, by the use of double-mass techniques, the change in runoff volumes from selected urbanizing watersheds;

3. Develop relationships to predict changes in runoff volume as a function of urban land use;

4. Discuss variations in runoff changes within and among watersheds used in this study; and

5. Discuss implications of the results of this study for water managers.

Effects Of Urbanization On The Hydrologic System

This study is concerned with the response of urban watersheds to a precipitation event. Total runoff, as defined here, is the streamflow at a given point in a watershed and is comprised of two components -- direct runoff and baseflow -- both of which may include precipitation on the land surface, waste-water effluent, and interbasin diversions. Direct runoff is defined for this study as channel precipitation and the surface and subsurface runoff that enters the stream channel promptly after a storm event and is represented by a temporary increase in stream discharge. Baseflow is defined as that part of the total runoff derived from delayed subsurface runoff including groundwater outflow, and continuous waste-water effluent and diversions.

As more and more roads, houses, parking lots and rooftops are constructed there is a decreased opportunity for rainfall to infiltrate the land surface and percolate through the ground to either recharge groundwater or discharge into streams. Instead, rain that falls on an impervious surface either is caught in depression storage and or, in most cases, flows quickly over the impervious surface where it is collected in gutters and storm sewers that discharge into nearby streams.

In the absence of structures to detain or conserve storm runoff on or in the urban watershed, urbanization can significantly alter the natural flow of storm water and the movement of water to the various

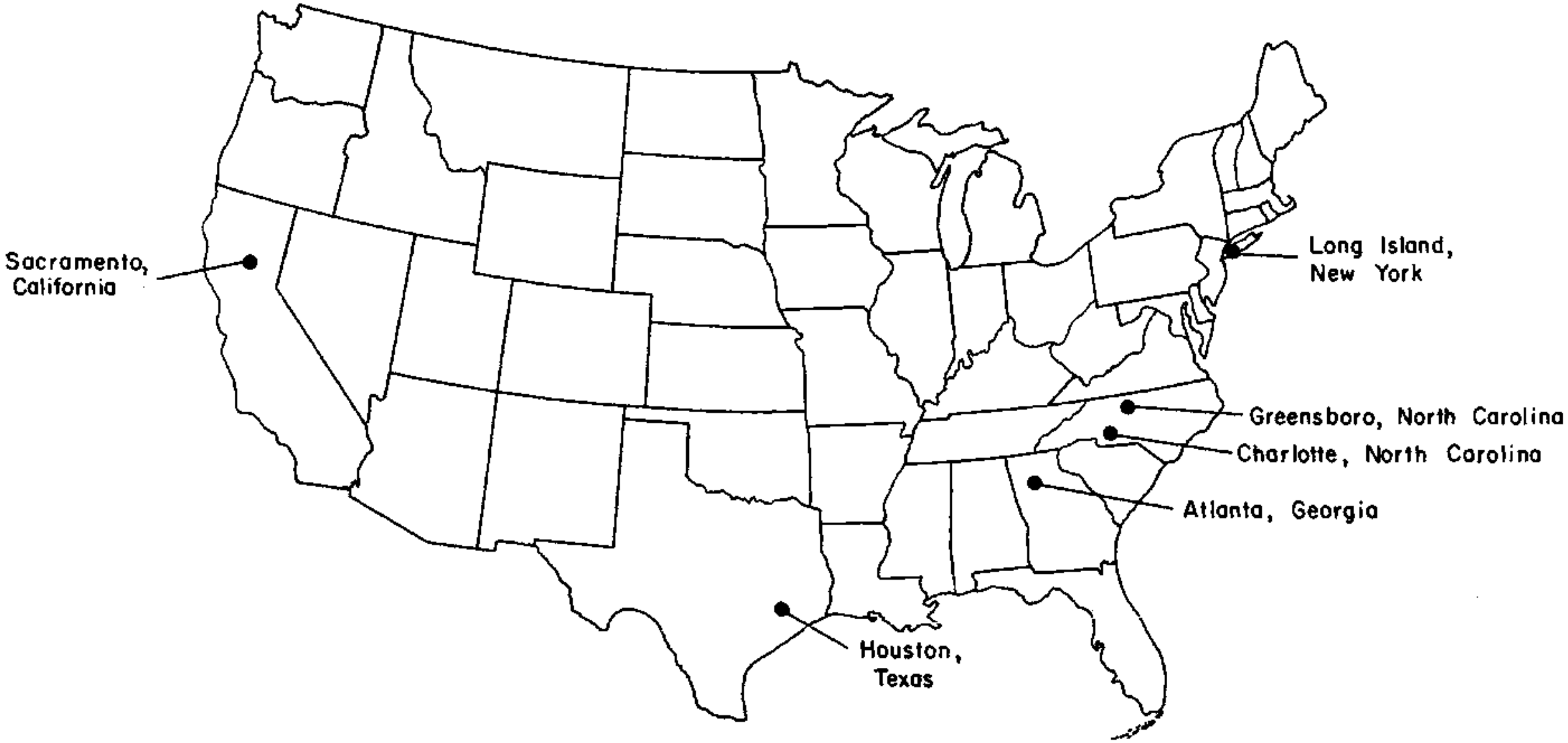

Figure 1. Map Of United States Showing Location Of Urban Areas Used In This Study.

components of the hydrologic cycle. For example, urbanization can result in a reduction in infiltration and groundwater recharge (Seaburn, 1970, and Seaburn and Aronson, 1974), accelerated erosion, sedimentation (Guy, 1970 and 1971), and pollution (Am. Pub. Works Assoc., 1969), changes in stream channel capacity (Hammer, 1972 and 1973), increased peak flows and flood hazards (Carter, 1961, Martens, 1966; Seaburn, 1969; Anderson, 1970; Putnam, 1972; Johnson and Sayre, 1973), reduced basin lag time (Waananen, 1961; Wiitala, 1961; and Crippen, 1965), and increased volumes of runoff (Sawyer, 1963; Harris and Rantz, 1964; Seaburn, 1969; Wallace, 1971; and Hammer, 1973). This is by no means a complete list of the effects of urbanization on the hydrology of an area and only a sampling of articles dealing with each item. Numerous other research projects dealing with these and other problems have been or are currently underway to determine the magnitude of the effect of urbanization on hydrology of an area and to suggest solutions or measures to control the problem. (See Am. Soc. Civil Eng. Task Force, 1969 and 1972 for a review of pertinent articles).

CHAPTER II

METHOD OF INVESTIGATION

Analysis of the factors that affect runoff from a watershed helped to determine the analytical approach used in this investigation. These factors are separated into two groups: meteorological and physiographic factors.

Meteorological factors consists of 1) precipitation, including effects of type, intensity, duration, magnitude, distribution and frequency; 2) interception, including effects of type and density of vegetation and season of year; 3) evaporation, including effects of temperature, wind, atmospheric pressure, humidity, exposure, and type of surface, and quality of water; 4) transpiration, including effects of temperature, wind, pressure, humidity, exposure, and type of vegetation. In addition to the variability of each of these factors during any given storm event, they all vary considerably from season to season.

Although these factors are highly variable from one storm to another and from one season to another, they tend to remain fairly constant over long periods of time. Annual and even seasonal rainfall amounts vary about some mean value while interception, evaporation, and transpiration, even though cyclic throughout the year, remain generally constant from year to year.

The second group of factors affecting runoff are physiographic factors which can be classified into two kinds: basin characteristics and channel characteristics. Basin characteristics include size, shape, slope, orientation, elevation, soil and geologic composition, infiltration capacity, groundwater and surface water storage capacities and man-related influences such as land use and improved drainage devices. Channel characteristics relate to the hydraulic properties of the stream channel and include such items as size and shape of the channel cross section; the length, slope, and roughness of the channel; channel storage capacity; diversions, and regulation.

Physiographic factors remain relatively constant from storm to storm. However, over long periods of time, slight and continuous changes in physical parameters within the watershed may significantly affect long term runoff patterns. Nearly all of the physiographic factors can be expected to change under certain conditions, but the factors most susceptible to change are those which can be affected by man's activities. These include changes in land use and changes in land surface cover, as well as related affects such as changes in size of watershed, changes in infiltration capacity, and changes in groundwater and surface-water storage capacities.

Direct runoff has been defined as the flow component directly associated with a storm event, and is , therefore, strongly influenced by land surface factors. It is hypothesized that changes in land use and surface cover will produce measurable changes in the direct runoff component. For this reason the direct runoff component was separated from total flow and studied because it was expected that direct runoff would more strongly reflect the effects of urbanization. However, baseflow and total flow are also affected by urbanization and, although the emphasis of this study is on direct runoff, baseflow and total flow were also analyzed.

With this basis for analysis, the following approach was used to quantify the effects of urban development on streamflow. To demonstrate changes in streamflow patterns resulting proncipally from changes in land use within the watershed, it is necessary to minimize the effects of meteorological factors. A simple way to accomplish this is to compare the streamflow pattern from an urbanized watershed with that from an undeveloped watershed within the same climatic region. The undeveloped watershed, herein called the control watershed, must meet two criteria; 1) it should be located near the urban watershed so that meteorological factors, such as rainfall magnitude and distribution, and soil moisture conditions are similar over both watersheds, and 2) no changes in physiographic factors of any hydrologic significance should occur during the period of analysis.

Double-Mass Curve Technique

A simple and straightforward tool for detecting changes in the streamflow characteristics of one watershed with respect to the streamflow characteristics of another watershed is by analysis of double-mass curves. A double-mass diagram is a plot of the accumulated values of one variable against the corresponding accumulated values of another variable and is useful in comparing long term trends between two variable and quantifying changes in those relationships. The values will plot as a straight line if the relationship between the two variables is linear. A break in the slope of the double-mass curve indicates a change in the proportionality constant between the two variables. The difference in the slope of the lines on either side of the break is a measure of the degree of change in the relation. In some cases the double-mass curve may be a curved line rather than a straght line. Such a situation is interpreted to imply a continuously varying relationship, or a non-linear relationship, between the variables being examined (Sharp, Gibbs, and Owen, 1968).

Several investigators have applied the double-mass curve technique to specific hydrologic studies. Hewlett and Hibbert (1961) studied the effect of logging operations on experimental watershed in the Coweeta Hydrologic Laboratory in North Carolina by comparing water yields from treated watersheds with yields from untreated watersheds. Franke (1968) used the technique to determine the effect of sanitary sewering on the average annual discharge of several streams on Long Island, N. Y. Harris and Rantz (1964) used the technique to study the relationship between rainfall and runoff in Permanente Creek, Mountain View, California. Wallace (1971) and Johnson and Sayre (1973) used the double-mass curve technique to compare runoff from urban watersheds and nonurban watersheds. These last two studies relate directly to this study and will be discussed later in this report. Other applications of the technique include checking the consistency of long term rainfall records and the consistency in sediment discharge.

The application and limitations of the double-mass curve technique to hydrology are discussed by Searcy and Hardison (1960), Sharp, Gibbs, and Owens (1968), Chang and Lee (1974) and to a limited extent by Harris and Rantz (1964). Searcy and Hardison discussed procedures to develop double mass curves for checking inconsistencies in precipitation streamflow, and sediment data. They also suggest a procedure for checking the statistical significance of breaks in the curves using analysis of covariance. Sharp, Gibbs, and Owens presented several techniques useful for analyzing and testing hydrologic data. They suggest careful evaluation of the data and the results of the double mass curve analysis to avoid making false conclusions based on breaks in the curves. Chang and Lee developed a computerized procedure for developing double mass curves and analyzing multiple inconsistencies in rainfall data. They suggest that double-mass analysis can be used to support or disprove suspected physical causes. Harris and Rantz used double-mass techniques to quantify increases in outflow of Permanente Creek, California, resulting from urbanization. They concluded that careful analysis of urban growth and its effect on streamflow must be made before trying to quantify these changes.

Other Methods

Other approaches that could have been taken to study the relationship between urban development and changes in runoff are 1) multiple-linear regression techniques and 2) watershed simulation using a digital model.

Multiple Regression Analysis

The purposes of the multiple regression analysis approach are similar to those in this report: (a) to study and determine the effects of urbanization on runoff volumes, (b) to develop a relationship, using regression analysis, to predict the changes in urban runoff as a function of physiographic and meteorological parameters, (c) to determine variations within the watersheds and among watersheds in the relationships developed, and (d) to provide guidelines for water managers and planners to control the impact of future development on watersheds.

The data required to perform this analysis are considerable. These include annual and seasonal components of total flow, baseflow, and direct runoff, annual and seasonal values of precipitation, annual and seasonal values of the departure from normal precipitation, estimates of evapotranspiration for each period, estimates of soil types, watershed and channel geometry, and an index to urbanization, such as the percentage of urban land in the watershed or the percentage of impervious area.

The following approach is suggested to perform a regression analysis and study changes in runoff volumes. Prepare a data matrix with the types of data that will be discussed subsequently. Because of the amount of data, computer storage is necessary. Perform a stepwise multiple linear regression analysis of the data to determine the independent variable required to give a "best" fit. The regression model may take the form

$$Y = A_o + A_1X_1 + A_2X_2 + \ldots + A_nX_n$$

where Y is the flow component of urban runoff, X's are the independent variables describing the physiographic and meteorological factors affecting runoff, and A's are regression coefficients.

Relationships should be developed for all data and also for regionalized or segregated data sets. The segregated data should porbably be separated by geographical regions, by soil types, or by degree of urbanization. Analyses can be made to determine the significance of each independent variable, thereby eliminating those variables that are not significant.

If valid and reasonable relationships are developed with this approach, a variety of planning information can be generated to predict the impact of future development. Predictive equations can be developed for use in making decisions regarding future developments.

Hammer (1973) attempted to relate by regression analysis the volumes of runoff from watersheds of various degrees of urban development in the metropolitan region of Philadelphia, Pennsylvania. He found the volume of runoff for a 48-hour period was proportional to an urbanization index (defined as 1 + I, where I is an impervious area index, which is a function of 1) the percentage of area of sewered streets and sidewalks, 2) percentage of impervious area associated with detached houses fronting on sewered streets and 3) other impervious area). However, the proportionality was different for different parts of the year. Also the volume was dependent on the recurrence interval and applied only to the western Philadelphia hydrologic area. The conclusions made regarding increased volumes of runoff are as follows: 1) It is highly probable that increases in runoff volumes due to urbanization become smaller with higher recurrence intervals; 2) runoff increases in the winter and spring (when the soils are frozen or near saturation) appear to be generally unimportant in that region.

Digital Watershed Simulation

The purpose of digital watershed simulation is: (a) to study and define the effects of urbanization on runoff volumes, (b) predict the impact of urbanization on runoff, (c) to study runoff relationships among watersheds of varying geographical locations, and (d) to assess the effects of alternative water management measures, such as detention and retention measures in the watershed, to aid in making water management decisions.

The simulation approach using a digital watershed model should follow these steps. Develop or find a watershed model that simulates the urban environment and is capable of simulating a variety of water management measures. The model should be versatile enough to simulate continuous or intermittent changes in watershed physiography over the years.

The model should be calibrated with two sets of data. One set should represent a period of 3-5 years at the beginning of the record. The second data set should represent the most recent 3-5 year period of watershed history. These periods should represent relatively stable watershed conditions as well as represent conditions before and after a significant period of urbanization. The results of this calibration will provide estimates of a range of parameters that can then be used for operation of the model over a long period of time.

The data required to perform a watershed simulation analysis include:

a. Precipitation data. This should include long-term hourly precipitation data representative of the rainfall over the watersheds being studied.

b. Evapotranspiration data.

c. Streamflow data. This should include diversions and waste effluents.

d. Physiographic data. This should include estimates of impervious area, changes in land use effecting drainage, and estimates of watershed parameters and initial watershed storage capacities.

The results of a simulation analysis will provide planners and water managers with a variety of information. A fully calibrated watershed model is useful not only in analyzing changes in runoff volumes but it can provide an instantaneous view of the hydrology of a watershed. Flood peaks and stage can be predicted. Effects of water management detentions and conservation measures can be evaluated quickly. Capacities of detention areas can be determined from model output to provide desired levels of streamflow. Frequency studies of flood peaks and volumes can be made using long term rainfall records. At ungaged watersheds, the model can be used with regionalized estimates of parameters to provide reasonable assessments of the impact of future development on flood peaks and volumes.

The digital watershed models suggested for use in this type of study are:

1. Kentucky Watershed Model (KWM)
2. STORM - Urban Storm Runoff Model
3. Illinois Urban Drainage Area Simulator (ILLUDAS)
4. USGS Rainfall-Runoff Model (Urban Model)

ILLUDAS and USGS Rain-Runoff Model are not continuous simulators but a suggested study approach is discussed along with the description of ILLUDAS. (See Appendix F).

James (1965) used the Stanford Watershed Model to develop a long term hydrograph (1905-1963) for Morrison Creek, Sacramento, California. The effects of urbanization on the volumes and seasonal distribution of flow were analyzed. Channel improvement increased yield slightly but substantially modified the hydrograph shape and the peak discharge. In the simulated watershed the effects of complete urbanization over a 10-year period results in 1) a reduction in baseflow of about 30 percent, 2) an increase in surface runoff by as much as six times the rural value in the wettest year, and 3) an increase in surface runoff of more than 125 times the rural value in the dryest year.

Dempsey (1968) developed a procedure to synthesize the volume of total runoff for the mean-annual and 200-year event as a function of urbanization and channelization. Runoff hydrograph data from Morrison Creek near Sacramento, California, and Pond Creek near Louisville, Kentucky were used in a computer model to simulate additional data on the volume of runoff for the mean annual event from each watershed under different conditions of urbanization, channelization and drainage area. The 200-year event was computed from the Gumbel equation using the mean-annual discharge events. The results of this procedure provided a method of estimating flood volumes for an area by knowing the desired flood frequency, drainage area, degree of urbanization and channelization. In the Dempsey study, volumes were used along with flood peaks to synthesize a flood hydrograph for use in a computer model that analyzed for economic advantages of alternative flood control measures.

The double-mass curve technique was chosen for use in this study because it was thought that by comparing two watersheds (one urbanizing and one undeveloped) that changes in runoff volumes would be related mainly to changes in physiographic factors and specifically those factors related to man activities. It was also thought that the influence of these factors (impervious area, drainage improvements, etc) could be lumped together and quantified in a single index, such as the amount of land converted to urban use, thus reducing data requirements. Other methods of analysis require detailed data describing all factors influencing the physical, hydrologic and meteorological system. In most cases, data describing physical changes in the watershed over the years has not been recorded and is difficult to quantify. Therefore, for the purpose of investigating changes in runoff volumes, the double-mass curve technique was selected as the method of analyzing streamflow records.

The following sections of this report describe the methods used to analyze land use data and streamflow data. The results of these analyses are discussed including a discussion of the relationship between changes in urban land and changes in runoff. Implications of the results of this study for the water manager is discussed along with a section on recommendations for further studies.

CHAPTER III

ANALYSIS OF DATA

The first step in the data analysis procedure was to determine the amount of urban development in each urban watershed and the change in urban land and impervious cover for selected periods of time. Streamflow records for the urban and control watersheds were analyzed and double-mass curves were prepared of the volumes of runoff from the urban watershed and the corresponding volumes from the control watershed. Changes in the slope of the double-mass curve relationship between selected periods of time were then determined. Where there was no evidence to the contrary, these changes in slope were assumed to represent changes in the runoff relationship resulting from urbanization. The relationship between the changes in urban land and the changes in runoff volumes was then analyzed.

Attempts were made to determine the double-mass relationship between runoff from an urban watershed and the precipitation recorded near that watershed. This analysis produced unreliable results because of the nonlinear relationship between rainfall and runoff and because of the influence of other meteorological factors, such as droughts. Results of this analysis are presented in Appendix C for the interested reader.

Land-Use Analysis

Figure 1 shows the locations of the urban watersheds selected for use in this study. The selection of watersheds was based principally on the availability of adequate long term hydrologic and land use data and on a desire to minimize the effects of snowfall. Table 1 lists the urban watersheds chosen for study, precipitation stations in or near the urban watersheds, and the control watersheds. The table includes pertinent information on drainage areas, length of record and location of the control with respect to the urban watershed. A detailed description of physiography, urban development and streamflow of each watershed is presented in Appendix A of this report. A description of pertinent data on the precipitation stations used in this study is given in Appendix B.

Historical land use information on each watershed in most cases was difficult to obtain. Available information on impervious cover and changing land use patterns was compiled from various publications. The portion of each watershed classified as "urban land" as well as other information was obtained from U. S. Geological Survey topographic maps. Urban land is defined, for purposes of this study, as all the red-tinted areas within the watershed boundaries on USGS 7-1/2 minute topographic maps. Red tint is used on USGS topographic maps to demark heavily built-up areas larger than approximately three-fourths of a square mile (U. S. Dept. of Interior, 1969). Some exceptions and additions were made in this study to the estimate of red tinted urban land where additional information was available or where parcels of land smaller than three-fourths of a square mile were heavily developed. Urban land includes roads, houses, commercial and industrial areas as well as associated land uses such as parks, ball fields, and golf courses. Land excluded from the "urban" category includes tracts of farmland, forestland, and other open spaces such as game preserves and institutional lands which have little or no impervious cover.

Urban land was planimetered from the USGS topographic maps and the

Table 1. List of Urban Watersheds and Their Corresponding Precipitation Station and Control Watershed Showing Common Periods and Length of Common Record.

Urban Watershed	Precipitation Station			Control Watershed		
	Name	Common Period of Record	Length of Common Period (years)	Name	Common Period of Record	Length of Common Period (years)
E. Meadow Brook, Freeport, N.Y.	JFK International Airport, N.Y.	1952-62	11	Connetquot River Oakdake, N.Y.	1944-62	19
Pines Brook, Malverne, N.Y.	JFK International Airport, N.Y.	1952-69	18	Connetquot River, Oakdale, N.Y.	1944-69	26
N. Buffalo Creek, Greensboro, N.C.	Greensboro Airport, Greensboro, N.C.	1949-70	22	E. Fork Deep Riv. High Point, N.C.	1929-70	42
Little Sugar Creek, Charlotte, N.C.	Charlotee Airport Charlotte, N.C.	1949-70	22	----		
Peachtree Creek, Atlanta, Georgia	Atlanta Airport and Norcross W.B. Sta.	1959-70	12	Yellow River, Snellville, Ga.	1959-70	12
Sims Bayou, Houston, Texas	Houston Airport, Houston, Texas	1953-70	18	Cypress Creek, Westfield, Texas	1953-70	18
Brays Bayou, Houston, Texas	Houston Airport, Houston, Texas	1949-70	22	Cypress Creek, Westfield, Texas	1949-70	22

Table 1. List of Urban Watersheds and Their Corresponding Precipitation Station and Control Watershed Showing Common Periods and Length of Common Record-- continued.

Urban Watershed	Precipitation Station			Control Watershed		
	Name	Common Period of Record	Length of Common Period (years)	Name	Common Period of Record	Length of Common Period (years)
Whiteoak Bayou, Houston, Texas	Houston Airport Houston, Texas	1949-70	22	Cypress Creek, Westfield, Texas	1949-70	22
Halls Bayou Houston, Texas	Houston Airport, Houston, Texas	1953-70	18	Cypress Creek, Westfield, Texas	1953-70	18
Greens Bayou Houston, Texas	Houston Airport, Houston, Texas	1953-70	18	Cypress Creek, Westfield, Texas	1953-70	18
Morrison Creek, Sacramento, Calif.	Sacramento Airport Sacramento, Calif.	1960-70	11	----		

percentage of the total watershed area was calculated for two points in time on most watersheds. These percentages are listed in Table 2.

The ratio of urban land to total area is a gross measure of the degree of watershed development and the difference in this ratio from one period to the next is a gross measure of the degree of urbanization that occurred during the period. Figure 2 shows the percentage of urban land at different times for each of the urban watersheds. This graph illustrates the magnitude of the increase in urban area in the watersheds.

There is a wide range in degree of urban development in the watersheds used in this study. Pines Brook, Long Island, New York, is the most heavily developed watershed with 91 percent of the total watershed in urban land uses in 1968. The least developed watershed is Greens Bayou near Houston, Texas, where only 5 percent of the watershed was developed for urban use in 1967.

Impervious area is defined as all areas rendered impervious to infiltration of rainfall and includes streets, rooftops, sidewalks, parking lots, highways and other surfaces. Estimates of impervious cover as a percentage of the total watershed area have been made for at least one point in time on each of the urban watersheds and for some watersheds for more than one point in time. These estimates are listed in Table 2 along with the source of the estimate.

The method of determining impervious area differed among the several sources. For example, Wallace (1971) and Martens (1968) used a sampling technique that involved counting the number of grid intersections overlying impervious areas on aerial photographs or maps. The proportion of intersections overlying impervious area to the total number of intersections

Table 2. Summary of Urban Land Use And Estimates Of Impervious Area For Each Watershed As A Percentage Of The Total Area.

Watershed	Drainage Area (smi)	Urban Land Use: Year of Estimate	Urban Land Use: Percentage Of Total Area	Increase in Urban Land Use: Percentage Of Total Area	Increase in Urban Land Use: Area (smi)	Impervious Area: Year of Estimate	Impervious Area: Percentage Of Total Area	Source
E. Meadow Brook	10.0	----	-----			1938	6	Seaburn (1969)
		----	-----			1949	8	-do-
		1955	41			1952	12	-do-
		1967-9	75	34	3.4	1968	20	-do-
Pines Brook	10.0	1955	60			----	----	
		1968	93	33	1.5	1968	30	-do-
N. Buffalo Creek	37.0	1951	25			----	----	
		1968	50	25	9.1	1972	5* (15)	Putnam (1972)
E. Sugar Creek	41.0	1948-9	40			----	----	
		1967-9	74	34	14.0	1972	15* (20)	Martens (1969)
Peachtree Creek	86.8	1949	23			1949	22	Wallace (1971)
		1954-55	32	9	7.8	1955	28	-do-
		1968	72	40	35	1966	35	-do-
Sims Bayou	64.0	1955	10			----	----	
		1969-70	29	19	12.2	1969	11	Johnson and Sayre (1973)
Brays Bayou	88.4	----	-----			1945	2	-do-
		1955	14			1955	4	-do-
		1967	35	21	18.6	1969	15	-do-
Whiteoak Bayou	84.7	1955	11			----	----	
		1967	17	6	5.1	1969	9	-do-
Halls Bayou	24.7	1955	20			----	----	
		1967	40	20	4.9	1969	7* (10)	-do-
Greens Bayou	72.7	1955	0			----	----	
		1967	5	5	3.6	1969	3	-do-
Morrison Creek	48.6	1955	19			----	----	
		1967	22	3	1.5	1961	10	James (1965)

* The published estimate of impervious cover is considered too low. The authors estimate based on independent computations of impervious cover are given in parenthesis.

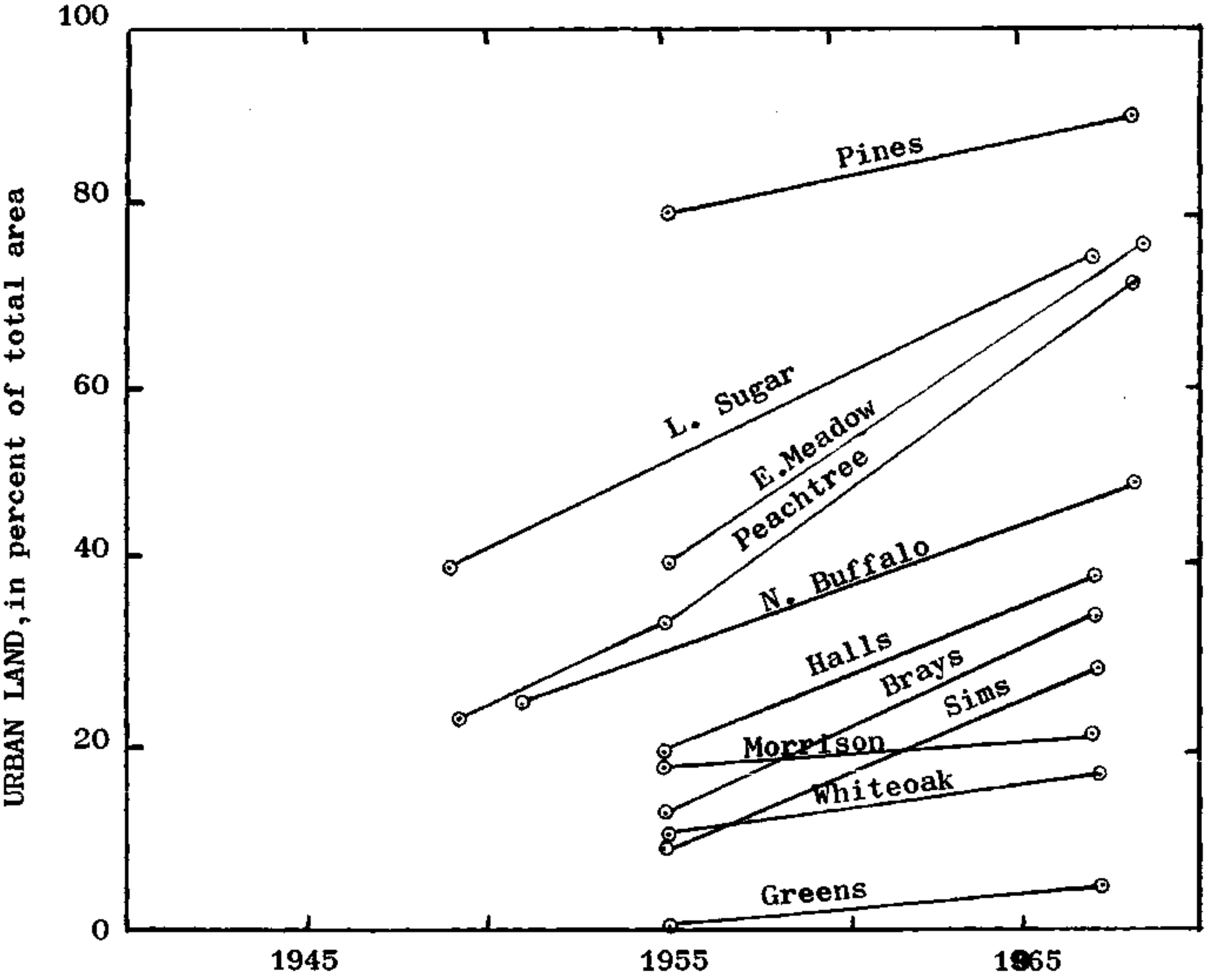

Figure 2. Change in Percentage of Urban Land in Each Urban Watershed.

is regarded as the percentage of impervious area. Seaburn (1969), Johnson and Sayre (1973), and James (1964) estimated impervious area by measuring the areas from maps and aerial photographs or by field observations. No attempt was made in this study to determine the accuracy or reliability among techniques.

However, certain published estimates of the percentage of impervious area appeared to be low, based on observation of the type and extent of land use in the watershed. On the recommendation of personnel familiar with the watershed characteristics (E. F. Hubbard, North Carolina and S. L. Johnson, Houston, Texas, personal communication, 1972), the published estimates of impervious cover for North Buffalo Creek and Little Sugar Creek in North Carolina and Halls Bayou in Houston, Texas, were adjusted upward by multiplying the area in each type of land use in the watershed by an average percentage of impervious area associated with that type of land use (see Martens, 1968, Seaburn, 1969, and Stankowski, 1972). The adjusted estimate of impervious area was then made by summing the products and dividing by the total watershed area. The adjusted estimates are listed in Table 2 and are the values used in the analysis.

Stankowski (1972) discussed a procedure whereby population density was used to predict a range of impervious cover. Although these procedures could provide a rough check of the estimates of urban land and impervious area, it was decided that the estimates did not provide the accuracy to warrant the work involved in compiling detailed census tract data on each watershed for several periods in time.

Streamflow Analysis

The objective of the streamflow analysis was to quantify changes in the volume of runoff from urbanizing areas. The procedure was to separate the total hydrograph into two runoff components -- baseflow and direct runoff. Annual and seasonal volumes of each of these flow components were accumulated. This was done for the period of streamflow record for the urban watershed and for the control watershed. The accumulated volumes from the urban watershed were plotted versus the corresponding volumes from the control watershed. The resulting double-mass curve was then analyzed for changes in slope in the relationship. The magnitude of the change in slope from one period to another was evaluated as a percentage change over an average base or beginning period.

This section describes the computational procedures used for the analysis of streamflow records.

Hydrograph Separation

The total streamflow hydrograph from each watershed (urban and control) was separated into two flow components -- baseflow and direct runoff. A separation technique had to be developed that 1) was easily adopted by use in a computer program and 2) provided results comparable among the watersheds.

In general, three techniques are available to separate total streamflow. These may be categorized as (1) gradient technique, (2) baseflow recession technique and (3) watershed simulation technique.

The gradient technique involves drawing a line or a combination of lines beginning at the point of rise on the storm runoff hydrograph to an arbitrary point on the recession limb. The volume of discharge above this line is said to be direct runoff and the volume below the line is said to be baseflow. One simple gradient technique is to extend a line horizontally from the point of rise of a storm hydrograph until it intersects the recession limb of the hydrograph. Variations of this procedure use gradients that increase baseflow an incremental amount while storm runoff is occurring. Another procedure is to extend the baseflow recession curve prior to the runoff event to a point beneath the hydrograph peak. From this point a line is drawn to intersect at some point on the recession limb of the hydrograph. The point at which direct runoff stops and the streamflow returns to baseflow on the recession limb of the hydrograph is arbitrarily chosen.

The baseflow recession technique for separating total streamflow into components was first described by Barnes (1940). The hydrograph of streamflow is plotted on semilogarithmic paper. The recession limb of the hydrograph must extend forward in time enough to ensure that baseflow is the only component of flow and plots approximately as a straight line. The recession curve is then extended backward under the hydrograph to a point beneath the inflection point of the hydrograph. This point and the point of rise are connected with a straight line to complete the baseflow separation line. Barnes suggests that the quantity of discharge above the separation line includes subsurface flow as well as direct runoff. By repeating the procedure described above on that portion of dishcarge above the line the subsurface component can also be separated out. This procedure is somewhat more complicated than the gradient technique and requires simple, well defined storm hydrographs to determine the recession lines.

The watershed simulation technique can also be used to estimate the quantities of each component making up the total streamflow. Several computer programs, such as the Stanford Watershed Model and its modified versions, are now available to synthesize the runoff cycle of a watershed. These programs account for moisture entering, stored in, and leaving a particular watershed as governed by estimates of hydrologic parameters. Output from an optimized simulation run can include estimates of the value of each component contributing to streamflow, thereby providing another estimate of a separation technique. However, use of this technique for the sole purpose of estimating the components of flows would be costly and time consuming.

The simple gradient method was chosen for this study because it is easy to incorporate into a computer program. The other two techniques were not formally investigated in this study because the level of work required to develop the procedures was considerably more than that required for the simple gradient method which provided comparable results.

Selecting a gradient that consistently intersected the recession limb approximately at the point where flow had returned to baseflow insured that the results -- that is the quantities of each flow component -- could be compared among watersheds. As illustrated in Figures 3 and 4, the technique was applied to both simple and complex hydrographs.

Figures 3 and 4 are graphs of daily discharge at Peachtree Creek showing examples of the hydrograph separation technique employed. The graphs are selected portions of the annual hydrograph where the peak flows have not been plotted in order to emphasize the baseflow component. Figure 3 covers the period March 15 to April 30, 1959, and Figure 4 covers the period March 15 to April 30, 1969. These two periods were chosen to

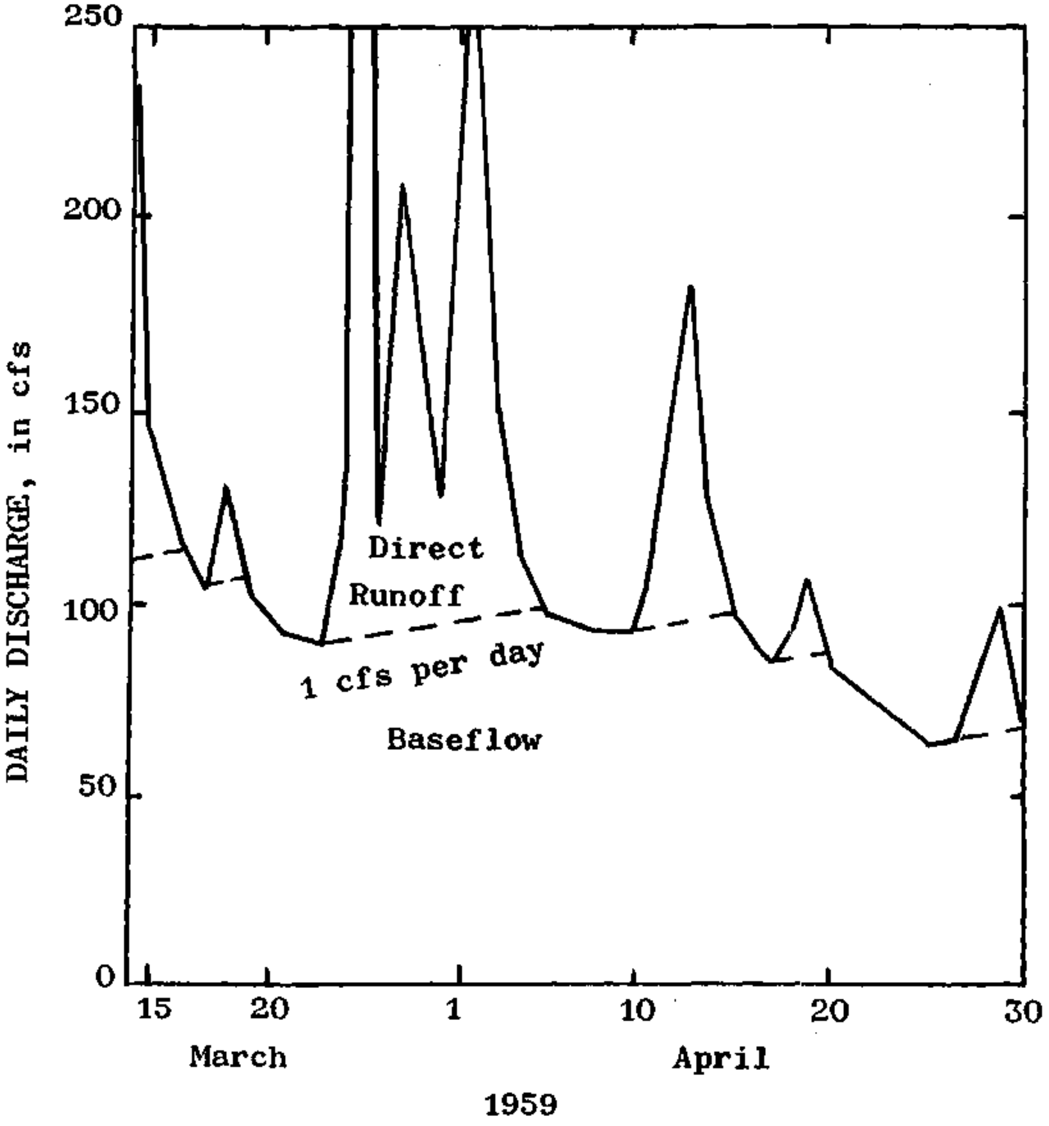

Figure 3. Segment Of Annual Hydrograph Illustrating Technique Used To Separate Direct Runoff And Baseflow For Peachtree Creek, Georgia, 1959.

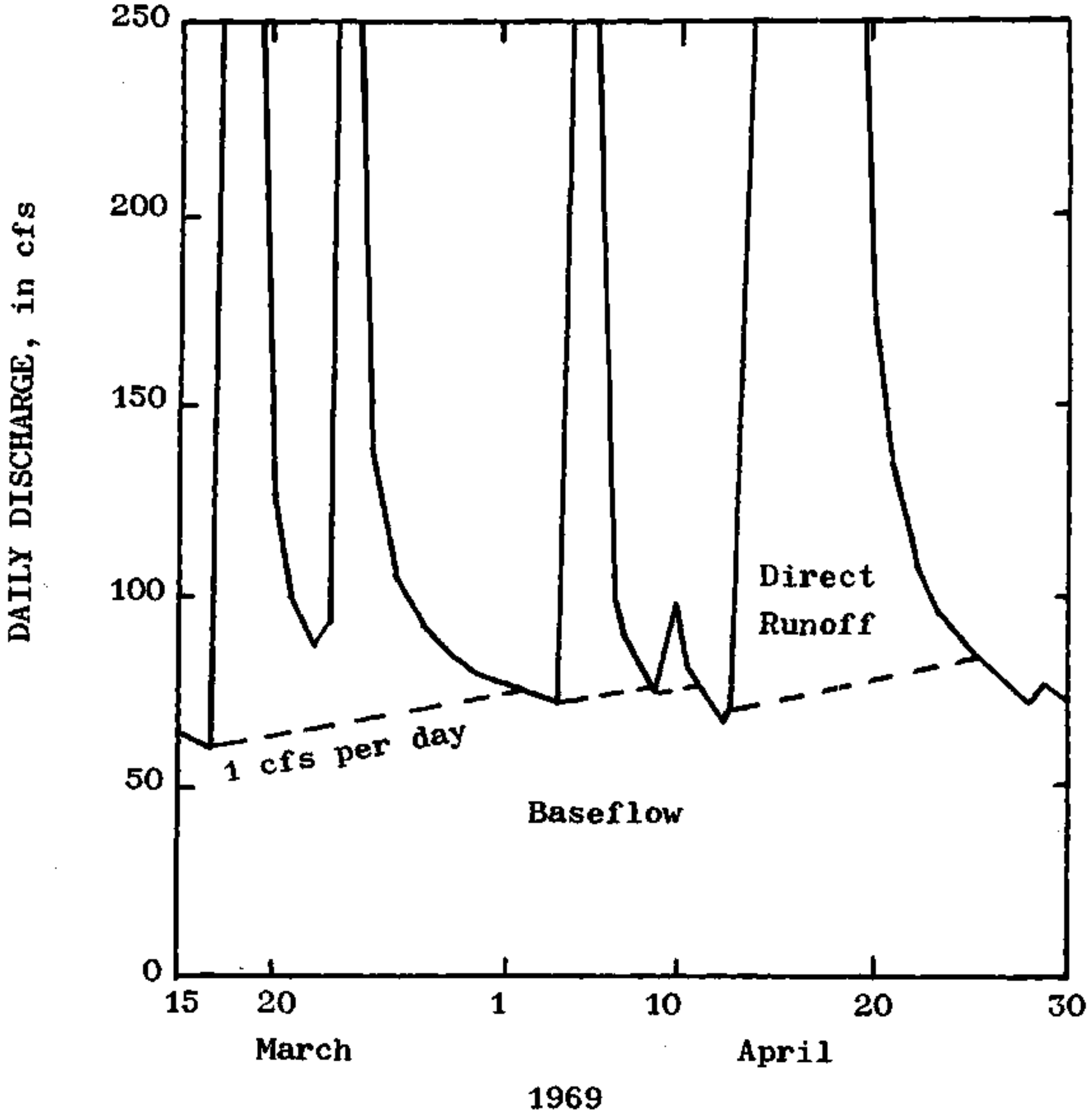

Figure 4. Segment Of Annual Hydrograph Illustrating Technique Used To Separate Direct Runoff And Baseflow For Peachtree Creek, Georgia, 1969.

illustrate the use of the separation gradient before and after urban development. Even though the Peachtree Creek watershed contained considerable urban development prior to 1959 a significant amount of urban development occurred between 1959 and 1969 (see Table 2).

