MAGNITUDE AND FREQUENCY OF FLOODS IN NEW JERSEY WITH EFFECTS OF URBANIZATION

SPECIAL REPORT 38

STATE OF NEW JERSEY
DEPARTMENT OF ENVIRONMENTAL PROTECTION
DIVISION OF WATER RESOURCES

Prepared in cooperation with
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

1974

Cover photograph.--Aerial view of Saddle River in Lodi, New Jersey. U.S. Highway 46 bridge is shown near the top and Passaic Avenue bridge is shown near the bottom. November 1972.

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STATE OF NEW JERSEY

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Floodplain Management Section

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Multiply English units	By	To obtain SI units
	LENGTH	
inches (in)	25.40	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
	AREA	
square feet (sq ft)	.093	square meters (m^2)
square miles (sq mi)	2.590	square kilometers (km^2)
	FLOW	
cubic feet per second (cfs)	.02832	cubic meters per second (m^3/s)

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ABSTRACT

Mathematical and graphical relations are presented to estimate flood-peak magnitudes having selected recurrence intervals ranging from 2 to 100 years for drainage basins larger than one square mile with various degrees of existing or projected urban and suburban development. Four parameters are required for use of the relations. Three of these may be measured from topographic maps; namely, basin size, channel slope, and surface storage within the basin. The fourth is an index of manmade impervious cover which can be determined for existing and future development conditions from census data and population projections that are readily available from regional, State, and local planning agencies. Developed from an analysis of flood information for 103 sites in New Jersey, the relations should be useful for design of bridge waterway openings, selection of optimum size for drainage structures, evaluation of flood hazards for alternative land-use plans, and for definition of floodway and flood-hazard-area limits. Urban and suburban development are shown to increase flood peaks up to 3 times at the 2-year recurrence interval and up to 1.8 times at the 100-year recurrence interval as statewide averages.

INTRODUCTION

Urban and suburban areas in New Jersey are growing at a remarkable rate. According to 1970 Census Bureau figures, ten percent of the population of the United States lives in two "super cities"; namely, New York-northeastern New Jersey with over 16 million persons and Philadelphia-nearby southern New Jersey with over 4 million persons. The rapid expansion of these two "super cities" has made New Jersey the most densely populated state in the nation with an average 1970 population density of over 950 persons per square mile. Streets, housing developments, apartment complexes, and shopping centers are replacing farms and woodlands. Continued growth is expected and will increase competition for available space. Careful guidance and planning of future development will be required to insure optimum land use.

Effects of flooding are a necessary consideration in planning land use and development, in designing culverts, bridges, and drainage systems, and in establishing flood insurance rates. Encroachment in flood-prone areas can be controlled through effective planning and zoning and adequate storm sewers and drainage structures can be constructed at a minimum cost in the new and growing communities if knowledge of flood characteristics is available.

Occasionally the maximum probable flood is used as a design criteria because the failure of a contemplated structure or project, such as the spillway of a dam or a system of flood retarding structures, may involve loss of human life. More often, design discharge is based on a calculated risk determined through frequency analysis. Only through reliable estimates of the magnitude of flooding and the related frequency of occurrence is it possible to obtain economically optimum designs, to prepare realistic zoning ordinances, or to establish equitable flood insurance rates. Given the magnitude of the flood to be designed for or protected against, reliable hydraulic techniques can be applied in the design of the drainage system needed or in the determination of the areas subject to inundation.

Hydrologists and engineers have defined reasonably accurate methods for estimating the magnitude and frequency of floods expected from drainage basins in a stable or mostly rural condition based on historical streamflow and flood data. However, the rapid growth of urban and suburban areas in New Jersey has created new and dynamic conditions in many of its basins -- conditions for which natural or historical flow-estimating relations are no longer applicable. Urbanization tends to increase peak flow magnitudes through the spread of manmade impervious cover, which increases the volume of runoff, and through drainage alterations such as the addition of curbing, gutters, and storm sewers, which facilitate runoff through the basin.

In order to design a structure or delineate a floodway that will be adequate for 25 or 50 years it becomes necessary to estimate the increase in flood peaks likely to be caused by future urbanization and development. New information and procedures for making such estimates have been developed in this study and are described in this report.

Purpose and scope

The purpose of this study was to develop an inexpensive and rapid method for estimating flood-peak magnitudes having recurrence intervals ranging up to 100 years for drainage basins larger than one square mile and with various degrees of urban and suburban development. It was required that the method be applicable at open-channel sites on any nontidal New Jersey stream where flood flow is not significantly affected by upstream reservoir operation. The method was also required to adhere to the following desirable constraints: (1) use flood frequency rather than a given frequency of rainfall, (2) require only data that can be readily obtained by the user, (3) use sound and simple hydrologic principles so that the practicing engineers can use it with confidence and understanding, (4) depend on a minimum of personal judgement factors in order to provide for relatively consistent results among determinations by different individuals, and (5) be presented in a simple and practical form for easy use.

Most of these goals are believed to have been met. Additional refinements and even greater reliability are possible with more time and additional data, but these aspects will be discussed later in this report.

FLOOD DATA

Flood-frequency relations were developed for each of 103 gaging stations in New Jersey. Gaging station data used were limited to that from stations gaging less than 1,000 square miles of drainage area and having periods of record not significantly affected by regulation or diversion. Only the Delaware River, which is extensively regulated, has a larger drainage area than 1,000 square miles in New Jersey. Records at the selected sites ranged in length from 6 to 74 years and included a total of 2,800 station years of data. The average period of record for the stations was approximately 27 years. A comprehensive summary of New Jersey flood records prior to 1961 can be found in a report by Thomas (1964). More recent data are published in annual reports of the U. S. Geological Survey. The distribution of gaging stations used relative to drainage-area size is shown on figure 1, which illustrates the significant effect of crest-stage gaging stations on sample coverage, especially for watersheds from 1 to 20 square miles in area. Most of these crest-stage stations, used for the first time in a regional analysis of flood magnitude and frequency, were established during 1957-66 to gage peak flow from drainage basins smaller than 20 square miles and to sample a wide range of basin characteristics in urban and suburban areas.

The recurrence interval is the average time, in years, in which a flood of a given magnitude can be expected to be exceeded once. Recurrence intervals are average figures based on historical data; because the occurrence of floods is erratic, a flood of a given recurrence interval may occur in any year, even in successive years, or it may not occur for a period much greater than the designated recurrence interval. Probability terms may be used to avoid any inference of regularity of occurrence. The recurrence interval is inversely related to the chance of a specific flood discharge being exceeded in any one year. Thus, a flood with a 100-year recurrence interval would have 1 chance in 100,