The procedure used was to choose the gradient that consistently intersected the recession limb of simple hydrographs at a point approximately $A^{0.2}$ days after the peak, where A is drainage area in square miles (Linsley, Kohler, and Paulhus, 1958). The point $A^{0.2}$ days after the peak was used only as a guide and was useful only for larger watersheds -- those greater than about 20-30 square miles -- where the time of concentration is on the order of days rather than hours. This point was about 2.5 days after the peak on the Peachtree watershed. Another useful guide was to inspect a linear plot of total flow for abrupt changes in slope in the recession limb. The point at which the abrupt change occurs indicate the cessation of direct runoff and the return to baseflow (Chow, 1964 p. 14-8 to 14-12). The final selection of a separation gradient, although arbitrary, was guided by these considerations.

The value of the separation gradient was chosen after inspecting plots similar to Figures 3 and 4 for different separation gradients. For the Peachtree Creek Watershed the separation gradient was 1 cfs per day. Different values were chosen for the other watersheds. These are listed in Table 3 and range from 0.25 to 2.00 cfs per day.

Appendix D contains an annual hydrograph for each of the urban and control streams used in this study, except for Brays Bayou, Whiteoak Bayou, Halls Bayou and Greens Bayou in Houston, Texas. Sims Bayou in Houston, Texas, is representative of the other urban streams in that area.

The hydrograph of the first calendar year of each streamflow record is presented to illustrate the gradient technique used to separate streamflow into baseflow and direct runoff components.

A study was made to determine the difference involumes of baseflow and direct runoff resulting from computation using different separation gradients. The total streamflow for one year at each stream was separated into the two components using two different separation gradients. The change in the volume of direct runoff resulting from a change in the separation gradient is reported in Table 3 as a percentage of total annual streamflow. The gradient chosen for use in the analysis is indicated by an asterisk in Table 3. This data illustrates that a moderate to large change in the separation gradient (200 and 400 percent change) results in a relatively small change in the volume of each of the components.

Therefore, this study of separation gradient shows that as long as the gradient separates the hydrograph reasonably well, based on the criteria discussed above, in both wet and dry periods and throughout the urbanizing process, the precise value of the gradient is unimportant because changes in the flow component are only about 3-4 percent of the total flow for large changes in the value of the gradient. In other words, the value of the flow component is relatively insensitive to the separation gradient, if the gradient is reasonable.

Analysis of Double-Mass Curves

After the total hydrograph for each watershed was separated into baseflow and direct runoff, annual and seasonal summaries of runoff were prepared. Annual and 3-month seasonal accumulations were made. The 3-month

Table 3. Values Of Baseflow And Direct Runoff Resulting From Selected Separation Gradients And The Percentage Change In Each Component Resulting From The Different Separation Gradients.

Watershed	Year	Separation Gradient (cfs per day)	Total Flow (in.)	Baseflow (in.)	Direct Runoff (in.)	Percentage Change In Flow Component To Total Flow
E. Meadow Brook	1938	0.25	7.11	5.78	1.23	
		.50*	7.11	6.06	1.05	2.67
Pines Brook	1938	.25	8.08	7.21	.88	
		.50*	8.08	7.42	.66	2.60
Connetquot River	1944	.50	21.04	19.45	1.59	
		1.00*	21.04	19.80	1.24	1.66
N. Buffalo Creek	1929	.50	16.72	6.63	10.09	
		1.00*	16.72	7.18	9.54	3.29
E. Fork Deep River	1929	.25*	15.17	6.53	8.64	
		.50	15.17	6.87	8.30	2.24
L. Sugar Creek+	1929	.50	12.35	5.42	6.93	
		1.00*	12.35	5.62	6.73	1.62
Peachtree Creek	1959	.50	11.68	5.93	5.75	
		1.00*	11.68	6.57	5.11	5.48
Yellow River	1943	1.00	20.68	8.93	11.75	
		2.00*	20.68	9.43	11.20	2.42
Sims Bayou	1953	.25*	10.10	1.32	8.88	
		1.00	10.10	1.72	8.38	3.96
Halls Bayou	1953	.25*	6.70	.41	6.30	
		1.00	6.70	.64	6.07	3.43
Greens Bayou	1953	.25*	6.30	.22	6.08	
		1.00	6.30	.48	5.82	4.13
Cypress Creek	1945	.50*	16.52	.78	15.74	
		1.00	16.52	.94	15.59	.97
Morrison Creek+	1960	.25*	2.04	.89	1.15	
		1.00	2.04	1.15	.89	12.74

* Separation gradient marked with an asterisk denotes the values selected for use in this study.

\+ These watersheds were only used in the rainfall-runoff analysis discussed in Appendix C.

seasons consisted of Fall (October, November and December), Winter (January, February and March), Spring (April, May and June), and Summer (July, August and September). Double-mass curves were then prepared by plotting accumulated annual or seasonal runoff from the urban watershed versus the corresponding accumulated values of runoff from the control watershed.

Each double-mass curve was inspected to determine periods with a more or less constant relationship between urban runoff and control runoff. These periods are referred to as periods of analysis. Table 4 lists the periods of analysis determined for the urban and control watersheds used in this study.

The following example is given to illustrate the procedure used to determine changes in runoff from the urban watershed compared with runoff from the control watershed. Figure 5 is a double-mass curve of annual direct runoff from East Meadow Brook Watershed (urban) versus annual direct runoff from Connetquot River Watershed (control) for the period 1944-62. Three periods of analysis are indicated -- 1944-51, 1952-57, and 1958-62. For purposes of discussion, the first period of analysis, as shown in Table 4, will be referred to as the "base period". The base period is used as a basis to demonstrate the magnitude of change in the runoff relationship in the subsequent period. The base period is not to be construed as representing watershed conditions prior to urban development because in most cases streamflow data do not exist for preurbanization periods. The base period represents watershed conditions prior to periods of additional urban growth.

Table 5 illustrates the computational procedures used to determine the percentage increase in the ratio of urban direct runoff to control di-

Table 4. Periods Of Analysis For The Relationship Between Runoff From The Urban Watershed And Runoff From The Control Watershed.

Urban Watershed and Control Watershed	Period of Analysis				
	1	2	3	4	5
East Meadow Brook and Connetquot River	1944-51	1952-57	1958-62		
Pines Brook and Connetquot River	1944-51	1952-57	1958-62		
North Buffalo Creek and East Fork Deep River	1929-41	1942-49	1950-56	1957-63	1964-70
Peachtree Creek and Yellow River	1959-62	1963-66	1967-70		
Sims Bayou and Cypress Creek	1953-57	1958-61	1962-65	1966-70	
Brays Bayou and Cypress Creek	1949-57	1958-61	1962-65	1966-70	
Whiteoak Bayou and Cypress Creek	1949-57	1957-61	1961-66	1966-70	
Halls Bayou and Cypress Creek	1953-57	1958-61	1962-65	1966-70	
Greens Bayou and Cypress Creek	1953-57	1958-61	1962-65	1966-70	

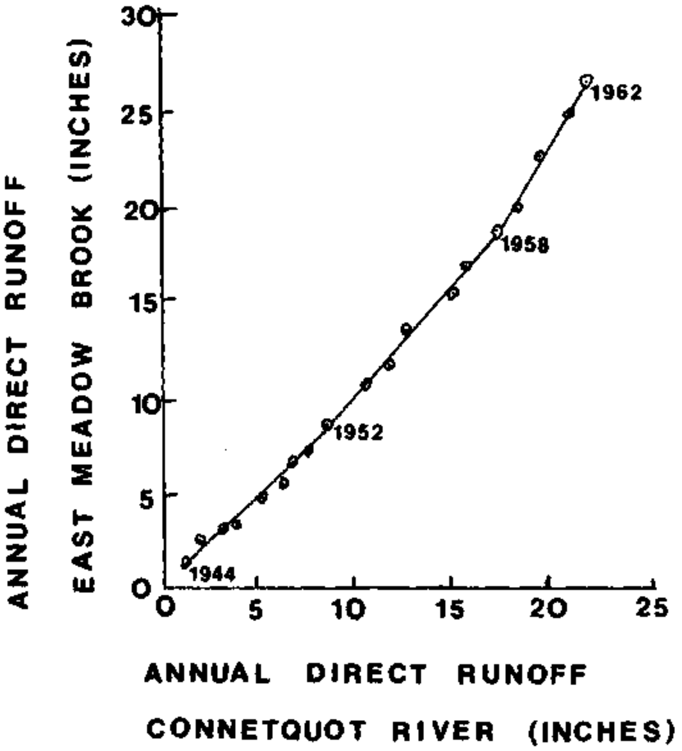

Figure 5. Double-Mass Diagram of Accumulated Annual Direct Runoff From East Meadow Brook Versus Accumulated Annual Direct Runoff From Connetquot River (1944-62).

rect runoff. The average ratio of annual direct runoff from the urban watershed to direct runoff from the control watershed for each period of analysis was determined by computing the average value of the annual ratios in each period. In this example, the average ratio for the base period 1944-51 was 0.9340. The average ratio for the succeeding period 1952-57 was 1.3004. This represents a 39 percent increase in the ratio over the base period. The average ratio for the next period, 1958-62, was 1.511, or a 18 percent increase in the ratio over the last period, and a 64 percent increase in the ratio over the base period. Because the control watersheds were chosen such that 1) the physiographic factors did not change over the period of streamflow record and 2) climatic factors were similar to those in the urban watershed, the percentage increase in the ratio of urban direct runoff to control direct runoff is an estimate of the percentage increase in the direct runoff from the urban watershed. That is to say, the 64 percent increase in the ratio from 1944-51 to 1958-62 is considered to represent the increase in direct runoff from East Meadow Brook Watershed during that time. A similar procedure was used to determine changes in total flow and baseflow among the corresponding periods of analysis. Changes in seasonal values were computed similarly.

Table E1 lists the results of the double-mass-curve analysis of runoff from each urban watershed. The table contains the average ratio of urban watershed runoff to control watershed runoff for each period of analysis including the percentage change in the ratio over the preceding period and the base period. The ratios of annual total flow, baselfow and direct runoff and the 3-month seasonal values of total flow, baseflow, and direct runoff have been compiled.

Table 5. Computational Procedure Used To Determine The Percentage Increase In The Ratio Of Urban Runoff (East Meadow Brook, 1944-62) To Control Runoff (Connetquot River, 1944-62) Over The Base Period

	Annual Direct Runoff (Inches)		Ratio Of Urban To Control	Percentage Increase Over Base Period
Water Year	Urban	Control		
1944	1.50	1.22	1.224	
1945	.76	.74	1.038	
1946	.97	1.25	.774	
1947	.45	.69	.655	
1948	1.13	1.23	.920	
1949	1.01	1.07	.942	
1950	.51	.49	1.035	
1951	.76	.86	.881	
Avg.			.9340	Base Period
1952	1.61	1.12	1.437	
1953	1.56	1.63	.960	
1954	1.33	1.49	.891	
1955	2.14	1.09	1.974	
1956	1.46	2.15	.677	
1957	1.03	.55	1.859	
Avg.			1.3004	39
1958	2.13	1.61	1.321	
1959	1.54	.99	1.555	
1960	2.56	1.46	1.746	
1961	2.04	1.24	1.642	
1962	1.64	1.19	1.370	
Avg.			1.5311	64

CHAPTER IV

DISCUSSION OF RESULTS

The results of this study are discussed in three parts. The first part is a discussion of the analysis of land use changes; the second is a discussion of the results of the streamflow analysis; and the third is a discussion of the relationship between the streamflow changes and land use changes.

Results Of The Analysis Of Land-Use Changes

Table 2 summarizes the data compiled on the magnitude of urban land use and estimates of impervious area at various times. The definition and methods used to determine urban land use are discussed earlier in this report. Estimates of impervious area were compiled from published reports which are referenced in Table 2.

At least two estimates or urban land use were made: The earlier estimate was for 1948-9, 1951 or 1955 and the later estimate was for 1967-70. In each watershed, except Greens Bayou watershed, there was a substantial amount of land being used for urban purposes during the earlier period. The available information does not allow one to estimate urban land use in these watersheds prior to about 1950. A wide range in the degree of watershed development is included in the watersheds selected for analysis. The most intensely developed watershed is the Pines Brooks watershed -- 91 percent of the area was urban land in 1968 -- and the least developed watershed was Greens Bayou -- five percent urban land in 1967.

The percentage increase between the earlier period and the later period is also listed in Table 2 along with the amount of area developed. The largest increase occurred in the Peachtree Creek watershed between 1954-55 and 1968. During this period 35 square miles or about 40 percent of the watershed was developed for urban uses. The smallest increase in terms of the amount of land converted to urban uses was in the Pines Brook watershed where only 1.1 square miles were developed between 1955 and 1968. In a comparable period the Morrison Creek watershed (a watershed used in the runoff-precipitation analysis discussed in Appendix C) had the smallest percentage increase, about three percent.

At least one estimate of impervious area for each watershed was made and these are also listed in Table 2. Three watersheds -- East Meadow Brook, Peachtree Creek and Brays Bayou -- have had estimates of impervious area made at several periods of time. The estimate of impervious cover for all watersheds range from about two percent to 35 percetn of the total area. The largest percentages of impervious area are associated with the most intensely developed watershed, that is, East Meadow Brook, Pines Brook and Peachtree Creek, and range up to about one-third of total watershed area.

In many cases, the year of estimate of urban land and the corresponding year of the estimate of impervious area differ by 2-4 years. Adjustments in the estimate of urban land were made by determining the percentage of urban land from Figure 2 for the year that the estimate of impervious area was made. These adjustments resulted in a change of 2-5 percentage points in the estimate of urban land, except for the Little Sugar Creek watershed (a watershed used only in the runoff-precipitation analy-

Table 6. Values Of Percentage Of Urban Land Adjusted Using Figure 2 And Corresponding Value Of Impervious Area.

Watershed	Year	Adjusted Urban Land (Percent)	Impervious Area (Percent)
E. Meadow Brook	1955	33	12
	1968	75	28
Pines Brook	1968	91	30
N. Buffalo Creek	1968	55	5 (15)
L. Sugar Creek	1968	84	15 (20)
Peachtree Creek	1949	23	22
	1955	32	28
	1968	65	35
Sims Bayou	1969	29	11
Brays Bayou	1955	14	4
	1967	38	15
Whiteoak Bayou	1967	18	9
Halls Bayou	1967	44	7 (10)
Greens Bayou	1967	7	3
Morrison Creek	1967	20	10

( ) indicates adjusted data.

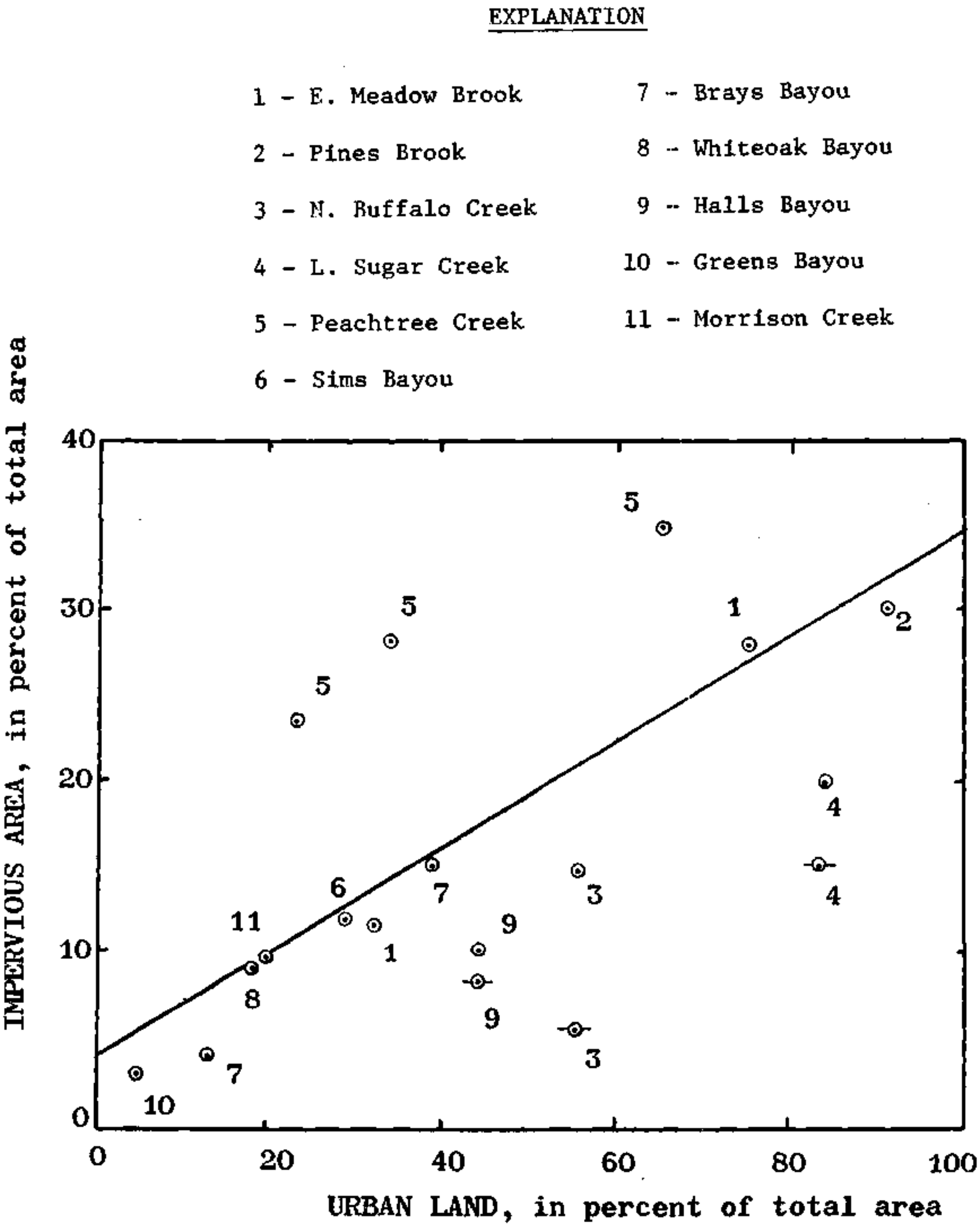

Figure 6. Relationship Between Percentage Urban Land and Percentage Impervious Area.

sis discussed in Appendix C) where the adjustment resulted in a change of 10 percentage points.

The adjusted estimated of urban land and the estimates of impervious area are shown in Table 6 and plotted in Figure 6. A line, determined by the method of least squares, was drawn through the data. A correlation coefficient of 0.70 and a standard error of 7.35 percent were determined.

Figure 6 also has plotted the published data of impervious area for North Buffalo Creek, Little Sugar Creek and Halls Bayou as flagged circles. Using this data rather than the adjusted estimates of impervious area (see Table 2) resulted in a correlation coefficient of 0.59 and a standard error of estimate of 8.72 percent.

The data used to prepared Figure 6 represent typical watershed conditions; that is to say, the watersheds contain a mixture of land uses and no one type of alnd use dominates the hydrology of the watershed. Figure 6 shows that the percentage of impervious area increases as the percentage of urban land in the watershed increases. The data indicates that if the watersheds examined in this study were fully developed (100 percent urban land) they would contain, on the average, about 35 percent impervious area. Watersheds with more open space and less urban area would contain a smaller percentage of impervious area. The relationship also indicates that with no urban land the percentage of impervious area in the watershed is about 4 percent. This is a reasonable estimate considering that in an unurbanized watershed the roads and scattered houses could account for this small percentage. Johnson and Sayre (1973) and Putnam (1972) have used an estimate of one percent to represent the average imperviousness of rural or undeveloped watersheds.

Results Of Streamflow Analysis

This section summarized the changes in annual and seasonal streamflow at each urban watershed over the period of record. As mentioned earlier, information on the amount of land used for urban pruposes or on the amount of impervious area is not available for the entire period to correlate with these changes in streamflow. Nevertheless, some information is available to help explain these changes even theough it is not quantifiable.

East Meadow Brook

Analysis of streamflow records were divided into three periods -- 1944-52, 1952-58, and 1958-62. The period 1962-66 was not analyzed because the streamflow gage was discontinued for a 12-month period beginning in 1963. Significant urban development occurred in the early 1950's in the East Meadow Brook watershed. Therefore, the base period, 1944-52, represents pre-urban conditions because only small areas had been developed up to this time (Seaburn, 1969). Between the base period and the period 1958-62 direct runoff increased nearly 64 percent while total flow increased only about eight percent and baseflow declined more than four percent. These changes were determined by comparison with the control watershed. The decline in baseflow resulted from the effects of increased pumpage from the groundwater reservoir to supply fresh water to the increased number of inhabitants.

The largest increase in direct runoff compared with direct runoff from the control watershed occurred in the summer (dry) months -- about 86 percent between 1944-52 and 1958-62 -- while the smallest increase occurred in the winter (wet) months -- about 34 percent between the same periods.

Baseflow declined slightly during winter, spring and summer and increased slightly during fall over the period of record. Total flow increased by 24 and 16 percent in the summer and fall season but was essentially unchanged in the winter and spring season.

Pines Brook

The Pines Brook watershed was affected by urbanization during approximately the same periods as the EAst Meadow Brook watershed. As a consequence of development direct runoff increased more than 75 percent between the base period, 1944-52, and the period 1958-62 when compared with runoff from the control watershed. However, between the same periods total flow and baseflow declined continually as a result of increased pumpage and the installation of sanitary sewers (Franke, 1968).

The period 1963-69 was a period of extreme drought in the Northeastern United States. The effect of this drought is exhibited in the data for Pines Brook. Between 1958-62, a period of about normal rainfall, and 1963-69, annual total flow decreased nearly 74 percent, baseflow decreased about 85 percent and direct runoff decreased nearly 32 percent compared with the control watershed. These decreases were uniform throughout the seasons. This dry period resulted in a drop in groundwater levels as pumpage was increased to satisfy domestic and industrial demand. This resulted in a reduction of groundwater seepage to Pines Brook as baseflow. Because Pines Brook is located in a heavily urbanized area where groundwater pumpage is greater than in the area of the control watershed, the baseflow component was lowered to a greater extent.

It is interesting to note that notwithstanding the extreme drought, the annual direct runoff component was nearly 20 percent greater in 1962-

69 than the base period 1944-51. Except during the extreme drought, direct runoff increased each season for the period of record and ranged from 30 percent in the summer season to nearly 120 percent in the spring season. Baseflow and total flow decrease continually each season throughout the period of record.

North Buffalo Creek

The analysis of streamflow records were divided into five periods -- 1929-41, 1941-49, 1949-56, 1956-63 and 1963-70. Between the first period, 1929-41, and the last period, 1963-70, direct runoff increased nearly 10 percent when compared with the direct runoff from the control watershed. One reason for the relatively small increase in direct runoff in the control watershed -- East Fork Deep River -- was affected by the construction of a highway and oil tank field in the upper reaches of the watershed as well as drainage from new facilities at the Greensboro Airport. The additional direct runoff from this construction is thought to be small but may be sufficient to mask some of the increase in direct runoff in the North Buffalo Creek. The largest increase between the two periods occurred in the summer months. Total flow increased more than 35 percent between 1929-41 and 1963-70. Baseflow accounts for the major part of this increase, as it increased by almost 64 percent between the same two periods when compared with the runoff from the control watershed.

Beginning in 1955, a paper mill company located about two miles upstream from the North Buffalo Creek stream gage, began diverting water into the watershed from Richland Lake. This water was pumped from the lake, located about five miles north of Greensboro, used in the industrial process, treated and then discharged into North Buffalo Creek upstream from the gage. Table 7 lists the recorded average annual diversions since 1955. Records for two years, 1957 and 1959, are not available, but it is assumed they were typical of the other records.

Additionally, public water supply in Greensboro is derived from a system of lake impoundments north of the city limits. Water is diverted from the lakes into the city where part of the total supply is used, treated and eventually discharged into North Buffalo Creek above the gaging station. The remaining part of the water supply is used, treated and discharged in the southern part of the city outside of the North Buffalo Creek watershed. In 1968 the water supply system was expanded to its current capacity of 37.4 mgd. In 1970 the total average annual water use in the municipal system was 21 mgd (14 cfs). Assuming that 50 percent of the public water supply is used in the North Buffalo watershed, the average combined diversion into this area in recent years is about 10.3 cfs. This combined diversion is about the order of magnitude of the increase in baseflow over the period of record (about 14 cfs) and is believed to be the major cause of the baseflow increase. Other factors that could contribute to increased baseflow are discharges from car washes, laundromats and private and public swimming polls.

Over the period of record, changes in the seasonal volumes of direct runoff has been variable. The largest increase (72 percent) occurred in the summer season while a decline of about 10 percent occurred in the fall season. Baseflow increased in all seasons, except the spring season, ranging from about 40 percent in the winter to 117 percent in the summer. As A result, total flow increased in all seasons throughout the period of record ranging from 24 percent in the winter to 89 percent in the summer.

Table 7. Diversions From Richland Lake To Cone Mills, Greensboro, North Carolina

Year	Diversion (cfs)
1955	5.2
1956	3.6
1958	2.4
1960	1.6
1961	2.4
1962	3.3
1963	3.3
1964	3.3
1965	3.0
1966	3.7
1967	4.7
1968	3.2
1969	3.1
1970	3.0
AVG	3.3

Peachtree Creek

Analysis of streamflow records was divided into three periods -- 1959-62, 1963-66, and 1967-70 -- and covers a time of significant urbanization of the Peachtree Creek watershed. Between the first period, 1959-62 and the last period, 1967-70, direct runoff increased by more than 45 percent compared with the runoff from the control watershed. Total flow increased by about 23 percent and baseflow decreased by about two percent between the same two periods.

Direct runoff increased in all seasons but the largest increases occurred in the spring and summer seasons -- 60 percent and 54 percent respectively. Changes in baseflow were variable with slight declines occuring in the fall, winter and spring and a 12 percent increase occurring in the summer. Total flow increased in all seasons but was greatly increased in the spring and summer as a result of the large increases in direct runoff.

Sims Bayou

Analysis of streamflow records was divided into four periods -- 1953-57, 1957-61, 1961-66 and 1966-70. Annual direct runoff from the watershed, when compared with the direct runoff from the control watershed, increased about 32 percent between 1953-57 and 1966-70. Total flow also increased by about 32 percent and baseflow remained relatively unchanged, increasing only about 1.5 percent.

Brays Bayou

Analysis of streamflow records was divided into four periods similar to those used in the analysis of Sims Bayou. However, the first period, 1949-57, was somewhat longer. Annual direct runoff increased about 54 percent, compared with the correcponding flow at the control watershed, between the first period, 1949-57, and the last period, 1966-70. Total flow and baseflow also increased nearly 57 percent and 31 percent, respectively between the same periods.

Whiteoak Bayou

Analysis of streamflow records were divided into four periods identical to those used for Brays Bayou -- 1949-57, 1957-61, 1961-66 and 1966-70. Annual direct runoff increased about 21 percent between the first and last period compared with the runoff from the control watershed. Total flow and baseflow increased about 20 percent and about 7 percent respectively.

Halls Bayou

Four periods of analysis were used -- 1953-57, 1957-61, 1961-66 and 1966-70. Between the first and last periods annual direct runoff increased about 34 percent compared with direct runoff from the control watershed. Total flow and baseflow increased about 39 percent and 81 percent, respectively, between the first and last periods.

Greens Bayou

Four periods were also used for this analysis -- 1953-57, 1957-61, 1961-66 and 1966-70. Between the first and last periods, annual direct runoff increased about 16 percent compared with runoff from the control watershed. Total flow increased about 25 percent and baseflow increased about 354 percent between the same periods.

Seasonal flows in all of the Houston watersheds are variable and generally inconsistent. Although all the variability can not be explained, some general observation can be made. Direct runoff increased in all watersheds during the winter season ranging from about 24 at Greens Bayou to more than 140 percent at Sims Bayou. Changes in direct runoff in other seasons were highly variable and inconsistent among the watersheds. For example, during the fall season direct runoff from Sims, Brays and Whiteoak and Greens Bayous declined while direct runoff in Halls Bayou increased. Baseflow in Halls and Greens Bayou increased in all seasons but was variable among the remaining watersheds. Total flow was also variable and inconsistent among watersheds.

The reasons the seasonal data is not reliable in the Houston watershed may be due to 1) variability of rainfall among the seasons and over the watersheds and 2) that only one control watershed is used to compare runoff from watersheds that range from 17 to 33 miles from the control. The data was developed in this study with the assumption that rainfall was uniform over both the urban and control watersheds. This assumption may not be valid for short periods, like a 3-month season, nor may it be valid in the Houston area where the watersheds are great distances from the control. Large errors would result in the seasonal data when comparing runoff from urban watersheds and a control watershed where there was large differences in wetness of the watershed. Data computed from annual values would tend to reduce the error by averaging differences in wetness resulting from rainfall variability.

Relationship Between Streamflow Changes And Urban Land Use Changes

The percentage of the total drainage area used for urban purposes at various times is listed in Table 2 and plotted in Figure 2. The average percentage of urban land in each watershed during the period of streamflow analysis was estimated from this data and is listed in Table 8 . Also listed in Table 9 is the change in urban land from one period of analysis to another and a summary of the percentage change in total flow, baseflow, and direct runoff over the base period of analysis.

For all urban watersheds, except Pines Brook, the average annual volume of total flow increased over the base period, ranging from about 8 percent at East Meadow Brook to about 57 percent at Brays Bayou. The average total flow at Pines Brook decreased about 3 percent. This decrease in total flow at Pines Brook is due to a decrease in baseflow resulting from local groundwater withdrawals.

Figure 7 is a graph of the percentage change in average annual total flow over the base period versus the change in urban land in percent of the total area. The correlation coefficient of this set of data is only 0.45 with a standard error of estimate of 16.8 The relationship is poor because urban land is not a good indicator of all processes contributing to total flow, or because different processes are affected by varying degrees. For example, baseflow may be affected by groundwater management practices and diversions, and may be unaffected by land use changes.

Table 8 lists the percentage change in baseflow over the base period. These changes vary from decreased baseflow at Pines Brook and Peachtree Creek to large percentage increases at Halls and Greens Bayou. With the set of data developed in this study and lack of detailed information regarding groundwater management practices in both the urban and control watersheds, it is not possible to relate changes in baseflow with changes in urban land. However, some observations can be made regarding the variations. The large decrease in baseflow at Pines Brook is attributed to groundwater withdrawals. The small percentage increases or decreases in baseflow (E. Meadow Brook, Peachtree Creek, Sims Bayou, and Whiteoak Ba-

Table 8. Summary Of Average Urban Land And Percentage Change In Annual Flows For The Indicated Periods Of Analysis At Each Urban Watershed.

Watershed	Drainage Area	Period Of Analysis	Average Urban Land	Change In Urban Land	Annual Total Flow	Annual Baseflow	Annual Direct Runoff
	smi		Percentage Of Total Area		Percentage Change Over Base Period		
East Meadow Brook	10.0	1952-57	41				
		1958-62	54	13	7.8	2.2	17.7
Pines Brook	10.0	1952-57	80				
		1958-62	84	4	-3.2	-13.1	20.0
N. Buffalo Creek	37.0	1950-56	25				
		1964-70	50	25	13.5	28.0	0.44
Peachtree Creek	86.8	1959-62	47				
		1967-70	72	25	23.0	-1.9	45.3
Sims Bayou	64.0	1953-57	10				
		1966-70	29	19	32.4	1.5	31.6
Brays Bayou	88.4	1949-57	14				
		1966-70	35	21	56.9	30.6	54.1
Whiteoak Bayou	84.7	1949-57	11				
		1966-70	17	6	20.0	7.1	20.8
Halls Bayou	24.7	1953-57	20				
		1966-70	40	20	38.5	81.1	33.8
Greens Bayou	72.7	1953-57	0				
		1966-70	5	5	25.4	354.2	15.9

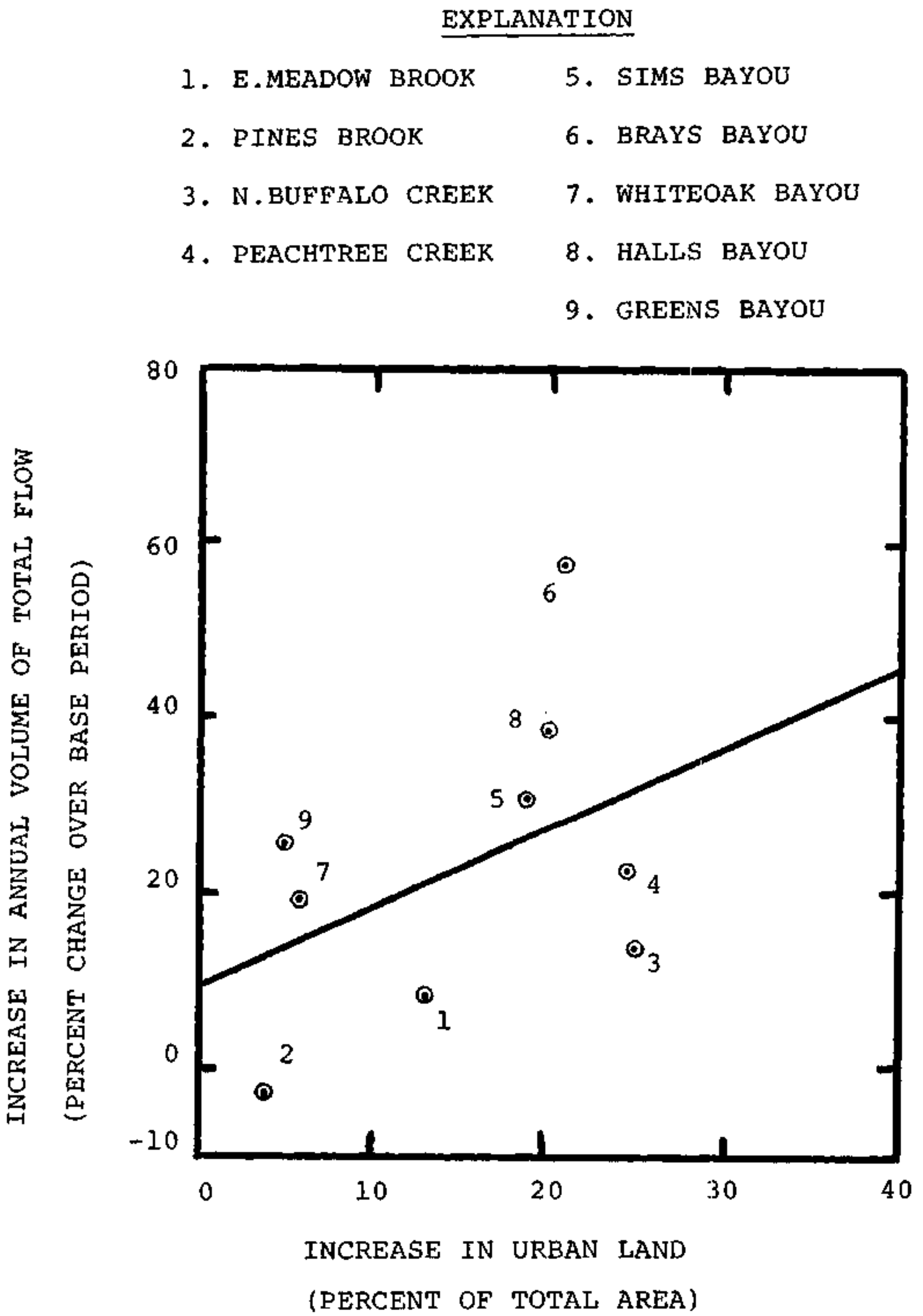

Figure 7. Relationship Between Increase In Total Runoff And The Percentage Increase In Urban Land.

you) probably indicate that no significant changes occurred in the groundwater reservoir or in the waste effluents from the watersheds between the periods of analysis. Some decreases in baseflow may be the result of reduced groundwater recharge caused by additional impervious cover. However, data is not available to adequately quantify this affect. It is suspected that the large increases in baseflow (N. Buffalo Creek, Brays Bayou, Halls Bayou, and Greens Bayou) resulted mainly from increased domestic and industrial waste discharges into the stream.

All urban watersheds exhibited increases in average annual volume of direct runoff over the base period as shown in Table 9. The percentage changes in direct runoff are plotted versus the change in urban land as a percent of the total area in Figure 8. The line drawn through the data was determined by the method of least squares disregarding the N. Buffalo Creek data point. N. Buffalo Creek is plotted but for reasons discussed earlier in the report this data is disregarded in determining the relationship. The correlation coefficient for the reamining data is 0.84 with a standard error of estimate of 8.11. Some of the scatter of the data is Figure 8 may be attributed to 1) effects of parameters other than urban land, such as watershed slope and soil permeability or 2) errors in the data.

The solid line drawn through the data points in Figure 8 is not extended to intersect the ordinate. It is logical to expect the relationship to pass through the origin. The hypothesis is that a change in land use, or more precisely an increase in urban land is the sole cause of an increase in direct runoff from the urban watershed. The face that the line does not pass through the origin may be due to insufficient data as

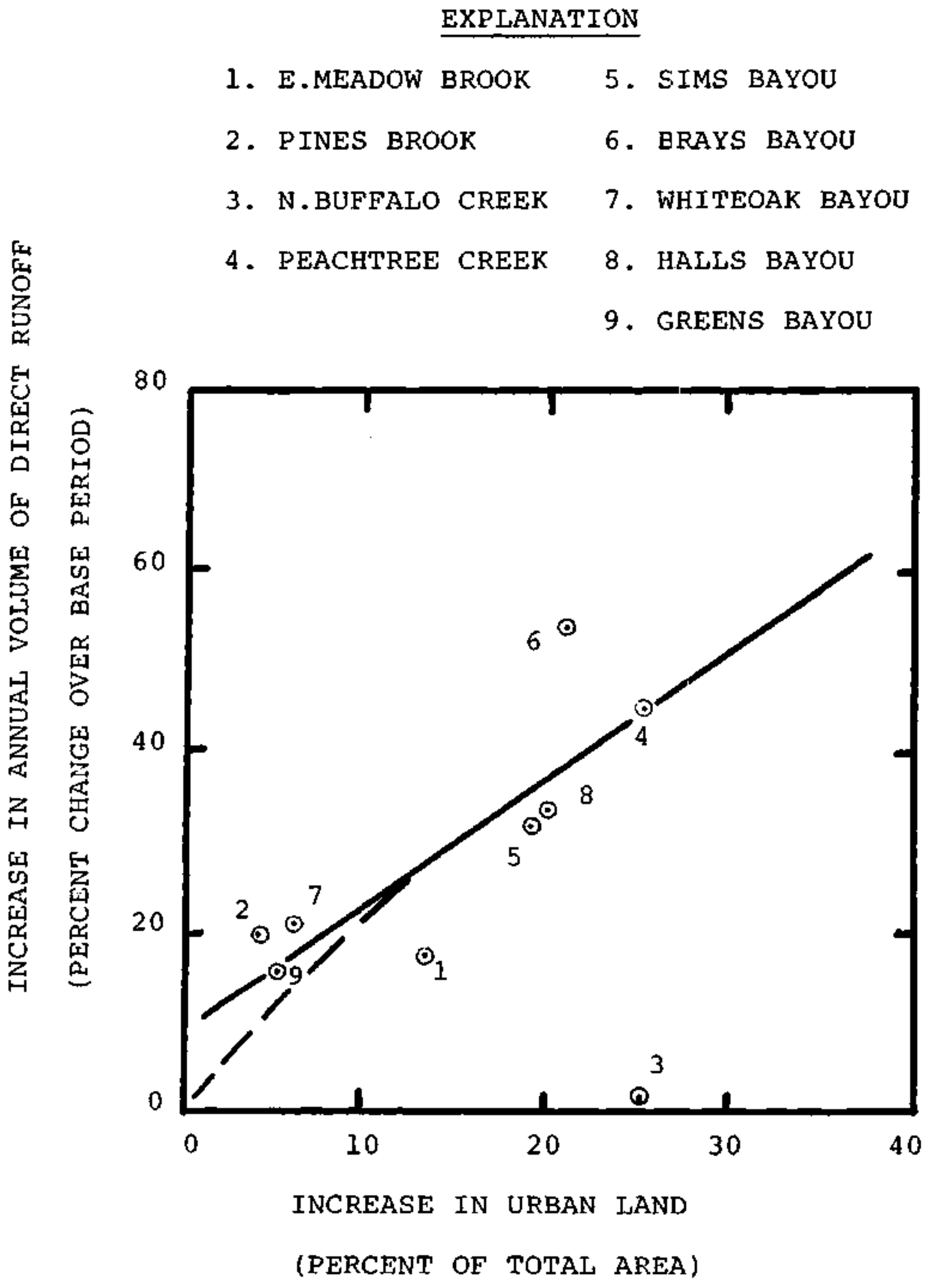

Figure 8. Relationship Between Increase In Direct Runoff And The Percentage Increase In Urban Land.

well as inaccuracies in the existing data. It may be well argued that the relationship between increases in direct runoff and increases in urban land use is not linear. The data used in Figure 8 represents watersheds ranging widely in the degree of urban development. Many other physiographic and geographic factors are also influencing this relationship. Much more detailed data is needed to define the precise relationship between increased direct runoff and increased land use. In view of this, the broken line shown in Figure 8 was arbitrarily drawn to intersect the origin.

The relationship shown in Figure 8 implies that an increase in urban land will result in a percentage increase in the average annual volume of direct runoff of approximately 1.8 times the percentage increase in urban land. For example, assume the urban area is a watershed is to increase from 10 percent to 40 percent of the total area -- a 30 percent increase in urban area -- over a period of years. Figure 8 indicates that the annual volume of direct runoff will increase about 50 percent over the same period as a result of the increased urban area.

Seasonal Variations Of Volumes Of Flow

Variations in streamflow from season to season is attributed in part to variations in seasonal rainfall. In some areas heavy rainfalls occur during one particular season while during another season of the year it is typically dry. For example, in the Atlanta area (Peachtree Creek) on the average the winter season is normally wet while the summer and fall seasons are typically dry. The same is true, in general, for North Carolina (N. Buffalo Creek). On Long Island, (E. Meadow Brook and Pines Brook) the spring and fall seasons are wet and the winter and summer are dry. In the Houston area, the winter season usually has below normal rainfall and the spring and fall are usually above normal.

During wet periods (above normal rianfall) runoff from an urbanized watershed and a natural watershed will be high. Soil moisture will approach saturation and the runoff from the urbanized watershed should be similar to that which would have occurred under the same meteorological conditions if the watershed were in a natural state. The amount of increased runoff resulting from impervious areas is expected to be a small proportion of the total runoff. Therefore, when comparing runoff during wet periods from an urban watershed and a control (natural) watershed, the percent change in volumes is expected to be small from one period to another.

During dry periods (below normal rainfall) runoff from urban watersheds and control watersheds is expected to be low. Soil moisture is low; therefore any rainfall during dry periods is used to satisfy soil moisture requirements before surface runoff occurs. In a natural watershed runoff may be reduced significantly because of soil moisture deficiencies. In an urbanized watershed,impervious areas catch and divert rainfall to streams before soil moisture requirements are satisfied. Under these conditions the volume of runoff from impervious areas is expected to be a larger proportion of the total runoff. Therefore, when comparing runoff during dry periods from an urban watershed and a control watershed, the percent change in the volumes is expected to be high from one period to another.

Tables 9-12 list the percentage change in total flow, baseflow and direct runoff over the base period for each of the four seasons between the two periods of analysis.

Table 9. Summary Of Average Urban Land And Percentage Change In Fall Flows For The Indicated Periods Of Analysis At Each Urban Watershed.