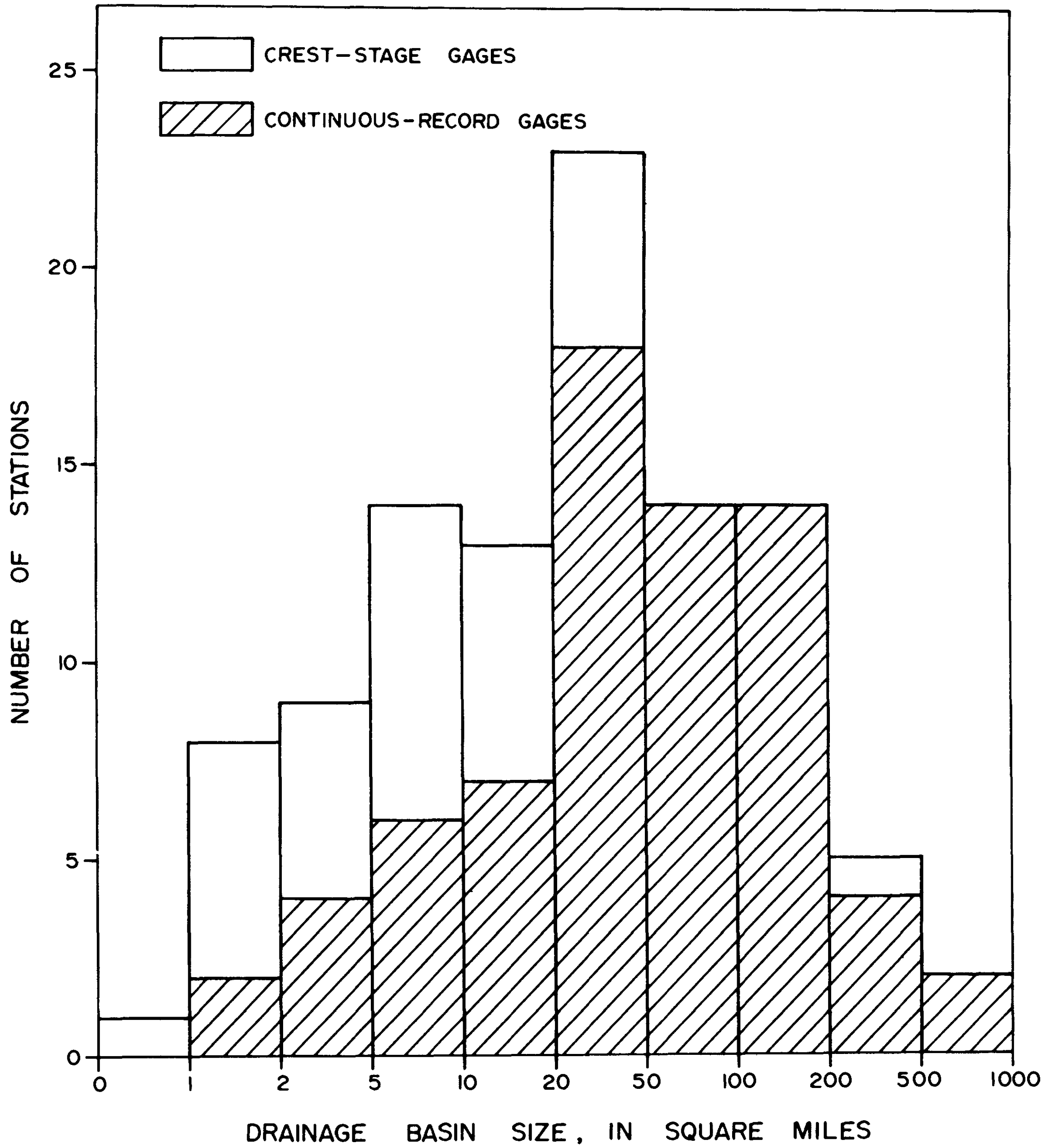

Figure 1.--Distribution of gaging stations used in regionalization by class of drainage-basin size.

or a 1-percent chance of being exceeded in any one year. A flood with a 25-year recurrence interval has a 4-percent chance of being exceeded in any given year.

To obtain recurrence interval or frequency estimates at gaging stations, values of annual peak discharge for periods of available record through the 1972 water year were fitted to frequency distributions by the log-Pearson Type III method, as described by the U. S. Water Resources Council (1967). Graphical relations (Dalrymple, 1960) were also used when the log-Pearson Type III curve did not provide a reasonable fit to the observed record or when significant historical flood records were available. These frequency analyses are based on the assumption that the annual peak data are random and homogeneous. Urban areas sometimes undergo sudden changes which destroy the homogeneity of the flood record. Flood-frequency estimates at gaging stations in urban areas are an integral part of this study. Accordingly, as described later, these flood records were examined for possible inherent defectiveness regarding the basic assumptions required in probabilistic frequency analysis.

Flood magnitudes corresponding to six recurrence intervals were taken from the frequency relation for each gaging station. These peak floods, exceeded on the average of once every 2, 5, 10, 25, 50, and 100 years, are denoted by Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, and Q_{100}, respectively. The flood frequency relation for each station represented a statistical sample with respect to both place and time and formed the basis for the regional analysis, which utilized data from many gaged sites to produce flood magnitude and frequency estimating relations applicable to ungaged sites in New Jersey.

HYDROLOGIC CHARACTERISTICS AFFECTING FLOODS

Many factors influence the rate of runoff after precipitation reaches the ground surface. Once the runoff has started, its pattern is controlled by the drainage basin characteristics and the rate of supply. The drainage basin and meteorologic characteristics used in this analysis were selected by considering all the factors most expected to influence flood peaks in New Jersey. A summary of 11 such factors tested is given in table 1.

Drainage area, main-channel length, main-channel slope, lake and swamp area, mean basin elevation, and forested area were measured from the latest U. S. Geological Survey 7.5-minute series topographic maps. Mean basin elevation was evaluated by laying a grid over the map, determining the elevation at each grid intersection, and averaging those elevations. The grid spacing was selected to give at least 25 intersections within the basin boundary. Mean annual precipitation was determined from an isohyetal map prepared by Hely, Nordenson, and

Table 1.--Summary of basin and meteorologic characteristics used in regionalization

Symbol	Definition
A	Drainage area, in square miles.
L	Main-channel length, from the runoff site to the watershed boundary, in miles.
S	Main-channel slope, in feet per mile, defined as the average slope of the main channel between points 10 and 85 percent of the distance upstream from the runoff site to the watershed boundary.
St	Surface storage index, in percent of drainage area occupied by lakes and swamps and increased by 1.00 percent.
E	Mean basin elevation, in thousands of feet above mean sea level.
F	Forest cover, in percent of drainage area and increased by 1.00 percent.
W	Soils index defined as the average minimum infiltration rate, in inches per hour.
I	Index of manmade impervious cover, in percent of total area, determined indirectly from basin population density data. $1\% \leq I \leq 100\%$.
P_a	Mean annual precipitation, in inches.
$I_{24,2}$	Maximum 24-hour precipitation with 2-year recurrence interval, in inches.
t	Mean minimum January temperature, in degrees Fahrenheit.

others (1961). Maximum 24-hour precipitation with 2-year recurrence interval was determined from isopluvials published by the U. S. Weather Bureau (1958). Mean minimum January temperature was determined from isothermal maps published by the U. S. Weather Bureau (1959).

Infiltration capacity of the soil and its cover influences the amount of direct runoff from a storm and the amount of delayed subsurface runoff. Generally, infiltration has a high initial rate that diminishes eventually during continued rainfall to a minimum rate that is reasonably constant and reproducible. Ranges of minimum infiltration rates have been determined by the U. S. Department of Agriculture (Musgrave, 1955) for four hydrologic soil groups, each with a minimum cover and thorough prior wetting and after a long rain in excess of the infiltration rate. The influences of both the surface and the horizons of a soil are thereby included. In addition, the U. S. Soil Conservation Service (1969) has classified a wide range of soils, in accordance with the runoff characteristics of the material, into these four hydrologic soil groups. A convenient source of comprehensive soil information are U. S. Soil Conservation Service county soil survey reports (Jablonski, 1972). Included in each county report is a map showing areas of various soil associations. A soil association consists of a distinctive pattern of one or more major soils and at least one minor soil. By use of the maximum infiltration rate in the range of minimum rates for each of the four hydrologic soil groups as weighting factors (assuming wet alluvial, fresh water, and tidal marsh soils have a zero rate of infiltration), a mean minimum infiltration rate can be determined for each soil association by summing the weighted proportions of land area in each soil group. The average minimum infiltration rate for a drainage basin can then be determined by superimposing an outline of the basin divide over corresponding soil association maps. Using the percentages of the soil association areas contained within the basin as weighting factors, the average minimum infiltration rate of the basin can be determined as the weighted sum of the soil association infiltration rates. This procedure was followed in determining the soils index (W) used in this analysis. Where generalized soil association information was not available, more detailed soil maps were condensed into the four hydrologic soil groups or into wet alluvial and fresh-water and tidal-marsh soils, and basin soil indexes were computed accordingly.

A new method was developed for determining an index of manmade impervious cover for application in this study. Detailed discussion of this index follows.

URBANIZATION

It has been widely recognized that urban development in a watershed causes change in streamflow regimen (Leopold, 1968). Urbanization can affect flood runoff in at least two ways: (1) the volume of water available for runoff increases because of reduced infiltration of rainfall over manmade impervious areas, and (2) changes in hydraulic efficiency associated with artificial stream channels, curbing, gutters, drains, and storm sewers increase the magnitudes of flood peaks because runoff time is shorter. The combined effect of these two changes is to increase peak discharges. In addition to affecting flood runoff, urbanization can affect the flood-frequency relation. This is brought about by the relatively greater effect of urbanization on the frequent floods than on the rarer floods, as will be shown later.

Many hydrologic studies have used the percentage of paved or manmade impervious surface of the land as a measure of urbanization. Percentages of impervious area are generally determined by laborious and expensive sampling processes directly from aerial photographs and large-scale maps. For example, Harris and Rantz (1964) determined the magnitude of impervious cover for a project area in Santa Clara County, California, by estimating an average impervious area for each of several types of building construction. Using these unit figures as a base, the structures were counted from aerial photographs and the total impervious area was computed. Martens (1968) determined the percentage of impervious area of watersheds within metropolitan Charlotte, North Carolina, by superimposing a transparent sheet containing a grid system over detailed topographic maps of the study area. Percentages of impervious area were estimated in relation to the proportion of grid intersections overlaying manmade impervious surfaces.

The time and expense of these detailed techniques and the lack of large-scale photographs or topographic maps hinder or preclude defining impervious cover in many basins. Further, aerial photographs and large-scale topographic maps made before about 1940 are not available for many basins.