Watershed	Period Of Analysis	Rainfall Compared To Normal	Average Urban Land	Change In Urban Land	Fall		
					Total Flow	Baseflow	Direct Runoff
			Percentage Of Total Area		Percentage Change Over Base Period		
East Meadow Brook	1952-57	Above	41				
	1958-62	Below	54	13	7.5	5.0	11.5
Pines Brook	1952-57	Above	80				
	1958-62	Below	84	4	-4.8	-10.1	9.5
N. Buffalo Creek	1950-56	Below	25				
	1964-70	Below	50	25	17.7	31.4	-21.0
Peachtree Creek	1954-62	Above	47				
	1967-70	Above	72	25	14.3	-5.1	14.7
Sims Bayou	1953-57	Below	10				
	1966-70	Above	20	10	-30.7	-36.3	-25.9
Brays Bayou	1949-57	Below	14				
	1966-70	Above	35	21	-29.8	-16.3	-30.2
Whiteoak Bayou	1949-57	Below	11				
	1966-70	Above	17	6	-34.2	-23.7	-37.9
Halls Bayou	1953-57	Below	20				
	1966-70	Above	40	20	7.7	35.8	3.6
Greens Bayou	1953-57	Below	0				
	1966-70	Above	5	5	-10.6	412.6	-26.3

Table 10. Summary Of Average Urban Land And Percentage Change In Winter Flows For The Indicated Periods Of Analysis At Each Urban Watershed.

Watershed	Period Of Analysis	Rainfall Compared To Normal	Average Urban Land	Change In Urban Land	Winter		
					Total Flow	Baseflow	Direct Runoff
			Percentage Of Total Area		Percentage Change Over Base Period		
East Meadow Brook	1952-57	Above	41				
	1958-62	Below	54	13	7.4	-1.2	18.1
Pines Brook	1952-57	Above	80				
	1958-62	Below	84	4	2.5	-11.0	17.5
N. Buffalo Creek	1950-56	Below	25				
	1964-70	Below	50	25	9.4	19.4	-0.9
Peachtree Creek	1954-62	Above	47				
	1967-70	Above	72	25	4.6	-8.6	19.4
Sims Bayou	1953-57	Below	10				
	1966-70	Above	20	10	139.5	182.1	141.3
Brays Bayou	1949-57	Below	14				
	1966-70	Above	35	21	123.9	203.5	98.5
Whiteoak Bayou	1949-57	Below	11				
	1966-70	Above	17	6	18.4	58.1	30.6
Halls Bayou	1953-57	Below	20				
	1966-70	Above	40	20	77.9	351.6	42.6
Greens Bayou	1953-57	Below	0				
	1966-70	Above	5	5	67.6	1421.6	24.2

Table 11. Summary Of Average Urban Land And Percentage Change In Spring Flows For The Indicated Periods Of Analysis At Each Urban Watershed.

Watershed	Period Of Analysis	Rainfall Compared To Normal	Average Urban Land	Change In Urban Land	Spring Total Flow	Spring Baseflow	Spring Direct Runoff
			Percentage Of Total Area		Percentage Change Over Base Period		
East Meadow Brook	1952-57	Above	41				
	1958-62	Below	54	13	1.0	-0.3	13.8
Pines Brook	1952-57	Above	80				
	1958-62	Below	84	4	-11.6	-17.9	32.2
N. Buffalo Creek	1950-56	Below	25				
	1964-70	Below	50	25	9.4	28.9	2.5
Peachtree Creek	1954-62	Above	47				
	1967-70	Above	72	25	23.2	-2.1	59.9
Sims Bayou	1953-57	Below	10				
	1966-70	Above	20	10	-46.1	-4.9	-39.9
Brays Bayou	1949-57	Below	14				
	1966-70	Above	35	21	-47.1	16.2	-50.6
Whiteoak Bayou	1949-57	Below	11				
	1966-70	Above	17	6	-31.0	16.4	-26.7
Halls Bayou	1953-57	Below	20				
	1966-70	Above	40	20	27.5	151.6	22.7
Greens Bayou	1953-57	Below	0				
	1966-70	Above	5	5	67.4	553.5	39.6

Table 12. Summary Of Average Urban Land And Percentage Change In Summer Flows For The Indicated Periods Of Analysis At Each Urban Watershed.

Watershed	Period Of Analysis	Rainfall Compared To Normal	Average Urban Land	Change In Urban Land	Summer Total Flow	Summer Baseflow	Summer Direct Runoff
			Percentage Of Total Area		Percentage Change Over Base Period		
East Meadow Brook	1952-57	Above	41				
	1958-62	Below	54	13	14.6	4.3	21.4
Pines Brook	1952-57	Above	80				
	1958-62	Below	84	4	-1.2	-16.2	6.9
N. Buffalo Creek	1950-56	Below	25				
	1964-70	Below	50	25	34.9	40.8	21.7
Peachtree Creek	1954-62	Above	47				
	1967-70	Above	72	25	47.3	12.5	54.2
Sims Bayou	1953-57	Below	10				
	1966-70	Above	20	10	-20.2	-23.2	-13.1
Brays Bayou	1949-57	Below	14				
	1966-70	Above	35	21	31.5	8.5	83.2
Whiteoak Bayou	1949-57	Below	11				
	1966-70	Above	17	6	32.8	-10.3	63.8
Halls Bayou	1953-57	Below	20				
	1966-70	Above	40	20	-33.9	13.9	-39.8
Greens Bayou	1953-57	Below	0				
	1966-70	Above	5	5	-69.7	127.2	-71.4

The data developed in this study do not exhibit any obvious trends among the four seasons. East Meadow Brook and Pines Brook had increased direct runoff in all seasons but East Meadow Brook had the largest in the winter and summer, as expected because these are dry seasons. Pines Brook, on the other hand, had the largest increase in direct runoff in the spring, which is typically a wet season. North Buffalo Creek had the largest increase in direct runoff in the summer season but this increase was offset by a decrease in the fall season of nearly the same magnitude. Direct runoff during winter and spring showed no change between the two periods of analysis. Peachtree Creek had large increases in direct runoff in the spring and summer (dry season) while the increase in the fall and winter (wet season) were not as large. The changes in the volume of runoff at Peachtree Creek are as one might expect from hydrologic considerations discussed above.

The variations in the percentage change of direct runoff between the two periods of analysis in the Houston watersheds also follow no pattern and are very difficult to explain. For example, during the same season, the percent change in direct runoff increased for some watersheds and decreased for other watersheds. Only in the winter season, which is typically a wet season, was there an increase in direct runoff among all Houston watersheds used in this study and these percentage increases ranged widely, from 141 percent in Sims Bayou to 24 percent in Greens Bayou.

Similarly, there are no consistent trends shown in the total flow or baseflow data developed in this study. No relationship between wet or dry periods are evident, however, effects of water management is evident in baseflow trends of PInes Brook and N. Buffalo Creek. Baseflow declined in the Pines Brook Watershed, as explained previously, because of groundwater pumpage in the area. Baseflow increased in the N. Buffalo Creek watershed because of the previously discussed diversion of water into the basin from outside sources.

In an attempt to help explain the variation in the seasonal data a regression analysis was made of the percentage change in season volumes of runoff from the urban watershed over the runoff from the control watersheds, the percentage change in urban land and the departure from normal rainfall. The simple regression model used in this analysis is:

$$UR = A_o + A_1 (UL) + A_2 DEP$$

where UR is the percentage change in the volume of runoff from the urban watershed compared to the runoff from the control watershed, UL is the percentage change in urban land over the previous period, DEP is the departure from normal rainfall, and A_o, A_1 and A_2 are regression coefficients.

Figure 9 illustrates the relationships developed for each season for changes in the volume of direct runoff. A family of curves are plotted for 2 inches above normal rainfall (DEP = +2), normal rainfall (DEP = 0) and 2 inches below normal rainfall (DEP = -2). The fall, winter and spring seasons exhibit a runoff relation that actually declines with increased urban land. The summer season is the only one that exhibits a runoff relation that increases with increased urban land. This relation also indicates that the dry periods (DEP = -2) result in larger percentage changes in runoff. The coefficient of multiple correlation determined for each relationship was less than 0.5 indicating a poor relationship among the variables.

There are several possible reasons why the analysis of changes in

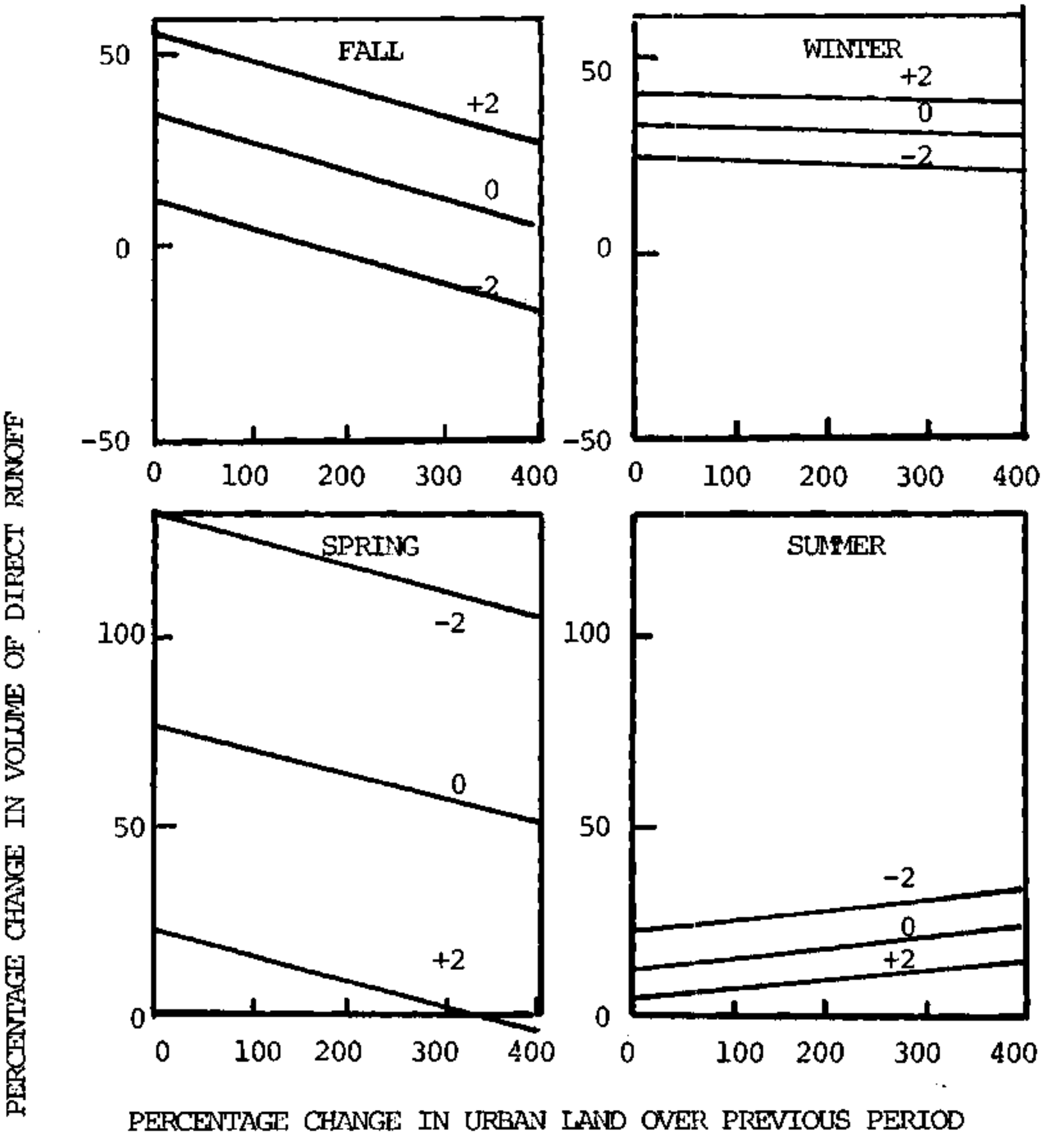

Figure 9. Relationship Developed By Linear Regression Analysis Of The Change In Direct Runoff Versus The Change In Urban Land And Departure From Normal Rainfall.

seasonal flow volumes is not conclusive. First the number of watersheds used in the analysis is limited to nine, five of which were in one geographic location. Much more data is needed, representing a larger number of geographic areas. Second, three months may be too short a period of time to accomodate streamflow fluctuations and make comparisons of runoff between urban watersheds and control watersheds with the type of analysis used in this study. Third, this analysis only considers average flow conditions over two selected periods of time. The variance in the streamflow data for these selected periods may cause considerable error in the average value calculated for each period. Longer periods of more stable watershed conditions would have been more desirable and contributed less variance in the data. However, in an urbanizing watershed this condition is highly unlikely. Fourth, rainfall variability over the urban and control watershed may lead to large error in the seasonal data because of differences in watershed wetness. These differences would tend to average out over a longer period of time.

Wallace (1971) investigated the effects of urbanization on the hydrology of urban watersheds. As a part of his study, he analyzed changes in runoff patterns in Peachtree Creek resulting from urbanization. He prepared double-mass curves of the highest and lowest daily flows for a wet period (February and March) 1958-68 and a dry period (August and September) 1958-68. Analysis of these curves led to the following conclusions: 1) during dry months the volume of direct runoff from Peachtree Creek is steadily increasing, and 2) no similar trend was indicated for wet months. Analysis of the average unit discharge of selected storm events during August and September indicated that storm runoff for 1963-69 was three times that which occurred during the same months during 1959-63. Analysis of wet periods (February and March) showed that storm runoff did not change during the entire period or record.

Results of the Wallace study cannot be compared directly with results of this study because only selected storm events were used and because only two month periods were used to characterize wet and dry periods. However, results of the present study show that for the period from 1959-63 to 1963-70, in the summer season (July, August and September) total flow increased 21 percent, baseflow decreased about 4 percent, and direct runoff increased about 35 percent; in the winter season (January, February and March) total flow increased about 2 percent, baseflow decreased about 18 percent and direct runoff increased about 16 percent.

Johnson and Sayre (1973) developed relationships for the magnitude and frequency of annual flood peaks in the Houston, Texas, metropolitan area using data from the same watersheds used in this study. As part of the study, a double-mass curve was developed of total runoff from Brays Bayou and Cypress Creek to illustrate the change in runoff resulting from increased development in the Brays Bayou watershed. The authors reported no quantitative measures of the increase in runoff. However, rough calculations from the graph developed in their study indicate that between the two periods 1945-57 and 1966-69, corresponding roughly to the periods of analysis used in this study, the percent change in total runoff was about 62 percent. The percent change in total runoff computed in this study between 1949-57 and 1966-70 was about 57 percent. Because changes in volumes of runoff was not the principal purpose of the Johnson and Sayre study no other analysis or conclusions were made regarding this data.

Relationship of Increased Direct Runoff Among Urban Watersheds

Figure 10 is a graph of the mean annual volume of direct runoff per square mile of watershed area versus the percentage of urban development. Computations of mean annual direct runoff from the urban watershed were made from the urban runoff versus control runoff relationship by multiplying the average ratio of annual direct runoff from the urban to control watershed (Table 13, column 5) by the average annual direct runoff from the control watershed (Table 13, column 6). The resulting volume in units of inches (col. 7) was multiplied by a conversion factor (0.073668 inches-square mile per feet-second per day) to get the volume of direct runoff per unit of drainage area (col. 8). This method of determining mean annual direct runoff from the urban watershed maintains the percentage increase in the direct runoff from the urban watershed determined from the double-mass analysis with the direct runoff from the control watershed or more simply, eliminates the variations in wetness from one year to the next. A summary of these computations is shown in Table 13.

Two observations can be made from the data plotted in Figure 10. First, the Houston, Texas watersheds, regardless of urban development, all produce greater discharge per unit area than the two watersheds on Long Island (E. Meadow Brook and Pines Brook). The soils in the Houston area are very tight and permeabilities are low and as a result direct runoff is high. Therefore, a unit of area produces a substantial amount of direct runoff under natural conditions. On the other hand, the soils on Long Island are very sandy and permeabilities are high. Direct runoff from these soils, even under the most severe storms is small and most of the rainfall quickly soaks into the ground. A unit of area on Long Island

Table 13. Mean Annual Direct Runoff From the Urban Watershed Computed From The Relationship of Direct Runoff From the Urban Watershed and Direct Runoff From the Control Watershed.

Watershed	Drainage Area (smi)	Period of Analysis	Percentage of Urban Area to Total	Percentage of Impervious Area to Total	Average Ratio of Direct Runoff from Urban to Control Watersheds	Average Annual Direct Runoff from Control Watershed (inches)	Mean Annual Direct Runoff From Urban Watershed	
							(inches)	From Drainage Area (cfs/smi)
East Meadow Brook	10.0	1952-58	41	16	4.0384	1.16	4.68	0.345
		1958-62	60	22	4.7331	-do-	5.49	.404
Pines Brook	10.0	1952-58	80	29	1.2384	-do-	1.44	.106
		1958-62	87	31	1.4742	-do-	1.71	.126
North Buffalo Creek	37.0	1949-56	25	11	1.2850	8.12	10.43	.769
		1963-70	50	19	1.2854	-do-	10.44	.769
Peachtree Creek	86.8	1959-62	44	17	1.2462	8.31	10.36	.763
		1967-70	72	26	1.8115	-do-	15.05	1.109
Sims Bayou	64.0	1953-57	10	6	2.4910	4.96	12.36	.910
		1966-70	29	12	3.2700	-do-	16.22	1.195
Brays Bayou	88.4	1949-57	14	7	2.3751	-do-	11.78	.868
		1966-70	35	14	3.7882	-do-	18.79	1.384
Whiteoak Bayou	84.7	1949-57	11	6	1.9799	-do-	9.82	.723
		1966-70	17	8	2.4952	-do-	12.38	.909
Halls Bayou	24.7	1953-57	20	9	2.5080	-do-	12.44	.916
		1966-70	40	16	3.3474	-do-	16.60	1.223
Greens Bayou	72.7	1953-57	0	3	1.9314	-do-	9.58	.706
		1966-70	5	4	2.2318	-do-	11.07	.815

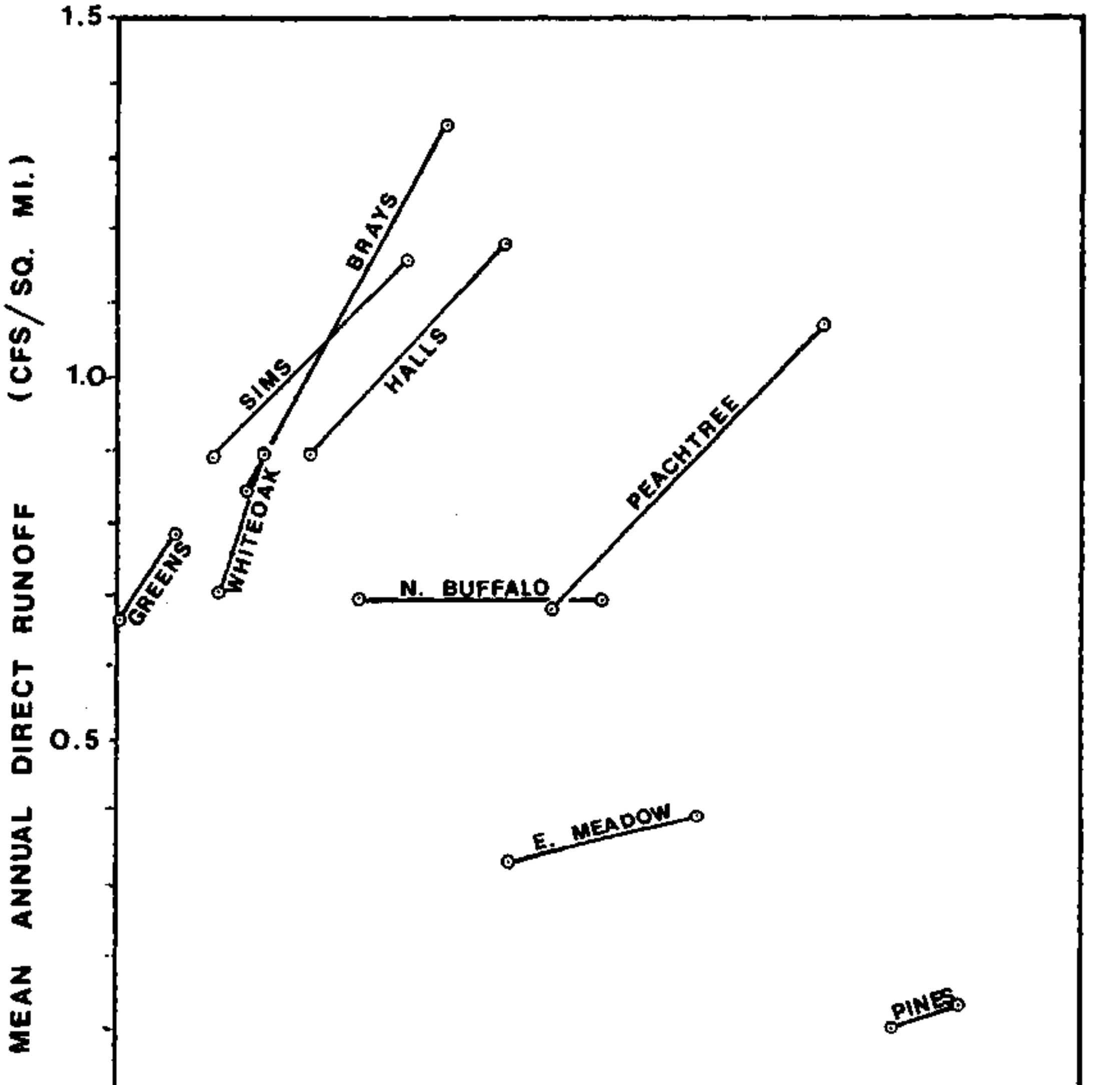

Figure 10. Relationship Between Mean Annual Direct Runoff and Percentage Urban Area, Derived from the Relationship Between Urban Runoff and Control Runoff.

under natural conditions will produce a relatively small amount of direct runoff.

In the Peachtree watershed the soils are clayey fine sands and silts, but permeabilities are higher than for the Houston soils. The discharge per unit of area is about the same magnitude as for the Houston watersheds but much of the production of direct runoff is the result of the urban development rather than surface runoff from natural areas.

The second observation is that the production of direct runoff increases at a faster rate, as urban area increases, in the Houston watersheds than in the Long Island watersheds. One explanation for this is that in the Houston area the watershed slopes are very flat. Under natural conditions storm water collected in poorly drained areas ponded until it either evaporated or soaked into the soils. It may take several days to a few weeks for water to disappear from some areas (S. L. Johnson, USGS, Houston, 1973, oral communication). As urbanization progressed into these natural areas direct runoff is increased by two components. One is the runoff of storm water on the impervious area and the other component is increased surface runoff from the natural area that flows into the improved drainage systems provided by the urban development. On the other hand, the increase in direct runoff from the Long Island watersheds is due almost entirely to the increased impervious area. Because surface runoff from undeveloped areas is negligible, urban development would not enhance drainage from natural areas on Long Island.

It is apparent from this analysis that urban runoff is affected not only by urbanization but by other factors related to climate and geology of the region. With a sufficient amount of regional data, it may be possible to determine a relationship between urbanization and runoff. However, as shown here it is not likely that relationships developed in one region could be extended to other regions, without including factors into the analysis governing regional parameters, such as soil type and slope, and rainfall magnitude and distribution.

CHAPTER V

SUMMARY AND CONCLUSIONS

The results of this study have been divided into three parts; 1) results of land-use analysis, 2) results of streamflow analysis, and 3) relationship between streamflow changes and land use changes. A summary of each of these parts is presented along with conclusions derived from this study.

Analysis of Land-Use Changes

Data on urban land use and impervious area were compiled. The amount or urban land in the 11 urban watersheds ranged from 91 percent in 1968 for the Pines Brook watershed to five percent in 1967 for the Greens Bayou watershed. Estimates of impervious area ranged from about two percent on the watershed with least development to 35 percent of the area on the most developed watershed. The watersheds represent a typical mixture of land uses.

A plot of percentage urban land versus percentage impervious area showed considerable scatter about a least squares line fit to these data. This scatter can probably be attributed to a number of inaccuracies inherent in the data collection and reduction techniques. These include 1) using the red tinted areas on the USGS maps as the measure of urban land, 2) using values of impervious area determined by different techniques on different watersheds, 3) interpolating from the impervious area versus time (date) curves for each watershed in order to get an estimate of impervious area which would coincide in time with the date of the USGS maps and 4) differences in density of impervious area as in a downtown area as opposed to a suburban residential area. In view of these factors, the scatter about the average line through the data does not appear extreme. On the basis of the average line through the data, an impervious area of about 4 percent is predicted for a watershed with zero urban land while a watershed with 100 percent urban land is predicted to be 35 percent impervious. The standard error in predicting the percentage of impervious area from urban land is about 7 percent.

Streamflow Analysis

Double-mass curve analysis was used to determine changes in streamflow characteristics resulting from urbanization in the watershed. Several observations were made from these analyses. First, all urban watersheds exhibited an increase in direct runoff between the base period of analysis and the final period, regardless of whether the increases were determined from a relationship with a control watershed or with precipitation. Increases in direct runoff ranged from 10 percent to more than 60 percent over the periods of streamflow record in the urban watersheds. Change in land use has been a major factor in these increases, although other factors may also have had an influence.

The effect of urbanization on baseflow depends on drainage practices, diversions in and out the watershed, infiltration capacities, and groundwater management practices. Construction of impervious areas throughout a watershed will tend to reduce the opportunity for storm water to soak into the soils and thereby reduce groundwater recharge. The effect of increased impervious cover could result in a loss of groundwater recharge, a reduction in water table levels, and consequently, a decline in baseflow. Groundwater pumpage may also reduce baseflow. On the other hand, drainage practices which are designed to delay storm runoff and perhaps aid groundwater recharge may have the effect of increasing water table levels and thus increasing baseflow.

The urban watersheds that showed a decline or, at least, no change in baseflow were East Meadow Brook, Pines Brook, Little Sugar Creek, Peachtree Creek and Morrison Creek watershed. The decline in baseflow in East Meadow Brook and Pines Brook can not be directly associated with an increase in impervious cover, but rather to complex groundwater management practices that have been developed to cope with the increased demand for groundwater on Long Island. Most important among these practices is the increased pumpage from the groundwater reservoir over the years to satisfy the fresh water needs of the increased numbers of inhabitants and the use of recharge basins. The declines in baseflow in Little Sugar Creek, Peachtree Creek and Morrison Creek are small and are probably associated with increased impervious cover and consequent decrease in filtration.

The five urban watersheds in the Houston area showed an increase in the magnitude of each of the flow components, and these increases appeared to be related to increases in impervious area. Each watershed exhibited large percentage increases in baseflow during the period of urbanization. However, the baseflow is a small proportion of the total flow in these streams (see Table A.2) and slight quantity changes represent large percentage changes. Increased baseflows may be due to increased industrial and domentic sewage effluent discharging to the streams.

North Buffalo Creek represents an anomaly among the urban watersheds used in this study. During the period of record, 1929-70, baseflow has increased continually compared with the baseflow of the control watershed as well as with precipitation. These increases are due largely to diversions into the watershed of water used in an industrial plant and municipal water supply.

Seasonal effects are apparent in the distribution of runoff from some of the urban watershed. Increases in direct runoff from the urban watersheds appear to be greatest during the dry months and smallest during the wet months when compared with the runoff from the control watershed. One explanation for this phenomenon is that in a wet season, soil moisture conditions are near saturation in both the urban and control watershed. Discharge per unit area is high for both watersheds simply because the soils cannot absorb much additional water. During a wet season the importance of impervious area on producing runoff is diminished. Additional impervious cover resulting from urban development results in only small percentage increases in runoff. However, during a dry season a greater amount of the storm water is used to replenish soil moisture. Discharge per unit area from the control watershed is low relative to that under wet conditions. Discharge per unit area from the urban watershed is probably reduced somewhat, but not to the extent of the control watershed. This is due to the increased runoff from impervious areas. Therefore, because impervious areas are the principal source of runoff during a dry season, construction of additional impervious area would have a greater effect on runoff during the dry season than during the wet season. Also, small increases in runoff represent a greater percentage of the total runoff because the total runoff is smaller in the dry seasons.

Dry seasons were assumed to occur in the summer months (July, August and September) and the wet seasons were assumed to occur in the winter or spring months (January, February and March), (April, May and June). Rainfall is fairly uniformly distributed throughout the year on all of the urban watersheds for which there was a control watershed (see Figure B.1). (The "dryness" of a season refers to runoff rather than rainfall; the summer is dry because of increased evapotranspiration in the summer.) The urban watersheds that experienced the largest increase in direct runoff during the summer of dry season were East Meadow Brook, North Buffalo Creek, Peachtree Creek and Whiteoak Bayou. Little Sugar Creek and Morrison Creek watersheds did not have control watershed to use for comparison. Pines Brook had the largest increase in the winter months as did Sims Bayou, Brays Bayou, Halls Bayou and Greens Bayou.

Analysis of Streamflow Changes and Land-Use Changes

A relationship between increased direct runoff from the urban watersheds versus the increase in urban land use was developed. The relationship indicates that an increase in urban land will result in a percentage increase in the annual volume of direct runoff by approximately 1.8 times the percentage increase in urban land. This relationship was developed from data from watersheds ranging in size from 10 square miles to about 90 square miles. Hydrology of watersheds outside of this size range may be such that the relationship may not be valid. Therefore, use of the relationship should be limited to watershed sizes in the range used in this study.

Future effects on streamflow from proposed urban development in a watershed may be estimated by determining the increase in urban land and entering Figure 7 to determine the percentage increase in annual direct runoff that will result. For example, on the average a 30 percent increase in urban area is estimated to cause a 50 percent increase in annual direct runoff.

An attempt to determine a relationship between changes in urban land and changes in seasonal values of the volume of direct runoff was not conclusive. There are several possible reasons for this. These include 1) the number of watersheds used in the study is too small, 2) a three-month period may be too short a period of time to accomodate streamflow fluctuations, 3) averaging processes over these short periods incorporate the large variance in the streamflow data and result in considerable error, and 4) rainfall variability over the urban and control watershed may lead to large error in the seasonal data as a result of differences in watershed wetness. These differences would tend to average out over longer periods of time.

Differences among watersheds was illustrated from the production of direct runoff per unit area. The Houston, Texas urban watersheds had higher amounts of runoff per unit area than the watersheds on Long Island, New York. This is probably due to the relatively impermeable soils in the Houston area compared with the more permeable soils on Long Island.

The rate of increased production of runoff as a result of urbanization was also greater in the Houston watersheds compared with the Long Island watersheds. This is due to the fact that in the Houston area the improved drainage systems associated with urban development probably drains the newly installed impervious area as well as large portions of nearly flat areas where natural drainage is poor. In contrast, Long Island soils are so permeable that little or no runoff is expected from these areas and the increased runoff come almost entirely from the inpervious areas.

An important finding of this study is that watersheds located in different climatic and geologic regions respond differently to urbanization. It may be possible to establish relationships within a more or less homogeneous region which will permit the prediction of effects or urbanization on volumes of direct runoff on the basis of simple parameters like impervious area or percent of the watershed that has been urbanized. Extrapolation of such relationships to other regions may not yield valid prediction unless estimates of the effects of parameters related to climatic and geologic variables are included.

CHAPTER VI

WATER MANAGEMENT IMPLICATIONS

The results of this study indicate that urbanization apparently increases the volume of storm runoff from a watershed. The increased volumes are related to the amount of land converted to urban use in a predictable way. Thus, urban planners and water managers can use these results in ways to improve land use and water management policy. The following discussion considers some of these alternatives.

The results of this study provide information to help design large storage facilities. For example, the data presented herein will permit planners and water managers to estimate the magnitude of runoff increases resulting from new urban development. If the accumulated runoff from all new development will result in a substantial shift in the water balance of the area and work to the detriment of the fresh water supply, measures can be taken to conserve storm water and replenish the fresh water supply.

To illustrate, assume a 100 square mile watershed similar to those used in this study will experience a 30 percent increase in urban area over the next several years. Also assume the total annual runoff is 10 inches, 90 percent of which is direct runoff and 10 percent is baseflow. This illustration is similar to the Houston, Texas area. Figure 7 shows that the increase in annual direct runoff resulting from the urban development is about 50 percent. Then, the average annual direct runoff from this hypothetical watershed will increase from 9 inches to 13.5 inches. Results of this study also indicate that baseflow can increase, remain unchanged, or decrease depending on such factors as groundwater management, and the occurrence of sewage and industrial effluent. In this illustration, assume baseflow is unchanged. Therefore, the total annual runoff from this watershed can be expected to increase by 4.5 inches, or 24,000 acre feet per year -- a 45 percent increase in total runoff.

This substantial volume of water may be conserved in the watershed in several ways and planners and water managers must decide among the alternatives. Some of these alternatives include artificial recharge of ground water through basins or wells, surface retention or storage reservoirs, subsurface storage reservoirs and land treatments to increase infiltration, and storage and treatment of storm water for beneficial uses.

However, if the accumulated runoff increases are small and do not warrant the expense of storage facilities, planners may decide that it is not economical to require water conservation. These decisions, of course, must be based on considerably more information but the data presented in this study will prove useful in making these decisions.

In areas where water conservation is important to the economic future of an area, legislation may be necessary to require measures to conserve storm runoff. Land developers are reluctant to voluntarily include conservation measures that increase their costs. Information developed in this study can be used to demonstrate the need and enhance arguments for a policy of storm water conservation.

Planners can also use this information to establish design criteria for selected water conservation measures. Increased volumes of direct runoff are related to increased impervious areas. Therefore, design alternatives can be developed to reduce or delay the runoff from the proposed artificial recharge of ground water through basins or wells, surface retention or storage reservoirs, subsurface storage reservoirs and land treatments to increase infiltration, and storage and treatment of storm water for beneficial uses.

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Planners can also use this information to establish design criteria for selected water conservation measures. Increased volumes of direct runoff are related to increased impervious areas. Therefore, design alternatives can be developed to reduce or delay the runoff from the proposed new development. Some of these measures include detention or retention basins, artificial recharge, and improvements in drainage design to retard runoff and enhance infiltration. It is less costly to incorporate these measures into the design of the development rather than require them after construction.

CHAPTER VII

RECCOMENDATION FOR ADDITIONAL STUDIES

The work performed as part of this study indicates several areas where additional study is needed. These areas of study are discussed below.

1. Future analysis of the effects of urbanization on streamflow, would be greatly facilitated by a study to compile a list of urbanizing watersheds and selected watershed characteristics. This list would be especially useful in selecting streams with specific watershed characteristics for further study. A considerable amount of time was spent in the present study in searching for streams with appropriate basic and accessory data. Some of the essential data that might be included in the list are location, drainage area, history of urban development, current land use, estimates of impervious area, and type of streamflow records available, if any.

2. More watersheds undergoing urbanization and more sophisticated analytic techniques should be included to improve the results reported herein. Based on information developed in the suggested study above, watersheds in other geographic and climatic regions could be found and analyzed.

3. The effect of other factors, such as watershed slope, size and shape, could also be studied with more and varied watersheds. The effect of snowmelt runoff may also be indorporated into the analysis.

4. Estimates or urban land and impervious area for both current and historic conditions should be improved or refined. Present methods of determining land use information include measurements obtained from aerial

photographs, maps or field reconnaissance or extrapolation from measurements of typical area. These methods are costly, tedious, time consuming, and often imprecise. A study should be made to determine the most efficient method of obtaining this information. Continuous collection and updating of land use information in computer based storage and retrieval systems is not impractical and can be easily incorporated into daily activities of local planning agencies. This procedure offers a reliable and consistent source of information for many potential uses.

5. Because increases in urban runoff are closely related to increases in impervious areas that discharge directly into the stream, a feasibility study should be made to determine whether it is practical to relate increased runoff solely to increased interconnected impervious area. The improved results may not, however, warrant the extra amount of work required to determine interconnected impervious area.

6. A study to determine an optimum baseflow separation technique should be undertaken. The separation technique should be applicable to watersheds from different geologic and climatic areas. The technique should be programmable for application on a digital computer.

7. There are at least two additional approaches that may be used to analyze the relationships between changes in runoff volumes from an urban watershed and the physical changes in the watershed. These general approaches are: (1) multiple regression techniques and (2) digital watershed simulation. Details of applying these procedures were discussed under Other Methods. Selected models that might be used in these approaches are evaluated in Appendix F.

8. Since one purpose of studying the effects of urbanization on run-

off volumes is for improved design information for urban flood control and water supply systems, the information needs for designing such systems and formulating future studies on urban hydrology should be addressed.

APPENDIX A

WATERSHED AND STREAMFLOW CHARACTERISTICS

The urban and control watersheds used in this study are listed in Table A.1. The urban watersheds range in area from 10.00 square miles to 88.40 square miles. The control watersheds range in area from 14.70 square miles to 285.00 square miles. Watershed and streamflow characteristics, as well as a description of the urban development of each watershed, are presented.

New York

Three watersheds are located on Long Island, New York (figure A.1). These are Pines Brook, East Meadow Brook and Connetquot River. Long Island extends about 120 miles northeastward from the mainland of New York State into the Atlantic Ocean. It contains four countries, two of which are part of New York City (Kings County and Queens County) and occupy slightly less than 200 square miles of the western part of the island. The combined population of these two counties was more than 4.5 million people in 1970. The remaining two Counties - Nassau and Suffolk Counties - comprise the rest of the island and occupy about 300 and 900 square miles, respectively. In 1970, Nassau County had a population of slightly less than 1.5 million people and Suffolk County had a population of slightly more than 1 million people.

Pines Brook and East Meadow Brook watersheds are located in south central Nassau County, about five and eight miles, respectively, from the New York City - Nassau County boundary. Connetquot River watershed is located in southwestern Suffolk County, which is

Table A.1. List of Streamflow Stations Used in This Study.

Watershed	U.S.G.S. Station Number	Drainage Area (mi²)	Type	Period of Record	Length of Record (years)	Precipitation Station			Control Watershed		
						Name	Distance[1] (miles)	Direction[2]	Name	Distance[3] (miles)	Direction[2]
East Meadow Brook at Freeport, N.Y.	1310500	31.00[5]	Urban	Oct. 1937– Sept. 1962	25	J.F. Kennedy Int. Airport, N.Y.C.,N.Y.	17(C) 12(E)	Southwest	Connetquot River near Oakdale, N.Y.	22	East
Pines Brook at Malverne, N.Y.	1311000	10.00	Urban	Oct. 1937– Sept. 1969	32	J.F. Kennedy Int. Airport, N.Y.C.,N.Y.	11(C) 10(E)	Southwest	Connetquot River near Oakdale, N.Y.	28	East
North Buffalo Creek near Greensboro, N.C.	209550	37.00	Urban	Oct. 1928– Sept. 1970	42	Greensboro Airport, Greensboro,N.C.	9(C) 6(E)	West	East Fork Deep River near High Point,N.C.	10	West
Little Sugar Creek near Charlotte,N.C.	2146500	41.00	Urban	Oct. 1924– Sept. 1970	46	Douglas Airport, Charlotte,N.C.	7(C) 4(E)	West	———		
Peachtree Creek, Atlanta Georgia	2336300	86.8	Urban	Oct. 1958– Sept. 1970	12	Atlanta Airport & Norcross W.B. Sta., Atlanta, Georgia	4(C)[4] 2(E)[4]	Southeast[4]	Yellow River near Snellville, Ga.	12.5	Northeast
Sims Bayou at Houston, Texas	8075500	64.00	Urban	Oct. 1952– Sept. 1970	18	Houston Airport, Houston, Texas	7(C) 0(E)	East	Cypress Creek near Westfield, Texas	33	Northwest
Brays Bayou at Houston, Texas	8075000	88.40	Urban	Oct. 1936– Sept. 1970	34	Houston Airport, Houston, Texas	16(C) 8(E)	Southeast	Cypress Creek near	24	Northwest
Whiteoak Bayou at Houston, Texas	8074500	84.70	Urban	Oct. 1936– Sept. 1970	34	Houston Airport, Houston, Texas	19(C) 11(E)	Southeast	Cypress Creek near Westfield, Texas	17	Northwest
Halls Bayou Houston, Texas	8076500	26.70	Urban	Oct. 1952– Sept. 1970	18	Houston Airport, Houston, Texas	18(C) 10(E)	Southeast	Cypress Creek near Westfield, Texas	21	Northwest
Greens Bayou Houston, Texas	8076000	72.70	Urban	Oct. 1952– Sept. 1970	18	Houston Airport, Houston, Texas	24(C) 18(E)	Southeast	Cypress Creek near Westfield, Texas	19	West
Morrison Creek Sacramento, California	11336580	40.60	Urban	Oct. 1959– Sept. 1970	11	Sacramento Exec. Airport, Sacramento, Calif.	9(C) 0(E)	West	———		
Connetquot River, near Oakdale,N.Y.	1306500	24.00	Control	Oct. 1943– Sept. 1970	27	J.F. Kennedy Int. Airport, N.Y.C.,N.Y.	30(C) 28(E)	Southwest	———		
East Fork Deep River, near HighPoint,N.C.	2099000	14.70	Control	Oct. 1928– Sept. 1970	42	Greensboro Airport, Greensboro, N.C.	1(C) 0(E)	Northeast	———		
Yellow River near, Snellville, Ga.	2206500	134.00	Control	Oct. 1942– Sept. 1970	28	Atlanta Airport & Norcross W.B. Sta. Atlanta, Georgia	17(C)[4] 8(E)[4]	Southwest[4]	———		
Cypress Creek near Westfield, Texas	8069000	285.00	Control	Oct. 1944– Sept. 1970	26	Houston Airport, Houston, Texas	36(C) 31(E)	Southeast	———		

1. Distance was measured along a line from the precipitation gage to the center of the Watershed (C) and to the nearest point on the urban watershed boundary (E).
2. Direction was determined as the general direction of the precipitation gage or the center of the control watershed from the center of the urban watershed.
3. Distance was measured along a line connecting watershed centers.
4. Distance and direction was measured from the center of the watershed to the midpoint along a line between the Atlanta Airport and Norcross W.B. Stations.
5. Seaburn (1969) suggests that the drainage area that actually contributes direct runoff to the stream channel is 10 square miles. Where appropriate 10 sq. mi. has been used in computations.

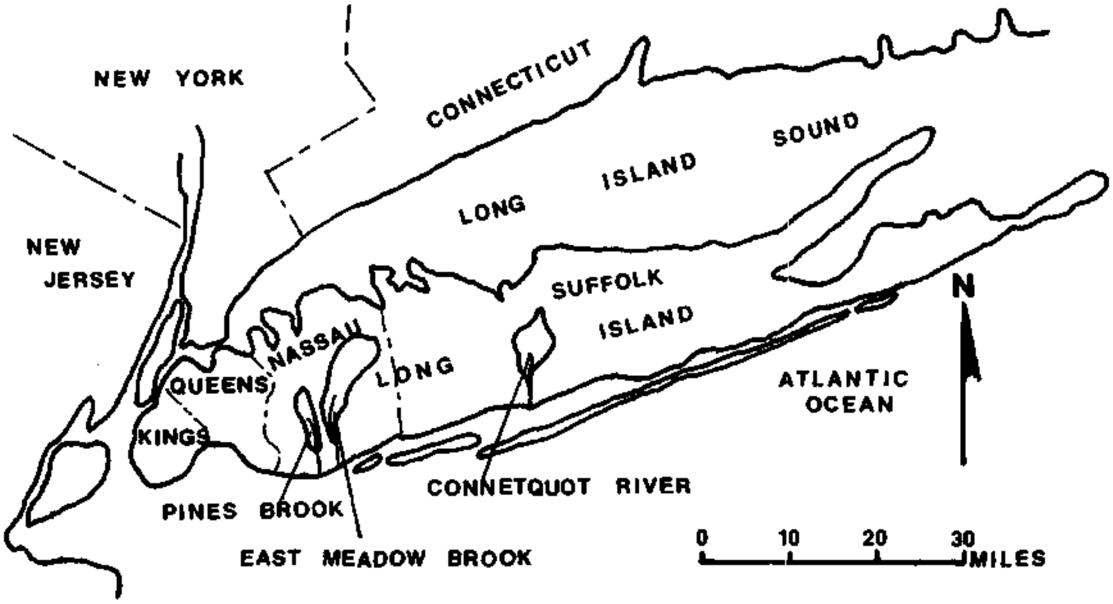

Figure A.1. Location of Pines Brook, East Meadow Brook and Connetquot River Watersheds on Long Island, New York.

adjacent to the eastern boundary of Nassau County. Connetquot River is about 22 miles east of East Meadow Brook (see figure A.1).

Pines Brook, East Meadow Brook and Connetquot River

Watershed Characteristics. All three watersheds are oriented in a north-south direction and lie in the same geologic setting -- surficial deposits of highly permeable sands and gravel of glacial origins with underlying deposits ranging from silts and fine sand to coarse gravel.

Pines Brook watershed is 10 square miles in area. The watershed is seven miles in length and 1.5 miles wide at the widest part. Both land and stream channel slope at about 12 feet per mile to the south. Relief is slight -- elevations range from 10 feet above mean sea level at the stream gage to 170 feet at the highest point on the watershed boundary.

East Meadow Brook watershed is 31 square miles in area, 16 miles in length and about four miles wide at its widest part. Both land and stream channel slope to the south at 12-13 feet per mile. Land elevations range from about 10 feet above mean sea level at the stream gage to about 330 feet at the highest point in the upper reaches of the watershed. Seaburn (1969,p.B4) notes that, because of the highly permeable nature of the surficial deposits and the practise of using recharge basins to dispose of storm runoff on Long Island, much of East Meadow Brook watershed does not contribute direct runoff to the stream channel. Only the lower one-third (about 10 square miles) of the East Meadow Brook watershed is considered to contribute direct runoff to the stream channel. This subarea, which is herein termed the "Hempstead subarea" (following Seaburn's notation), will be used where it is appropriate in any further discussions and description of the watershed. The Hempstead subarea is six miles in length and two miles wide. Elevation range from about 10 feet above mean sea level at the stream gage to 120 feet at the highest point of the subarea.

Connetquot River watershed is 24 square miles in area, seven miles in length and about five miles wide. Land slopes are more variable than the other two Long Island watersheds and average about 15-20 feet per mile. The stream channel slope averages about ten feet per mile. Elevation range from about two feet to about 240 feet above mean sea level.

Streamflow Characteristics. All three streams flow southward through glacial outwash deposits along the southern one-half of Long Island and discharge into the Great South Bay along the southern boundary of Long Island. They have no tributaries although each has several small ponds located along the channel. The average discharge for the period of record at each stream is shown in the following table.

Stream	Period of Record	Mean daily discharge
Pines Brook	Dec. 1936-Sept. 1970	4.48 cfs
East Meadow Brook	Jan. 1937-Sept. 1970	15.6 cfs
Connetquot River	Oct. 1943-Sept. 1970	37.7 cfs

Streamflow varies uniformly throughout the year from high flows in March, April and May to low flows in September and October. The major portion of the total discharge in each of the Long Island streams is baseflow derived from groundwater outflow. Table A.2 of Appendix A shows that about 80 percent of the total flow in Pines Brook, 84 percent in East Meadow Brook and nearly 95 percent in Connetquot River is baseflow. The remaining 20, 16, and five percent, respectively, is direct runoff.

Urban Development. Urban development on Long Island accelerated following World War II, moving in a continuous wave from west to east from New York City across Nassau County and into Suffolk County. This development, which was manifested principally by the construction of single family houses in large scale housing developments, reached the Pines Brook and East Meadow Brook watersheds in the late 1940's and early 1950's and reached a peak in those watershed in the mid 1950's.

The Pines Brook watershed had a similar experience although somewhat prior to the East Meadow Brook watershed development because it is closer to New York City (see figure A.1). Urban development in this watershed is also characterized by the construction of large scale single family type housing developments with local schools and shopping areas. Small scale industrial parks for the manufacture of light industrial products are scattered throughout the watershed. Two golf courses are located along the stream channel near the center of the watershed. Except for these golf courses, there is little open space remaining in the Pines Brook watershed.

Development in the East Meadow Brook watershed was studied by Seaburn (1969) and the following excerpts from that article summarize the urban development over the period of streamflow record (1937-62). This description emphasizes urban development in the Hempstead subarea of the East Meadow Brook watershed for the reason discussed above.

> The Hempstead subarea can be divided conveniently into three parts: a northern, a middle, and a southern part. The southern part is a part of the village of Westbury . . . . The middle part is a tract of about 2.5 square miles which extends eastward across the subarea; it consists almost entirely of an airfield and a park. The southern part of the Hempstead subarea, the area south of Hempstead Turnpike . . . , was almost entirely open fields and forests in 1937. Since 1937, most of the urban development in the East Meadow Brook drainage area has been in the southern part of the Hempstead subarea. This development has been characterized mainly by the construction or road and housing developments, including the construction of storm sewers. All storm sewers in the Hempstead subarea discharge either into recharge basins or directly into the channel of East Meadow Brook; thus, none of the runoff is diverted outside of the East Meadow Brook drainage area.
>
> Virtually no additional urban development took place from 1937 to 1943 in the Hempstead subarea . . . . The total sewered sewered area in the subarea in 1943 was about 570 acres, and most of this area was in the village of Westbury. During the period 1944-51 . . . , about 150 additional acres in the Hempstead subarea were sewered, mainly to provide storm drainage for several new highways. As is described subsequently . . . even this small increase in sewered area caused a clearly defined increased in direct runoff to East Meadow Brook.
>
> The period 1952-59 . . . was the time of most rapid urban development in the Hempstead subarea. The area drained by storm sewers discharging into East Meadow Brook increased by about 2,560 acres. Most of this increase was related to the construction of housing developments and additional highways.
>
> During the years 1960-62 . . . , storm sewers that emptied into East Meadow Brook were constructed in about 315 additional acres in the Hempstead subarea. The marked decrease in sewer construction, compared with construction during the previous period, largely reflected the fact that by 1960 most of the available land in the subarea was already developed. In 1962

> only about 320 acres in the Hempstead subarea, excluding the aforementioned park and airfield in the middle part, remained undeveloped and unsewered.

Urbanization of a sample area of 0.41 square miles in the East Meadow Brook watershed is discussed by Seaburn (1969, p.B6) and is representative of the urban development of the entire area.

> In this sample area, which was largely farmland and woodland in 1937, the number of houses increased from about 200 in 1938, to 350 in 1947, to 620 in 1953, and to 760 in 1966. The impervious cover (streets, highways, parking lots, rooftops and other surfaces) increased from 6.0 percent in 1938 to 7.8 percent in 1947 and 12.8 percent in 1953, and to 27.6 percent in 1966.

During the time from about 1940 to the present the drainage patterns of much of the urbanized areas of Long Island have become markedly modified as a result of the construction of recharge basins. Recharge basins are used to dispose of storm runoff from newly developed urban areas and to help augment natural ground water recharge. The effect of recharge basins, with regard to this study, is to remove those areas draining to recharge basins as sources of direct runoff to the streams.

Much of the watershed of Connetquot River is a protected game preserve and, as such, has not experienced and probably will not experience significant urbanization. In recent years, however, some development has occurred along the watershed boundaries. This development is characterized predominately as large scale single family housing developments, typical of the rest of Long Island. The majority of this new construction is drained by recharge basins with the effect of reducing the drainage area for direct runoff. However, because of the long distances of these newly developed areas from the stream channel and due to the high permeabilities of the Long Island soils, the new development is considered to have little effect on the streamflow of Connetquot River.

North Carolina

Three watersheds in North Carolina used in this study -- North Buffalo Creek near Greensboro, Little Sugar Creek near Charlotte, and East Fork Deep River near High Point. All three watersheds are located in the Piedmont physiographic province about midway between the Atlantic Coastal Plain and the Appalachian Mountains. The population of the Standard Metropolitan Statistical Area (SMSA) of the Greensboro, Winston-Salem, High Point, N.C., was about 640,000 people in 1970 and the population of Greensboro was about 144,000 people in 1970. The population of the SMSA of Charlotte, N.C., was slightly more than 409,000 people in 1970 and the population of Charlotte was sightly more than 241,000 people in 1970.

North Buffalo Creek

Watershed Characteristics. North Buffalo Creek watershed is 37.00 square miles in area and comprises the northern one-half of the city of Greensboro (figure A.2). It is 15.3 miles in length and about 4.5 miles in width. The stream channel slope average 10 feet per miles toward the east. Typical of the Piedmont plateau, the land is gently rolling hills sloping to the nearest stream channel and therefore land slopes are highly variable. Elevations range from 680 feet above mean sea level at the stream gage to 950 feet at the highest points on the western boundary of the watershed.

Streamflow Characteristics. North Buffalo Creek has several tributaries contributing flow from throughout the watershed. The

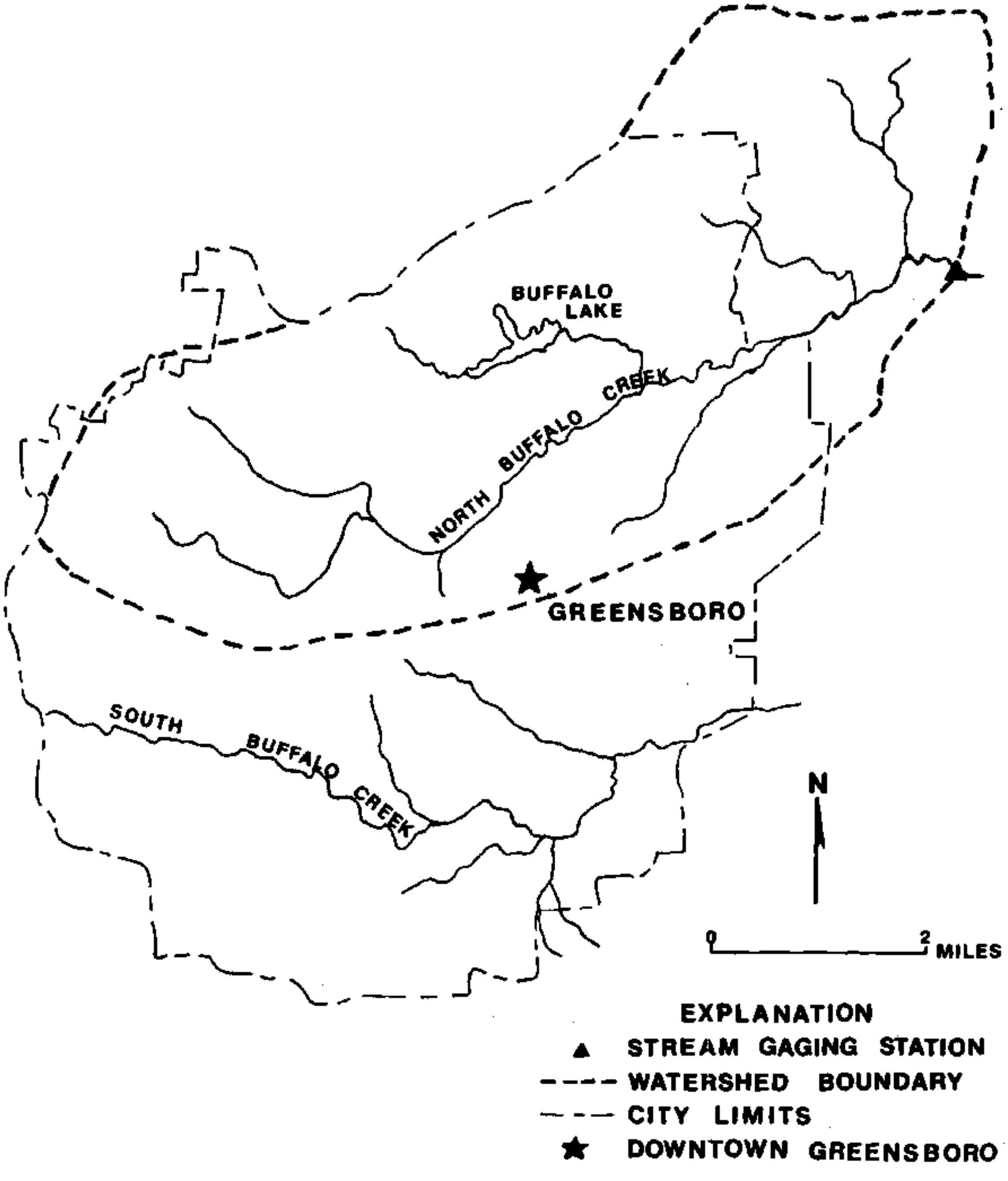

Figure A.2. Location of North Buffalo Creek Watershed in Greensboro North Carolina Metropolitan Area.

stream flows eastward into the Haw River and to the Cape Fear River that eventually discharges into the Atlantic Ocean near Wilmington, North Carolina. The mean daily discharge of North Buffalo Creek for 42 years (1929-70 water years) was about 50 cfs and is about evenly divided between baseflow and direct runoff (see Table A.2 of Appendix A). Discharge varies uniformly throughout the year with maximums occurring during March and minimums occurring during September.

Urban Development. The southern boundary of the North Buffalo Creek watershed runs through the center of downtown Greensboro. Much of the lower one-half of the watershed therefore has been developed for some time and has experienced only a "filling in" of areas with additional buildings and parking lots in recent years. Major new development in the past 15-20 years has occurred in the area north and east of the downtown area. This urbanization has been mainly the construction of single-family housing development, although there has also been significant construction of industrial areas, large scale shopping areas and new highways. Large blocks of open space still remain along the northern boundary of the watershed and just upstream from the stream gage in the eastern part of the watershed. The remainder of the open space is currently used for golf courses, cemeteries, floodways or is unsuitable for development, such as steeply sloping and swampy areas. Future development will move into the large tracts of open land as well as filling in of other areas. Urbanization will rapidly move beyond the northern and western boundaries of the watershed along new highways recently constructed. Development along these routes within the watershed is already extensive.

East Fork Deep River

Watershed Characteristics. East Fork Deep River watershed is 14.70 square miles in area and is located about four miles west of the western boundary of the North Buffalo Creek watershed. It is about 6.5 miles long and about four miles wide. The stream channel slopes about 16 feet per mile generally toward the south. Elevations range from about 770 feet above mean sea level at the stream gage to 970 feet at the highest point on the watershed boundary.

Streamflow Characteristics. East Fork Deep River has several minor tributaries and several small ponds. The stream flows generally southward into Hight Point Lake, which in turn flows into Deep River and Cape Fear River before discharging into the Atlantic Ocean. Mean daily discharges for 42 years (1929-1970) is 15 cfs. Baseflow accounts for about 42 percent of the total annual flow and direct runoff accounts for about 58 percent (see table A.2 of Appendix A). Similar to North Buffalo Creek, high flows occur during March and low flows occur during September.

Urban Development. The watershed of the East Fork Deep River is essentially rural. The only new development within the area in the past 15-20 years is the construction of Interstate Route 40 through the center of the watershed and the construction of three small scale storage tank areas for oil and gasoline storage near the northern boundary of a tributary. The remainder of the watershed contains several improved and unimproved roads and widely scattered farm houses. There is no threat of any urban development in the watershed in the near future. The Greensboro airport is located adjacent to the northern boundary of the watershed.

Little Sugar Creek

Watershed Characteristics. Little Sugar Creek watershed is 41.00 square miles in area and comprises the major part of the downtown area and the eastern and southeastern suburbs of the city Charlotte (figure A.3). It is 11.5 miles long and 4.5 miles wide at the widest point. Land slopes are variable, but the streams channel slopes about 16 feet per mile generally toward the south. Elevations range from 575 feet above mean sea level at the stream gage to about 820 feet at the highest point on the watershed boundary.

Streamflow Characteristics. Little Sugar Creek has two major tributaries (Brier Creek and Little Hope Creek) and several minor tributaries upstream from the stream gage. The stream flows southward to the Catawba River and through several lakes before eventually discharging into the Atlantic Ocean near Charleston, South Carolina. Mean daily discharge for 46 years (1925-70) is 46 cfs. Baseflow accounts for about 37 percent of the annual discharge and direct runoff accounts for about 63 percent (Table A.2 of Appendix A). Discharge varies uniformly throughout the year with highs flows occurring in February and March and low flows occurring in September and October.

Urban Development. Urban development in Charlotte has expanded in all directions from the downtown area. In the Little Sugar Creek watershed urbanization has moved northeastward, eastward and southeastward across the watershed. The western boundary of the watershed runs through the center of downtown Charlotte and approximately the western one-half of the watershed is currently very heavily urbanized. The eastern one-half on the watershed is

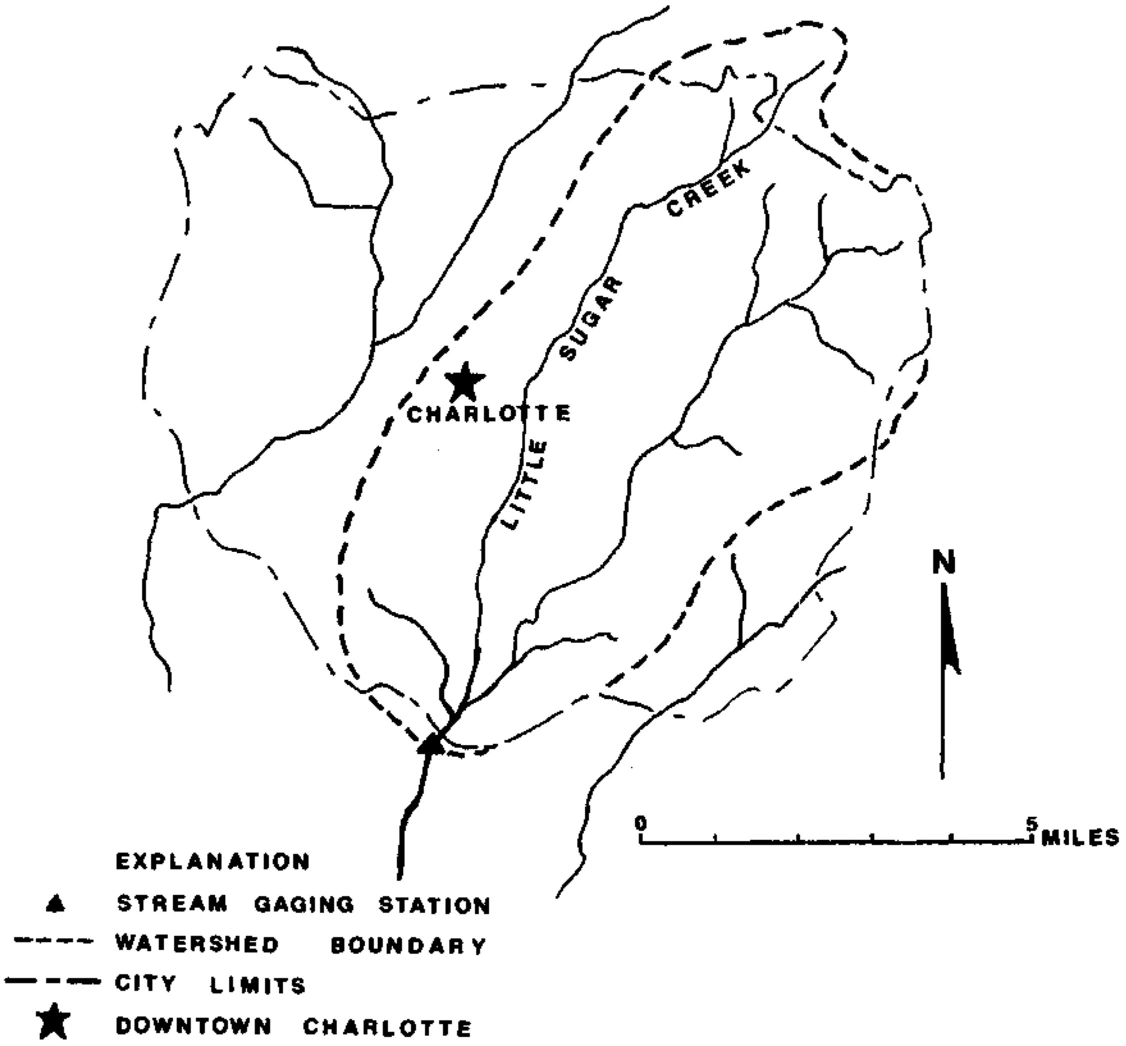

Figure A.3. Location of Little Sugar Creek Watershed in Charlotte, North Carolina Metropolitan Area.

experiencing considerable urban development but still has a moderate amount of open space. Much of this new urban development has manifested itself in large scale single-family housing developemnts with local schools and shopping areas. There are only a few industrial areas: One major area is located in the northwest part of the watershed at the headwaters of the Little Sugar Creek; others are small scale industrial parks most of which are located in close proximity to a stream channel. There are two golf courses centrally located within the watershed and along a stream channel. The predominate influence on runoff results from the construction of single-family housing and other associated land use changes which are progressing outward from the downtown area of Charlotte. Future development in the area will include filling in existing open spaces, probably with additional housing developments, and movement of the urbanization process beyond the northern, eastern and southern boundaries of the watershed. Changes in these effects on the hydrology will continue, principally causing increased flood hazards in lowlying areas.

Georgia

Two watersheds are located in Georgia -- Peachtree Creek and Yellow River watersheds. They both are located in the Piedmont Physiographic province near Atlanta, Georgia. The SMSA population of Atlanta was slightly less than 1.4 million people in 1970 and the population of the city of Atlanta was slightly under 500,000 people in 1970.

Peachtree Creek

Watershed Characteristics. Peachtree Creek watershed is 86.8 square miles in area and comprises the northern part of the city of Atlanta and suburban DeKalb County (figure A.4). It is about 14 miles long and about seven miles wide at the widest part. Land slopes are variable but the stream channel slopes about 15 feet per miles generally westward. Elevation in the watershed range from about 765 feet above mean sea level at the stream gage to 1090 feet at the highest point.

Streamflow Characteristics. Peachtree Creek is comprised of two main stems -- North Fork and South Fork -- which join to form the main channel approximately 2.5 miles upstream from the stream gage. There are many minor tributaries draining the watershed. The stream flows generally westward and discharges into the Chattahoochee River about three miles downstream from the stream gage which eventually discharge into Lake Seminole, the Appalachicola River and the Gulf of Mexico near Appalachicola, Florida. Mean daily discharge of Peachtree Creek for 12 years (1959-70) is 130 cfs. Direct runoff accounts for 63 percent of the annual flow while baseflow accounts for the remaining 37 percent. Flows vary uniformly throughout the year with high flows occurring in March and low flows occurring in August and September.

Urban Development. The Peachtree Creek watershed contains parts of downtown Atlanta and the city of Decatur which have been heavily developed for some time. The type of development in this area range from heavy concentrations of high rise buildings in

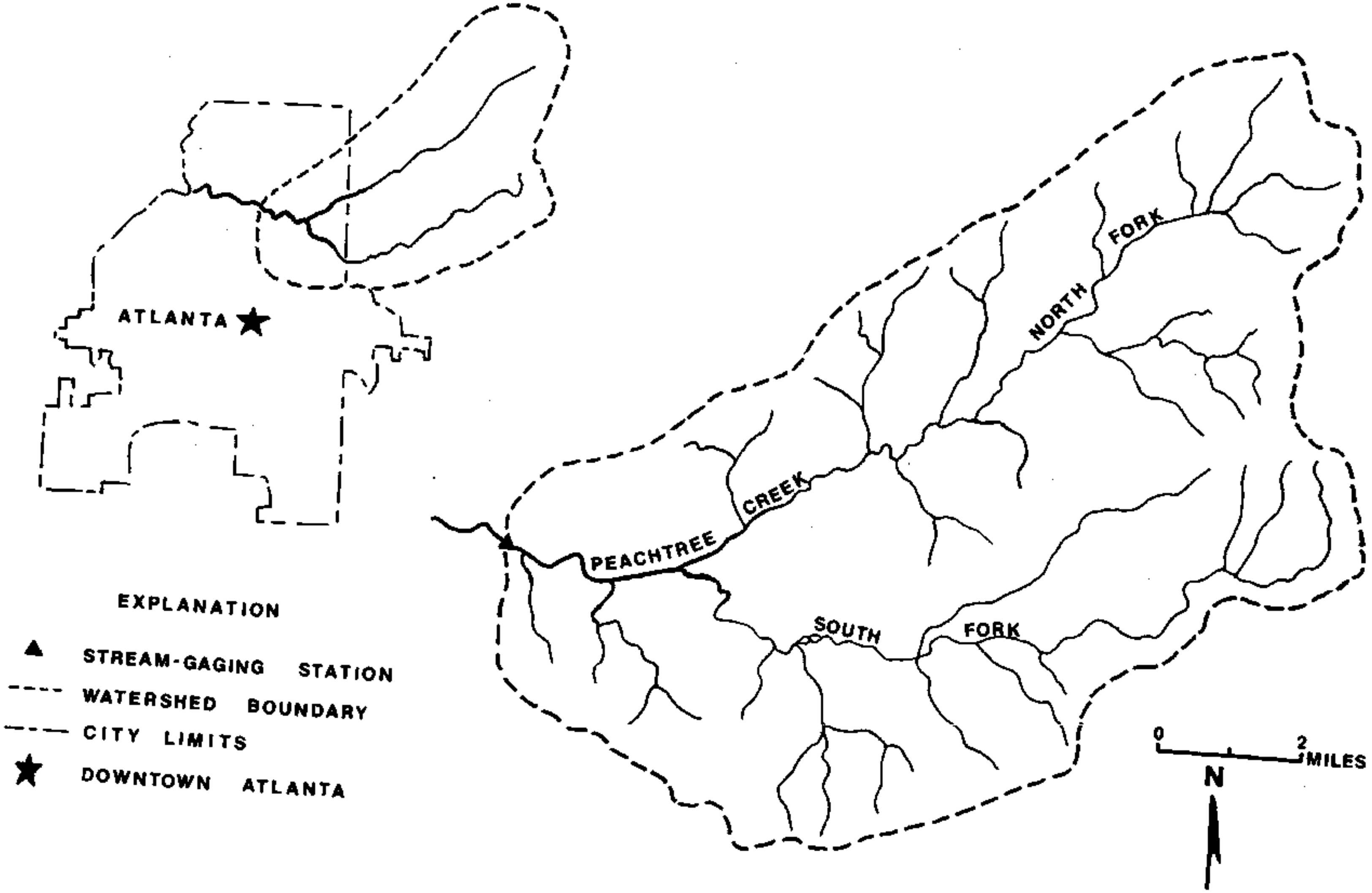

Figure A.4. Location of Peachtree Creek Watershed near Atlanta, Georgia.

the central business district to sprawling estates in suburban Decatur. Extensive new urban development has occurred in the past 20-25 years along the center of the watershed radiating northeastward from Atlanta. This movement has been strongly influenced by the construction of new highway systems through the watersheds. Much of the land use has been converted to single family housing developments and multiple family housing, principally large scale garden-type apartment complexes. Large tracts of land have also been developed as shopping centers and industrial and commercial parks. The little open space that remains in the watershed exists mainly in the upper reaches and is very greatly susceptible to developments in the near future.

Wallace (1971) briefly describes the reasons for regional growth of Atlanta and the affect on the Peachtree Creek watershed:

> Atlanta came into existence as a railroad terminal, and the city has grown to become the transportation hub of the southeastern portion of the country. The location of new development during the last fifteen years has been strongly influenced by the interstate highway system while prior development was concentrated along major city thoroghfares. It is interesting to note that these older roads as well as the railroads established early in the city's history lies on the divide separating drainage flowing southeastward to the Atlantic from that flowing southwestward to the Gulf of Mexico, and the ridge lines radiating outward from this central location have had a strong influence on the developing of the city. The more recent interstate highways were not constructed along drainage divides; hence, the development of the city relative to the watershed topography has been changed. In fact Interstate 85 parallels the North Fork of Peachtree Creek, and this has resulted in the growth of high density development adjacent to the creek.

Wallace (1971) describes the historical development of the watershed in terms of changes in the concentrations of impervious area. In this study, impervious area was determined by a sampling procedure at the intersection of a grid system overlying aerial photographs of the watershed at three points in time -- 1949, 1955, and 1968. The results of that sampling study show that the percentage impervious cover in each of the three years listed above was 22.30, 28.08 and 34.96, respectively. He also mentions that by 1968 in all but one grid sampling area, the impervious area in each subarea exceeded 10 percent.

Yellow River

Watershed Characteristics. Yellow River watershed is 134 square miles in area and is located adjacent to and northeast of the Peachtree Creek watershed. It is 15 miles long and 13 miles wide. Land slopes are variable but the stream channel slope averages about 12 feet per mile toward the south. Elevations in the watershed range from 810 feet above mean sea level at the stream gage to 1200 feet at the highest point an the watershed boundary.

Streamflow Characteristics. Yellow River has many minor tributaries contributing flow to the main stem upstream from the stream gage location. There are a great many small farm ponds and detention basins scattered throughout the watershed. The stream flows generally southward to Lake Jackson and the Ocmulgee River and to the Altamaha River which eventually discharges to the Atlantic Ocean north of Brunswick, Georgia. Mean daily discharge of the Yellow River for 28 years (1943-1970) is 169 cfs. Flows vary uniformly throughout the year with high flows occurring in March and low flows occurring in September and October.

Urban Development: The Yellow River watershed is rural farmland and forest land and until only recently has experienced little urban development. In recent years the urbanization process occurring in the adjacent Peachtree Creek watershed has begun to overflow into the western part of the Yellow River watershed. This development currently (1973) is not extensive and is hydrologically insignificant for purposes of this study. This recent urban growth is almost solely single-family housing developments and scattered housing. Interstate 85 and Georgia Route 216 pass through the northern parts of watershed but growth along these transportation routes has not yet developed.

Impetus for future growth in the Yellow River watershed will come mainly from encroaching urbanization from the Peachtree Creek watershed. Development will move eastward across the watershed. The existing transportation routes will substantially influence the development pattern.

Texas

All six Texas watersheds are located in the Houston metropolitan area. They are Sims Bayou, Brays Bayou, Whiteoak Bayou, Halls Bayou, Greens Bayou and Cypress Creek. The area is part of a nearly level, almost featureless coastal plain, located about 35 miles from the Gulf of Mexico. The population of the SMSA of Houston was slightly more than 1.2 million people in 1970.

A general description of the physiography of the Houston area was given by Johnson and Smith (1965):

The Houston study area is within a 30 square mile area about 35 miles from the Gulf of Mexico. It is part of a level almost featureless plain. Elevations in the are increased gently from about 35 feet above mean sea level to the southeast to about 135 feet in the northwest.

The major streams draining the area is Buffalo Bayou . . . , a tributary to the San Jacinto River. Buffalo Bayou is regulated by Barker and Addicks flood detention reservoirs near the western limits of the area. From these reservoirs Buffalo Bayou meanders generally to the east where it is fed by five major streams: Whiteoak, Brays, Sims, Hunting and Greens Bayou. The drainage area of Buffalo Bayou, downstream from the flood detention reservoirs is about 810 square miles.

The climate of the Houston area is characterized by short mild winters, long hot summers, and high relative humidity. The prevailing winds are from the south and southwest. The mean annual temperature is 69.2°F varying from a maximum of 108° to a minimum of 5°F.

The 30-year average (1931-60) rainfall for Houston is 45.5 inches and is distributed fairly uniformly throughout the year. The maximum annual rainfall for Houston was 72.86 inches in 1900; the minimum, 17.66 inches in 1917.

Soils in the area are predominately clays, clay loams, and fine sandy loams which have a low permeability.

Sims Bayou

Watershed Characteristics. Sims Bayou watershed is 64.0 square miles in area and is located along the souther boundary of the city (figure A.5). It is 18.5 miles long and five miles wide. Topography in the Houston area is very flat -- land surfaces slopes are generally 3 to 8 feet per mile to the east and southeast. The stream channel slopes about three feet per mile to the east. Elevations in the Sims Bayou watershed range from 30 feet above mean sea level near the stream gage to 90 feet above mean sea level at the highest point on the watershed boundary.

Streamflow Characteristics. Sims Bayou has only a few minor natural tributaries, although there are several man-made drainage

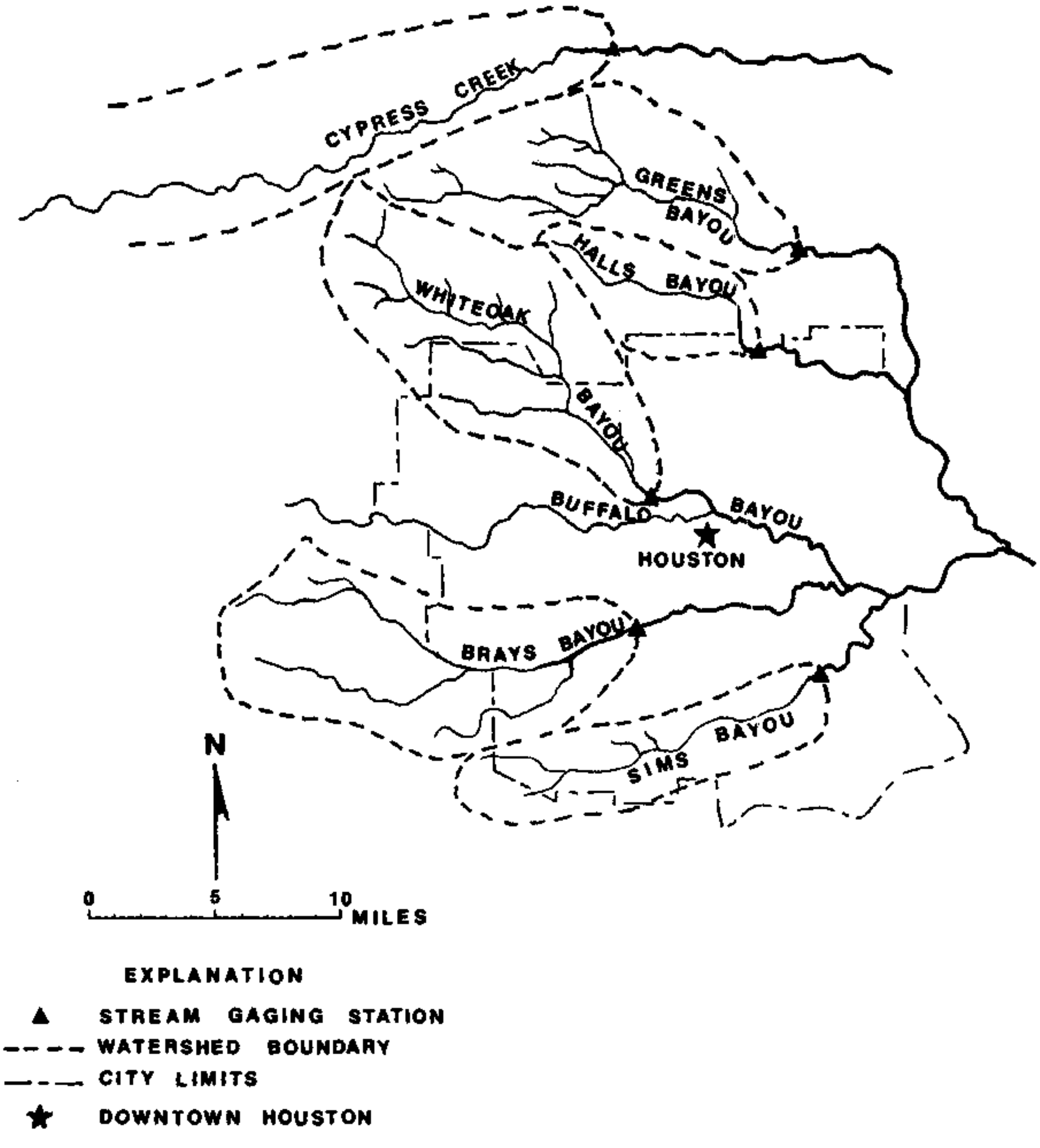

Figure A.5. Location of Watersheds in Houston, Texas Metropolitan Area.

ditches which deliver storm runoff to the stream channel. The stream flows east and northeastward into Buffalo Bayou, which in turn discharges into Galveston Bay and the Gulf of Mexico. The mean daily discharge for 19 years (1953-71) is 61.5 cfs. Direct runoff accounts for about 82 percent of the total annual flow in Sims Bayou while baseflow accounts for about 18 percent. Flow varies during the year with high flows occurring in March and low flows occurring in July and August. Low flows are largely sustained by sewage effluent.

Urban Development. The Sims Bayou watershed is situated along the southern boundary of the city limits of Houston and development is therefore progressing southward across the watershed. The lower reaches of the watershed near the stream gage are heavily developed, principally with single-family housing developments, local schools, shopping areas and industrial parks. The Houston International Airport is located just outside the eastern boundary of the watershed near the stream gage. Development in the remaining parts of the watershed is scattered and widespread, developing along roads leading into the city. This development consists of single-family and multiple-family housing units, schools, shopping centers, and industrial parks. Located near the center of the watershed is the Blue Ridge State Prison Farm which is predominately open space. The watershed has considerable open space remaining, mainly in the western and southern fringes.

Brays Bayou

Watershed Characteristics. Brays Bayou watershed is 88.4 square miles in area and is located north and west and adjacent to

Sims Bayou in the southwestern sector of Houston (figureA.5). It is 17.5 miles long and seven miles wide. The stream channels slopes four feet per mile toward to east. Elevations range from about 45 feet above mean sea level at the highest point.

Brays Bayou has two major tributaries (Keegans Bayou and Willow Waterhole), a few minor tributaries and several man-made drainage ditches contributing flow. The stream flows eastward into Buffalo Bayou and into Galveston Bay as described above. Mean daily discharge for 35 years of record (1937-71 water years) is 94.3 cfs. Direct runoff accounts for 86 percent of the total flow and baseflow accounts for the remaining 16 percent. Flows are fairly uniformly distributed throughout the year. Low flows are partly sustained by sewage effluent.

Urban Development. Much of the lower reaches of the Brays Bayou watershed has been extensively developed with single-family houses and some industrial areas for most of the period of streamflow record (1949-70). This development was situated along the north side of the stream channel and radiates westward from the city. With the construction of several major highways system through the watershed since about 1955 urbanization has advanced further west until now (1973) most of the eastern one-half of the watershed is extensively development. The development consists mainly of single and multi-family housing with associated schools and churches. The area also includes large industrial and commercial parks and large shopping areas. There is little remaining open space available for development in this eastern one-half of the watershed.

The western one-half of Brays Bayou watershed is relatively undeveloped, mainly because of a lack of adequate highways leading into the area. There are currently only a few isolated areas that have been developed and these consist mainly of single family houses. The remaining area is essentially open space with widely scattered houses and roads.

Whiteoak Bayou

Watershed Characteristics. Whiteoak Bayou watershed is 84.7 square miles in area except in extreme floods when the capacity of the drainage ditches are exceeded. In those cases the drainage area, defined by natural ridges, is 92 square miles. The watershed is located in the northwest sector of metropolitan Houston. It is 19 miles long and 7.5 miles wide. The stream channel slopes five feet per miles to the southeast. Elevations range from 50 feet above mean sea level near the stream gage to 140 geet above mean dea level at the highest point on the watershed boundary.

Streamflow Characteristics. Whiteoak Bayou has three major tributaries (Vogel Creek, Cole Creek and Brickhouse Gully), several minor natural tributaries and several drainage ditches that contribute flow to the main channel. The stream flows southeastward into Buffalo Bayou near the center of downtown Houston. Mean daily discharge for 35 years (1938-71 water years) is 68.5 cfs. Direct runoff accounts for 91 percent of total flow and baseflow accounts for the remaining nine percent. Flows are fairly uniform throughout the year. Low flows are partly sustained by industrial waste effluent.

Urban Development. The area immediately upstream from the stream gage has been extensively urbanized for the entire period of streamflow record (1949-70). The area is situated mainly along the east side of the stream channel for about six miles and includes mainly single and multi-family housing. A large industrial area is located on the west side of channel about one mile upstream from the gage.

Urban development over the past 15 years has been concentrated mainly in this same area and is manifested principally by construction of additional housing, industrial and commercial areas in the available open areas. A perimeter highway has been constructed through this lower part of the watershed and has aided the development of the area. Adequate roads leading to the outer reaches of the watershed are still lacking and as a consequence most of the outlying area remains undeveloped. Improved and unimproved roads with widely scattered farm houses exist in this area.

Halls Bayou

Watershed Characteristics. Halls Bayou watershed is 24.7 square miles in area and is located adjacent to the Whiteoak Bayou watershed along the northern boundary of the city limits of Houston. It is 10.5 miles long and three miles wide. The stream channel slopes about seven feet per miles toward the southeast elevations range from 60 feet above sea level near the stream gage to 110 feet above sea level at the highest point on the watershed boundary.

Streamflow Characteristic. Halls Bayou has only a few natural tributaries and several drainage ditches contributing flow. The stream flows southeastward into Greens Bayou which, in turn, discharges into Buffalo Bayou. Mean daily discharge for 19 years (1952-71 water years) is 20.3 cfs. Direct runoff accounts for 89 percent of the total annual flow and baseflow accounts for the remaining 11 percent. Flows are fairly uniformly distributed throughout the year. Low flows are partly sustained by sewage effluent.

Urban Development. The area approximately two miles upstream from the stream gage has been extensively urbanized for the entire period of streamflow record (1953-70). Additional urbanization over the past 15 years was aided by the improved highway system, (U.S. Routes 75 and 59) leading from the downtown area through the watershed area. The additional development has been concentrated principally in the downstream parts of the watershed and moving from south to north across the area. The development is mainly single-family housing with associated schools, churches, and shopping centers. Some areas are used for light industry. The area is under intensive pressure for continued development. A large part of the watershed, located in the northwestern section, remains undeveloped. This area is adjacent to the upper reaches of the Whiteoak Bayou watershed. As roads are improved and pressure for development increases, these areas will experience considerable urbanization in the near future.

Greens Bayou

Watershed Characteristics. Greens Bayou watershed is 72.7 square miles in area and is located north of both the Whiteoak and Halls Bayou watersheds in the northern parts of metropolitan Houston. It is 18 miles long and 5.5 miles wide. The stream channel slopes about seven feet per mile toward the east. Elevations in the watershed range from about 65 feet above mean sea level near the stream gage to 135 feet above mean sea level at the highest point on the watershed boundary.

Streamflow Characteristics - Greens Bayou has only a few minor tributaries and several drainage ditches contributing flow to the stream channel. The stream flows eastward through the watershed and then turns southeastward a short distance downstream from the stream gage and discharges into Buffalo Bayou. Mean daily discharge for 19 years (1952-71 water years) is 41.1 cfs. Direct runoff accounts for more than 93 percent of the total annual flow and baseflow accounts for the remaining seven percent. Flows are fairly uniformly distributed throughout the year. Low flows are sustained by effluent from Houston Light and Power Company.

Urban Development. The Greens Bayou watershed is the most distant from the downtown area of Houston. As development seems to radiate outward from the center city, one would expect that the Greens Bayou watershed would be the least developed of urban watershed in Houston. Currently (1973) development consists only of scattered, but large scale single-family housing developments most of which are not yet completed. Future development is dependent on the progress of urbanization to the south of the watershed in Halls Bayou watershed and adjacent areas. Major transportation routes exist, but secondary highways need to be constructed to adequately serve the area.