In an attempt to overcome some of these problems, population density was employed as an estimator of manmade impervious area. The formulation is based on correlations between population density and the proportions of land area in each of six urban and suburban land-use categories. By weighting the proportions of land use with average percentages of manmade impervious cover found in corresponding land-use categories, the total percentage of manmade impervious cover created by urban and suburban development can be estimated from easily obtainable population-density data. This method, previously illustrated using county land-use and population-density data for New Jersey (Stankowski, 1972) was applied to similar data from 567 New Jersey municipalities with population densities ranging from less than 100 persons per square mile to over 40,000 persons per square mile.

On the basis of this technique and the hypothesis that a similar relation existed in the past as at present for intensity of land use and concomitant population density and on the assumption that the relation will continue into the future, quantitative manmade-impervious-area data that might otherwise be indeterminate can be generated for the past, present, and future. Census data, available since the beginning of the twentieth century for States, counties, cities, townships, boroughs, and wards, may be used to investigate hydrologic relations that existed when the earliest reliable streamflow data were collected. Furthermore, it should be possible to project estimates of changes in the hydrologic regimen into the future because population estimates, which are an element of every comprehensive planning study, are readily available from various regional, State, and local planning agencies.

Urbanization begins with the occupancy of rural lands by small concentrated communities with close groupings of homes, schools, churches, and commercial facilities. Further growth is characterized by large residential subdivisions, additional schools and shopping centers, some industrial buildings, and an enlarged network of streets and sidewalks. Central business districts evolve which contain large stores and offices and often the cultural and civic centers. Industrial growth continues along waterways, railroad lines, and major highways. The process continues until homes, apartment complexes, commercial and industrial buildings, streets, parking lots, and sidewalks occupy all or most of the former rural land area.

In terms of general lumped-sum parameters, the obvious effects of urbanization are to increase population density and the concentration of residential, industrial, and commercial buildings and facilities with a resultant increase in the areal proportion of impervious cover, as represented by the percentage of roof area, paved streets, driveways, sidewalks, and parking lots. For the purpose of this study, artificial ponds, lakes, and reservoirs, though manmade and impervious, are considered to be included with the areas of natural streams, ponds, and lakes as a category independent of population density.

Land Use

A most important phase in any comprehensive planning program is the land-use survey. It provides the basic pattern which serves as a foundation for the study of existing problems and the drafting of future land-use plans. The following six categories, for which data are readily available in New Jersey, provide a convenient and generally applicable land-use classification in relation to regional water resources investigations:

1. Single-family residential; single-family dwellings predominate.

2. Multiple-family residential; multiple-family units predominate. These units include multiple-family homes, garden apartments, and high-rise apartments.

3. Commercial; wholesale and retail business, personal and business services, and other related business.

4. Industrial; research and development, light and heavy manufacturing, large utility installations, and railroad yards.

5. Public and quasi-public; hospitals, institutions, schools, other public buildings, churches, airports, golf courses, and government installations. For water-resources and especially storm-runoff considerations, the golf courses would fit better under the sixth category, but available data included them in the fifth.

6. Conservational, recreational, and open land; parks and preserves; public and private watersheds; agricultural, forest, and vacant lands.

Manmade impervious area

In order to transform the details of land-use patterns to a single numerical index that characterizes the hydrology of an urban area, a range of average percentages of impervious cover representing the effects of typical urban and suburban land-surface modifications found in each land-use category was estimated. These estimates, given in table 2, are based on general field observations and studies by Carter (1961); Felton and Lull (1963); Antoine (1964); and Stall, Terstriep, and Huff (1970).

Table 2.--Impervious land area within land-use categories

Land-use category	Impervious land area (percent)		
	Low	Intermediate	High
Single-family residential....	12	25	40
Multiple-family residential..	60	70	80
Commercial..................	80	90	100
Industrial..................	40	70	90
Public and quasi-public......	50	60	75
Conservational, recreational, and open..................	0	0	1

Each land-use category contains a wide variation in proportions of impervious land area. For example, the proportion of impervious land surface is generally maximum within central city neighborhoods, intermediate in suburban neighborhoods, and lowest in rural areas. The proportion of impervious cover in residential areas decreases markedly as size of lot increases. Carter (1961) found the percentage of impervious surface area in suburban Washington, D. C., to be about 12 percent. Antoine (1964) concluded that 25 percent of the surface area is impervious on lots averaging 15,000 sq ft, whereas 80 percent of the surface area is impervious on lots averaging 6,000 sq ft. The industrial land-use category includes both industrial parks, with lawns occupying a large percentage of the land area, and central city manufacturing complexes, where asphalt and concrete dominate the landscape. The public and quasi-public land-use category includes some relatively large tracts of rural land where impervious surfaces are almost nonexistent. These variations, which are an inherent part of any generalized land-use classification, were taken into account in arriving at the range of estimates given in table 2. The intermediate values given in table 2 are approximate average estimates for New Jersey.

By use of the intermediate values of percentage of manmade impervious area (table 2) as weighting factors, the impervious area in each of 567 municipalities in New Jersey was determined as the sum of the weighted proportions of land area in each land-use category. Figure 2 shows 1966 municipal population-density data plotted against corresponding percentages of manmade impervious land area. The curve shown fitted to the plotted data is a second-degree polynomial defined by the logarithmic transform of the following equation:

$$I = 0.117 \; D^{0.792-0.039 \log D}$$

where

I = index of manmade impervious cover, in percent of total land area, and

D = population density in persons per square mile.

Municipal population density data were obtained from reports of the Research and Statistics Section, Department of Conservation and Economic Development, State of New Jersey. Percentages of land area in each land-use category were compiled from reports of the Division of State and Regional Planning, Department of Community Affairs, State of New Jersey.

Much of the scatter in figure 2 results from the fact that municipal boundaries in places cut across the uniform mixture of various land uses normally associated with a city or town. Consider

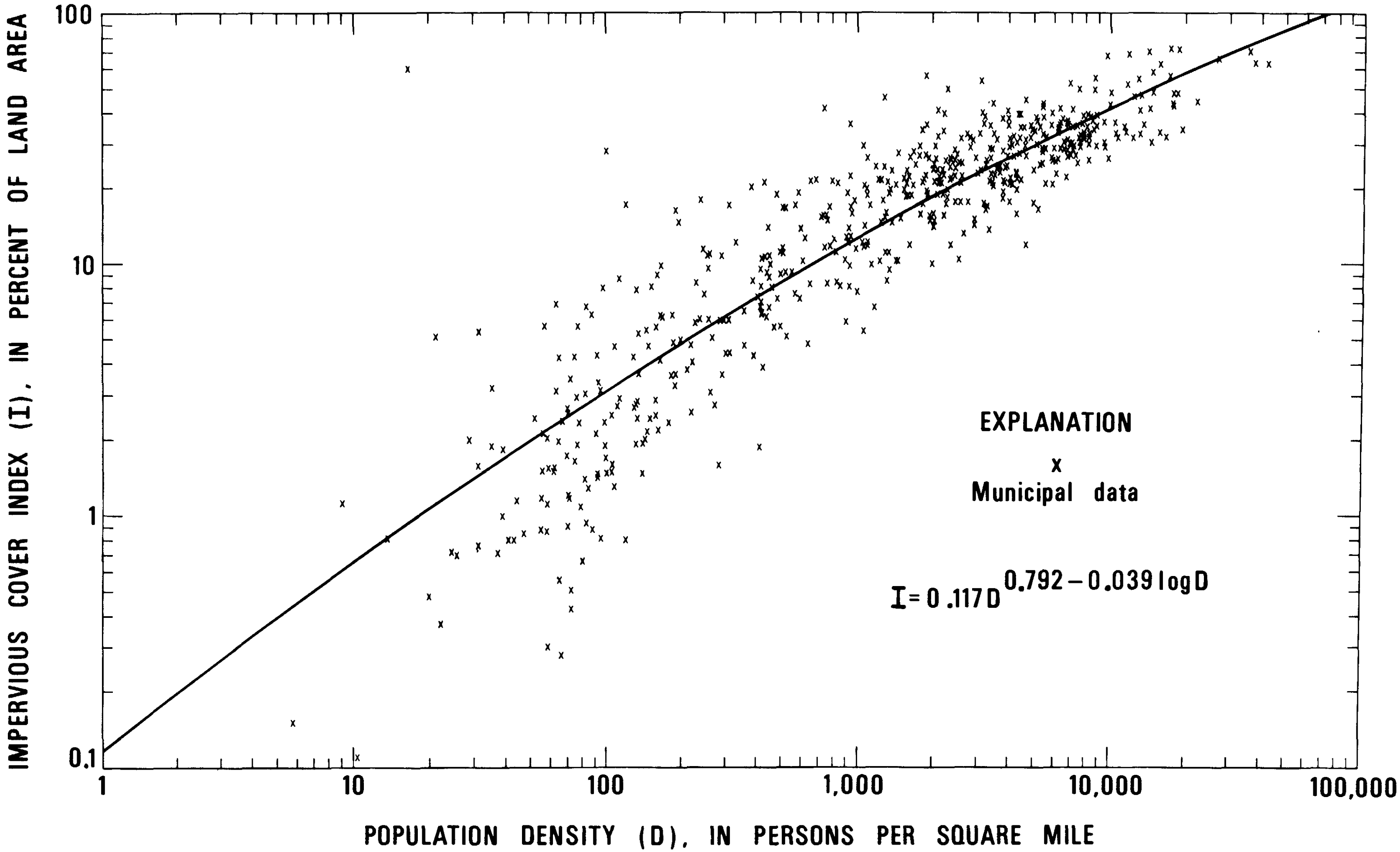

Figure 2.—Relation between manmade-impervious-cover index and population density for 567 municipalities in New Jersey.

Teterboro, New Jersey, a 1.20 square mile municipality in densely populated Bergen County. The manmade-impervious-cover index for Teterboro was computed from 1966 land-use data to be 59 percent. According to 1966 population data, however, Teterboro had a population density of only 17 persons per square mile. This deviation from the developed relation between population density and concomitant manmade impervious cover can be explained by the fact that the land area of Teterboro is 41 percent industrial, 51 percent public and quasi-public, and 8 percent open. With no single-family residential, multiple-family residential, and commercial land area, Teterboro, although it is incorporated, deviates markedly from the essential land-use characteristics of a typical self-sufficient community.

Most communities, however, contain a complete range of land-use categories. The more severe anomalies tend to occur when the total land area considered is small, 1 square mile or less.

A convenient source of population data is the National Location Code Manual prepared by the U. S. Bureau of the Census (1962). This manual divides the United States into approximately 43,000 small areas known as standard location areas. The manual includes large-scale maps showing the geographic boundaries of the standard location areas and data listings containing their names, populations, and geographic coordinates. To determine the population within each of the 103 New Jersey drainage basins used in this analysis, an outline of each basin divide was superimposed over corresponding standard-location-area maps. Using the percentages of the standard location areas contained within the basin as weighting factors, the total basin population was determined as the weighted sum of the 1960 standard-location-area populations listed in the manual. The inherent assumption of a uniform distribution of population within each standard location area is reasonable because each area is designed to achieve uniformity of population characteristics, economic status, and living conditions.

Standard-location-area data are not available prior to the 1960 census and were not available for the 1970 census at the time of this study. Therefore, basin population densities were determined decennially (1970, 1960, 1950, ..., 1900) from municipal data and maps for the period of streamflow record for each of the 103 basins. Because municipalities do not contain uniform distributions of population, some differences were found between basin population densities determined from the uniform standard-location-area data and those determined from municipal data as computed for the 1960 census. Using each 1960 basin population determined from standard-location-area data as a base, a correction factor was determined for each 1960 basin population determined from municipal data, and the decennial basin populations obtained from municipal data were adjusted accordingly. Based on these decennial data, an average population density was computed for the period of streamflow record for each of the 103 basins. Application of the relationship between manmade impervious cover and population density (figure 2) to these data yielded an average index of manmade impervious cover (I) for the period of streamflow record for each basin. Values of these indexes ranged between 1 percent and 5 percent for 42 basins; between 5 percent and 10 percent for 28 basins; between 10 percent and 25 percent for 20 basins; between 25 percent and 45 percent for 10 basins; and between 45 percent and 72 percent for 3 basins.

The computational procedures resulting from the inclusion of manmade impervious cover in the analysis of flood frequency made it necessary to assume that rural watersheds contained at least 1 percent manmade impervious cover. In most drainage basins in New Jersey this assumption is acceptable because nearly all basins contain paved highways and houses.

As described earlier, the station-frequency analyses of annual peak data were based on the assumption of random occurrences. Significant changes in urban development during the period of record can destroy the homogeneity of the flood data. For this reason a "run test" was performed on the annual flood series from those basins that had a 5 percent or greater change in the manmade-impervious-cover index during the period of record. Of the 103 basins considered in this study, 24 basins had a 5 percent or greater change. The manmade-impervious-cover index at the beginning of record for each of these 24 basins ranged from 3 percent to 29 percent. Only four of these basins had a greater than 8 percent change in the manmade-impervious-cover index during the period of record; the maximum change was 13 percent. The manmade-impervious-cover index at the beginning of record for each of these four basins ranged from 9 percent to 19 percent.

The "run test" (McCuen and James, 1972; Siegel, 1956) is a nonparametric test designed to test the randomness of an ordered series of data. The "run test", in brief, involves converting a time series of numerical data to a series consisting of two symbols (e.g., + and -). To detect a trend in the sample, a value above the median is represented by a plus sign; and a minus sign is used to represent values less than the median. If a run is defined as a succession of identical symbols contained between different symbols, then the number of runs in a sequence of observations can be used as an indication of the randomness of the series. A series having a very small or very large number of runs is not randomly distributed.

Results of the run tests revealed that of the 24 annual flood series tested, 23 were randomly distributed at the 5 percent probability level. The one nonrandom series was separated into two periods of record. The most recent record was tested, found to be random at the 5 percent probability level, and used as the station-frequency-curve data base.

ANALYTICAL METHOD

Multiple regression analysis was used to develop mathematical relationships between the T-year flood discharges (T = 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals) obtained from the gaging station flood-frequency curves and the hydrologic characteristics. The linear regression model used to define these relations requires a base-10 logarithmic transformation of both the dependent and independent variables. The resulting equations are of the form:

$$\log Q_T = \log a_T + \sum_{j=1}^{m} (b_T)_j \log X_j$$

where

Q_T is the peak discharge for a selected recurrence interval, T;

X_j are basin and meteorologic characteristics;

a_T, $(b_T)_j$ are regression constants to be determined for a selected recurrence interval, T; and

m is the number of basin and meteorologic characteristics selected.

An equivalent form of this model is:

$$Q_T = a_T X_1^{(b_T)_1} X_2^{(b_T)_2} \ldots X_m^{(b_T)_m}$$

where the notation remains defined as in the previous equation.

The analysis defines relationships between peak discharge for a selected recurrence interval, the dependent variable, and the drainage basin characteristics and meteorologic factors, as independent variables. The multiple linear regression technique used in the analysis is a stepwise procedure described by Efroymson (1962) and programmed for digital computer by the U. S. Geological

Survey. Independent variables are added one at a time to the regression equation in the following manner. Each independent variable is tested for the proportion of the total sum of the squares in the dependent variable that it might explain. The most significant variable in this respect is entered into the regression equation. Because the significance of an independent variable in the equation changes with the addition of each new variable, each variable in the equation is tested upon the addition of a new variable, and any variable shown to be no longer significant is temporarily deleted from the equation. If a variable is repeatedly added and deleted from the equation, then the variable is permanently eliminated from further processing in the regression analysis. The variables included in the derived regression equation are those which are significant at a prescribed confidence level, that is, those which, when included in the regression equation, account for sufficiently large portions of the total variance in the dependent variable that the relationship is unlikely to have resulted from chance alone.

RESULTS OF REGRESSION ANALYSIS

Results of the regression analysis revealed that of the eleven hydrologic characteristics initially selected for use in the study (table 1) only the drainage area, main-channel slope, surface storage index, and the index of manmade impervious cover were significant at the 1 percent probability level. The estimating equations summarized in table 3 proved to be the best representation of the data on the basis of both reliability and simplicity of use. In these equations, the exponents for the index of manmade impervious cover (I) become smaller as the recurrence interval increases. This indicates that urban development has proportionally less effect on large floods than on small ones. The uniformity of variation in the regression constants indicates both consistency and continuity in the relationships.

Standard error of estimate is a range of error such that the value estimated by the regression equation is within this range at about two out of three sites and is within twice this range at about 19 out of 20 sites. As shown in table 3, the standard error of estimate for these equations was determined to range from an average of 48 percent for the 2-year recurrence interval to an average of 54 percent for the 100-year recurrence interval.

To demonstrate the reliability of the estimating equations, flood-frequency data were taken from the station-frequency curve for each gaging station and plotted against values computed from the equations. Gaging station data used were limited to those stations with sufficient years of streamflow record to provide for about equal reliability in defining magnitudes of floods for the full range of recurrence intervals considered in this study (Hardison, 1969). The results are shown on figures 3 through 8. All data would plot on the line of equal

Table 3.--Summary of flood magnitude and frequency estimating relations

Regional equations	Standard error		
	+%	-%	Average %
$Q_2 = 25.6\ A^{0.89}\ S^{0.25}\ St^{-0.56}\ I^{0.25}$	59	37	48
$Q_5 = 39.7\ A^{0.88}\ S^{0.26}\ St^{-0.54}\ I^{0.22}$	59	37	48
$Q_{10} = 54.0\ A^{0.88}\ S^{0.27}\ St^{-0.53}\ I^{0.20}$	60	38	49
$Q_{25} = 78.2\ A^{0.86}\ S^{0.27}\ St^{-0.52}\ I^{0.18}$	62	38	50
$Q_{50} = 104\ A^{0.85}\ S^{0.26}\ St^{-0.51}\ I^{0.16}$	64	39	52
$Q_{100} = 136\ A^{0.84}\ S^{0.26}\ St^{-0.51}\ I^{0.14}$	68	40	54

where

Q_T = peak discharge for T-year recurrence interval, in cubic feet per second.