Future development in the Houston area will apparently continue to radiate outward from the city center. In the five urban watershed studied herein, there remains considerable open space, mainly in the outlying parts of each watershed, for continued growth. Even though some parts of each watershed were heavily urbanized, some for the entire length of streamflow record, no watershed has even begun to reach a fully developed stage. All five watersheds will experience considerable urbanization in the future, greatly affecting the runoff behavior of each stream.

Cypress Creek

Watershed Characteristics. Cypress Creek watershed is 285 square miles in area and is located 18-20 miles north and west of downtown Houston. It is northwest of and adjacent to Greens Bayou watershed. It is about 35 miles long and about 10 miles wide. The stream channel slopes about five feet per miles toward the east. Elevations range from about 90 feet above mean sea level near the stream gage to 275 feet at the highest point on the watershed boundary.

Streamflow Characteristics. Cypress Creek has few natural or man-made tributaries. The stream flows eastward into San Jacinto River and Lake Houston before discharging into Buffalo Bayou, Galveston Bay and the Gulf of Mexico. Mean daily discharge for 27 years (1945-71 water years) is 134 cfs. Direct runoff accounts for 93 percent of the total annual flow and baseflow accounts for the remaining seven percent. Flows vary slightly throughout the year with high flows occurring in the spring (April, May, June) and low flows occurring in the summer season (July, August and September). Low flows are partly sustained by sewage effluent.

Urban Development. The Cypress Creek watershed has no urban development of any sinigicance within its boundary at the present time. Widely scattered farms and farm houses, and local improved and unimproved roads are the only type of development that exists. The watershed remains essentially in its natural state.

California

One watershed located near Sacramento California was used in the study. It is the Morrison Creek watershed which is located south and southeast of Sacramento, California. James (1964) describes the physiography of the area, as it existed in the early 1960's:

> Urban land now occupies about 14 square miles of the watershed. Most of this consists of the southern fringes of Sacramento along the northwestern edge of the Morrison Creek drainage. Future urban growth can be expected to proceed southward and eastward present watershed population is about 75,000. About 60,000 line in the southern fringes of Sacramento and about 2500 in Elk Grove in the Loguna watershed. The remainder live in rural areas. Downtown Sacramento is about four miles northwest of the nearest point within the watershed.
>
> The watershed contains two military installations. An army signal depot covers about 480 acres within the urban fringes of Sacramento; Mather Air Force Base occupies about 6100 acres in the upper middle portion of the Morrison Creek watershed. In addition, Aerojet General Corp. and Douglas Aircraft Corp. occupy large blocks of land upstream from Mather Field.
>
> About one-third of the non-urban land is cultivated, and about one-third of this is irrigated. The balance is in native grasses used largely for grazing. However, the Bureau of Reclamation in the Falsom South Unit of the Central Valley Project is comtemplating providing irrigation water for over two-thirds of the rural area. About 4.8 sq. mi. in the extreme upper watershed consists of dredge tailings from gold mining in early 1900's.
>
> Elevations range from 330 ft. at the dredge tailings to within 5 ft. of mean sea level at the railroad. At these elevations in Calfiornia, snow is almost entirely unknown. Land slopes range from 5 ft./mi. in the lower area to 50 ft./mi. in the upper watershed. Average slope along the Morrison Creek watercourse is 13 ft./mi.

Mean annual rainfall within the basin ranges from 15.5 in. at the downstream end to 22 in. at the upstream end. The overall average is close to 18 in. Mean annual lake evaporation is 50 in.

Population estimates of the SMSA of Sacramento Ca. in 1970 was just over 800,000 people; the population of the city of Sacramento was over 254,000 people in 1970.

Morrison Creek

Watershed Characteristics. The Morrison Creek watershed is 48.6 square miles in area (figure A.6). It is 19.5 miles long and 4.5 miles wide. Elevations in the watershed range from 15 feet above mean sea level near the stream gage to 320 feet above sea level at the dredge tailings in the upper reaches of the watershed. Soils in the remaining parts of the watershed were developed on old alluvial plains and terraces which are characterized by a layer of hardpan or Claypan, generally one to four feet below the surface (DeWante and Stowell, 1961).

Streamflow Characteristics. Morrison Creek has no major tributaries but several minor natural tributaries and improved drainage ditches. Drainage in the area of the dredge tailings is ill defined and probably contributes little direct runoff to the stream. The stream flows generally westward along the southern fringes of the city of Sacramento then turns southward and discharges into Beach Lake, through Snodgrass Slough and other channels and eventually flows into Mokelumne River. The Mokelumne River discharges into the Sacramento River -- the major stream draining the northern part of the Central Valley of California -- which flows generally southward and discharges into the San Francisco Bay and the Pacific

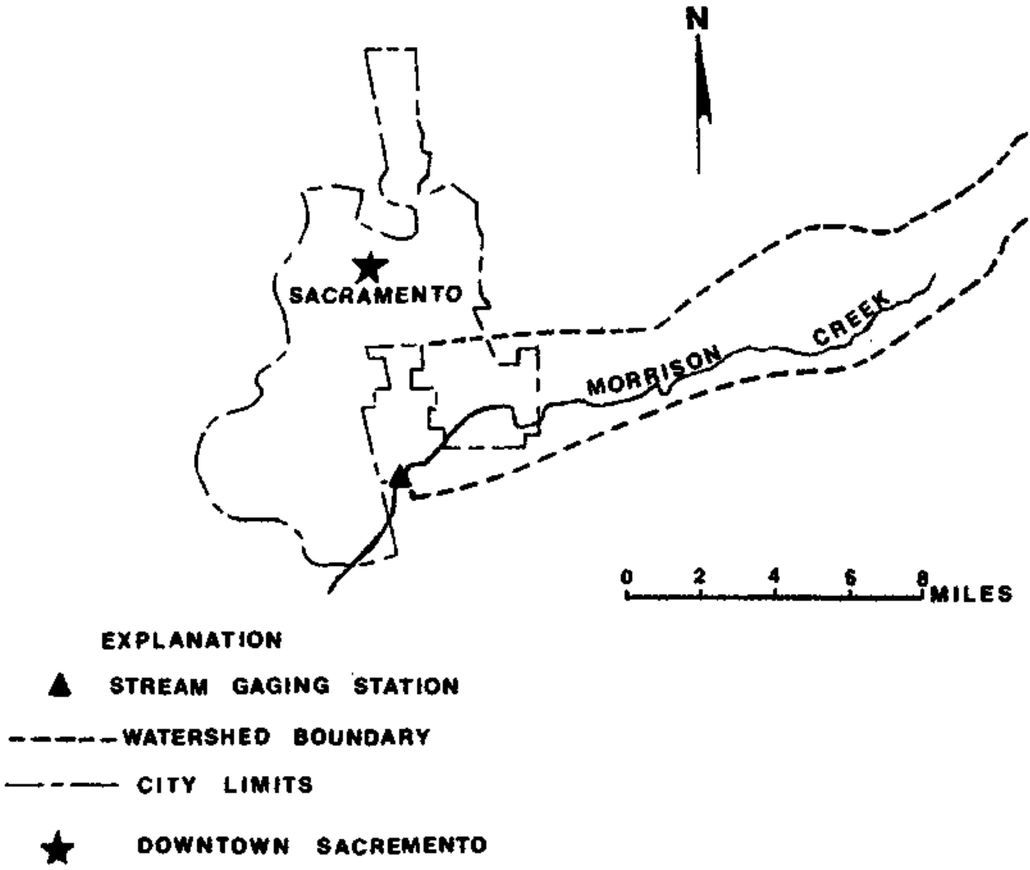

Figure A.6 Location of Morrison Creek Watershed near Sacramento, California.

Ocean. The mean daily discharge at Morrison Creek for 10 years (1960-70 water years) is 18.3 cfs. Direct runoff accounts for about 71 percent of the total annual discharge and baseflow accounts for the remaining 29 percent. Flows vary considerably throughout the year with high flow occurring during the winter months (January, February and March) and low flows occurring during the summer months (July, August and September). Low flows are sustained by sewage effluent.

Urban Development. During the period of streamflow analysis (1960-70) much of the lower portions of the Morrison Creek watershed was already extensively developed. Type of land use in this area ranged widely including single and multi-family housing, schools, parks, cemeteries, industrial and commercial parks, shopping centers, major and secondary highways and the Sacramento Army Depot. Current development in this area consists of "filling in" the available open space, mainly near the stream channel.

Development in the remaining parts of the watershed is sparse, except for Mather Air Force Base situated near the center watershed about 10 miles east of downtown Sacramento. This installation consists of a large complex of building near the northern watershed boundary, several landing strips and service roads and a separate, large scale housing development. The remaining parts of the watershed contains widely scattered houses and roads.

Future developments in the Morrison Creek watershed will probably be concentrated in the area between the existing development in the lower reaches and Mather Air Force Base. However, an adequate highway system serving this area is yet to be developed. The dredge tailings in the outlying eastern parts of the watershed are not conducive to construction and therefore this area does not face any important threat of development in the near future.

Table A.2. Summary Table Of Streamflow Data For Urban Watersheds.

Watershed	Period	Season	Total Flow	Baseflow		Direct Flow			Remarks
			Average (inches)	Average (inches)	Percent of Total Flow	Average (inches)	Percent of Total Flow	Percent of Baseflow	
E. Meadow	(of record)	Annual	7.89	6.64	84.22	1.24	15.78	18.74	
Brook	1938-62	Fall	1.73	1.45	84.41	0.28	15.59	19.38	
		Winter	2.17	1.83	85.27	.33	14.73	18.01	
		Spring	2.20	1.96	89.33	.24	10.67	12.16	
		Summer	1.79	1.41	80.85	.38	19.15	27.40	
	(of analysis)	Annual	8.62	6.89	79.93	1.73	20.06	25.11	
	1952-62	Fall	1.92	1.55	80.73	.41	21.25	26.45	
		Winter	2.29	1.88	82.10	.41	17.90	21.81	
		Spring	2.38	2.05	86.13	.33	13.84	16.10	
		Summer	2.00	1.41	70.50	.58	29.00	41.13	
Pines	(of record)	Annual	6.25	5.08	81.35	1.17	18.65	22.93	includes
Brook	1938-70	Fall	1.35	1.10	71.80	0.25	28.20	90.09	drought
		Winter	1.74	1.44	75.83	.29	24.17	31.86	period
		Spring	1.78	1.51	77.51	.27	22.49	57.49	(1962-66)
		Summer	1.39	1.06	65.72	.33	34.28	144.52	
	(of analysis)	Annual	4.92	3.60	73.17	1.32	26.83	36.67	
	1952-69	Fall	1.13	.81	72.32	.31	27.68	38.27	includes
		Winter	1.36	1.03	75.73	.34	25.00	33.01	drought
		Spring	1.37	1.09	79.56	.28	20.44	25.69	period
		Summer	1.07	.68	63.55	.39	36.45	57.35	(1962-66)
N. Buffalo	(of record)	Annual	18.34	8.75	47.72	9.59	52.28	109.56	
Creek	1929-70	Fall	3.81	1.98	57.33	1.84	42.67	89.75	
		Winter	6.57	2.88	44.64	3.71	55.36	129.77	
		Spring	4.30	2.25	54.84	2.05	45.16	91.68	
		Summer	3.43	1.66	49.13	1.98	50.87	123.00	
	(of analysis)	Annual	20.06	9.99	49.80	10.09	50.30	100.70	
	1949-70	Fall	4.39	2.25	51.25	2.15	48.97	95.56	
		Winter	6.94	3.14	45.24	3.80	54.74	121.03	
		Spring	4.70	2.55	54.26	2.14	45.53	83.92	
		Summer	4.04	2.05	50.74	1.99	49.26	97.07	
L. Sugar	(of record)	Annual	15.09	5.36	34.89	9.32	65.11	171.10	
Creek	1925-70	Fall	2.79	1.12	40.18	1.67	59.82	151.71	
		Winter	5.85	2.12	40.31	3.73	59.69	175.90	
		Spring	3.44	1.50	49.09	1.94	50.91	126.54	
		Summer	3.00	.83	33.44	2.18	66.56	249.91	
	(of analysis)	Annual	15.03	5.27	35.02	9.76	64.98	185.38	
	1949-70	Fall	2.79	1.04	37.28	1.76	63.08	169.23	
		Winter	5.88	2.01	34.18	3.88	65.65	192.04	
		Spring	3.58	1.46	40.78	2.12	59.22	145.20	
		Summer	2.79	.76	27.24	2.03	72.74	267.10	

Table A.1. Summary Table Of Streamflow Data For Urban Watersheds. — Continued.

Watershed	Period	Season	Total Flow	Baseflow		Direct Flow			Remarks
			Average (inches)	Average (inches)	Percent of Total Flow	Average (inches)	Percent of Total Flow	Percent of Baseflow	
Peachtree	(of record)	Annual	20.34	7.47	36.70	12.88	63.30	172.49	
Creek	1959-70	Fall	3.79	1.49	44.16	2.30	55.84	157.96	
		Winter	7.10	2.50	36.62	4.60	63.38	191.36	
		Spring	5.98	2.29	41.11	3.69	58.89	162.66	
		Summer	3.47	1.28	41.95	2.19	58.05	159.46	
Sims	(of record)	Annual	13.11	2.34	17.89	10.76	82.11	458.87	
Bayou	1953-70	Fall	2.83	0.54	33.05	2.29	66.95	401.67	
		Winter	3.86	.67	26.23	3.19	73.77	505.85	
		Spring	4.04	.63	27.68	3.40	72.32	543.34	
		Summer	2.38	.55	37.78	1.83	62.22	378.11	
Brays	(of record)	Annual	14.28	2.02	14.14	12.26	85.86	607.36	
Bayou	1937-70	Fall	3.71	.48	24.83	3.23	75.17	1127.52	
		Winter	3.72	.58	18.99	3.14	81.01	680.96	
		Spring	3.83	.69	21.81	3.34	78.19	935.17	
		Summer	3.01	.50	29.41	2.51	70.59	1195.54	
	(of analysis)	Annual	13.42	2.66	19.82	10.76	80.18	404.51	
	1949-70	Fall	3.28	.62	18.90	2.66	81.10	429.03	
		Winter	3.60	.68	18.89	2.91	80.83	427.94	
		Spring	4.07	.67	16.46	3.41	83.54	508.93	
		Summer	2.47	.69	27.93	1.77	71.64	256.52	
Whiteoak	(of record)	Annual	10.98	.95	8.65	10.03	91.35	1055.47	
Bayou	1937-70	Fall	2.88	.23	17.18	2.65	82.82	1111.46	
		Winter	3.08	.32	13.63	2.76	86.37	863.53	
		Spring	2.92	.22	14.00	2.71	86.00	1229.84	
		Summer	2.09	.19	18.05	1.91	81.95	1071.64	
	(of analysis)	Annual	9.29	1.03	11.09	8.26	88.91	801.94	
	1949-70	Fall	2.33	.24	10.30	2.09	89.70	870.83	
		Winter	2.60	.32	12.31	2.28	87.69	712.50	
		Spring	2.53	.24	9.49	2.29	90.51	954.17	
		Summer	1.83	.23	12.57	1.60	87.43	695.65	
Halls	(of record)	Annual	11.24	1.22	10.89	10.02	89.11	818.43	
Bayou	1953-70	Fall	2.36	.25	17.46	2.11	82.54	1028.37	
		Winter	3.14	.45	19.07	2.69	80.93	791.89	
		Spring	3.21	.30	16.57	2.91	83.43	1277.75	
		Summer	2.52	.23	17.43	2.29	82.57	1770.36	
Greens	(of record)	Annual	7.80	.53	6.82	7.27	93.18	1365.79	
Bayou	1953-70	Fall	1.67	.11	9.55	1.56	90.45	3319.01	
		Winter	2.07	.16	12.57	1.91	87.43	2774.75	
		Spring	2.35	.13	13.69	2.21	86.31	2731.99	
		Summer	1.71	.14	18.95	1.57	81.05	3027.01	
Morrison	(of record)	Annual	5.12	1.48	28.91	3.64	71.09	245.86	
Creek	1960-70	Fall	1.16	.33	36.80	.83	63.20	229.43	
		Winter	2.98	.48	24.08	2.50	75.92	478.44	
		Spring	.60	.38	72.29	.23	27.71	50.83	
		Summer	.38	.30	80.39	.08	19.61	23.87	

Table A.3. Summary Table of Streamflow Data for Control Watersheds.

Watershed	Period	Season	Total Flow	Baseflow		Direct Flow			Remarks
			Average (inches)	Average (inches)	Percent of Total Flow	Average (inches)	Percent of Total Flow	Percent of Baseflow	
Connetquot	(of record)	Annual	21.40	20.31	94.93	1.09	5.07	5.34	
River	1944-70	Fall	5.08	4.78	94.54	.30	5.46	5.90	includes
		Winter	5.67	5.36	94.55	.32	5.45	5.84	drought
		Spring	5.76	5.54	96.23	.22	3.77	3.94	(1962-66)
		Summer	4.89	4.66	93.51	.23	4.49	4.78	
	(of analysis)	Annual	22.81	21.65	94.92	1.16	5.08	5.36	
	1944-62	Fall	5.37	5.03	94.04	.32	5.96	6.34	
		Winter	6.05	5.70	94.22	.35	5.78	6.14	
		Spring	6.13	5.91	96.41	.23	3.56	3.89	
		Summer	5.25	4.98	94.86	.27	5.14	5.42	
E. Fork Deep	(of record)	Annual	13.91	5.78	41.58	8.12	58.42	140.49	
River	1929-70	Fall	2.80	1.27	55.73	1.52	44.27	114.02	
		Winter	5.43	2.08	40.79	3.43	59.21	169.36	
		Spring	3.18	1.54	52.72	1.64	47.28	103.88	
		Summer	2.50	.97	49.55	1.53	50.45	152.49	
Yellow River	(of record)	Annual	17.18	8.88	51.66	8.31	48.34	93.57	
	1943-70	Fall	3.09	1.58	60.52	1.51	39.48	87.15	
		Winter	7.30	3.37	48.21	3.93	51.79	116.08	
		Spring	4.91	3.03	61.15	2.08	38.85	71.59	
		Summer	1.88	1.12	64.96	.77	35.04	68.79	
	(of analysis)	Annual	18.38	9.44	51.36	8.93	48.64	94.60	
	1959-70	Fall	3.15	1.68	53.33	1.46	46.67	86.90	
		Winter	7.59	3.53	46.51	4.07	53.49	115.30	
		Spring	5.67	2.99	52.73	2.68	47.27	89.63	
		Summer	1.97	1.24	62.94	.73	37.06	58.87	
Cypress	(of record)	Annual	6.51	0.42	6.53	6.08	93.47	1432.22	
Creek	1945-70	Fall	1.51	.11	23.69	1.40	76.31	1049.83	
		Winter	1.84	.17	12.03	1.80	87.97	1137.59	
		Spring	2.30	.07	8.69	2.22	91.31	2763.19	
		Summer	0.86	.08	21.81	0.78	78.19	1076.10	
	(of analysis)	Annual	5.34	.38	7.12	4.96	92.88	1305.26	
	1953-70	Fall	1.00	.09	9.00	.92	91.00	1022.22	
		Winter	1.51	.15	9.93	1.35	90.07	900.00	
		Spring	2.02	.06	2.97	1.96	97.03	3266.67	
		Summer	.81	.08	9.88	.73	90.12	912.50	

APPENDIX B

PRECIPITATION DATA

Except for one station, all precipitation was obatined from long-term Class A recording station, maintained by the National Weather Service (formerly U.S. Weather Bureau) (Table A.1). The gage closest to each of the study watersheds in the region was chosen and the daily or monthly totals for the period of record were obtained from the Environmental Data Service of the National Climatic Center in Asheville, North Carolina.

The one exception in the data is the precipitation data for the Peachtree Creek and Yellow River Watersheds. Sufficient data was readily available at several stations in the region to permit the computation of a weighted- value of precipitation over the watershed by the Thiessen method (1911). The records of two stations -- Atlanta Airport and Norcorss 4N -- were chosen to compute the representative rainfall over the Peachtree Creek watershed. The Atlanta Airport station is located south of the watershed and the Atlanta Airport precipitation record and 71 percent of the Norcross 4N precipitation record were used to compute the representative precipitation for the Peachtree Creek and Yellow River watersheds. This data is referred to in this report as Atlanta-Norcross precipitation data.

The location of each precipitation gage with respect to the urban watershed is given in Table A.2 Appendix A. The period of precipitation record obtained at each gage is shown in Table B.1 along with the mean annual precipitation for the period of analysis at each

Table B.1. List of Precipitation Stations Used In This Study.

Weather Station	National Weather Service Sta. No.	Type Record	Period of Record	Length of Record (years)
J.F.K. Airport, N.Y.C., N.Y.	94789	Monthly	Oct. 1951 to Sept. 1971	20
Greensboro Airport, Greensboro, N.C.	13723	Daily	1 Oct. 1948 to 20 Sept. 1971	23
Douglas Airport, Charlotte, N.C.	13881	Daily	1 Oct. 1948 to 30 Sept. 1971	23
Atlanta - Norcross Atlanta, Georgia[1]	-----	Monthly	Oct. 1957 to Sept. 1971	14
Houston Airport, Houston, Texas[2]	12918 and 12960	Daily Daily	1 Jan. 1948 to 31 Dec. 1969 1 Jan. 1969 to 31 Dec. 1971	23
Sacramento Airport, Sacramento, Ca.	23232	Monthly	Oct. 1951 to Sept. 1971	20

[1] Record at these stations were combined by the Thiessen Method: 29% Atlanta Airport, W.B. Station, 71% Norcross W.B. Station.

[2] Gage was moved from Downtown Houston to present location. Records are combined without adjustments.

Table B.2. Mean Annual Precipitation During Period of Analysis.

Station	Period of Analysis	Mean Annual Precipitation (inches)
J. F. Kennedy Airport, New York	1952-62	43.95
Greensboro Airport, North Carolina	1949-70	41.95
Douglas Airport, Charlotte, N.C.	1949-70	41.21
Atlanta - Norcross, Georgia	1959-70	51.28
Houston Airport, Texas	1949-70	45.80
Sacramento Airport, California	1960-70	16.95

weather station.

Time budget limitations did not allow for efforts to refine the precipitation data representative of each watershed. However, in a time interbal of one-year or even 3-months, spatial variation in rainfall patterns are minimal and the records are expected to be fairly representative of rainfall over the watershed.

The fluctuations in mean monthly precipitation at each of the National Weather Service Station and the Atlanta-Norcross data are shown in Figure B.1. The precipitation data was checked against published data and adjustments were made to agree with the published data. A test of the long term consistency of the rainfall record was not made because of the lack of data from nearby station with long-term records.

Figures B.2, B.3, B.4, B.5,B.6 and B.7 are mass diagrams of cumulative annual precipitation plotted versus time and indicate extended periods of above normal or below normal (drought) precipitation within the record of each gage. Figure B.2 shows the record for the JFK Airport, New York, to be fairly uniform until about 1962 when a serious drought affecting the entire northeastern United Station began. Analysis involving this record and the Long Island watersheds included only those periods up to and including 1962. The period following the drought was also excluded from analysis for lack of adequate data. Figure B.3 and B.4 shows three distinct periods of different rainfall catch at Greensboro Airport, North Carolina and Douglas Airport, Charlotte, North Carolina, respectively. The middle period of both records (about 1957 to 1963-5) is a period of above average rainfall

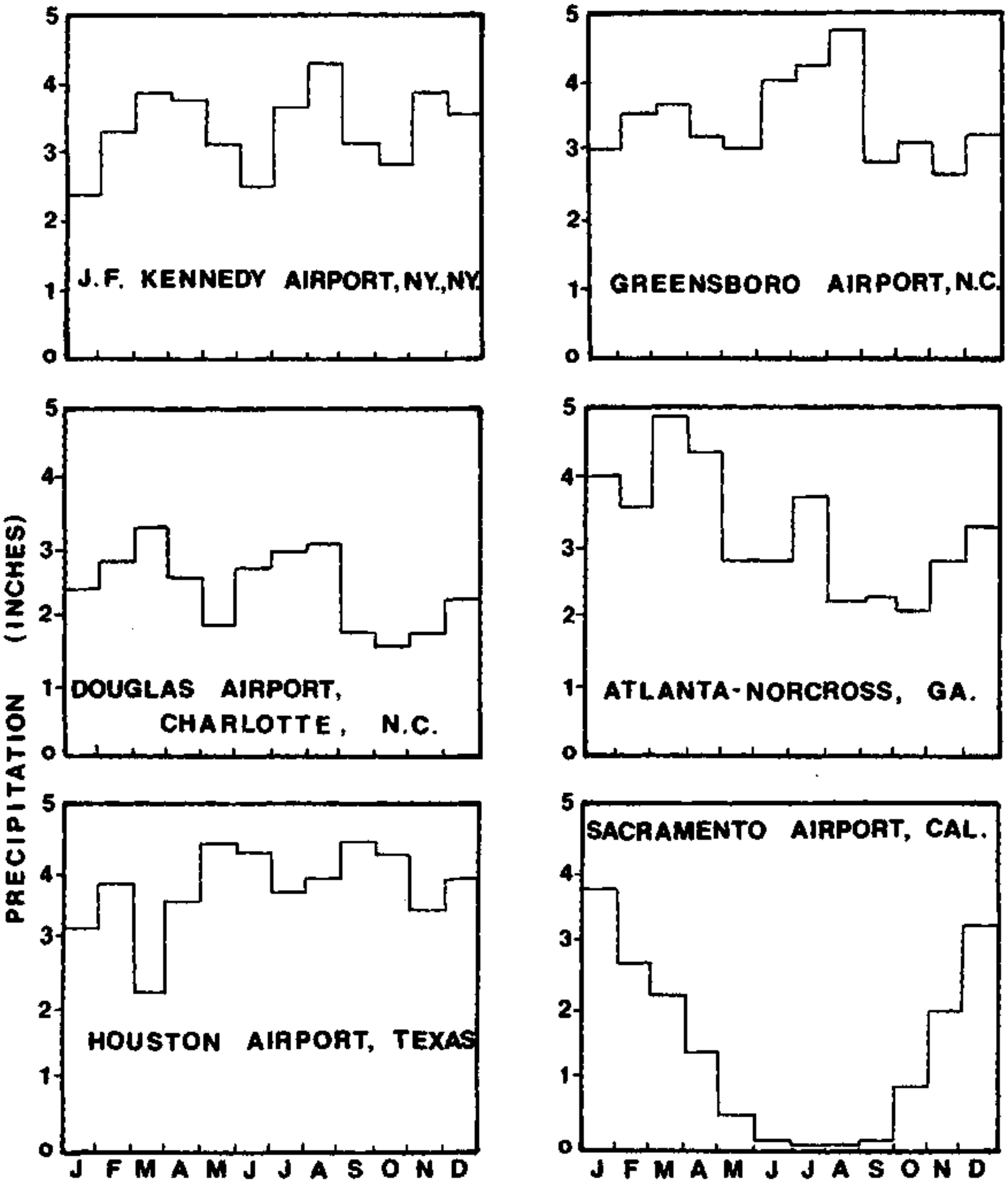

Figure B.1. Mean Monthly Precipitation at National Weather Service Stations and Atlanta-Norcross Data Used in This Study.

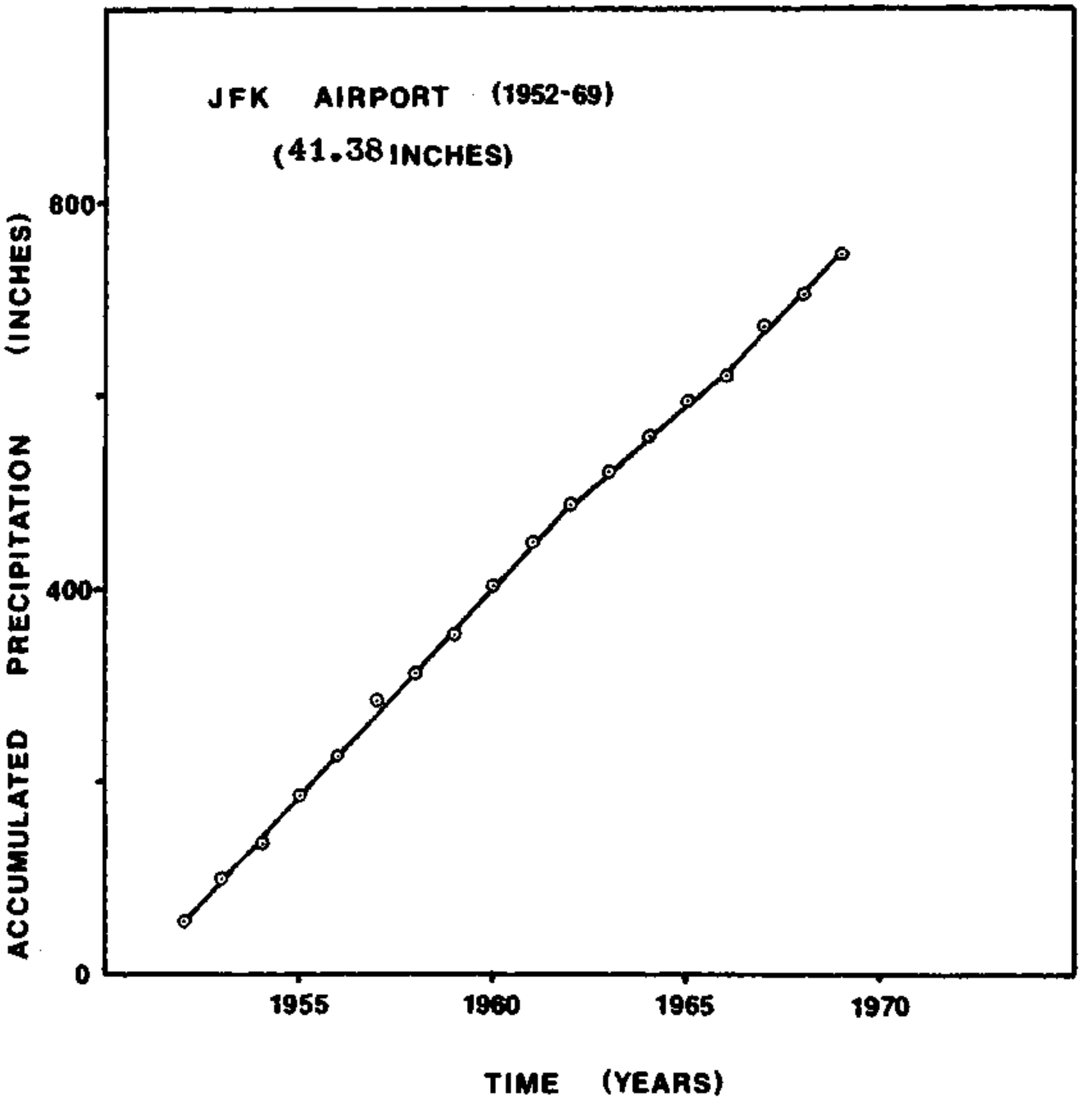

Figure B.2. Mass Diagram of Annual Precipitation at J. F. Kennedy Airport, New York.

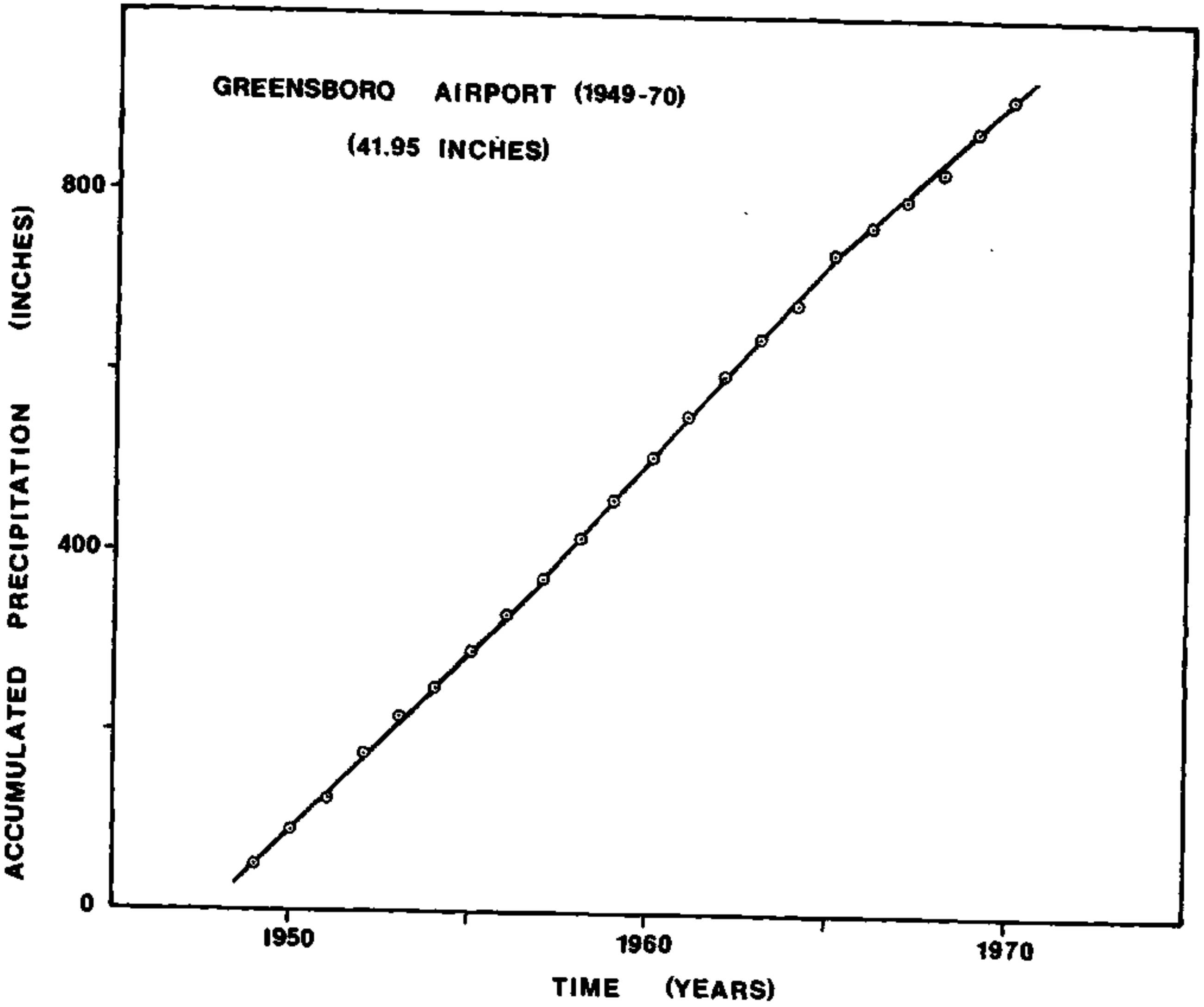

Figure B.3 Mass Diagram of Annual Precipitation at Greensboro Airport, North Carolina.

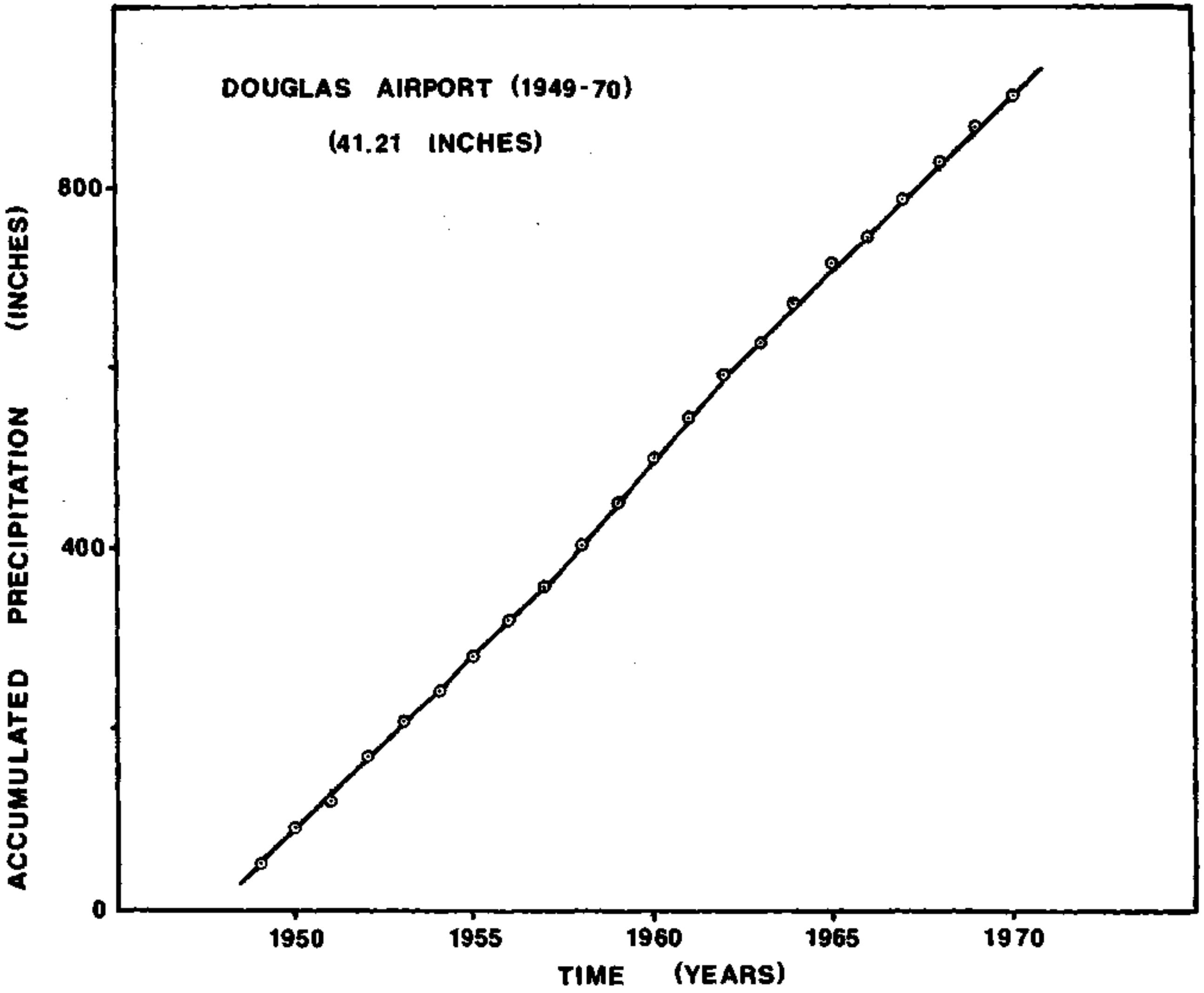

Figure B.4. Mass Diagram of Annual Precipitation at Douglas Airport, Charlotte, North Carolina.

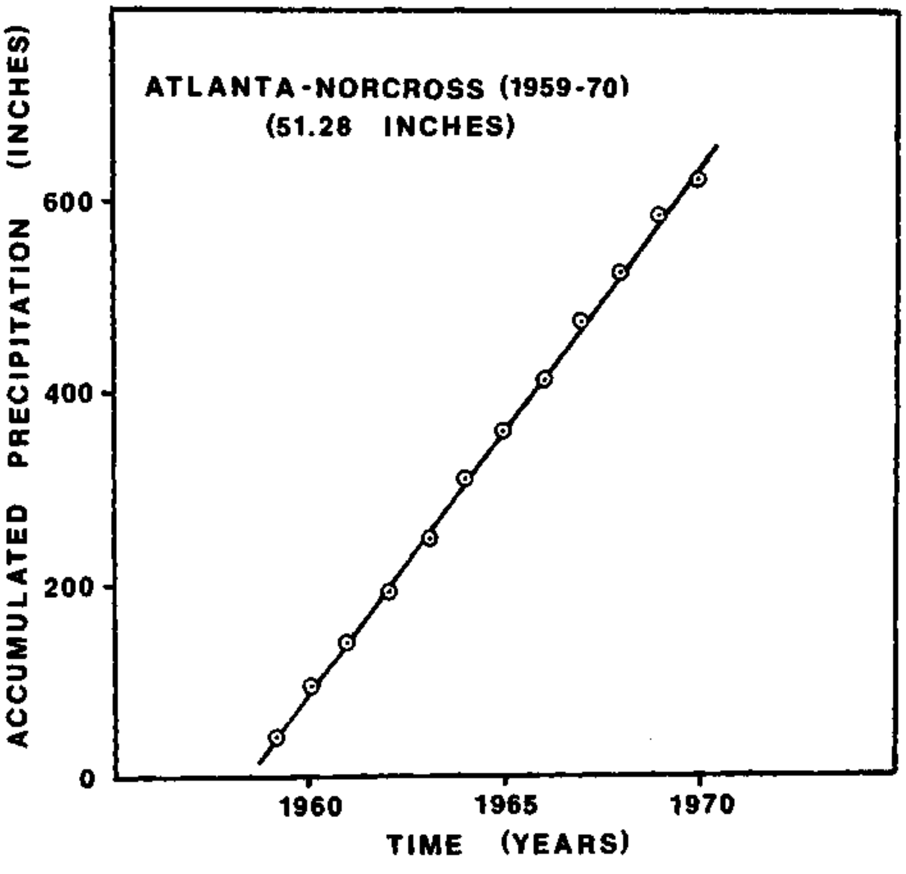

Figure B.5. Mass Diagram of Annual Precipitation at Atlanta-Norcross, Georgia.

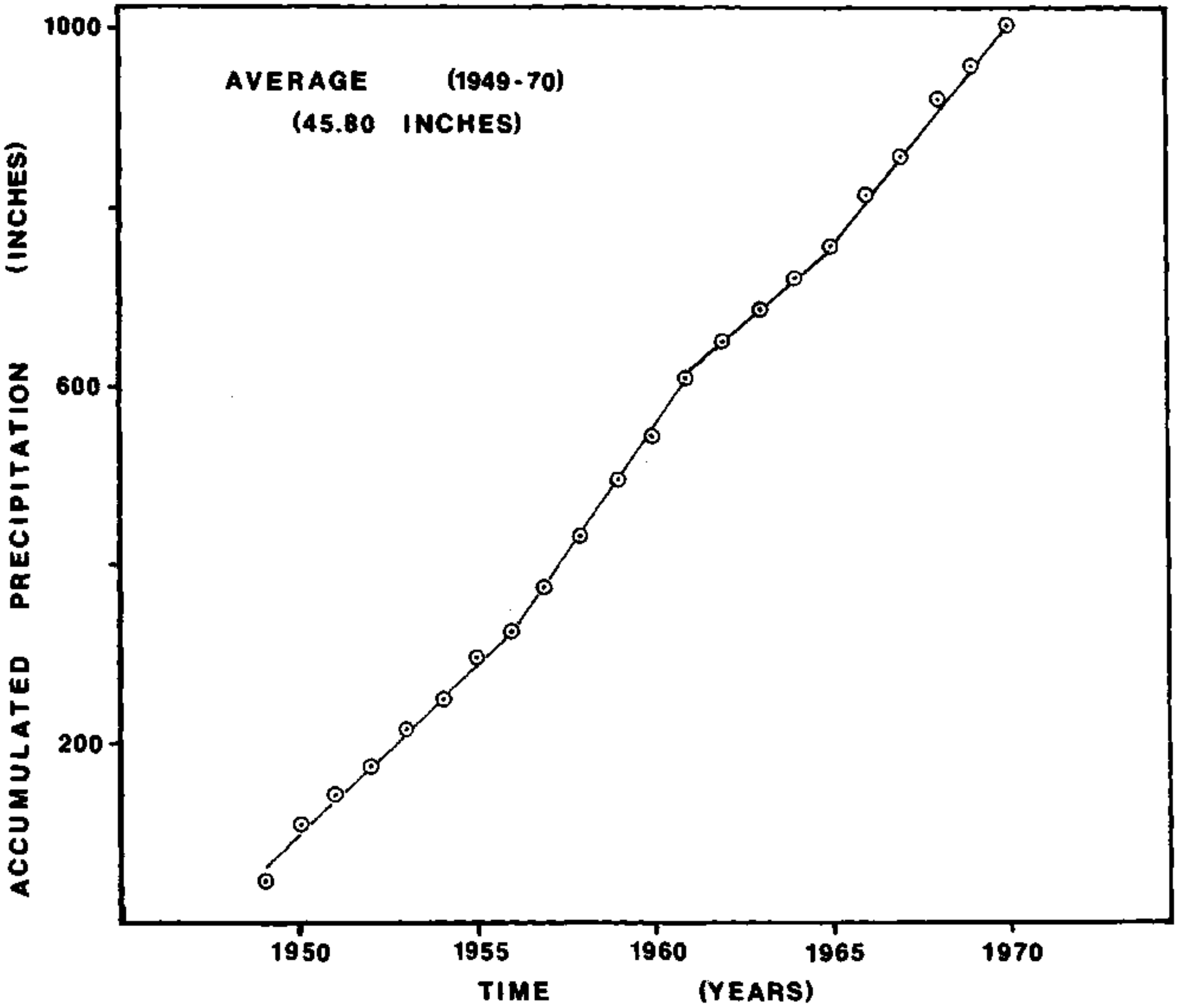

Figure B.6. Mass Diagram of Annual Precipitation at Houston Airport, Texas.