A = drainage area in square miles.

S = main-channel slope, in feet per mile, defined as the average slope of the main channel between points 10 and 85 percent of the distance upstream from the runoff site to the watershed boundary.

St = surface storage index, in percent of drainage area occupied by lakes and swamps and increased by 1.00 percent.

I = index of manmade impervious cover, in percent, which can be determined for existing and future development conditions from population data and projections by use of the relation:

$$I = 0.117\ D^{0.792 - 0.039 \log D};\ 1\% \leq I \leq 100\%$$

where

D = basin population density in persons per square mile.

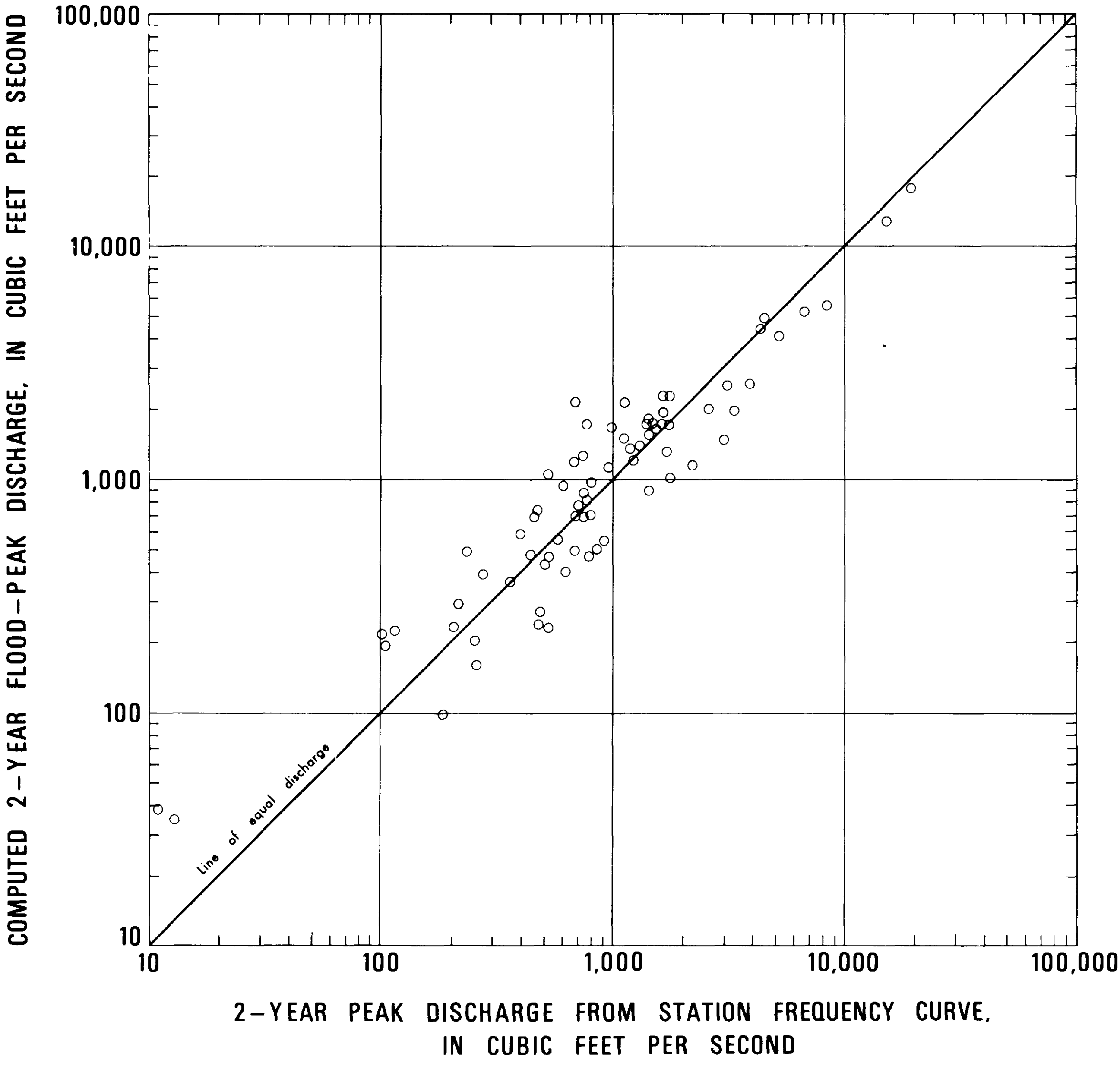

Figure 3.--Relation between computed 2-year flood-peak discharge and observed 2-year flood-peak discharge for 73 gaging stations with 10 or more years of record.

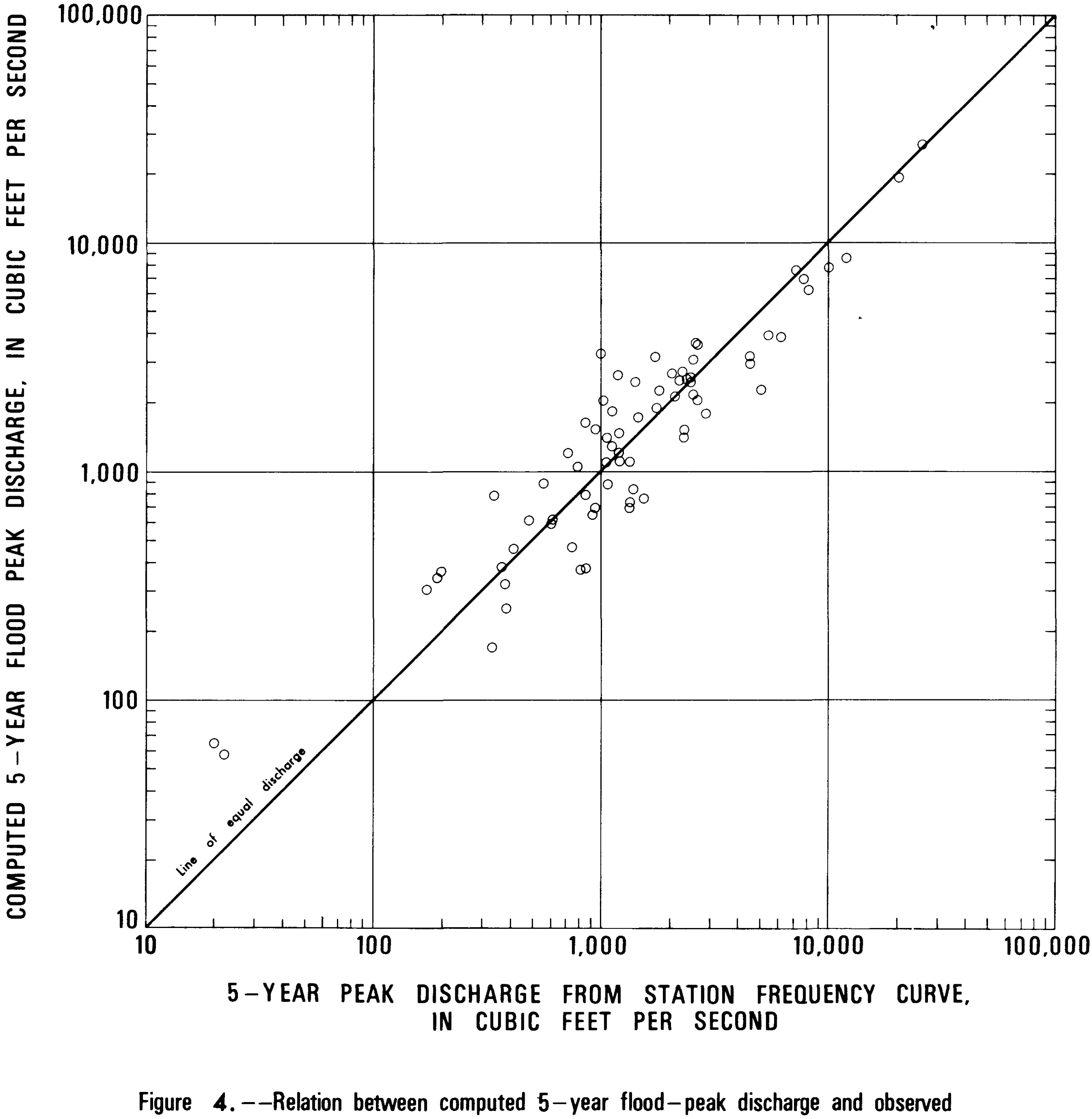

Figure 4.--Relation between computed 5-year flood-peak discharge and observed 5-year flood-peak discharge for 73 gaging stations with 10 or more years of record.

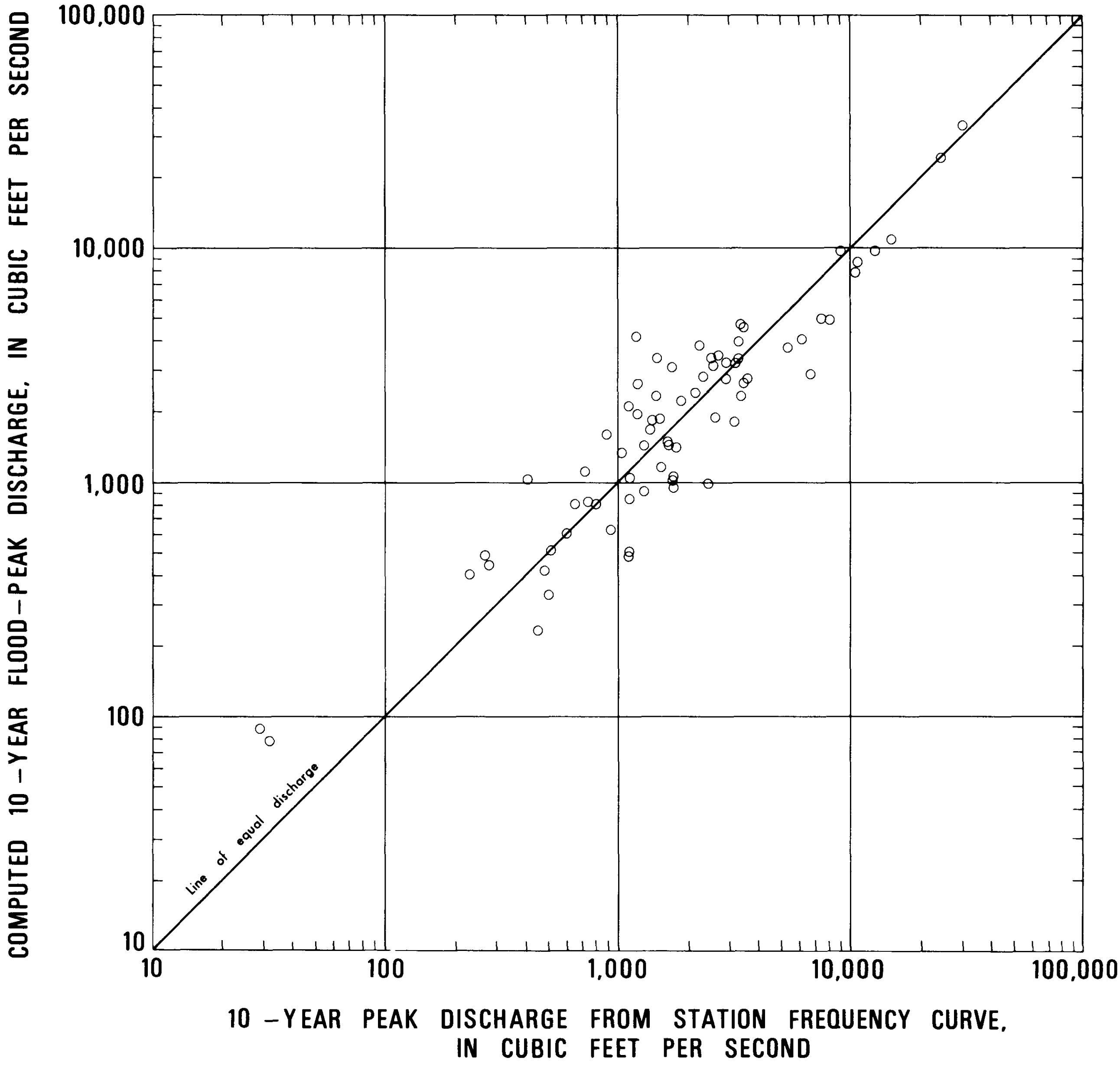

Figure 5.—Relation between computed 10-year flood-peak discharge and observed 10-year flood-peak discharge for 73 gaging stations with 10 or more years of record.

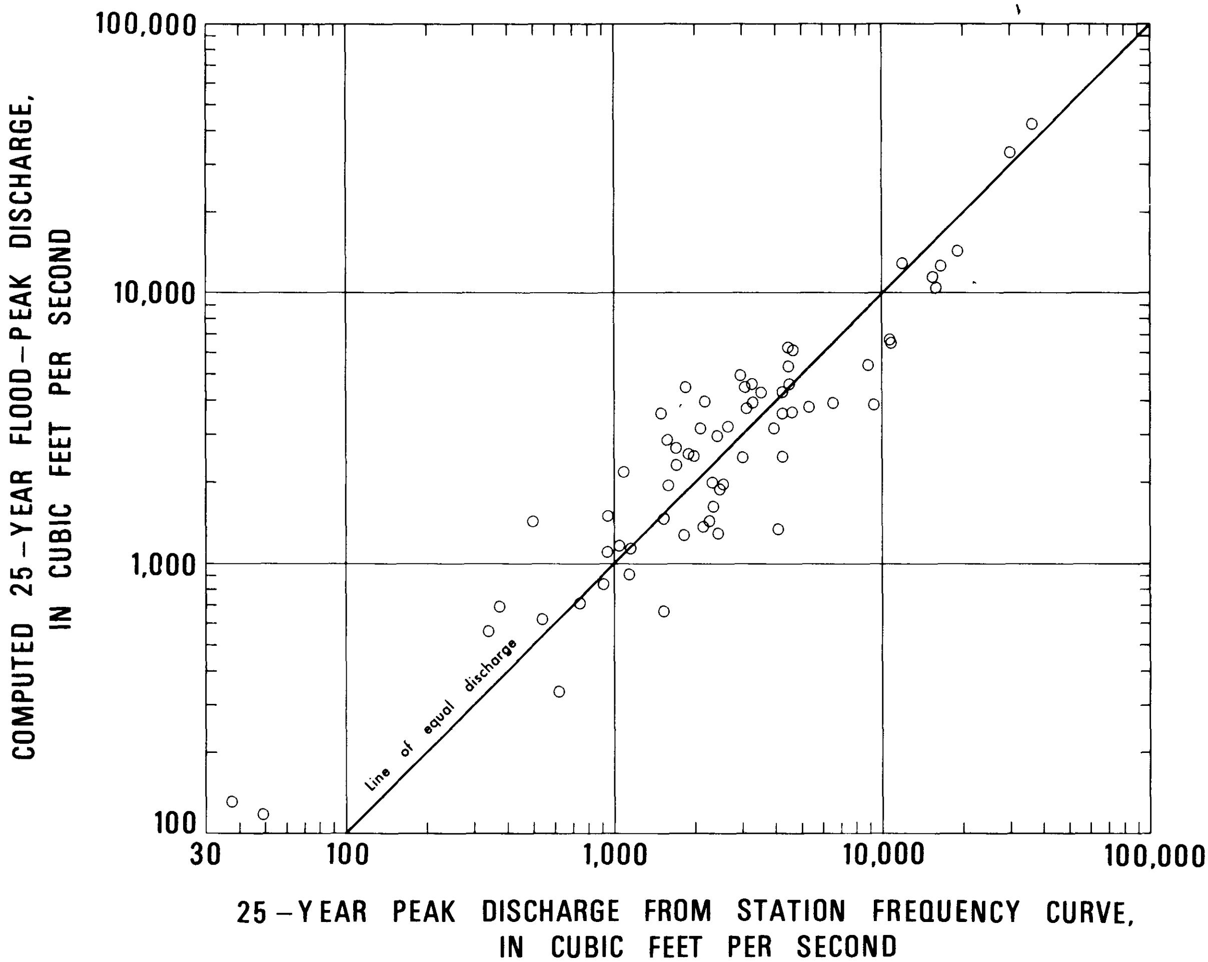

Figure 6.—Relation between computed 25-year flood-peak discharge and observed 25-year flood-peak discharge for 65 gaging stations with 15 or more years of record.