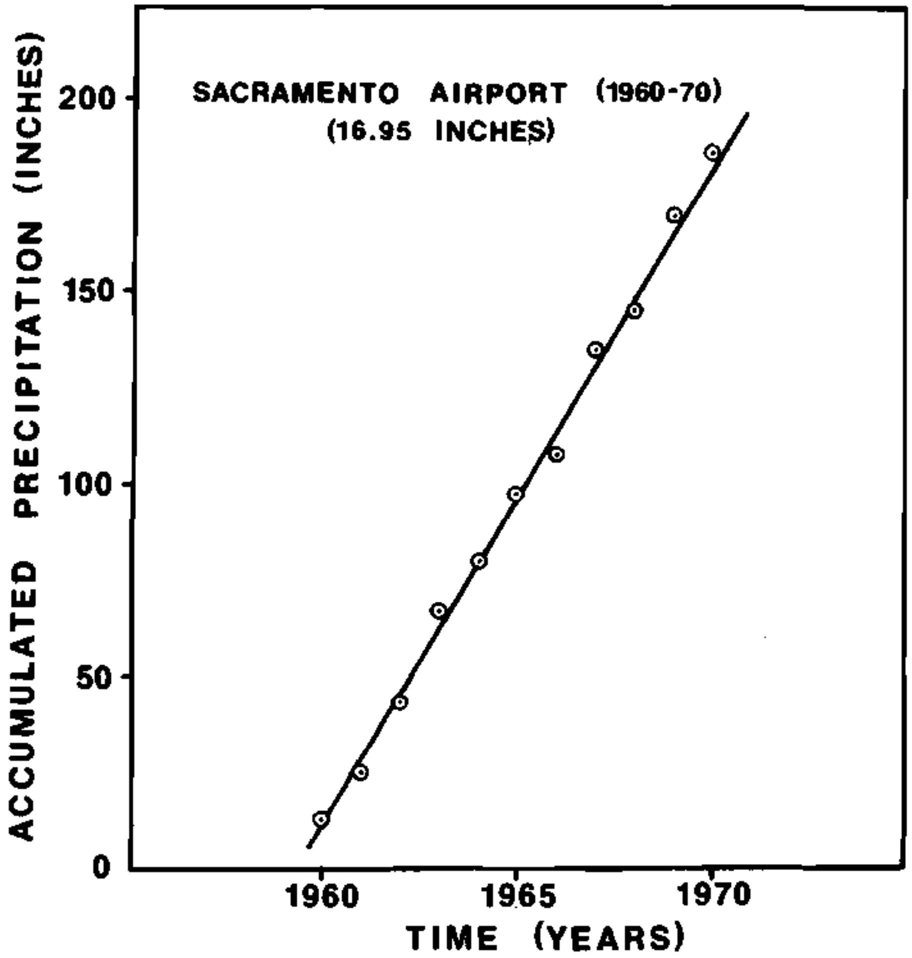

Figure B.7. Mass Diagram of Annual Precipitation at Sacramento Airport, California.

while the period before and after are about average. Figure B.5 indicates no breaks in the trend of annual precipitation of the Atlanta-Norcross data. Four periods are indicated in the Houston Airport record (figure B.6); two periods averaging above the long-term mean and two period below the long-term mean. The precipitation record of Sacramento Airport show no breaks in the trend (figure B.7) indicating that no excessive wet periods or drought periods occurred during the period of analysis.

Table B. 3 summarized the mean annual rainfall for the periods indicated by figures B.2, B.3, B.4, B.5, B.6 and B.7 including the percentage change in the mean between our period and the preceeding period and the percentage change in the mean compared with the first period.

Table B.3. Mean Annual Precipitation for Periods of Above Normal and Below Normal Rainfall, With the Percentage Change over Previous Periods and Percentage Change Over First Period.

Weather Station	Period	Mean Annual Precipitation (inches)	Percentage Change over Previous Period	Percentage Change over First Period
JFK Airport, New York	1952-62	43.95	No Changes	
Greensboro Airport, North Carolina	1949-57	41.51		
	1957-65	44.63	7.52	
	1965-70	39.14	-12.30	-5.71
Douglas Airport Charlotte, N.C..	1949-57	40.04		
	1957-62	45.30	13.14	
	1962-70	40.23	-11.19	0.47
Atlanta-Norcross, Georgia	1959-70	51.28	No Changes	
Houston Airport Texas	1949-56	41.66		
	1956-61	51.33	23.21	
	1961-65	43.04	-16.15	3.31
	1965-70	47.91	11.32	15.00
Sacramento Airport, California	1960-70	16.95	No Changes	

APPENDIX C

ANALYSIS OF RUNOFF AND PRECIPITATION

An attempt was made to compare the volumes of runoff from the urban watershed with the amount of precipitation that fell on the watershed. The results of this analysis were not conclusive because the relationship between runoff and precipitation reflects both meterological factors and physiographic factors. The relationship varies with changes in precipitation patterns, droughts, and soil and vegetation conditions, as well as changes in land use and impervious cover. The relationship between runoff and precipitation is generally nonlinear because larger rainfall usually produce larger percentages of runoff.

The results of this analysis are presented here for the interested reader. Watersheds used in this study include those used in the analysis of urban and control watersheds and include two additional watersheds -- Little Sugar Creek at Charlotte, North Carolina and Morrison Creek near Sacramento, California. Land use data for all watersheds are compiled and discussed previously. Precipitation gages and length of record are listed in Table 1. Analysis and discussion of the precipitation records used in this study is presented in Appendix B.

The analysis followed a similar procedure as discussed in the body of the text, except that annual or seasonal precipitation summaries were used, instead of runoff values from a control watershed. Table C.1 lists the periods of analysis determined from analysis of the doublemass curves for each watershed.

The following example illustrates the procedure used to determine the changes in runoff from the urban watershed when the change is based on precipitation over the watershed. Figure C.1 is a doublemass diagram of accumulated annual direct runoff from East Meadow Brook watershed and accumulated annual precipitation recorded at J. F. Kennedy Airport, New York, for the period 1952-62. Two periods of analysis are indicated from this graph -- 1952-58 and 1958-62.

Table C.2 illustrates the computational procedures used to determine the percentage increase in the ratio of urban direct runoff to precipitation on the watershed. The average ratio of annual direct runoff from the urban watershed to annual precipitation over the watershed for each period of analysis was determined by computing the average value of the annual ratios in each period. In this example, the average ratio for the period 1952-58 was 0.036. The average ratio for the next period, 1958-62, was 0.045. This represents a 25 percent increase in the ratio over the previous period. However, as discussed above, a comparison of runoff to precipitation values does not eliminate the affect of meterological factors on runoff. Therefore, the 25 percent increase in the ratio between 1952-58 and 1958-62 represents not only increased runoff due to changes in physiographic factors in the watershed but also the affect of such factors as magnitude, duration, frequency and intensity of rainfall. A similar procedure was used to determine changes in total flow and baseflow compared with precipitation. Changes in seasonal values were computed similarly.

Table C.3 lists results determined from the double-mass relationship between runoff from the urban watershed and the corresponding precipitation over the watershed.

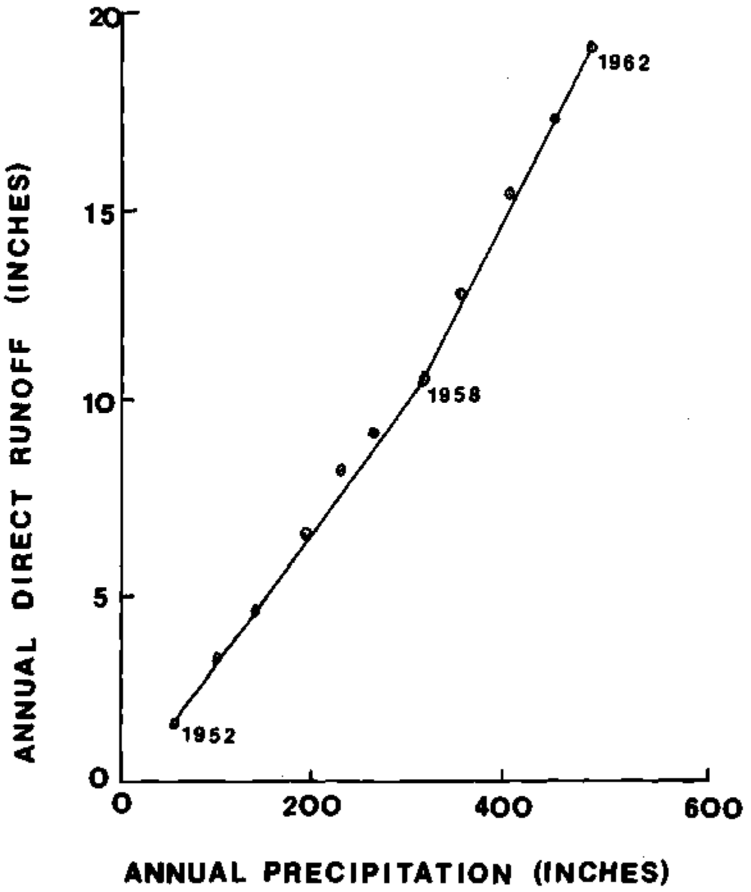

Figure C1. Double-Mass Diagram of Accumulated Annual Direct Runoff at East Meadow Brook Versus Accumulated Precipitation at JFK Airport, New York (1952-1962).

Table C1. Periods Of Analysis For The Relationship Between Runoff From The Urban Watershed And Precipitation Over The Watershed.

Urban Watershed and Precipitation Station	Period of Analysis			
	1	2	3	4
East Meadow Brook and JFK Airport	1952-58	1958-62		
Pines Brook and JFK Airport	1952-58	1958-62		
North Buffalo Creek and Greensboro Airport	1949-56	1956-63	1963-70	
Little Sugar Creek and Douglas Airport	1949-56	1956-63	1963-70	
Peachtree Creek and Atlanta-Norcross	1959-62	1963-66	1967-70	
Sims Bayou and Houston Airport	1949-57	1957-61	1961-66	1966-70
Brays Bayou and Houston Airport	1949-57	1957-61	1961-66	1966-70
Whiteoak Bayou and Houston Airport	1949-57	1957-61	1961-66	1966-70
Halls Bayou and Houston Airport	1953-57	1957-61	1961-66	1966-70
Greens Bayou and Houston Airport	1953-57	1957-61	1961-66	1966-70
Morrison Creek and Sacramento Airport	1960-63	1963-67	1967-70	

Table C2. Computational Procedure Used To Determine The Percentage Increase In The Ratio Of Urban Runoff (East Meadow Brook 1952-62) To Precipitation (Kennedy Airport, 1952-62), Over The Base Period.

Water Year	Annual Precipitation (Inches)	Annual Urban Direct Runoff (Inches)	Ratio Of Urban Runoff To Precipitation	Percentage Increase Over Base Period
1952	54.51	1.61	.030	
1953	45.18	1.56	.035	
1954	39.34	1.33	.034	
1955	47.02	2.14	.046	
1956	41.79	1.46	.035	
1957	36.08	1.03	.028	
1958	48.51	2.13	.044	
Avg.			.036	Base Period
1958	48.51	2.13	.044	
1959	36.84	1.54	.042	
1960	51.10	2.56	.050	
1961	46.47	2.04	.044	
1962	36.76	1.64	.045	
Avg.			.045	25

East Meadow Brook

It was possible to use only two periods of analysis in comparing runoff to precipitation in the East Meadow Brook watershed. The first period, 1952-58, was a period of intense urban development and rapidly changing streamflow conditions. While development continued in the second period, 1958-62, it was less intense due to the fact that the area was reaching full development. Direct runoff increased 25 percent between these two periods compared with the annual precipitation over the watershed. Total flow and baseflow also increased by almost six percent and two percent respectively.

Pines Brook

Annual direct runoff, when compared to the precipitation over the watershed, increased by more than 28 percent between the periods 1952-58 and 1958-62. Total flow and baseflow declined by almost seven percent and more than 15 percent, respectively, between the same two periods. Rainfall was fairly consistent throughout the period 1952-62.

North Buffalo Creek

Analysis of runoff, when compared with precipitations over the watershed, was divided into three periods -- 1949-56, 1956-63, and 1963-70. Direct runoff increased by slightly less than two percent, while total flow and baseflow increased by more than 15 percent and 29 percent, respectively. Mean annual precipitation varied somewhat among the periods (see Table B.2).

Table 3. Results of Analysis Showing Percentage Changes in Average Ratio of Runoff From the Urban Watershed to Precipitation for Annual and 3-month Seasonal Values.

Watershed	Flow Regime	Period of Analysis	Average Ratio of Runoff to Precipitation															
			Annual			Fall			Winter			Spring			Summer		
			Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period
East	Total	1952-58	0.1924			0.145			0.243			0.243			0.166		
Meadow	Flow	1958-62	.2030	5.73	5.73	.200	20.97	20.97	.217	-10.45	-10.45	.246	1.32	1.32	.169	3.40	3.40
Brook	Base-	1952-58	.1560														
	Flow	1958-62	.1593	1.53	1.53												
	Direct	1952-58	.0360			.0344			.0353			.0301			.0360		
	Runoff	1958-62	.0450	25.00	25.00	.0398	15.70	15.70	.0480	35.98	35.98	.0352	16.94	16.94	.0518	43.89	43.89
Pines	Total	1952-58	.1695			.1443			.2138			.2038			.1446		
Brook	Flow	1958-62	.1582	-6.67	-6.67	.1496	3.67	3.67	.1826	-14.59	-14.59	.1868	-8.36	-8.36	.1242	-14.11	-14.11
	Base-	1952-58	.1357														
	Flow	1958-62	.1150	-15.25	-15.25												
	Direct	1952-58	.0337			.0301			.0380			.0290			.0336		
	Runoff	1958-62	.0432	28.19	28.19	.0362	20.26	20.26	.0512	34.74	34.74	.0380	31.03	31.03	.0448	33.33	33.33
North	Total	1949-56	.4387			.4930			.6077			.4139			.3037		
Buffalo	Flow	1956-63	.4934	12.46		.5177	5.02		.6635	9.18		.4879	17.87		.3321	9.26	
Creek		1963-70	.5056	2.48	15.25	.4952	-4.34	0.45	.7280	9.72	19.79	.4490	-7.97	8.48	.3830	15.33	26.11
	Base-	1949-56	.2140														
	Flow	1956-63	.2349	9.75													
		1963-70	.2768	17.82	29.34												
	Direct	1949-56	.2249			.2201			.3050			.1882			.1522		
	Runoff	1956-63	.2584	14.86		.2219	0.81		.3790	24.26		.2415	28.32		.1600	5.12	
		1963-70	.2288	-11.43	1.73	.2133	-3.84	-3.09	.3669	-3.20	20.29	.1624	-32.76	-13.71	.1584	-1.01	4.07
Little	Total	1949-56	.3348			.3000			.4887			.2645			.2225		
Sugar	Flow	1956-63	.3889	16.15		.3107	3.58		.5099	4.33		.4026	52.22		.2883	29.75	
Creek		1964-70	.3591	-7.66	7.26	.3167	1.93	5.57	.4975	-2.43	1.80	.3330	-17.29	25.90	.2625	-8.95	18.11
	Base-	1949-56	.1378														
	Flow	1956-63	.1298	-5.81													
		1963-70	.1150	-11.36	-16.53												
	Direct	1949-56	.1972			.1644			.2829			.1434			.1474		
	Runoff	1956-63	.2591	31.37		.1760	7.06		.3440	21.60		.2582	80.09		.2070	38.40	
		1963-70	.2460	-5.06	23.70	.2135	21.31	29.87	.3299	-4.11	16.61	.1966	-23.85	37.11	.2011	-1.41	36.43

Table C 3. Results of Analysis Showing Percentage Changes in Average Ratio of Runoff From the Urban Watershed to Precipitation for Annual and 3-month Seasonal Values - - continued.

Watershed	Flow Regime	Period of Analysis	Average Ratio to Runoff to Precipitation														
			Annual			Fall			Winter			Spring			Summer		
			Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period
Peachtree	Total	1959-62	.3252			.2610			.3872			.4117			.1912		
Creek	Flow	1963-66	.4100	26.52		.3090	18.49		.4470	15.43		.5332	29.51		.3410	78.30	
		1967-70	.4440	6.22	36.51	.3988	29.04	52.78	.5222	16.83	34.86	.4535	-14.96	10.14	.4002	17.38	109.26
	Base-	1959-62	.1410														
	Flow	1963-66	.1452	3.01													
		1967-70	.1607	10.66	13.97												
	Direct	1959-62	.1840			.1180			.2447			.2082			.0970		
	Runoff	1963-66	.2725	48.10		.1715	45.33		.3022	23.49		.3650	75.27		.2022	108.50	
		1967-70	.2835	4.04	54.08	.2550	48.70	116.10	.3160	4.55	29.11	.2762	-24.31	32.65	.2735	35.23	181.96
Sims	Total	1953-57	.1652			.1086			.2818			.1512			.1280		
Bayou	Flow	1957-61	.3288	99.03		.2822	159.85		.5024	78.28		.2834	87.43		.2330	82.03	
		1961-66	.2722	-17.21	64.78	.2680	-5.03	146.77	.4105	-18.29	45.67	.2283	-19.44	50.99	.1705	-26.82	33.20
		1966-70	.3372	23.88	104.12	.2026	-24.40	138.15	.5550	35.22	96.97	.4438	94.38	193.52	.1808	6.04	41.25
	Base-	1953-57	.0324														
	Flow	1957-61	.0368	12.88													
		1961-66	.0547	48.64	67.79												
		1966-70	.0794	45.22	143.56												
	Direct	1953-57	.1332			.0760			.2148			.1218			.0964		
	Runoff	1957-61	.2922	119.37		.2334	207.10		.4404	105.03		.2468	102.63		.2026	110.16	
		1961-66	.2173	-25.63	63.14	.2273	-2.60	199.08	.3077	-30.13	43.25	.1802	-26.98	48.11	.1112	-45.11	15.35
		1966-70	.2578	18.62	93.54	.1216	-46.50	60.00	.3596	16.88	67.41	.3626	101.24	197.70	.1286	15.68	33.40
Brays	Total	1949-57	.1943			.1427			.2698			.2193			.1410		
Bayou	Flow	1957-61	.3008	54.81		.3608	152.84		.4810	78.28		.2690	22.66		.1920	36.11	
		1961-66	.3225	7.21	65.98	.2965	-17.82	107.78	.4803	0.14	78.02	.2952	9.73	34.61	.2493	29.86	75.81
		1966-70	.3722	15.41	91.56	.2758	-6.98	93.27	.4152	-13.55	53.89	.4626	56.70	110.94	.3008	20.66	112.13
	Base-	1949-57	.0352														
	Flow	1957-61	.0448	27.27													
		1961-66	.0778	72.77	121.02												
		1966-70	.0966	24.16	174.43												

Table C1 Results of Analysis Showing Percentage Changes in Average Ratio of Runoff From the Urban Watershed to Precipitation for Annual and 3-month Seasonal Values - - continued.

Watershed	Flow Regime	Period of Analysis	Annual Average	Annual Percent Change Over Last Period	Annual Percent Change Over Base Period	Fall Average	Fall Percent Change Over Last Period	Fall Percent Change Over Base Period	Winter Average	Winter Percent Change Over Last Period	Winter Percent Change Over Base Period	Spring Average	Spring Percent Change Over Last Period	Spring Percent Change Over Base Period	Summer Average	Summer Percent Change Over Last Period	Summer Percent Change Over Base Period
Greens	Total	1953-57	.1034			.0456			.1384			.0912			.1680		
Bayou	Flow	1957-61	.1884	82.20		.1588	248.24		.3262	135.69		.1232	35.09		.1790	6.55	
		1961-66	.1987	5.45	91.90	.1738	9.47	281.14	.3086	-5.38	122.98	.2413	95.89	164.58	.1507	-15.83	-10.30
		1966-70	.1766	-11.12	70.79	.1450	-16.57	217.98	.2188	-58.39	58.09	.2216	-8.16	142.98	.0706	-53.15	-57.98
	Base-	1953-57	.0018														
	Flow	1957-61	.0078	333.33													
		1961-66	.0183	135.04	916.67												
		1966-70	.0176	-3.82	877.78												
	Direct	1953-57	.1014			.0448			.1336			.0900			.1646		
	Runoff	1957-61	.1808	78.30		.1500	234.82		.3100	132.03		.1180	31.11		.1722	4.62	
		1961-66	.1803	-0.26	77.81	.1622	8.11	262.05	.2715	-12.42	103.22	.2235	89.41	148.33	.1297	-24.70	-21.20
		1966-70	.1590	-11.81	56.80	.1310	-19.23	192.41	.1938	-28.62	45.06	.2038	-8.81	126.44	.0530	-59.13	-67.80
Morrison	Total	1960-63	.2255			.1670			.2120			.7392			6.3390		
Creek	Flow	1963-67	.2844	26.12		.2054	22.99		.3080	45.28		.4156	-43.78		1.4884	-76.52	
		1967-70	.3472	22.08	53.99	.1955	-4.82	17.06	.3755	21.92	77.12	.6937	125.46	-6.15	10.1252	580.27	59.73
	Base-	1960-63	.0825														
	Flow	1963-67	.0982	19.03													
		1967-70	.0840	-14.46	1.82												
	Direct	1960-63	.1430			.0968			.1683			.1230			1.0012		
	Runoff	1963-67	.1862	30.24		.1562	61.44		.2294	36.37		.1188	-3.41		.3054	-69.50	
		1967-70	.2632	41.35	84.09	.1330	-14.85	37.44	.3300	43.60	95.04	.1865	56.99	51.63	2.8378	827.55	182.92

Little Sugar Creek

The analysis of runoff versus precipitation over the watershed was divided into three periods -- 1949-56, 1956-63, and 1963-70. Between 1949-56 and 1963-70, annual direct runoff increased almost 24 percent while total flow increased a little more than seven percent. Between the same period baseflow decreased by more than 16 percent. Precipitation during the two periods was essentially the same -- slightly more than 40 inches. A decrease in baseflow is the expected result of urbanization because the additional impervious cover reduces the opportunity for groundwater recharge; hence, water table levels decline and groundwater outflow is diminished.

Peachtree Creek

Analysis of runoff versus precipitation over the watershed was made for the same three periods listed above. Annual direct runoff increased about 54 percent, while total flow and baseflow increased about 36 percent and nearly 14 percent, respectively, between the first period, 1959-63 and the last period, 1967-70. Mean annual precipitation was fairly consistent throughtout the entire period.

Sims Bayou

Analysis of runoff versus precipitation over the watershed was made for the same four periods listed above. Annual direct runoff increased almost 94 percent between 1953-57 and 1966-70. Total flow increased about 104 percent and baseflow increased about 144 percent between the same periods. These values are probably misleading because mean annual precipitation in all succeeding periods was greater than the mean annual precipitation during the first period (see Table B.2). Larger storms generally produce proportionally larger runoff.

Brays Bayou

Analysis of runoff versus precipitation covered the same periods as noted above. Between 1949-57 and 1966-70 direct runoff increased about 73 percent compared with the precipitation over the basin. Total flow and baseflow increased by about 92 percent and 174 percent, respectively. As mentioned in the discussion of Sims Bayou, these values may be misleading due to varying mean annual precipitation among the periods.

Whiteoak Bayou

Analysis of runoff versus presipitation covered the same four periods noted above. Between 1949-57 and 1966-70, annual direct runoff increased almost 33 percent. Total flow and baseflow increased about 39 percent and 100 percent, respectively. Mean annual precipitation among the periods of analysis is variable and these results may be misleading.

Halls Bayou

Analysis of runoff versus precipitation cover the same four periods. Direct runoff increased nearly 90 percent while total flow and baseflow increased 110 and 421 percent respectively. As noted earlier these values may not be representative because of the variability in precipitation among the periods.

Greens Bayou

Analysis of runoff versus precipitation covered the same four periods. Direct runoff increased nearly 57 percent, total flow increased about 71 percent and baseflow increased 878 percent between the first period 1953-57 and the last period 1966-70.

Morrison Creek

Analysis of runoff versus precipitation over the watershed was divided into three periods -- 1960-63, 1963-67, and 1967-70. Direct runoff between the first and last period increased about 84 percent compared with the precipitation over the basin. Total flow increased about 54 percent and baseflow remained relatively unchanged; increasing only by about two percent. The largest increase in direct runoff occurred in the summer months.

Relationship Between Runoff And Urban Land

Table C.4 is a summary of the percentage change in annual direct runoff, baseflow and total flow determined for each urban watershed based on the runoff-precipitation relationship. Percentage changes vary widely among all flow components. Direct runoff increase in all watersheds with the Houston watersheds exhibiting the largest percentage increase.

Baseflow changes varied from decreases in the Pines Brook and Little Sugar Creek watershed, to essentially no change in the East Meadow Brook and Morrison Creek watersheds, to extremely large increases in the Houston watersheds. Decreases in baseflow probably reflects groundwater pumping.

Large percentage increases in the baseflow results from increased sewage effluent and other low flow discharges from industrial and commercial sites.

Total flow increased in all watersheds, except Pines Brook. Large percentage increases resulted in the Houston watersheds, some of which doubled. Pines Brook was the only watershed that decreased in total flow. This was because of heavy groundwater pumping in the area for public water supply. East Meadow Brook increased in total flow only slightly, also because of groundwater pumping.

Figure C.2 is a graph showing the relationship between the percentage change in annual direct runoff and the percentage change in the amount of urban land in urban watershed. There is no definite trends shown in this graph and no conclusions can be drawn. The simple relationship between runoff and precipitation is not sufficient to describe the runoff phenomenon from the urban watersheds. Other factors must be included to describe physiographic effects as well as other meteorological effects.

One very general trend is exhibited in Figure C.2. Watersheds with clayey soils, such as the Houston watershed and Morrison Creek watershed, exhibit the larger percentage increases in direct runoff. Sufficient data is not available to determine the effect of soil type on runoff.

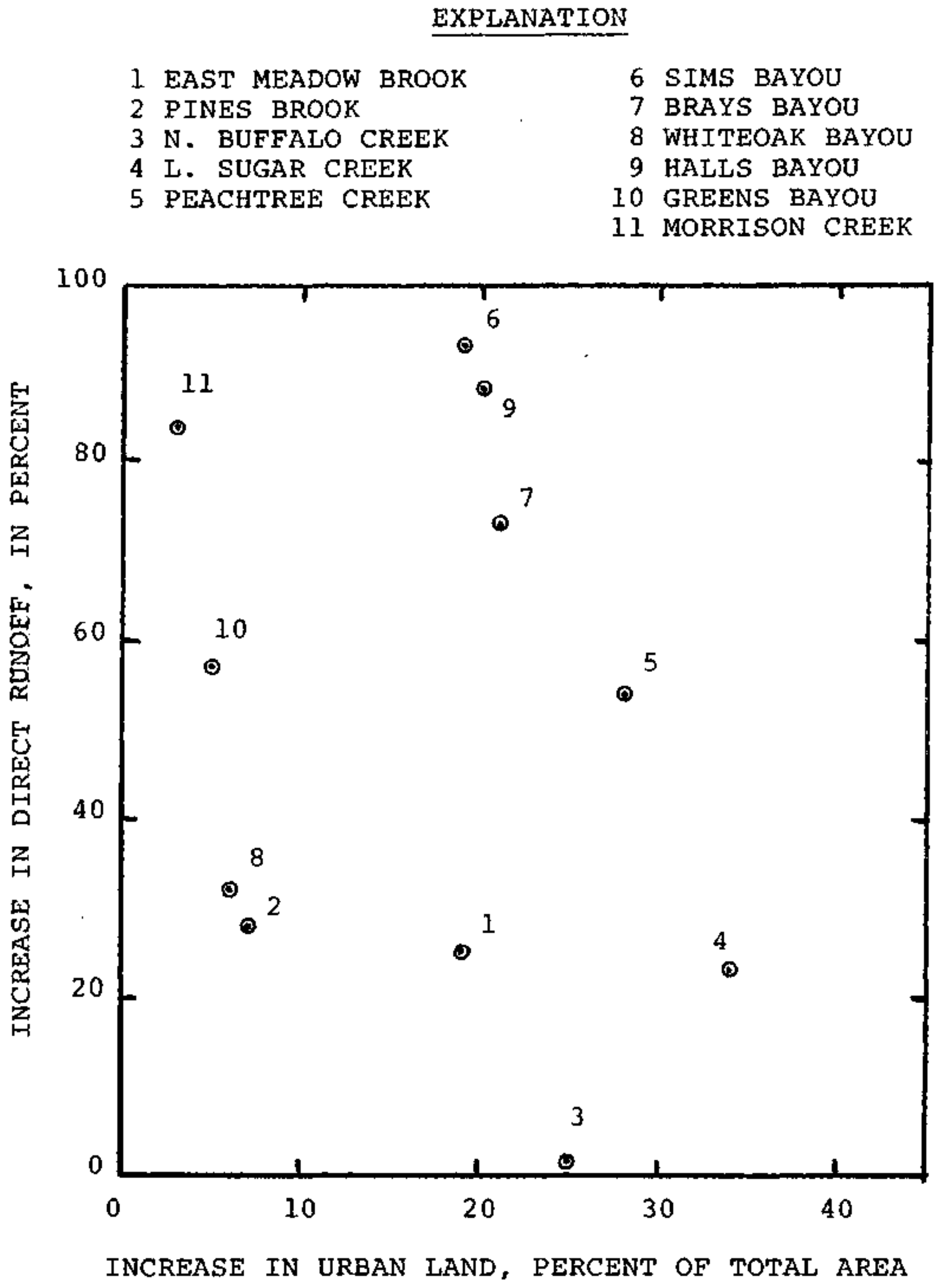

Figure C.2. Relationship Between Percentage Increase In Urban Direct Runoff Compared With Precipitation And The Percentage Increase In Urban Land Use.

Table C4 Summary of Percentage Changes in Annual Direct Runoff, Baseflow and Total Runoff for the Period of Analysis, Based on the Runoff - Precipitation Relationship Developed for Each Urban Watershed.

Watershed	Period of Analysis	Direct Runoff Percentage Change	Baseflow Percentage Change	Total Flow Percentage Change
East Meadow Creek	1952-58 1958-62	25.00	1.53	5.92
Pines Brook	1952-58 1958-62	28.19	-15.25	-6.67
N. Buffalo Creek	1949-56 1963-70	1.73	29.34	15.25
L. Sugar Creek	1949-56 1963-70	23.70	-16.52	7.26
Peachtree Creek	1959-62 1967-70	54.08	13.97	36.51
Sims Bayou	1953-57 1966-70	93.54	143.43	104.12
Brays Bayou	1949-57 1966-70	73.12	174.43	91.56
Whiteoak Bayou	1949-57 1966-70	32.72	100.00	39.28
Halls Bayou	1953-57 1966-70	88.80	440.93	110.32
Greens Bayou	1953-57 1966-70	56.80	877.78	70.79
Morrison Creek	1960-63 1967-70	84.09	1.82	53.99

APPENDIX D

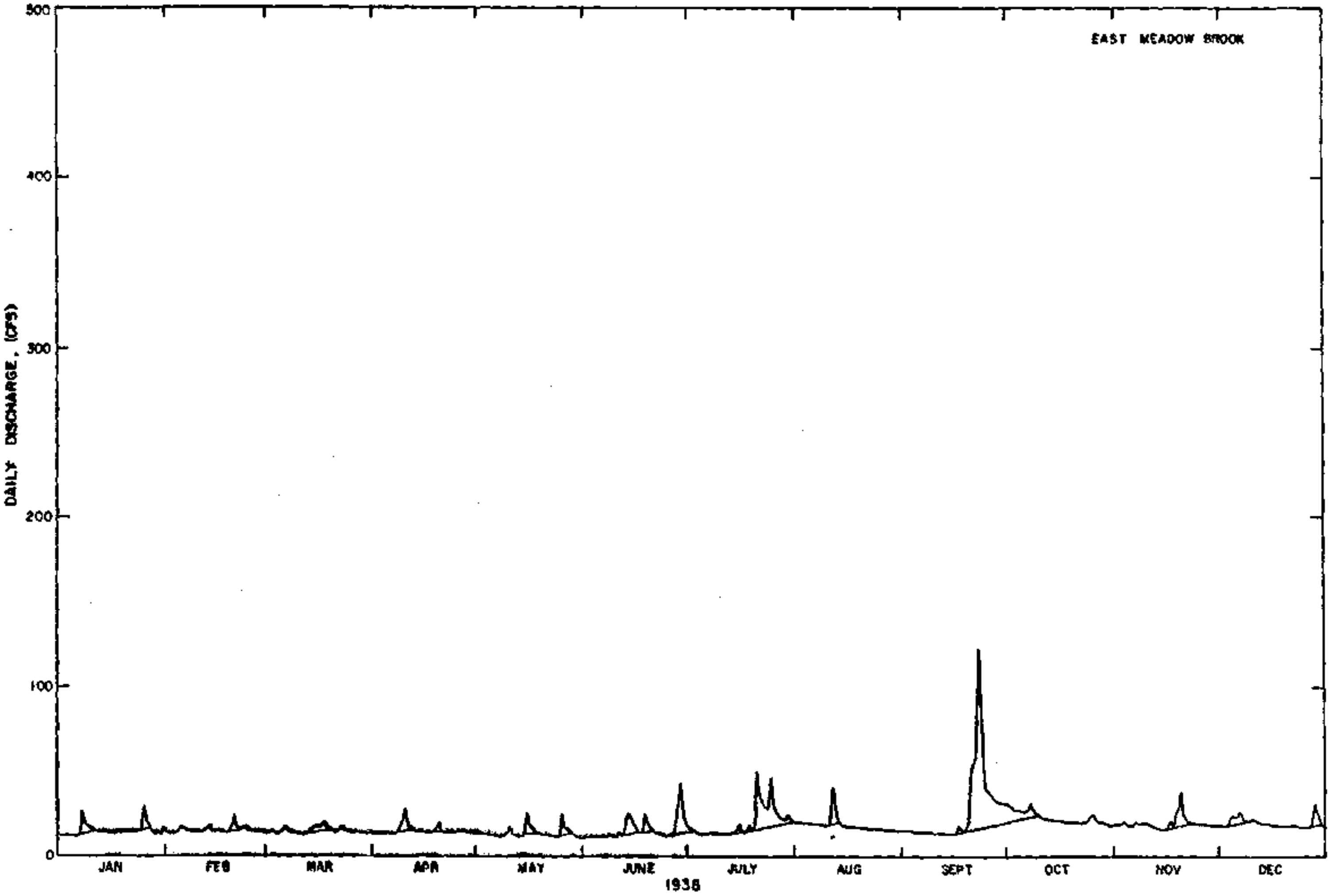

Figure D.1. Annual hydrographs of daily discharge at East Meadow Brook, Long Island, New York, 1938, Separation gradient is 0.50 cfs per day.

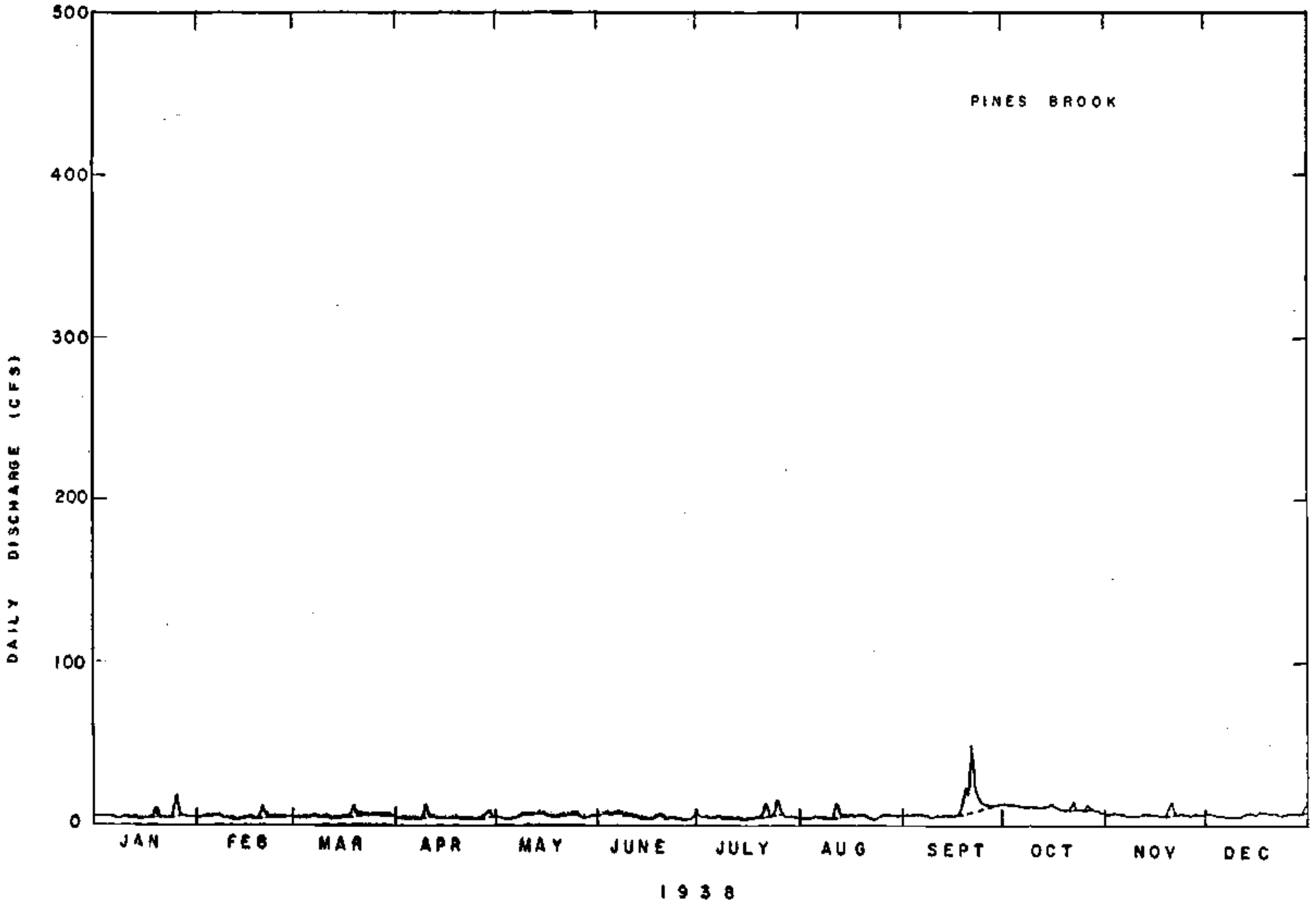

Figure D.2. Annual hydrographs of daily discharge at Pines Brook, Long, Island, New York, 1938, Separation gradient is 0.50 cfs per day.

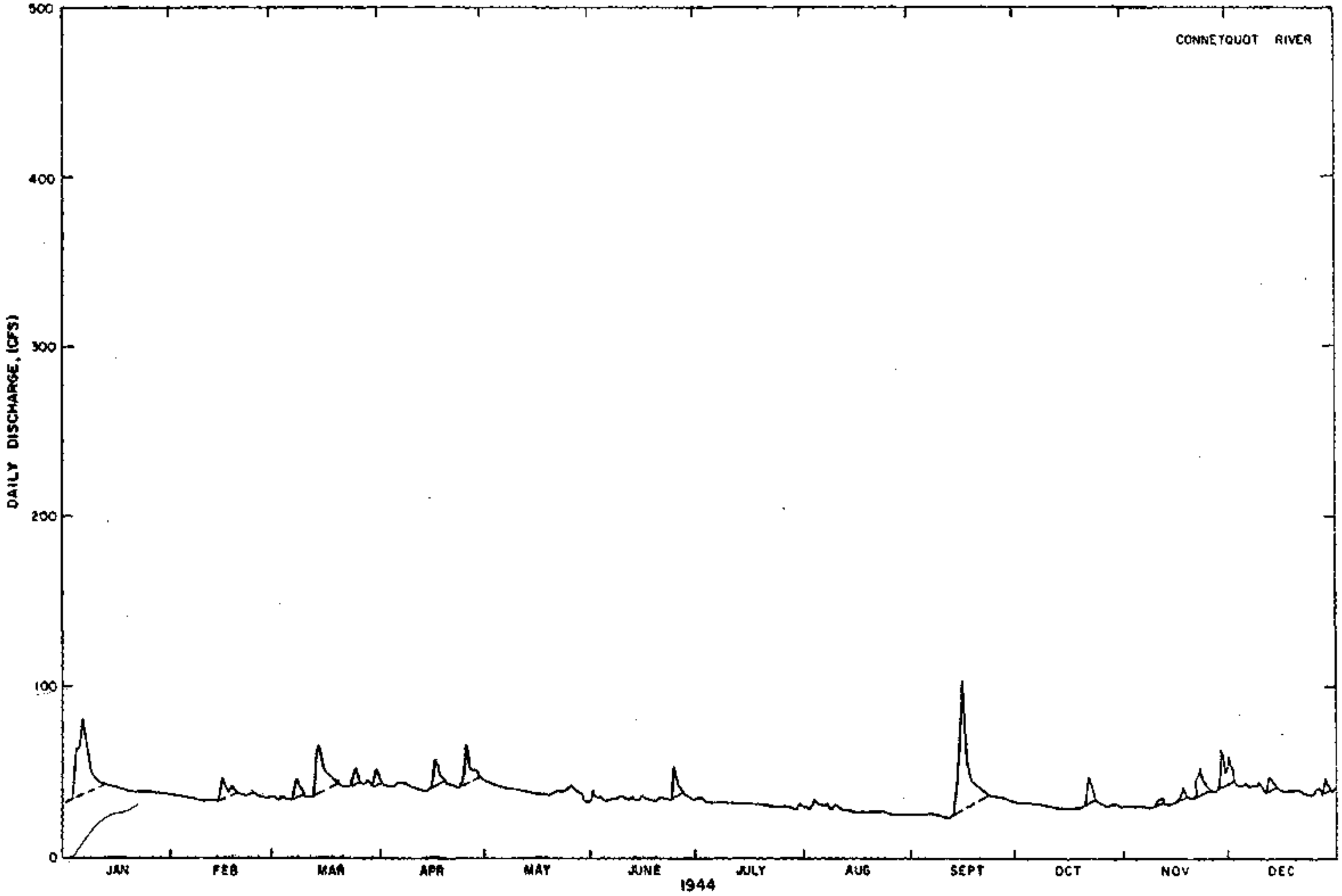

Figure D.3. Annual hydrograph of daily discharge at Connetquot River, Long Island, New York, 1944. Separation gradient is 1.0 cfs per day.