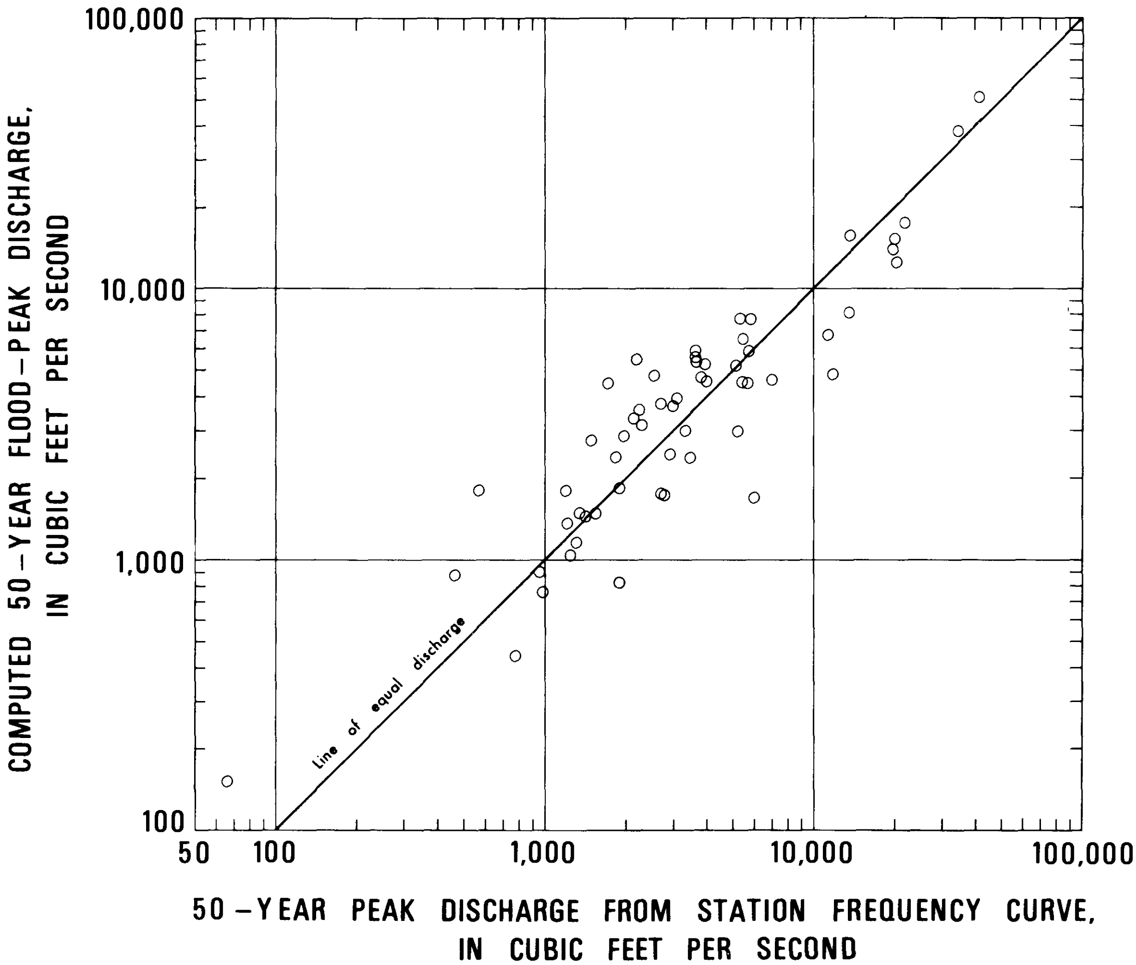

Figure 7.—Relation between computed 50-year flood-peak discharge and observed 50-year flood-peak discharge for 57 gaging stations with 20 or more years of record.

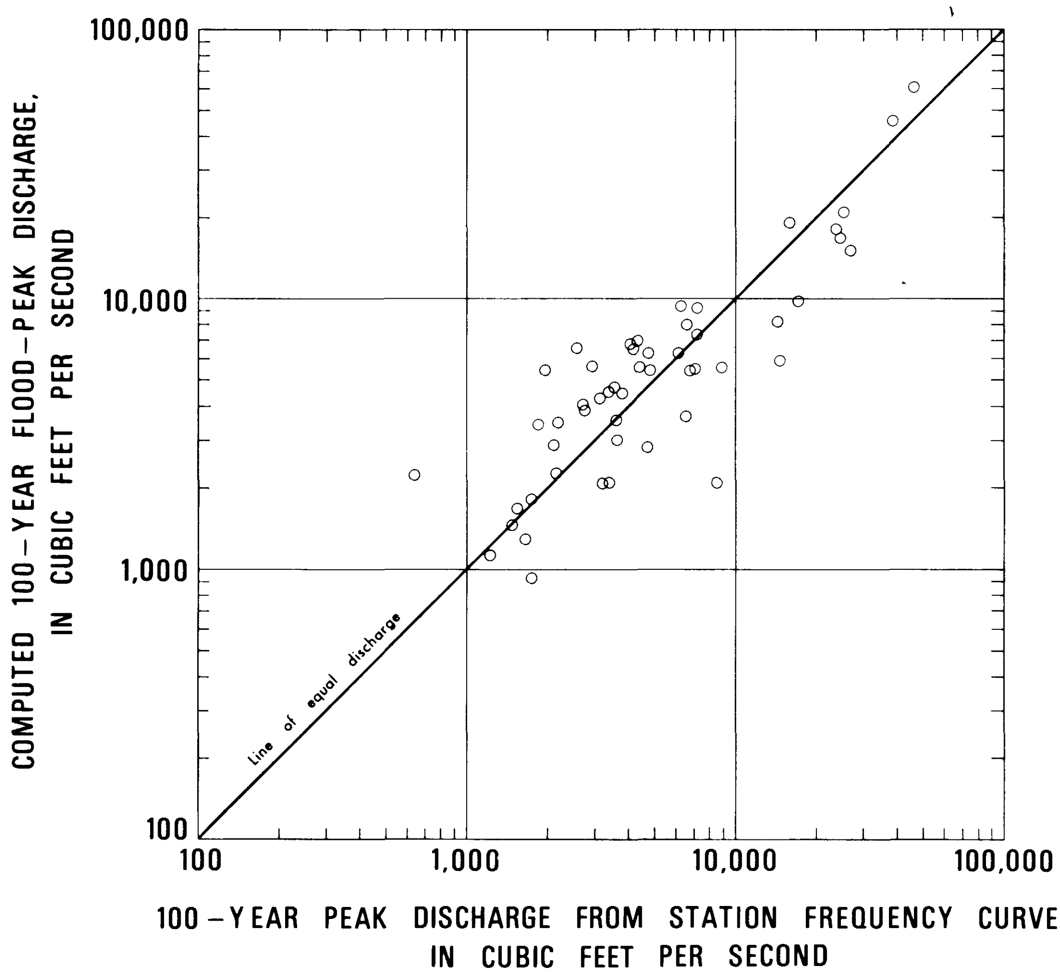

Figure 8.—Relation between computed 100-year flood-peak discharge and observed 100-year flood-peak discharge for 51 gaging stations with 25 or more years of record.

discharge on figures 3 through 8, if the computed values agreed exactly with the values from the station-frequency curves. Some of the scatter around the lines of equal discharge reflect errors that are inherent in the equations. Empirical equations of this kind, like most equations in scientific and engineering works, will not give perfect answers all the time. Some of the scatter, however, results from uncertainties in determining the observed flood-frequency values from the relatively short lengths of available streamflow record.

There appears to be little bias in the flood estimating equations. The points are balanced fairly evenly around the lines of equal discharge on figures 3 through 8. The data fit well for floods of different magnitudes and recurrence intervals and for different kinds of basins throughout New Jersey.

EFFECTS OF URBANIZATION

The effects of urbanization on flood-peak discharges may now be assessed by using the defined relations in a ratio form. For the 2-year flood discharge the ratio form would be as follows:

$$\frac{(Q_2)_d}{(Q_2)_r} = \frac{25.6\ A_d^{0.89}\ S_d^{0.25}\ St_d^{-0.56}\ I_d^{0.25}}{25.6\ A_r^{0.89}\ S_r^{0.25}\ St_r^{-0.56}\ I_r^{0.25}}$$

where the subscripts d and r refer to developed and rural conditions respectively. If the drainage area, main-channel slope, and surface storage index are considered to remain constant during urban development, which seems reasonable, although storage could change slightly, this equation reduces to:

$$\frac{(Q_2)_d}{(Q_2)_r} = \frac{I_d^{0.25}}{I_r^{0.25}}$$

Using this equation and similar equations developed for the remaining recurrence intervals, peak flood ratios were computed for 1-, 10-, 25-, 50-, and 80-percent manmade-impervious-cover indexes. Results are shown in table 4. Thus, for a small watershed that could conceivably change from a 1 percent (rural) to an 80 percent index of manmade impervious cover, the flood peak discharge would be increased by a factor of 3.0 for the 2-year flood, 2.2 for the 25-year flood, and 1.8 for the 100-year flood. These are average figures, of course, based on the basins sampled in New Jersey, and it must be recognized that the factors may be higher in some basins and lower in others. For purposes of prediction, however, the average values are most useful.