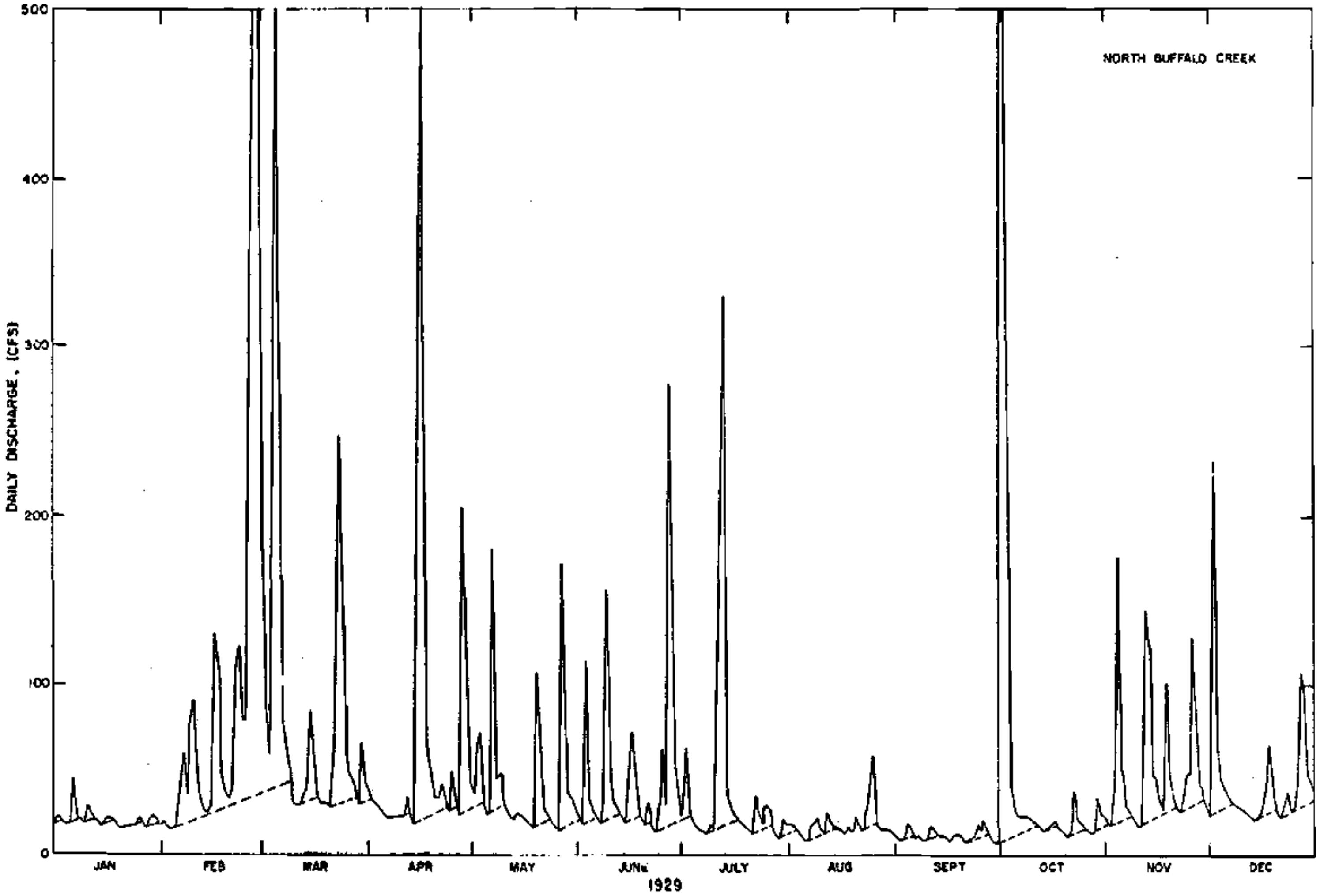

Figure D.4. Annual hydrograph of daily discharge at North Buffalo Creek at Greensboro, North Carolina, 1929. Separation gradient is 1.0 cfs per day.

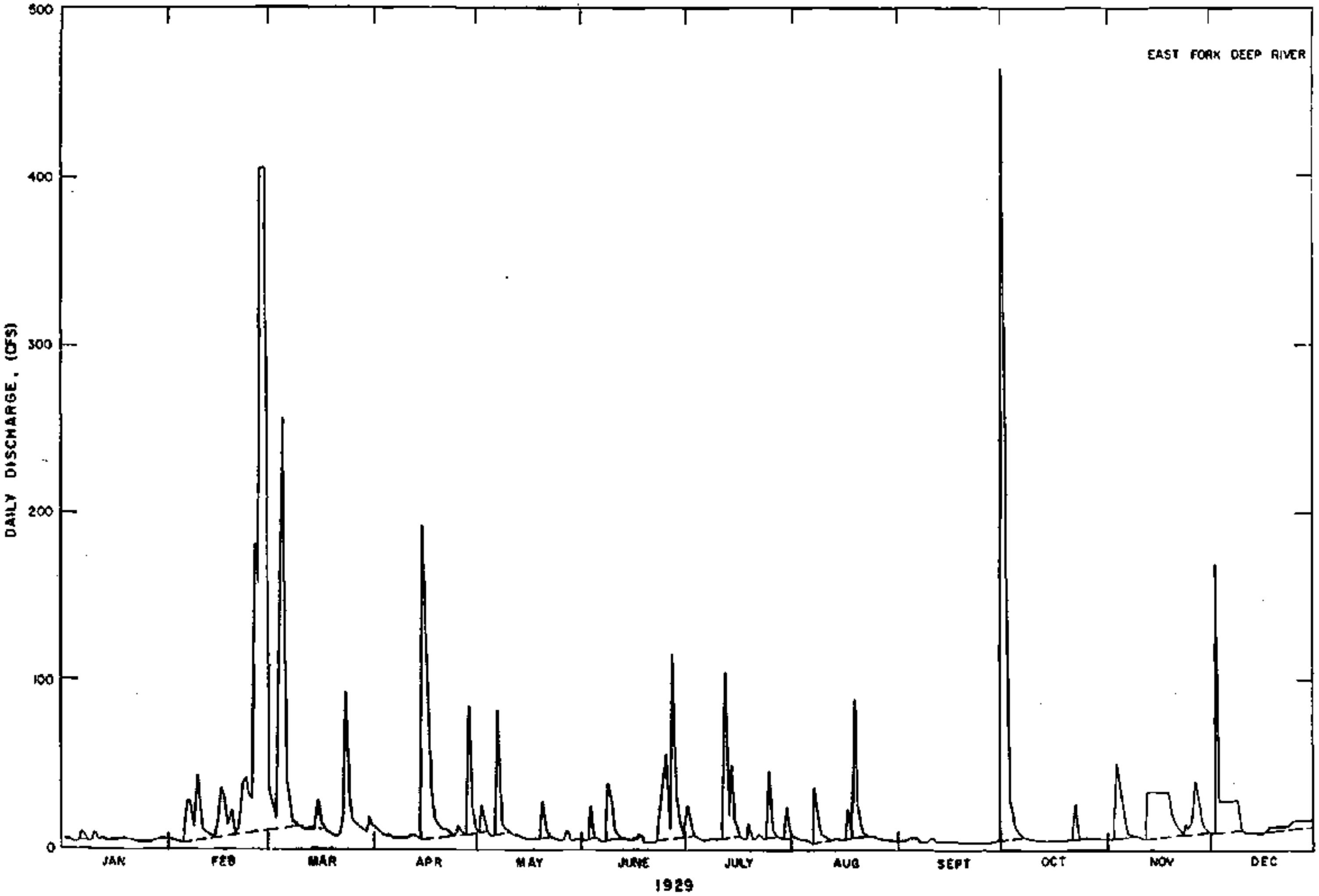

Figure D.5. Annual hydrograph of daily discharge at East Fork Deep River near Highpoint, North Carolina, 1929. Separation gradient is 0.25 cfs per day.

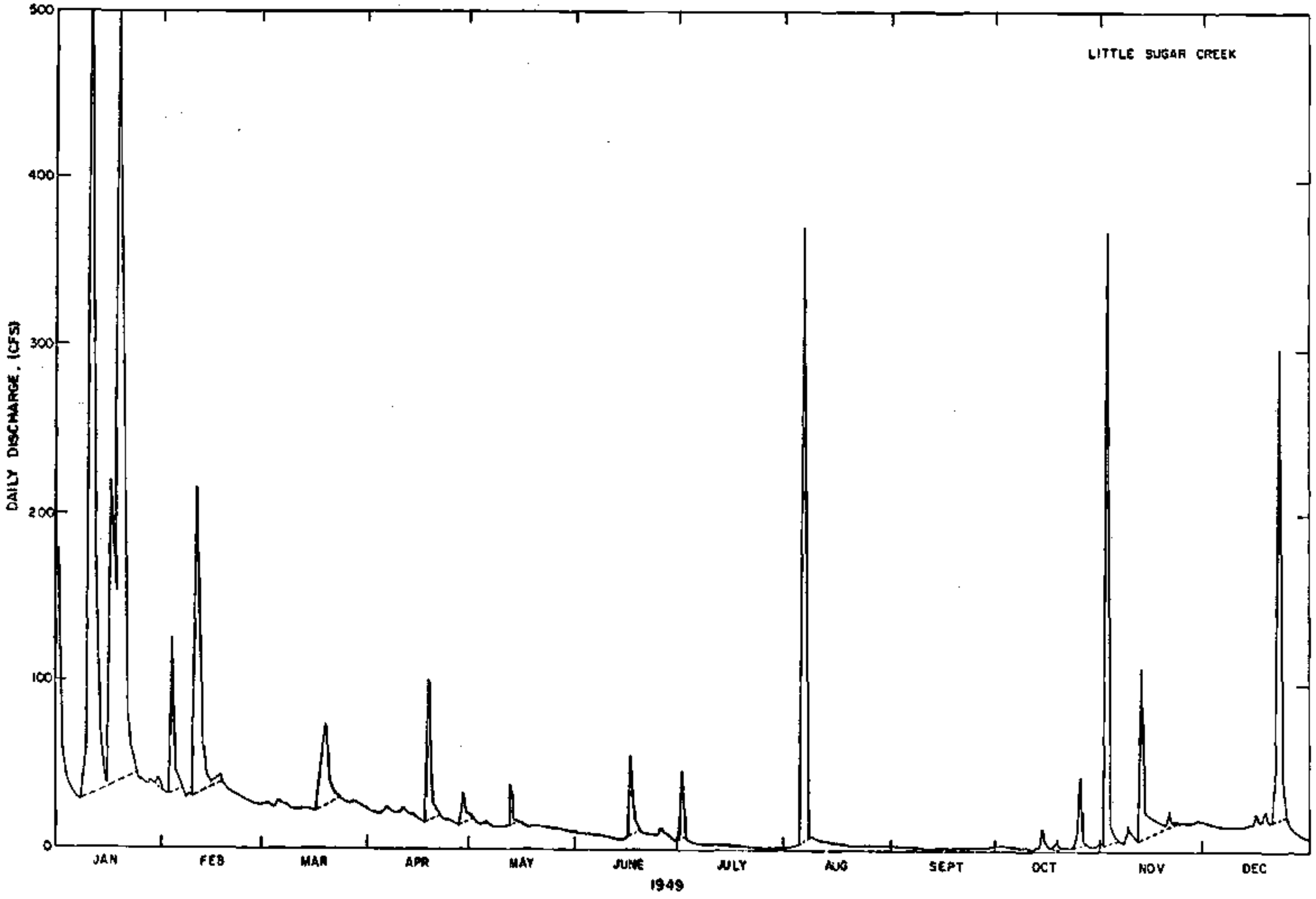

Figure D.6. Annual hydrograph of daily discharge at Little Sugar Creek near Charlotte, North Carolina, 1949. Separation gradient is 1.0 cfs per day.

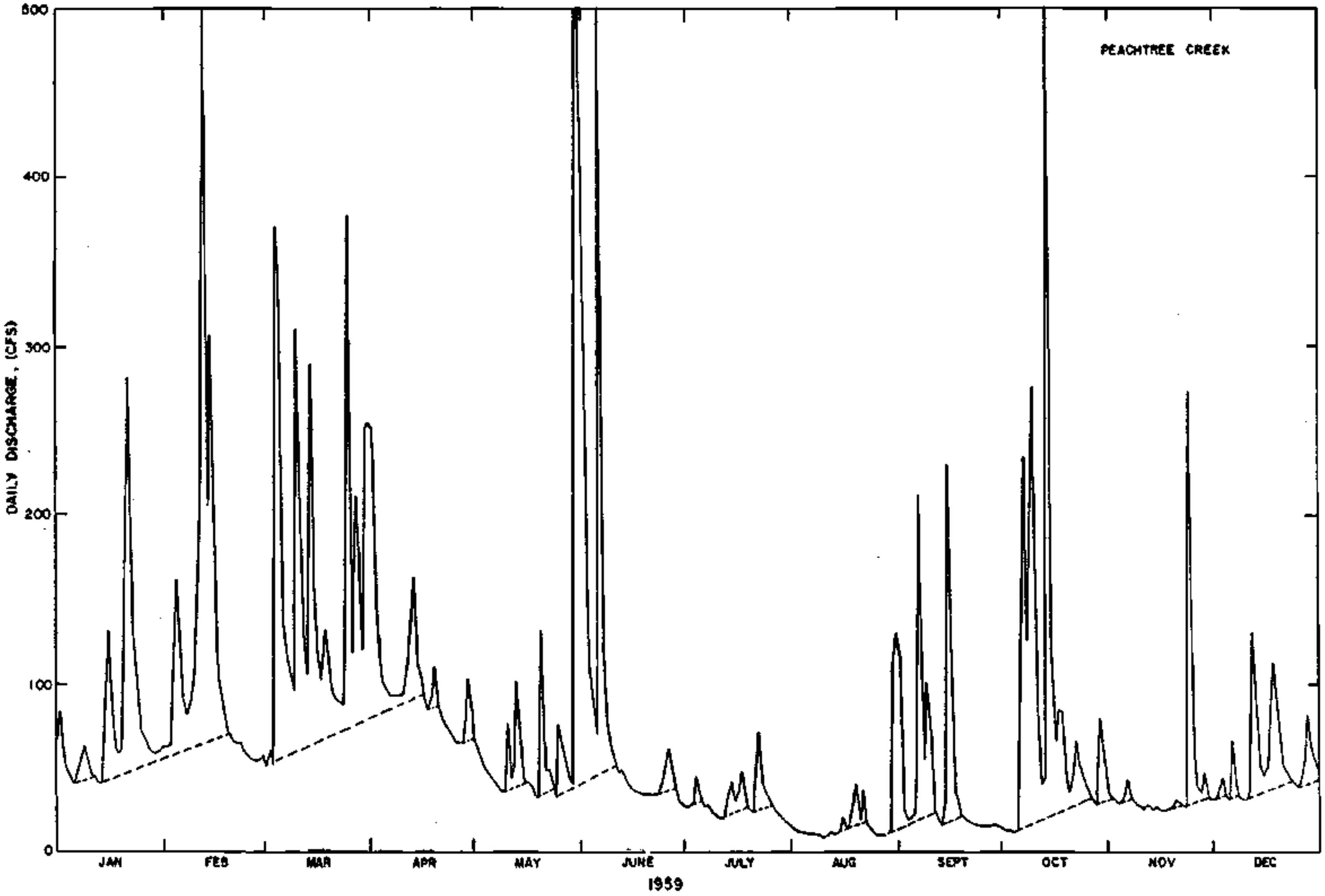

Figure D.7. Annual hydrograph of daily discharge at Peachtree Creek near Atlanta, Georgia, 1959. Separation gradient is 1.0 cfs per day.

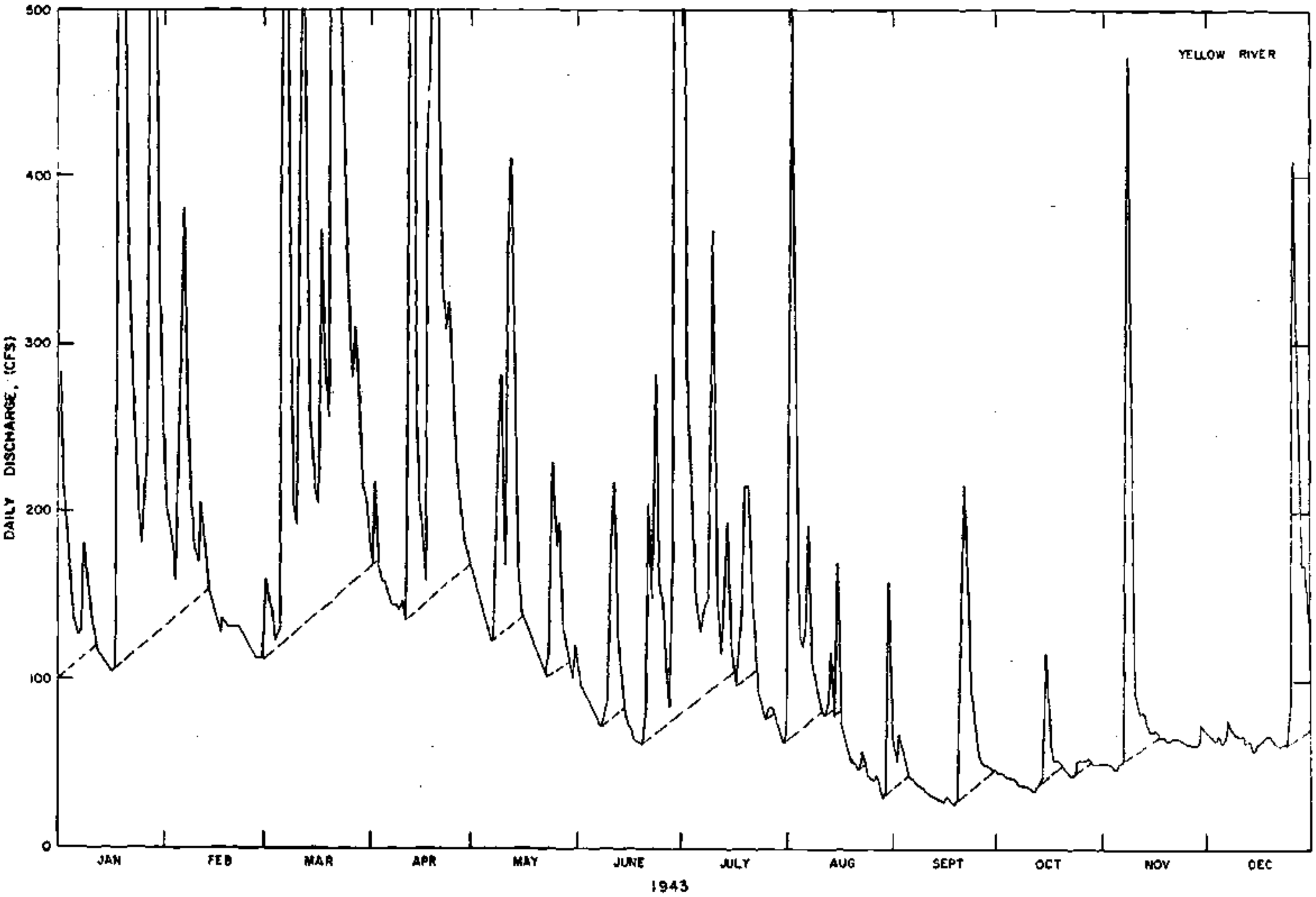

Figure D.8. Annual hydrograph of daily discharge at Yellow River near Snellville, Georgia, 1943. Separation gradient is 2.0 cfs per day.

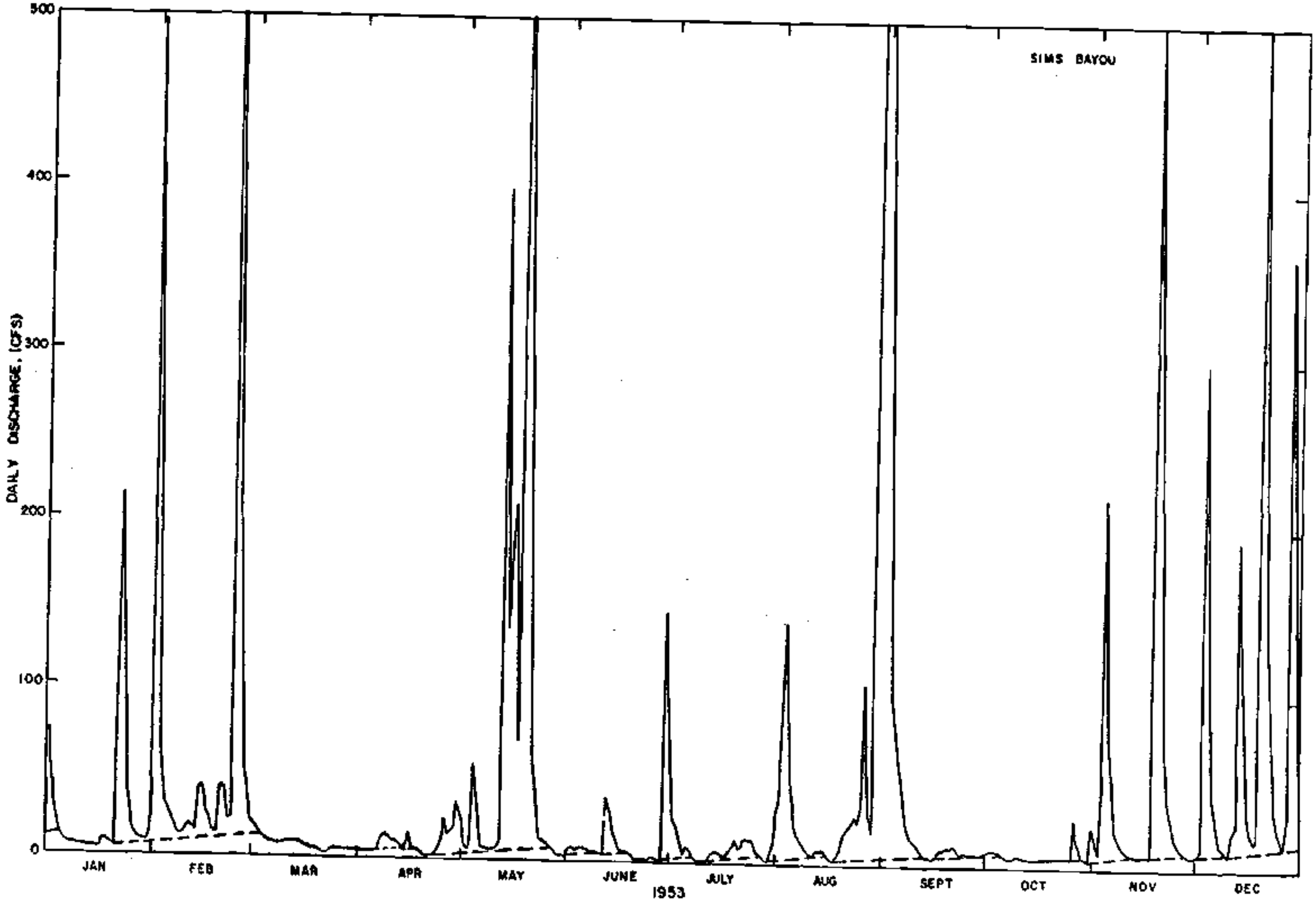

Figure D.9. Annual hydrograph of daily discharge at Sims Bayou near Houston, Texas, 1953. Separation gradient is 0.25 cfs per day.

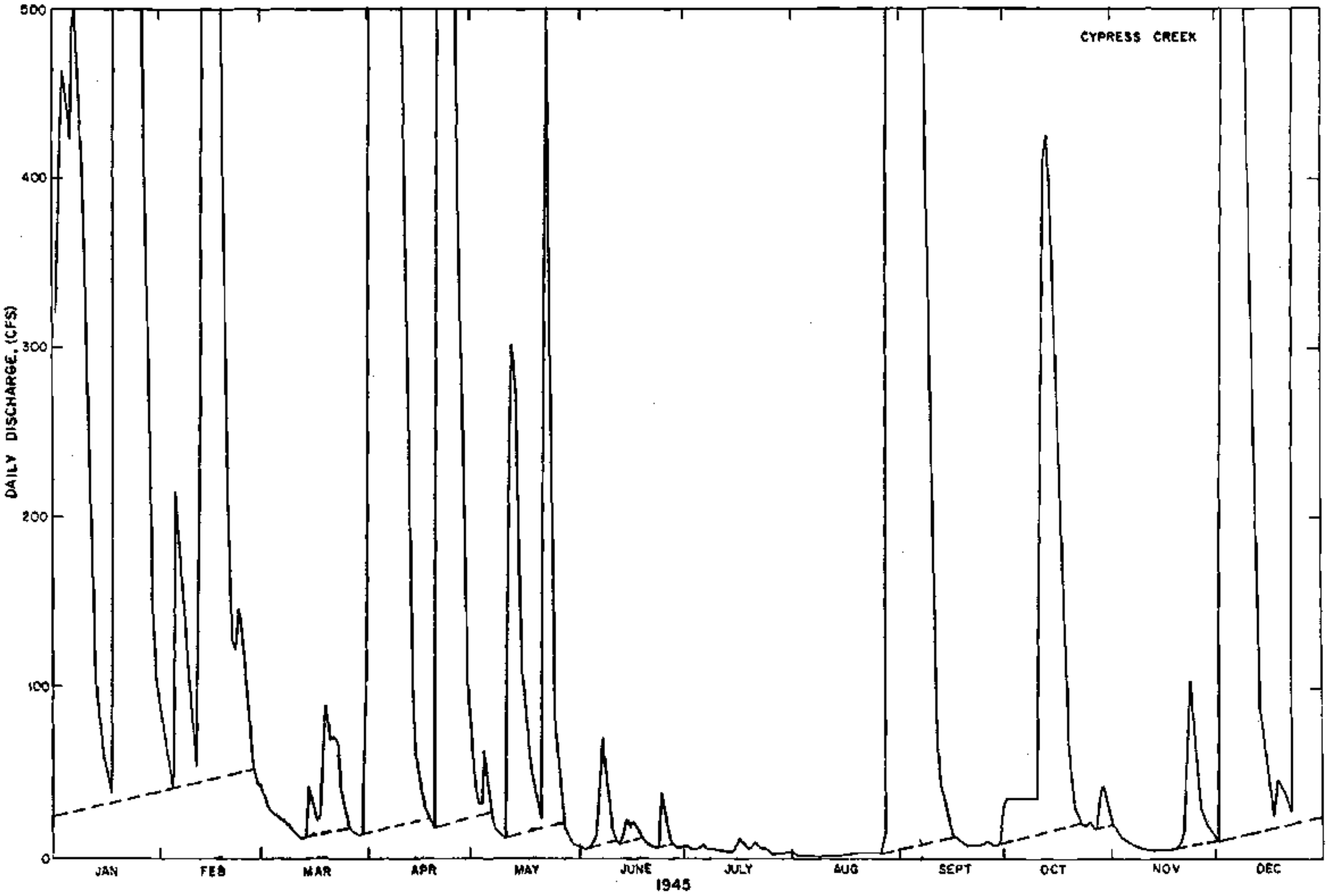

Figure D.10. Annual hydrograph of daily discharge at Cypress Creek near Houston, Texas, 1945. Separation gradient is 0.50 cfs per day.

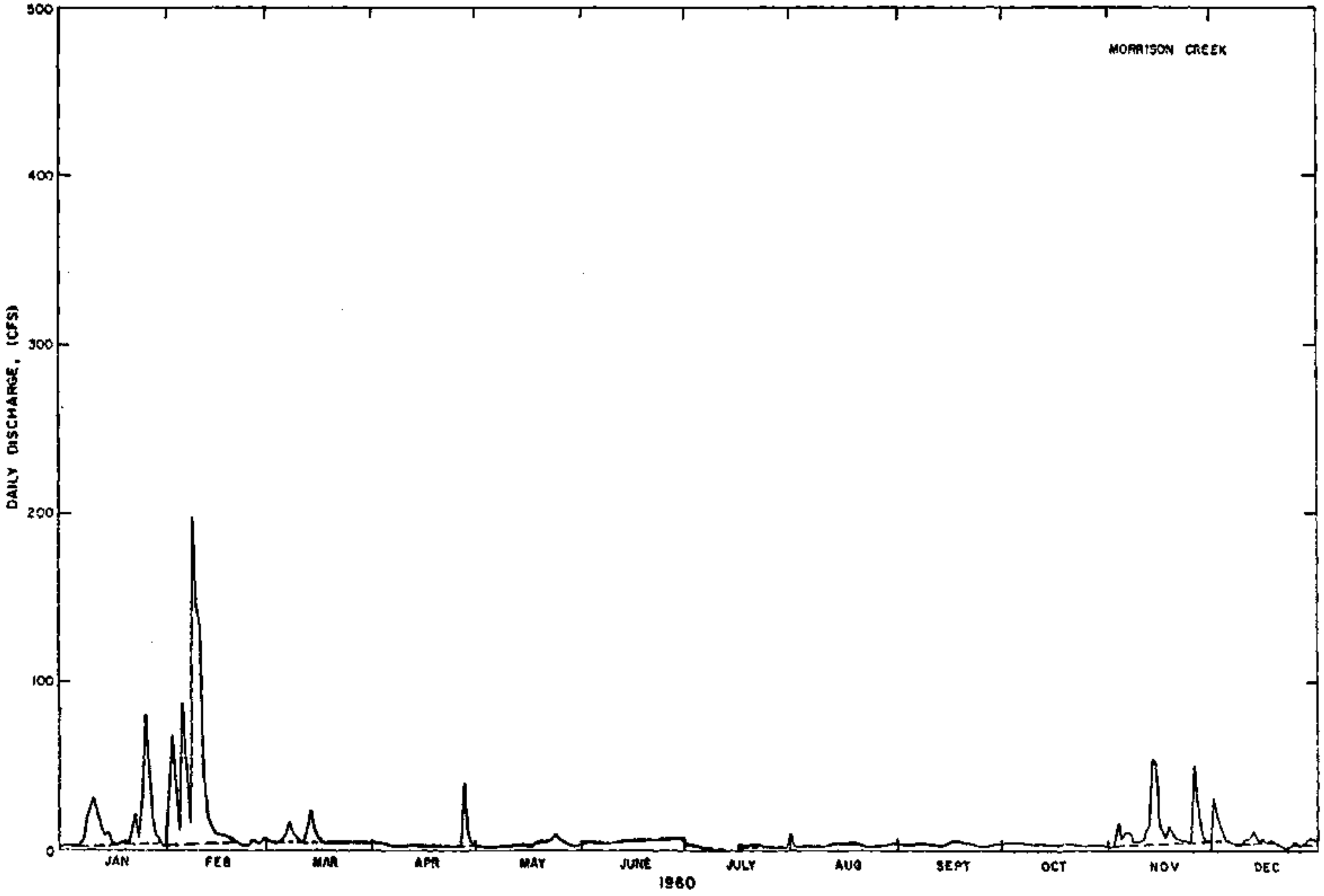

Figure D.11. Annual hydrograph of daily discharge at Morrison Creek near Sacramento, California, 1960. Separation gradient is 0.25 cfs per day.

APPENDIX E

Table E1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values

		Average Ratio Of Urban Runoff To Control Runoff													
		Annual			Fall			Winter			Spring			Summer	
Period Of Analysis	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period
EAST MEADOW BROOK															
TOTAL FLOW															
1944-51	0.8379			0.7409			0.9182			0.9015			0.7629		
1952-57	0.8364	-0.2	-0.2	0.7984	7.8	7.8	0.8320	-9.4	-9.4	0.8740	-3.1	-3.1	0.8244	8.1	8.1
1958-62	0.9014	7.8	7.6	0.8585	7.5	15.9	0.8933	7.4	-2.7	0.8825	1.0	-2.1	0.9446	14.6	23.8
BASEFLOW															
1944-51	0.7735			0.6800			0.8399			0.8506			0.6919		
1952-57	0.7232	-6.5	-6.5	0.6818	0.3	0.3	0.7584	-9.7	-9.7	0.7838	-7.9	-7.9	0.6445	-6.8	-6.8
1958-62	0.7392	2.2	-4.4	0.7160	5.0	5.3	0.7494	-1.2	-10.8	0.7814	-0.3	-8.1	0.6722	4.3	-2.8
DIRECT RUNOFF															
1944-51	2.2416			2.1313			2.2883			2.1673			2.6893		
1952-57	3.1209	39.2	39.2	3.2352	51.8	51.8	2.5899	13.2	13.2	3.3594	55.0	55.0	4.1141	53.0	53.0
1958-62	3.6745	17.7	63.9	3.6071	11.5	69.2	3.0591	18.1	33.7	3.8216	13.8	76.3	4.9935	21.4	85.7

Table B1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

	Average Ratio Of Urban Runoff To Control Runoff														
	Annual			Fall			Winter			Spring			Summer		
Period Of Average Analysis	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period
PINES BROOK															
TOTAL FLOW															
1944-51	0.9016			0.7979			0.9831			0.9658			0.8248		
1952-57	0.7271	-19.4	-19.4	0.6945	-13.0	-13.0	0.7314	-25.6	-25.6	0.7668	-20.6	-20.6	0.7066	-14.3	-14.3
1958-62	0.7038	-3.2	-21.9	0.6611	-4.8	-17.1	0.7494	2.5	-23.8	0.6780	-11.6	-29.8	0.6980	-1.2	-15.4
1963-69	0.1852	-73.7	-79.5	0.1922	-70.9	-75.9	0.2013	-73.1	-79.5	0.1930	-71.5	-80.0	0.1389	-80.1	-83.2
BASEFLOW															
1944-51	0.8509			0.7557			0.9424			0.9276			0.7422		
1952-57	0.6189	-27.3	-27.3	0.5861	-22.4	-22.4	0.6501	-31.0	-31.0	0.6798	-26.7	-26.7	0.5452	-26.5	-26.5
1958-62	0.5378	-13.1	-36.8	0.5271	-10.1	-30.3	0.5788	-11.0	-38.6	0.5582	-17.9	-39.8	0.4570	-16.2	-38.4
1963-69	0.0792	-85.3	-90.7	0.0705	-86.6	-90.7	0.1098	-81.0	-88.3	0.0961	-82.8	-89.6	0.0269	-94.1	-96.4
DIRECT RUNOFF															
1944-51	2.0233			1.9272			1.5810			1.9254			3.2709		
1952-57	2.9584	46.2	46.2	3.0670	59.1	59.1	2.8827	82.3	82.3	3.1906	65.7	65.7	3.9951	22.1	22.1
1958-62	3.5503	20.0	75.5	3.3578	9.5	74.2	3.3866	17.5	114.2	4.2175	32.2	119.0	4.2689	6.9	30.5
1963-69	2.4242	-31.7	19.8	2.5525	-24.0	32.4	1.8380	-45.7	16.3	2.8425	-32.6	47.6	3.0763	-27.9	-6.0

Table E1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

Average Ratio Of Urban Runoff To Control Runoff

Period Of Average Analysis	Annual Percent Change Over Last Period	Annual Percent Change Over Base Period	Annual Average	Fall Percent Change Over Last Period	Fall Percent Change Over Base Period	Fall Average	Winter Percent Change Over Last Period	Winter Percent Change Over Base Period	Winter Average	Spring Percent Change Over Last Period	Spring Percent Change Over Base Period	Spring Average	Summer Percent Change Over Last Period	Summer Percent Change Over Base Period
N. BUFFALO CREEK														
TOTAL FLOW														
1929-41 0.4724			0.5123			0.4636			0.4758			0.5167		
1942-49 0.5149	9.0	9.0	0.6089	18.9	18.9	0.4647	0.2	0.2	0.6119	28.6	28.6	0.5629	9.0	9.0
1950-56 0.5639	9.5	19.4	0.6155	1.1	20.1	0.5239	12.7	13.0	0.5859	-4.2	23.1	0.7247	28.7	40.3
1957-63 0.5624	-0.3	19.1	0.6208	0.9	21.2	0.5014	-4.3	8.2	0.5881	0.4	23.6	0.9305	28.4	80.1
1964-70 0.6399	13.8	35.5	0.7244	16.7	41.4	0.5734	14.4	23.7	0.6412	9.0	34.7	0.9776	5.1	89.2
BASEFLOW														
1929-41 0.4893			0.4921			0.5016			0.8328			0.4918		
1942-49 0.5777	18.1	18.1	0.6356	29.1	29.1	0.5613	11.9	11.9	0.5557	-33.3	-33.3	0.5875	19.4	19.4
1950-56 0.6274	8.6	28.2	0.6447	1.4	31.0	0.5869	4.6	17.0	0.5957	7.2	-28.5	0.7587	29.1	54.2
1957-63 0.6626	5.6	35.4	0.7209	11.8	46.5	0.6038	2.9	20.4	0.6244	4.8	-25.0	0.8147	7.4	65.7
1964-70 0.8029	21.2	64.1	0.8471	17.5	72.1	0.7010	16.1	39.8	0.7677	23.0	-7.8	1.0685	31.2	117.3
DIRECT RUNOFF														
1929-41 0.4683			0.7308			0.4384			0.4732			0.6510		
1942-49 0.4777	2.0	2.0	0.7284	-0.3	-0.3	0.4106	-6.3	-6.3	0.7319	54.7	54.7	0.6946	6.7	6.7
1950-56 0.5226	9.4	11.6	0.8254	13.3	12.9	0.4898	19.3	11.7	0.5775	-21.1	22.1	0.9207	32.5	41.4
1957-63 0.4973	-4.8	6.2	0.6523	-21.0	-10.7	0.4476	-8.6	2.1	0.5859	1.5	23.8	1.2555	36.4	92.9
1964-70 0.5249	5.5	12.1	0.6517	-0.1	-10.8	0.4853	8.4	10.7	0.5921	1.1	25.1	1.1205	-10.8	72.1

Table E1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

		Average Ratio Of Urban Runoff To Control Runoff													
		Annual			Fall			Winter			Spring			Summer	
Period Of Analysis	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period
PEACHTREE CREEK															
TOTAL FLOW															
1959-62	1.6145			1.8267			1.4370			1.5868			2.5274		
1963-66	1.6088	-0.4	-0.4	1.8255	-0.1	-0.1	1.4362	-0.1	-0.1	1.4884	-6.2	-6.2	2.4196	-4.3	-4.3
1967-70	1.9859	23.4	23.0	2.0878	14.4	14.3	1.5033	4.7	4.6	1.9542	31.3	23.2	3.7218	53.8	47.3
BASEFLOW															
1959-62	1.3464			1.5134			1.2040			1.3173			1.7525		
1963-66	1.1196	-16.9	-16.9	1.2760	-15.7	-15.7	1.0177	-15.5	-15.5	1.0478	-20.5	-20.5	1.3893	-20.7	-20.7
1967-70	1.3203	17.9	-1.9	1.4367	12.6	-5.1	1.1001	8.1	-8.6	1.2894	23.1	-2.1	1.9715	41.9	12.5
DIRECT RUNOFF															
1959-62	1.9192			2.5068			1.6335			2.0101			4.4650		
1963-66	2.1128	10.1	10.1	3.0382	21.2	21.2	1.8256	11.8	11.8	1.8904	-6.0	-6.0	5.1736	15.9	15.9
1967-70	2.7892	32.0	45.3	2.8747	-5.4	14.7	1.9507	6.9	19.4	3.2133	70.0	59.9	6.8867	33.1	54.2

Table E1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

Average Ratio Of Urban Runoff To Control Runoff

Period Of Analysis	Annual Average	Annual Percent Change Over Last Period	Annual Percent Change Over Base Period	Fall Average	Fall Percent Change Over Last Period	Fall Percent Change Over Base Period	Winter Average	Winter Percent Change Over Last Period	Winter Percent Change Over Base Period	Spring Average	Spring Percent Change Over Last Period	Spring Percent Change Over Base Period	Summer Average	Summer Percent Change Over Last Period	Summer Percent Change Over Base Period
SIMS BAYOU															
TOTAL FLOW															
1953-57	14.1197			29.7832			16.0678			37.2010			31.0358		
1958-61	9.6593	-31.6	-31.6	14.5533	-51.1	-51.1	21.4951	33.8	33.8	7.3233	-80.3	-80.3	26.7611	-13.8	-13.8
1962-65	23.6455	144.8	67.5	55.5434	281.7	86.5	16.9064	-21.3	5.2	30.2621	313.2	-18.7	20.7318	-22.5	-33.2
1966-70	18.6991	-20.9	32.4	20.6387	-62.8	-30.7	38.4828	127.6	139.5	20.0669	-33.7	-46.1	24.7809	19.5	-20.2
BASEFLOW															
1953-57	50.4108			58.4433			35.8967			79.5913			66.7076		
1958-61	14.5754	-71.1	-71.1	19.0094	-67.5	-67.5	16.1272	-55.1	-55.1	42.4604	-46.7	-46.7	28.2323	-57.7	-57.7
1962-65	45.1828	210.0	-10.4	47.9302	152.1	-18.0	48.1977	198.9	34.3	60.9279	43.5	-23.4	35.9139	27.2	-46.2
1966-70	51.1851	13.3	1.5	37.2193	-22.3	-36.3	*******	110.1	182.1	75.7105	24.3	-4.9	50.8977	41.7	-23.7
DIRECT RUNOFF															
1953-57	11.0312			20.4209			13.8168			26.8488			21.9975		
1958-61	9.3108	-15.6	-15.6	18.0644	-11.5	-11.5	22.7120	64.4	64.4	5.5774	-79.2	-79.2	27.6873	25.9	25.9
1962-65	21.2815	128.6	92.9	62.5486	246.3	206.3	10.9232	-51.9	-20.9	25.9484	365.2	-3.4	14.3951	-48.0	-34.6
1966-70	14.5187	-31.8	31.6	15.1299	-75.8	-25.9	33.3337	205.2	141.3	16.1451	-37.8	-39.9	19.1202	32.8	-13.1

Table 21. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

Average Ratio Of Urban Runoff To Control Runoff

		Annual			Fall			Winter			Spring			Summer	
Period Of Average Analysis		Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period
BRAYS BAYOU															
TOTAL FLOW															
1949-57	10.2689			32.2254			12.8072			31.5593			22.9287		
1958-61	6.1830	-39.8	-39.8	17.7187	-45.0	-45.0	14.1590	10.6	10.6	6.3036	-80.0	-80.0	10.3877	-54.7	-54.7
1962-65	23.3655	277.9	127.5	40.0724	126.2	24.4	16.5434	16.8	29.2	38.7513	514.8	22.8	30.4756	193.4	32.9
1966-70	16.1120	-31.0	56.9	22.6181	-43.6	-29.8	28.6742	73.3	123.9	16.7059	-56.9	-47.1	30.1533	-1.1	31.5
BASEFLOW															
1949-57	35.0138			45.6708			30.5125			51.6784			46.2527		
1958-61	12.8104	-63.4	-63.4	17.2526	-62.2	-62.2	11.1265	-63.5	-63.5	34.3466	-33.5	-33.5	29.7798	-35.6	-35.6
1962-65	45.3166	253.7	29.4	44.1408	155.8	-3.4	43.3895	290.0	42.2	69.6056	102.7	34.7	38.8039	30.3	-16.1
1966-70	45.7205	0.9	30.6	38.2094	-13.4	-16.3	92.5999	113.4	203.5	60.0690	-13.7	16.2	50.1875	29.3	8.5
DIRECT RUNOFF															
1949-57	7.9034			27.2255			10.6611			26.8996			14.9525		
1958-61	5.7143	-27.7	-27.7	39.9394	46.7	46.7	14.8969	39.7	39.7	5.5588	-79.3	-79.3	8.8617	-40.7	-40.7
1962-65	20.8210	264.4	163.4	41.8719	4.8	53.8	11.8609	-20.4	11.3	35.0663	530.8	30.4	28.3340	219.7	89.5
1966-70	12.1822	-41.5	54.1	18.9922	-54.6	-30.2	21.1666	78.5	98.5	13.2824	-62.1	-50.6	27.3875	-3.3	83.2

Table B1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

Period Of Average Analysis	Annual Percent Change Over Last Period	Annual Percent Change Over Base Period	Average	Fall Percent Change Over Last Period	Fall Percent Change Over Base Period	Average	Winter Percent Change Over Last Period	Winter Percent Change Over Base Period	Average	Spring Percent Change Over Last Period	Spring Percent Change Over Base Period	Average	Summer Percent Change Over Last Period	Summer Percent Change Over Base Period
WHITEOAK BAYOU														
TOTAL FLOW														
1949-57 7.2858			18.7842			9.7537			10.9487			13.6859		
1958-61 5.3583	-26.5	-26.5	8.5051	-54.7	-54.7	8.4331	-13.5	-13.5	4.9098	-55.2	-55.2	12.8859	-5.8	-5.8
1962-6516.3134	204.5	123.9	29.1128	242.3	55.0	12.8136	51.9	31.4	20.7859	323.4	89.8	14.5641	13.0	6.4
1966-70 8.7432	-46.4	20.0	12.3564	-57.6	-34.2	11.5452	-9.9	18.4	7.5553	-63.7	-31.0	18.1700	24.8	32.8
BASEFLOW														
1949-5712.1969			13.6606			13.7822			15.0893			15.1185		
1958-61 6.7085	-45.0	-45.0	10.5111	-23.1	-23.1	5.8815	-57.3	-57.3	17.7100	17.4	17.4	11.2436	-25.6	-25.6
1962-6516.6157	147.7	36.2	17.0100	61.8	24.5	19.6320	233.8	42.4	23.6040	33.3	56.4	10.7760	-4.2	-28.7
1966-7013.0571	-21.4	7.1	10.4173	-38.8	-23.7	21.7952	11.0	58.1	17.5705	-25.6	16.4	13.5609	25.8	-10.3
DIRECT RUNOFF														
1949-57 6.9150			25.0809			9.0438			9.4539			13.2423		
1958-61 5.2655	-23.9	-23.9	14.5674	-41.9	-41.9	9.1110	0.7	0.7	4.6042	-51.3	-51.3	13.6267	2.9	2.9
1962-6517.1977	226.6	148.7	31.4289	115.7	25.3	11.5513	26.8	27.7	20.4591	344.4	116.4	18.6044	36.5	40.5
1966-70 8.3554	-51.4	20.8	15.5867	-50.4	-37.9	11.8099	2.2	30.6	6.9303	-66.1	-26.7	21.6948	16.6	63.8

Table B1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

	Average Ratio Of Urban Runoff To Control Runoff														
		Annual			Fall			Winter			Spring			Summer	
Period Of Average Analysis		Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period	Average	Percent Change Over Last Period	Percent Change Over Base Period
GREENS BAYOU															
TOTAL FLOW															
1953-57	7.1099			14.4614			6.0584			5.3680			27.3561		
1958-61	4.6797	-34.2	-34.2	6.1410	-57.5	-57.5	6.0726	0.2	0.2	2.6749	-50.2	-50.2	9.1205	-66.7	-66.7
1962-65	14.1120	201.6	98.5	24.6666	301.7	70.6	11.3221	86.4	86.9	12.2351	357.4	127.9	11.5121	26.2	-57.9
1966-70	8.9147	-36.8	25.4	12.9284	-47.6	-10.6	10.1508	-10.3	67.6	8.9860	-26.6	67.4	8.2964	-27.9	-69.7
BASEFLOW															
1953-57	2.2547			1.1760			1.6987			2.2176			4.7662		
1958-61	2.6409	17.1	17.1	3.9737	237.9	237.9	2.3444	38.0	38.0	6.5333	194.6	194.6	4.7579	-0.2	-0.2
1962-65	12.9856	391.7	475.9	11.5150	189.8	879.2	14.7047	527.2	765.7	19.3223	195.8	771.3	10.7263	125.4	125.0
1966-70	10.2418	-21.1	354.2	6.0278	-47.7	412.6	25.8468	75.8	1421.6	14.4924	-25.0	553.5	10.8283	1.0	127.2
DIRECT RUNOFF															
1953-57	7.5313			26.3211			6.5424			6.1010			28.0608		
1958-61	4.8373	-35.8	-35.8	9.9326	-62.3	-62.3	6.9121	5.7	5.7	2.5636	-58.0	-58.0	9.8507	-64.9	-64.9
1962-65	15.0273	210.7	99.5	29.6966	199.0	12.8	11.4348	65.4	74.8	10.6490	315.4	74.5	12.1176	23.0	-56.8
1966-70	8.7255	-41.9	15.9	19.3955	-34.7	-26.3	8.1268	-28.9	24.2	8.5192	-20.0	39.6	8.0192	-33.8	-71.4

Table E1. Results Of Analysis Showing Percentage Changes In Average Ratio Of Runoff From The Urban Watershed To Control Watershed For Annual And 3-month Seasonal Values --Continued

Average Ratio Of Urban Runoff To Control Runoff

Period Of Analysis	Average	Annual Percent Change Over Last Period	Annual Percent Change Over Base Period	Average	Fall Percent Change Over Last Period	Fall Percent Change Over Base Period	Average	Winter Percent Change Over Last Period	Winter Percent Change Over Base Period	Average	Spring Percent Change Over Last Period	Spring Percent Change Over Base Period	Average	Summer Percent Change Over Last Period	Summer Percent Change Over Base Period
HALLS BAYOU															
TOTAL FLOW															
1953-57	29.7827			56.9962			28.9109			31.1801			69.0958		
1958-61	20.9043	-29.8	-29.8	26.6779	-53.2	-53.2	36.3756	25.8	25.8	19.4929	-37.5	-37.5	56.7014	-17.9	-17.9
1962-65	60.6038	189.9	103.5	88.7582	232.7	55.7	55.1403	51.6	90.7	56.3687	189.2	80.8	72.2014	27.3	4.5
1966-70	41.2353	-32.0	38.5	61.3723	-30.9	7.7	51.4254	-6.7	77.9	39.7572	-29.5	27.5	45.6824	-36.7	-33.9
BASEFLOW															
1953-57	38.1098			35.0047			33.0813			37.0599			49.4938		
1958-61	23.3596	-38.7	-38.7	29.1732	-16.7	-16.7	25.8073	-22.0	-22.0	62.0275	67.4	67.4	31.3103	-36.7	-36.7
1962-65	53.0935	127.3	39.3	42.9144	47.1	22.6	83.4177	223.2	152.2	67.5571	8.9	82.3	28.6989	-8.3	-42.0
1966-70	69.0037	30.0	81.1	47.5384	10.8	35.8	*******	79.1	351.6	93.2485	38.0	151.6	56.3948	96.5	13.9
DIRECT RUNOFF															
1953-57	28.7981			80.8167			28.3552			29.5465			73.2031		
1958-61	20.7222	-28.0	-28.0	30.6503	-62.1	-62.1	39.1868	38.2	38.2	17.6861	-40.1	-40.1	61.6548	-15.8	-15.8
1962-65	66.0197	218.6	129.2	*******	243.6	30.3	53.9089	37.6	90.1	54.3016	207.0	83.8	*******	68.9	42.2
1966-70	38.5201	-41.7	33.8	83.7280	-20.5	3.6	40.4333	-25.0	42.6	36.2474	-33.2	22.7	44.0677	-57.7	-39.8

APPENDIX F

EVALUATIONS OF REGRESSION MODELS AND DIGITAL WATERSHED MODELS

In order to analyze general approaches to studying changes in urban runoff volumes that might provide better results than using double-mass curve technique, a literature search was made of models that might be useful for this purpose. The following sections describe some models found in the literature with an evaluation of their usefulness and ease of modification for studying urban runoff volumes. It was not the intent of this analysis to concentrate on the results of the various studies, but to analyze and comment on the technique's usefulness in explaining changes in runoff volumes. A large number of models and various approaches were studied. Those reported in the following pages are by no means an exhaustive listing, but rather an adequate sampling of the current literature. The titles given in the following summaries were written by this writer.

Regression Models

Title: Annual Runoff in Finland

Ref: Mustonen, S. E., 1967, Effects of Climatologic and Basin Characteristics on Annual Runoff: Water Res. Research, Vol. 3, N. 1, p. 123-130.

Synopsis: Normal linear multiple regression techniques are used on selected climatologic and basin characteristics to determine the important parameter affecting annual runoff in Finland. Thirty-three watersheds were studies. Stepwise orthogonal regression analysis is performed to determine significant variables.

Data: Annual Runoff, Annual and seasonal precipitation, Potential evaporation, Average annual temperature, Change in soil moisture deficit, Frost depth on March 31, Volume of forest growing stock, Percentage of area in coarse soils, Drainage area, Percentage of cultivated land, Average land slope.

Output: 1. Statistical significance of independent input variables,

2. Predictive equations of annual runoff using selected climatologic and basin characteristics.

Remarks: This procedure is suggested for use by eliminating frost depth and adding to the data the following parameters:

Annual and seasonal components of flow;
Variation from normal of annual and seasonal precipitation, and;
Indices of urbanization.

The author makes a significant point that the variables may only be indices of the true hydrologic factors and therefore do not directly represent hydrologic processes.

Title: Predicting On-Site Runoff

Reference: Schreiber, H. A., and Kincaid, D. R., 1967, Regression Models for Predicting On-Site Runoff From Short-Duration Convective Storms: Water Resources Research, Vol. 3, N.2, p. 389-395.

Synopsis: Stepwise multiple linear regression analysis was used to determine the significance of precipitation, vegetation and antecedent soil moisture on runoff from two small (6 x 12 foot) experimental plots.

Data; Average storm rainfall
Maximum storm rainfall intensity
Duration of storm event
Antecedent soil moisture
Basal area
Crown spread vegetation
Average runoff per plot per storm.

Output: 1. Statistical significance of each independent variable,
2. Predictive equation for runoff based on independent variables.

Remarks: The approach does not include as comprehensive a list of independent variables as required to predict runoff resulting from urban watersheds. The plots used are small experimental watersheds (highly special cases). However, the general approach of regression analysis is recommended with an expanded list of independent variables.

Title: Streamflow Characteristics in the Northeast

Reference: Sopper, W. E. and Lull, H. W., 1965, Streamflow Characteristics of Physiographic Units in the Northeast: Water Resources Research, Vol. 1, No. 1, p. 115-124.

Synopsis: Variations (mean, std. deviation, range, etc.) in annual and seasonal runoff and flow duration among physiographic units in the Northeast were studied.

Data: Mean daily discharge

Annual and seasonal discharge

Flow duration

Number and magnitude of flows greater than 10 cubic feet per second per square mile.

Output: Discussion of variations among physiographic units.

Remarks: This approach is not useful because it does not analyze watershed factors affecting the runoff process nor does it consider temporal effects of watershed changes.

Title: Rainfall-Runoff Model

Reference: Diskin, M. H., 1970, Definition and Uses of the Linear Regression Model: Water Resources Research, Vol. 6, No. 6, p. 1668-1673.

Synopsis: A simple three element model is developed to predict annual runoff and annual losses from annual precipitation. The method requires evaluation of three parameters (not easily associated with physical processes) determined by regression analysis.

Data: Annual Precipitation, and Runoff

Output: A simple runoff model useful for grossly predicting runoff and losses.

Remarks: This approach is not promising. It would require a study of the three regression constants which are not easily defined or associated with physical processes.

Title: Streamflow in the Northeast

Reference: Lull, H. W. and Sopper, W. E., 1966, Factors that Influence Streamflow in the Northeast: Water Resources Research, Vol. 2, N. 3, p. 371-379.

Synopsis: Average annual and seasonal daily mean discharges from 137 watersheds in the Northeast were related by stepwise multiple linear regression analysis to selected climatic, topographic, and land-use variables. The watersheds were all non-urban and principally forested. The significant variables affecting runoff were precipitation, forest cover, elevation, latitude, July temperature and swamp area.

Data: Dependent Variables --

Average annual runoff
Average Fall runoff
Average Winter runoff
Average Spring runoff
Average Summer runoff
Mean daily discharge

Independent Variables --

Average station precipitatonn
Average isohyetal precipitation
Average seasonal precipitation
Precipitation intensity
Average maximum July temperature
Latitude

Elevation

Relief - difference between max. and min. elevation

Relief Ratio - Relief/longest watershed length

Main channel slope

Circulatory ratio

Percentage of area in forest

Percentage of area in swamp

Percentage of area in surface water

Output: 1. Statistical significance of each independent variable,

2. Predictive equations for annual and seasonal runoff based on selected independent variables.

Remarks: This study represents the suggested approach applied to urban watersheds. The list of independent variables requires adjustments to include departures from normal rainfall, estimates of evapotranspiration, soil types, and indices of urbanization. Careful analysis of the results of the stepwise multiple linear regression analysis is necessary to understand, describe, explain and often disregard many suggested relationships. Understanding the physical hydrologic phenomenon is necessary to analyze results of regression analysis.

Title: Effects of Urbanization on Stream Channels and Streamflow

Reference: Hammer, T. R., 1973, Effects of urbanization on stream channels and streamflow: Reg. Sci. Res. Inst., Phila., 272 p.

Synopsis: As part of a long-term and comprehensive study of factors affecting channel enlargement and streamflow characteristics, Hammer studied the affect of selected basin parameters on flood peaks, volume and lag time. Multivariate regression analysis incorporating a variety of transformations were used throughout the study. Results of studies related to runoff volumes were not conclusive because of the data reduction techniques and small sample size.

Data: (Related to urbanization and runoff volumes)

Average storm precipitation--segregated by seasons.

Impervious area

Average 48-hour runoff (total flow)

Output: Analysis and possible explanations of differences between regression coefficients. Predictive equations for several discharges based on rainfall and impervious cover.

Remarks: The difficulty with this approach is that relationships are developed for runoff volume (also peak discharge and lag time) based solely on indices of urbanization. To predict runoff volumes it is imperative that a complete list of factors most directly related to the runoff process be evaluated in the analysis. The large number of relationships developed by Hammer among basin characteristics are worthy of additional study in other studies or as supporting or design data for assessing basin management alternatives.

Digital Watershed Models

Title: Stanford Watershed Model (SWM)

References: Crawford, N. H. and Linsley, R. K., 1966, Digital Simulation in Hydrology: Stanford Watershed Model: Stanford Univ. Tech. Rept. N. 39, 187 p.

Synopsis: The Stanford Watershed Model was one of the first comprehensive parametric hydrologic models to be developed. A number of modifications and improved versions of the original model have been made and some of these are reported subsequently. SWM uses a moisture accounting system to synthesize a continuous streamflow hydrograph. A complete and continuous accounting is kept of moisture entering the watershed, movement through the watershed until it leaves by streamflow, evapotranspiration and subsurface outflow. A series of relations, each based on empirical observations or theoretical description of a specific hydrologic process, is used to estimate rates and volumes of water movement from one storage category to another, in accordance with current storage capacities and the calibrated watershed parameters. The model routes channel inflow from the point where it enters a tributary channel to the downstream point for which a hydrograph is required. Snowmelt moisture accounting is also included.

Data:

1. Recorded climatological data,
   Hourly precipitation,
   Potential evapotranspiration,
   Temperature

Streamflow data - for calibration phase.

2. Measurable watershed characteristics such as drainage area, impervious area lengths and slopes of channels, Theissen area for rainfall distribution and forest cover.
3. Parameters used in the computation process which are known to vary in magnitude among watersheds but have not been quantitatively tied to specific measurable watershed properties. For example, one parameter indexes the capacity of soils to retain water. These parameters are determined by trial and error calibration of the model with observed data.

Output: Once the model is calibrated and verified, it can be operated to provide a wide range of hydrologic information for watersheds represented by the calibrated parameters. The model can extend current data to provide information for flood and low flow frequency analysis. By varying selected parameters, the effect of urbanization can be synthesized and alternate development plans can be tested. Streamflow from ungaged watersheds can be synthesized. Drainage design information under a variety of conditions can be estimated.

Remarks: The SWM has been modified extensively by several investigators from its original state. Some updated versions provide better estimates of the effects of urbanization on streamflow. However, the general approach of using a comprehensive digital watershed model to synthesize effects of urban development is highly desirable. The approach allows the investigator the flexibility of studying the effects of several alternatives (as represented by model parameters) on streamflow. This information can then be used (1) to decide on the most efficient and economical development approach, and (2) to design detention or retention areas to reduce flood flows and provide storage to augment low flows.

Because the model is based on a moisture accounting system, estimates are provided of the volumes of flow contributed by each component of total flow. Adjusting appropriate model parameters and re-running the model will provide an understanding of the processes affecting the volumes of streamflow from urbanizing watersheds.

Title: Kentucky Watershed Model (KWM)

Reference: James, L.D., 1970, An evaluation of relationships between streamflow patterns and watershed characteristics through the use of OPSET - A self-calibrating version of the Stanford Watershed Model: Univ. of Kentucky Research Rept. No. 36, 117 p.

Synopsis: This model is a streamline version of the Stanford Watershed Model translated into Fortran IV. A number of adaptations were made to represent the climate and topography of Kentucky and the eastern U. S. More importantly, a procedure was developed for selfcalibrating model parameters. Additional manual calibration is necessary to develop a set of model parameters that best represent the watershed but OPSET significantly aids the calibration phase of model studies.

Data:
1. Climatological Data, Hourly Precipitation data, Annual Potential evapotranspiration, Monthly pan coefficients, Mean number of rainy days
2. Overland flow Parameters, Manning n for impervious area, Manning n for overland flow, Length and slope of flow
3. Watershed Parameters, Land use density by types, Fraction of area in water surface, Fraction of area in impervious cover, Drainage area, Time area histogram of watershed
4. Parameter estimates of rate and volume of water movement through watershed.

Output: Essentially the same as that described under SWM. Estimates of the volumes contributed by each flow component are provided.

Remarks: This model is an improvement on SWM. With careful selection and adjustment of model parameters representing physical factors affecting runoff, studies can be made to determine changes in runoff volumes among many other output volumes. Correlation relations can be developed between physical factors and runoff volumes to provide important planning information.

A suggested approach would be to compile the required data to calibrate the model for one watershed. Using the calibrated model, systematically varying model parameters associated with urbanizations (impervious cover, time-area histograms, subsurface storage capacities, interception, depression, detention and retention capacities, etc.) and observe the changes in runoff volumes. This approach requires long term precipitation and evapotranspiration estimates in order to develop frequency relationships. By judicious selection of model parameters a minimum number of computer runs can be made. The results can be analyzed to provide a variety of information useful for making water management decisions. For example, flood peak, volume and low flow frequency data can be generated and related to watershed conditions (i.e., degree of urban development); flow duration and changes in flow duration related to urban conditions can be generated; storage or detention requirements (as well as frequency of use of detention facilities) can be estimated from flood flow and channel capacity data.

Title: Ohio State Watershed Model (OSWM)

Reference: Ricca, V. T., 1972, Ohio State University version of the Stanford Streamflow Simulation Model Part 1, Technical Aspects: Water Resources Center, Ohio St. Univ. Columbus, 144 p.

Synopsis: This model is a modified version of KWM (the Fortran IV version of SWM). Some of the modifications and additions include (1) machine plotting of hydrographs, (2) sensitivity analysis of key parameters, (3) storage routines for swamps and soil cracks, (4) snowmelt routine, and (5) variable time increment.

Data: Essentially the same as required by SWM and KWM with the addition of estimates of the fraction of area used for swamp and soil crack storage and climatological data to perform calculations for snowmelt, i.e., temperature and radiation.

Output: A variety of output is available to provide information for the (1) analysis of water resources systems, (2) assessment of induced climatological changes, (3) quantifying the effects of land use, such as urbanization, upon the hydrology of the area, (4) the evaluation of structural modifications on stream channels, and (5) the extension of short-term streamflow records from long-term precipitation records.

Remarks: This particular model with its modification is probably no better or worse than other versions of the model for assessing effects of urban development on streamflow. The approach would be similar to that already discussed under SWM and KWM and would consist of evaluating the change in volumes of each flow component resulting from changes in model parameters affecting runoff.

Title: Georgia Tech Watershed Model (GTWS)

Reference: Lumb, A. M., Currie, F. L., Hassett, T. D. and Zorich, John, 1975, GTWS: Georgia Tech Watershed Simulation Model: Env. Res. Center, Georgia Inst. of Tech., 153 p.

Synopsis: GTWS is a version of the Stanford Watershed Model and Kansas Watershed Model adapted for use on the Georgia Tech computer system. This is a continuous simulation model based on moisture accounting procedures in various conceptual storage reservoirs. The model is capable of simulating flows from a drainage basin which has been divided into several subwatersheds and channel reaches. The volume of runoff generated each hour on each subwatershed is distributed in time to the outlet of the subwatershed using a unit-graph or routing a time-area diagram for the subwatershed through a linear reservoir. Flow from subwatersheds enter the upstream end of specified channel reaches and are routed through the channel reaches with the Muskingham method.

Data: Hourly precipitation
Daily pan evaporation
Daily streamflow - if comparison of computed and observed discharges are desired
Drainage area parameters
Watershed storage capacity parameters
Drainage rate parameters
Evapotranspiration parameters
Initial storage values

Output: Summaries of rate of movement and amount of storage of moisture in the basin annually by months or days

Plotted streamflow hydrograph

Streamflow statistics

Remarks: This model is not recommended for use in studying changes in volumes of runoff from urbanizing watersheds because is does not model urban watershed as well as other models. A component of surface runoff is derived from an estimate of impervious area. Varying this estimate to simulate urbanization would not be sufficient to model changes in runoff volume.

Title: National Weather Service River Forecast Model

Reference: U. S. Dept. of Commerce, 1972, National Weather Service River Forecast System--Forecast Procedures: NOAA Technical Memo NWS HYDRO-14, Silver Springs, Md., 7 Ch.

Synopsis: A modified version of the Stanford Watershed Model (Fortran IV) was selected by the staff of the Hydrologic Research Laboratory, NOAA for extensive modification and use in hydrologic forecasting by NWS. Significant modifications include (1) computation of mean basin precipitation, (2) parameter optimization based on direct-search techniques, and (3) a 6-hour time increment for operation.

Data: Continuous and/or daily precipitation
Daily potential evapotranspiration
Daily streamflow - for calibration
For forecasting purposes -- current estimates of watershed parameters (disucssed under SWM, KWM and OSWM)

Output: This model is used for forecasting purposes principally and as such provides information on a current basis of hydrologic events. Streamflow volumes and rates are generated from current rainfall inputs and knowledge or accounting of antecedent conditions. Hydrographs and listings of streamflow for each watershed outflow point on a continuous time increment are produced.

Remarks: This model is adapted for short term forecasting of hydrologic events. As such, it is not as useful as some other versions of SWM for studying volume changes resulting from varying model parameters.

Title: Storm Water Management Model (SWMM)

Reference: U. S. Dept. of Interior, 1971, Storm Water Management Model, Volume 1 - Final Report: prepared for the Env. Protection Agency by Metcalf and Eddy, Inc., Univ. of Florida, and Water Res. Engineers, 352 p.

Synopsis: This comprehensive mathematical model, capable of representing urban storm water runoff was developed for use in planning, evaluation and management of water quality abatement alternatives. The model uses rainfall and watershed characterization to predict outputs of storm hydrographs and pollutographs (time varying quality concentrations). The simulation technique involves accounting for water movement through a physical system represented by an integrated system of volume storages. It does not simulate continually therefore, knowledge of antecedent conditions is important.

Data: To Define:

1. Area --
   Land use, topography, population distribution census tract data, area boundaries.
2. Collection System --
   Size, length, and slope of pipes.
   System of interconnections.
3. System Specialties --
   Diversions, regulations and storage
4. Maintenance --
   Street sweeping frequency

Catch basin cleaning

Trouble spots.

5. Receiving Waters --

General description (Estuary, river, or lake)

Flow, tides, topography and water quality

6. Base Flow --

Amount and variation

Augmentation by industry, diversions, etc.

7. Stream Flow --

6-months of daily rainfall - for antecedent conditions

Continuous hyetograph

Runoff hydrograph

Water quality measurements

Output: This model is used principally to estimate runoff and pollutant concentrations from urban watersheds from discrete storm events. The output therefore is geared to representing individual storm events and resulting pollutographs. Listings and plots of runoff and pollutant fluctuations are provided at variable time increments.

Remarks: This model is not suitable for a study of the effects of urban development on stream volumes because: (1) it is not a continuous streamflow model, (2) it places more emphasis on effects of physical facilities withing the watershed than on hydrologic processes affecting runoff, and (3) major concern in on representing pollutant variations and effects of storage and treatment facilities. Accuracy of simulating components of runoff is sacrificed for overall correlation of flow values with observed values.

Title: Streamflow Synthesis and Reservoir Regulation Model (SSARR)

Reference: U. S. Department of Army, 1972, Program description and user manual for SSARR - Streamflow Synthesis and Reservoir Regulation: U. S. Army Engineers Division, North Pacific, Portland, Ore., 188 p.

Synopsis: This model was initially developed in 1956 and conceptually parallels the development of SWM. SSARR is a mathematical hydrologic model of a river basin system throughout which streamflow can be synthesized by moisture accounting of snowmelt and rainfall. The model has three general components -- the watershed, the river and the reservoir. Calibration and operation of the model requires a trial-and-error determination of a variety of model parameters describing watershed characteristics and hydrologic processes.

Data: Nonvariable Characteristics Data which describe drainage area reservoir storage capacity, and watershed characteristics that affect runoff.

Initial Conditions Data for specifying current conditions of all watershed runoff indexes, flow in each increment of each channel reach, and initial reservoir or lake elevations and outflows.

Time Variable Data which include physical data expressed as time series; for example precipitation, air temperature and thermal budget data used for snowmelt determinations, streamflow data, reservoir regulation data, and other hydrometeorological elements.

Output: Tabular listings of input variables and model parameters used; Listing of pertinent data and flow contributions from all flow and storage components and combined total flow for each specified time increment and watershed outflow. These listings are either continuous (annual) or for specified periods (detailed storm hydrograph); Machine plots of hydrographs and hyctographs are also available.

Remarks: SSARR would not be useful for studying urban runoff volumes because the runoff component of the model does not consider runoff variability as a function of land use. Gross estimates of runoff are made by accounting for available soil moisture. The remaining volume of runoff is then partitioned into baseflow, subsurface and surface runoff. In its present form the model would not provide the flexibility of adjusting model parameters associated with land use that affect runoff. Modification of the model to accomodate various land uses would require a comprehensive study and programming of the generalized watershed model.

Title: Urban Storm Water Runoff (STORM)

Reference: U. S. Department of Army, 1974, Urban storm water runoff -- STORM: U. S. Army Corps of Engineers, Hydrologic Engineering Center, C.P. 723-58-L2520, 74 p.

Synopsis: This model estimates the quantity and quality of runoff from small, primarily urban, watersheds. Time distributions of runoff are not evaluated. Total runoff volumes are computed by a runoff coefficient method considering up to 5 land use types. Water quality parameters from both urban and nonurban areas are estimated. The purpose of the analysis is to aid in the selection of storage and treatment facilities to control the quantity and quality of urban storm water runoff and land surface erosion.

Data: Average length of summer
- Hourly Precipitation for
- Daily temperature data, Mean, Max, and Min.
- Initial Snowpack data
- Watershed characteristics - nonurban and urban
  - fraction of area in each land use
  - fraction of each land use that is impervious
  - total area
  - Theissen weights
  - length of street gutter
  - number of days between street sweeping
- Water Quality Characteristics
  - Exponent for dust and dirt washoff

- Street sweeping efficiency
- Pollutant accumulation rate and contents

Initial loss rate and recovery data

- Evaporation
- Depression storage
- Diversions

Unit hydrograph data

Soil erosion data

- Ground slope
- Soil types
- Erosion potential
- Sediment trap data - Trap efficiency

Treatment rates

Storage capacities

Overflow units

Output: Storm produces four optional output reports. They are:

1. Quantity Analysis,
2. Quality Analysis,
3. Pollutograph Analysis,
4. Land Surface Erosion Analysis.

All are generated on the line printer and summize all events or selected events. The quantity and quality reports also include average annual statistics of the rainfall/snowmelt, runoff, pollutant washoff and the quantity, quality, and frequency of overflows to the receiving waters. The land surface erosion report shows average annual values for sediment production and delivery to the receiving waters.

Remarks: This model would be useful in studying changes in urban runoff volumes. The section of the model used to compute runoff could be separated and used to generate runoff volumes for a variety of land use conditions. Computation of runoff by the runoff coefficient method is not very sophisticated and leaves a lot to be desired. However, by correlating and adjusting computed results with observed runoff, exceptable coefficients might be obtained. By studying the variations of the coefficients and by judiciously varying the coefficients to simulate urban runoff for different land use conditions, an understanding can be gained of the urban runoff process. Estimates of the increase in direct runoff resulting from increasing selected runoff coefficients that represent changes in land use, can be studied and easily correlated. Development of these relations could provide planners with gross but nonetheless valuable information and insight as to the hydrologic effect of planned development.

Title: The Illinois Urban Drainage Area Simulator (ILLUDAS)

Reference: Terstriep, M. L. and Stall, J. B., 1974, The Illinois Urban Drainage Area Simulator, ILLUDA: Illinois State Water Survey Bulletin 58, Urbana, 90 p.

Synopsis: ILLUDAS is a digital watershed model developed after the British Road Research Laboratory method specifically for urban drainage areas. It uses an observed or specific temporal rainfall pattern uniformly distributed over the basin as the primary input. The watershed is divided into subbasins. Paved-area and grassed area hydrographs are produced from each subbasin by applying the rainfall to the appropriate contributing area. These hydrographs are combined and routed downstream from one design point to the next until the outlet is reached. Pipe sizes are determined at each design point. Detention storage can be included as part of the design in any subbasin.

Data: Basin Parameters: Total area, Initial rainfall abstraction for paved area, Initial rainfall abstraction for grassed areas, Predominant soil type, Design data - minimum pipe size and Manning's n.

Rainfall Parameters: Time interval, Duration, Distribution, Return period, Total amounts, Antecedent Moisture Index, Rainfall data.

Reach Data: Interconnection, Length, Slope, Manning's n, Geometry of section, Storage.

Sub-basin data: Total area, Percent and amount of directly connected paved area, Percent and amount of supplemental paved area, Paved area entry time, Paved area flow length, Paved area slope, Percent and amount of contributing grassed area, Grassed area entry time, Grassed area flow length, Grassed area slope, Soil group.

Output: ILLUDAS provides output for either

(1) new design;

or (2) evaluation of existing system.

The format of the new design output provides flow, velocities and required pipe sizes for each selected design point. The format of the evaluation output provides flow, and velocities in the existing system as well as detention capacity for areas controlled by undersized pipes or constrictions.

Remarks: ILLUDAS could be used to study changes in runoff volumes resulting from urbanization. The model is based on a physical configuration of land uses in the watershed and the details of location and extent of the urban development must be accurately specified. This detailed specification does not preclude the use of large watersheds, but the task becomes increasingly difficult. The model was tested on watersheds up to 8.3 square miles in size. ILLUDAS does not continually account for moisture in watershed and does not produce a continuous annual hydrograph. However, provisions are made for antecedent moisture.

A suggested approach for using ILLUDAS to study increased runoff volumes is:

(1) Make a detailed study of changes in runoff volumes from one actual watershed by (a) varying the amount of paved area from 0 to 100 percent (simulate actual urban development) using a specified design storm, and (b) repeat (a) for various design storms.

(2) Repeat the procedure of (1) for other watersheds with different

shapes, sizes, slopes and soil types.

(3) The results of (1) and (2) can be combined by regression analysis to provide flood peak and volume frequency, flow duration, and detention capacity requirements based on variables associated with the physical characteristics of watersheds.

Title: Time-Varying Rainfall-Runoff Model

Reference: Chiu, C. L., and Bittler, R. P., 1969, Linear Time-Varying Model of Rainfall-Runoff Relation: Water Resources Research, Vol. 5, N.2, p. 426-436.

Synopsis: A "black box" linear model relating rainfall to runoff by the use of three parameters. By calibrating and defining the value of the parameters, the model can be used to predict runoff at various times during the year or as a function of changing watershed characteristics. A knowledge of the variability of the parameters is essential. The parameters define system response functions and as such do not relate well to physical watershed characteristics.

Data: Hourly rainfall data

Hourly discharge data

including detailed hydrograph analysis of variation in runoff responses to define time varying coefficients K and b

Output: Predicted individual hydrographs are produced from observed or arbitrary rainfall input. These can be compared with observed hydrographs and analyzed.

Remarks: This approach could be used to study runoff volumes in an indirect way. Three parameters govern the runoff response and these could be varyied to simulate changes in urban development. However, the difficulty in relating or defining the parameters in terms of physical characteristics within the watershed make the approach undesirable.

Title: Urbanization Effects on Response

Reference: Bras, R. L. and Perkins, F. E., 1975, Effects of Urbanization on Catchment Response: ASCE Journ. Hyd. Div., Vol. 101, No. HY3, p. 451-470.

Synopsis: This is a mathematical model for simulating hydrologic response of urban watersheds. Rainfall input is used to generate flow from a variety of land uses. Flow is governed by conditions and controls imposed by the physical system and is routed by kinematic wave equations to the watershed outlet. The model accomodates infiltration, depression storage, and detention storage to produce an individual storm hydrograph from observed or arbitrary rainfall input. No mention is made of evaporation and it is, therefore, presumed to be neglected.

Data: Watershed data

- Total area
- Channel slope, shape, length and roughness.
- Infiltration capacities, initial rate and decay rate
- Average roof area
- Number of roof and drains per roof
- Average plot slope
- Width, length and slope of roads
- Drainage pipe data
  - interconnections
  - slope
  - length

pipe size

roughness

Rainfall data - observed hourly or arbitrary (design storm)

hourly data

Output: Tabular listing of input data

Tabular listing of output hydrographs

Plotted hydrographs

Summary of storm data -- peaks, volume, duration

Remarks: This model appears to be no better or worse than some other models evaluated, based on an assessment of information provided in the reference. The model output has not been properly calibrated and evaluated with observed data, so no statements can be made regarding its validity. Additional work should be done on this phase of the model before attempting to use it to study effects of urbanization on runoff volumes. As is the case with most watershed models, this one required a large volume of detailed data. This volume would become prohibitive for most large complex urban watersheds.

Title: U. S. Geological Survey Rainfall-Runoff Model (Urban Hydrograph Model)

Reference: Boning, C. W., 1974, Users guide for a U. S. Geological Survey Rainfall-Runoff Model: U. S. Geol. Survey Open-File Rept. 17 chs.

Synopsis: The USGS has developed digital rainfall-runoff models applicable to both urban and non-urban watersheds. The urban model uses the lumped parameter moisture accounting procedures to determine rainfall excess and to synthesize flood hydrographs from urbanized watershed. The model uses two additional capabilities over the non-urban model: the capability of utilizing multigage rainfall data for the purpose of model calibration and error analysis; and the capability of computing and routing runoff from localized impervious areas caused by urban development. Rainfall excess is determined for undeveloped and developed areas in the watershed and routed by time-area histograms (one for each type of area) to the watershed outlet.

Data: Daily rainfall record - max 5 gages
Daily discharge data
Pan evaporation
Time-area histograms
Routing interval
Drainage area - total and sub-basins
Thiesson rainfall weights
Watershed storage capacities

Rates of water movement through watershed

Optimization options

Land use-type, area, percent impervious, location within isochrone

Output: Summaries of input data

Summaries of storage changes in watershed, and outflow hydrograph

Comparisons between observed and computed hydrographs

Plotted outflow hydrograph

Remarks: This model uses moisture accounting techniques similar to versions of SWM and routing techniques similar (but more generalized) to ILLUDAS. Continuous watershed simulation is not provided. Optimization of flood volumes or routing parameters is available. This model could be used in a similar manner as described for ILLUDAS to study urban runoff volumes. It would be helpful, however, to develop an automated technique for changing the time-area histograms, as these are the principal data reflecting urbanized conditions in the watershed.

REFERENCES

Am. Public Works Assoc., 1969, Water Pollution Aspects of Urban Runoff: Fed. Water Poll. Control Admin., Water Poll. Control Res. Service, WP-20-15, 272 p.

ASCE Task Force, 1969, Effect of urban development on flood discharges - Current knowledge and future needs: Journ. of the Hydr. Div., ASCE Proc., Vol. 95, No. HY1, Paper 6355.

ASCE Task Committee, 1972, Effects of Urbanization on lowflow, total runoff infiltration and ground water recharge - Preliminary report: ASCE National Water Resources Eng. Meeting, Jan. 24-28, 1972, Preprint No. 1620.

Anderson, D. G., 1970, Effects of urban development of floods in Northern Virginia: U. S. Geol. Survey Water Supply Paper 2001-C, 22p.

Barnes, B.S., 1940, Discussion On Analysis of Runoff Characteristics, by O. H. Meyer, Trans. Am. Society Civil Engineers, Vol. 105, pp. 104-106.

Carter, R. W., 1961, Magnitude and frequency of floods in suburban areas, _in_ short papers in the geologic and hydrologic sciences: U. S. Geol. Survey Prof. Paper 424-B, B9-B11.

Chang, Mingeth, and Lee, Richard, 1974, Objective double-mass analysis: Water Res. Research, Vol. 10, No. 6, p. 1123-1126.

Chow, V. T., 1964, Handbook of applied hydrology: New York, McGraw-Hill Book Co.

Crippen, J. R., 1965, Changes in the character of unit hydrographs, Sharon Creek, California, after suburban development, _in_ Geological Survey Research 1965: U. S. Geol. Survey Prof. Paper 525-D, p. D196-D198.

Dempsey, C. R., 1968, The effects of geographical and climatic setting on the economic advantages of alternative flood control measures: U. of Kentucky, Res. Rept. No. 10, 165p.

Franke, O. L., 1968, Double-mass-curve analysis of the effects of sewering on ground-water levels on Long Island, New York, _in_ Geological Survey Research, 1968: U. S. Geol. Survey Prof. Paper 600-B, p. B205-B209.

Guy, H. P., 1970, Sediment problems in urban areas: U. S. Geol. Survey Circ. 601-E, 8p.

Guy, H. P., 1971, Control of sediment in the urban environment, in Treatise on Urban Water Systems, Albertson, M. L., Tucker, L. S., and Taylor, D. C., eds.: Fort Collins, Colorado State University, p. 509-517.

Hammer, T. R., 1972, Stream channel enlargement due to urbanization: Water Resources Res., Vol. 8, No. 6, p. 1530-1540.

Hammer, T. R., 1973, Effects of urbanization on stream channels and streamflow: Regional Sciences Res. Inst., Phila, Pa., 270p.

Harris, E. E., and Rantz, S. E., 1964, Effect of urban growth on streamflow regimen of Permanente Creek, Santa Clara County, California: U. S. Geol. Survey Water Supply Paper 1591-B, 18p.

Hewlett, J. D. and Hibbert, A. R., 1961, Increases in water yield after several types of forest cutting: Quart. Bull. Intern. Assoc. Sci. Hydro., Vol. 6, p. 5-17.

James, L. D., 1964, A time-dependent planning process for combining structural measures, land use, and flood proofing to minimize the economic cost of floods: Inst. in Eng-Econ. Systems, Stanford University Report EEp-12, Aug., 238 p.

James L. D., 1965, Using a digital computer to estimate the effects of urban development on flood peaks: Water Resources Res., pp. 223-234.

Johnson, S. L., and Sayre, D. M., 1973, Method of predicting magnitude and frequency of floods in Houston Metropolitan Area, Texas: U.S. Geol. Survey Open-file Rept.

Johnson, S. L., and Smith, R. E., 1965, Urban hydrology, Houston Metropolitan Area, Texas 1965: U.S. Geol. Survey Open-file Rept., 209p.

Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H., 1958, Hydrology for Engineers: New York McGraw-Hill Book Co., pp 158-157.

Martens, L. A., 1968, Flood inundation and effects of urbanization in Metropolitan Charlotte, N.C.: U.S. Geol. Survey Water-Supply Paper 1591-C, 60p.

Meinzer, O. E., 1942, Hydrology: New York, Dover Pub., Inc., Ch. 1.

Putnam, A. L., 1972, Effects of urban development on floods in the Piedmont Province of North Carolina: U.S. Geol. Survey Open-file Rep. 87p.

Savini, John and Kammerer, J. C., 1961, Urban growth and the water regimen: U.S. Geol. Survey Water Supply Paper 1591-A.

Sawyer, R. M., 1963, Effects of urbanization on storm discharge and groundwater recharge in Nassau County, N.Y.: U.S. Geol. Survey Prof. Paper 475-C, p. C185-C187.

Seaburn, G. E., 1969, Effects on urban development on direct runoff to East Meadow Brook, Nassua County, Long Island, New York: U.S. Geol. Survey Prof. Paper 627-B, 14p.

Seaburn, G. E., 1970, Preliminary results of hydrologic studies at two recharge basins on Long Island, N.Y.: U.S. Geol. Survey Prof. Paper 629-C, 17p.

Seaburn, G. E., and Aronson, D. A., 1974, Influence of recharge basins on the hydrology of Nassau and Suffolk Counties, Long Island, N.Y.: U.S. Geol. Survey Water-Supply Paper 2031, 66p.

Searcy, J. K. and Hardison, C.H., 1960, Double-mass curves; U.S. Geol. Survey Water Supply Paper 1541-B, p. 66.

Sharp, A. L., Gibbs, A. E., and Owen, W. J., 1968, A history of the cooperative water yield procedures study project, Res. Rept. No. 403: Rept. published cooperatively by U.S. Dept. of Agriculture and U.S. Dept. of Interior, 755p.

Stankowski, S. J., 1962, Population density as an indirect indicator of urban and suburban land-surface modifications: U.S. Geol. Survey Prof. Paper 800-B, p. B219-B224.

Thiessen, A. H., 1911, Precipitation for large areas: Monthly Weather Rec., V. 39, pp. 1082-1084.

U.S. Dept. of Interior, 1969, Topographic Maps: Brochure published by U.S. Geol. Survey, Washington, D. C., 20p.

Waananen, A. O., 1961, Hydrologic effects of urban growth some characteristic of urban runoff, in short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424-C, P. C353-C356.

Wallace, J.R., 1971, The effects of land use change on the hydrology on an urban watershed: School of Civil Eng., Georgia Inst. of Tech., OWRR Report No. ERC-0871, Oct. 66p.

Wiitala, S. W., 1961, Some aspects of the effects of urban and suburban development upon runoff: U.S. Geol. Survey Open-file Rep.

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