Table 4.--Increase in peak discharge as a result of urbanization

Recurrence interval (years)	Ratio of discharge after urbanization to discharge before urbanization				
	Index of manmade impervious cover (percent)				
	1	10	25	50	80
2	1.0	1.8	2.2	2.6	3.0
5	1.0	1.6	2.0	2.4	2.6
10	1.0	1.6	1.9	2.2	2.4
25	1.0	1.5	1.8	2.0	2.2
50	1.0	1.4	1.7	1.9	2.0
100	1.0	1.4	1.6	1.7	1.8

USE OF RELATIONS

The impervious cover and flood-peak discharge equations have been converted to the nomographs shown in figures 9 through 15. These nomographs are presented as a convenient graphical solution to the complex equations resulting from this study.

As with the mathematical equations, four variables are needed to use the nomographs. The first three are natural basin characteristics consisting of drainage area, main-channel slope, and the surface storage index, all of which may be measured from topographic maps. For consistency with the data used in the analysis, the use of U. S. Geological Survey 7.5-minute series topographic maps is recommended.

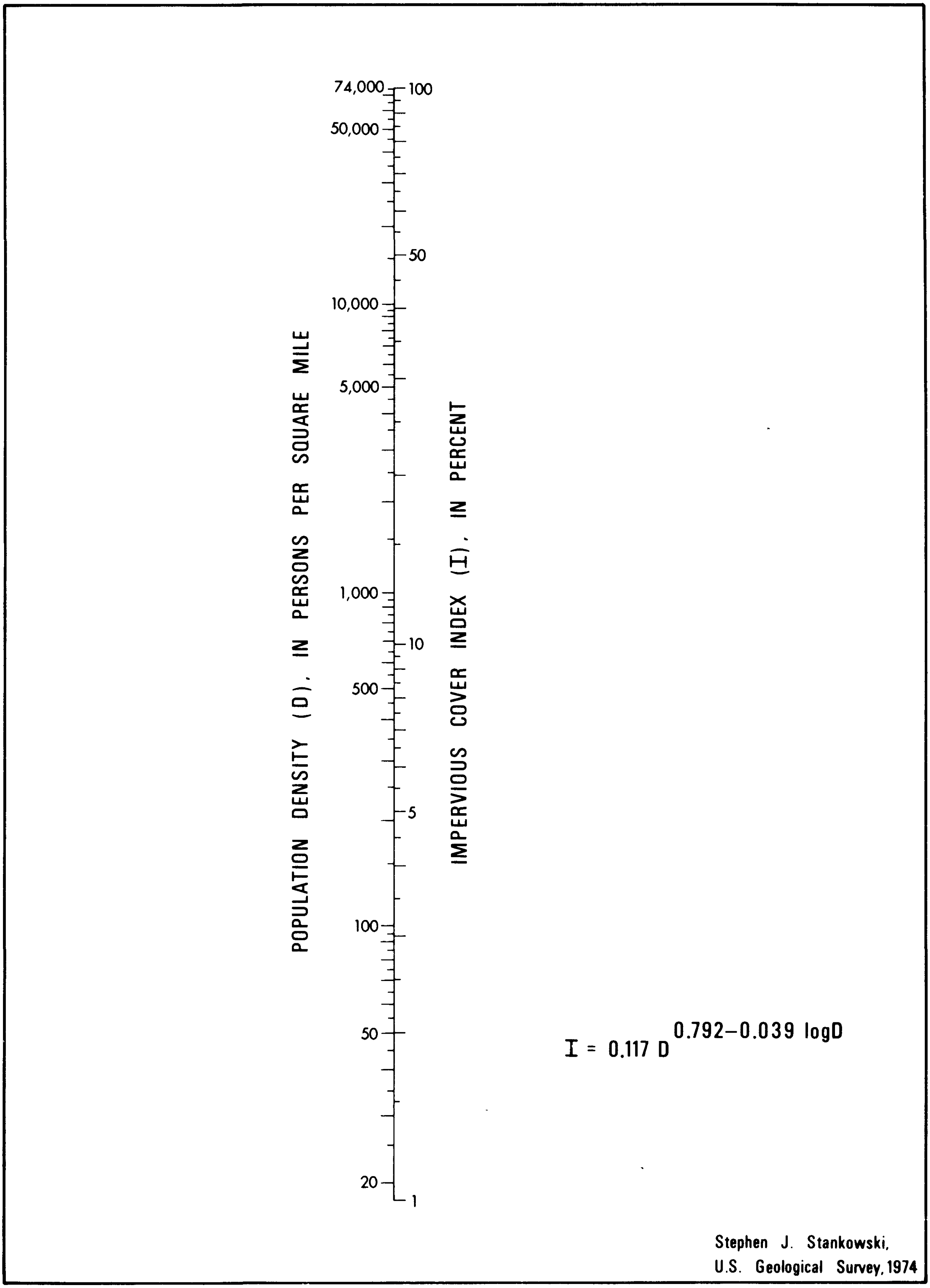

Figure 9.—Nomograph for determining manmade-impervious-cover index.

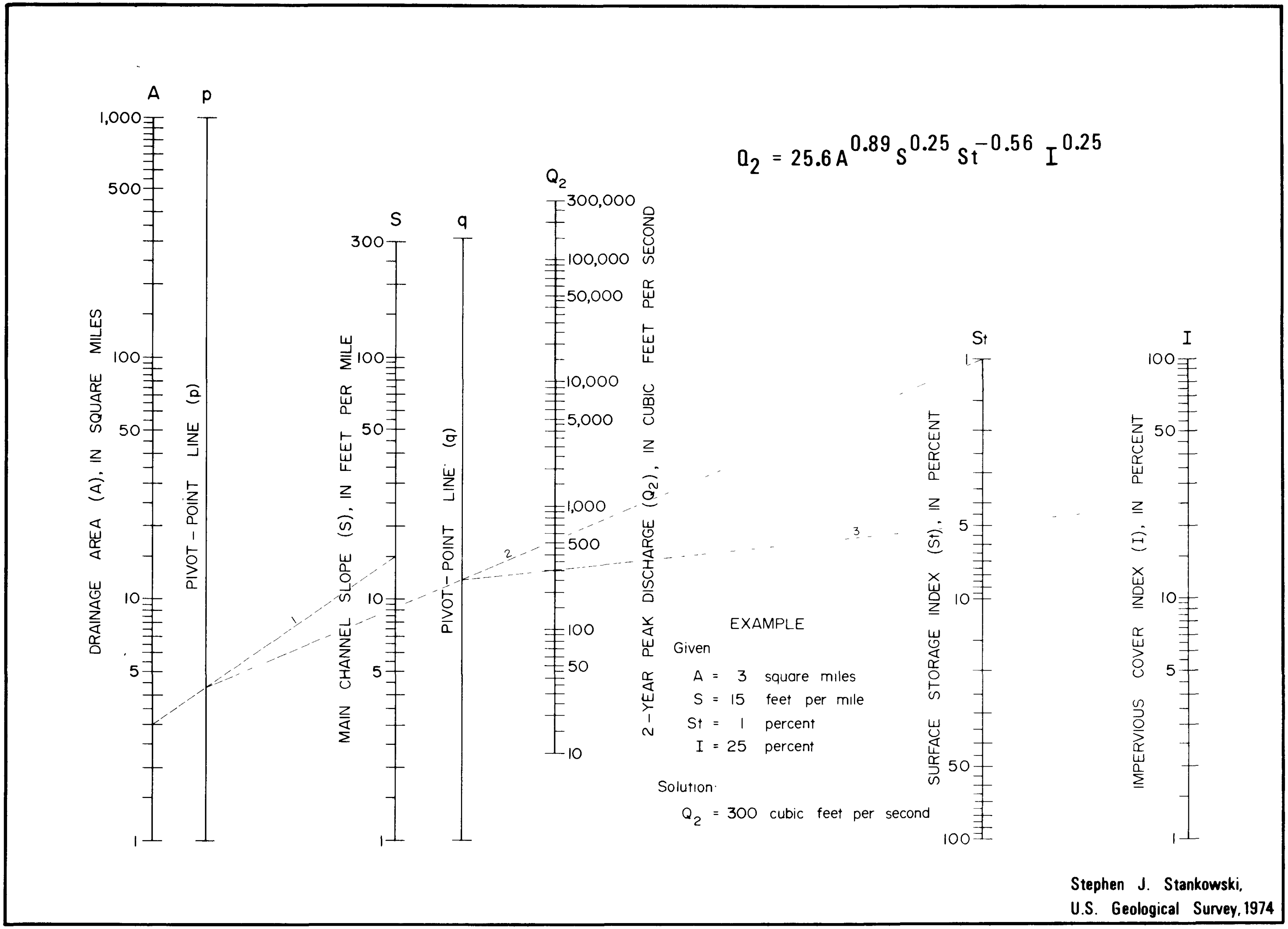

Figure 10.—Nomograph for estimating 2-year flood-peak discharge.

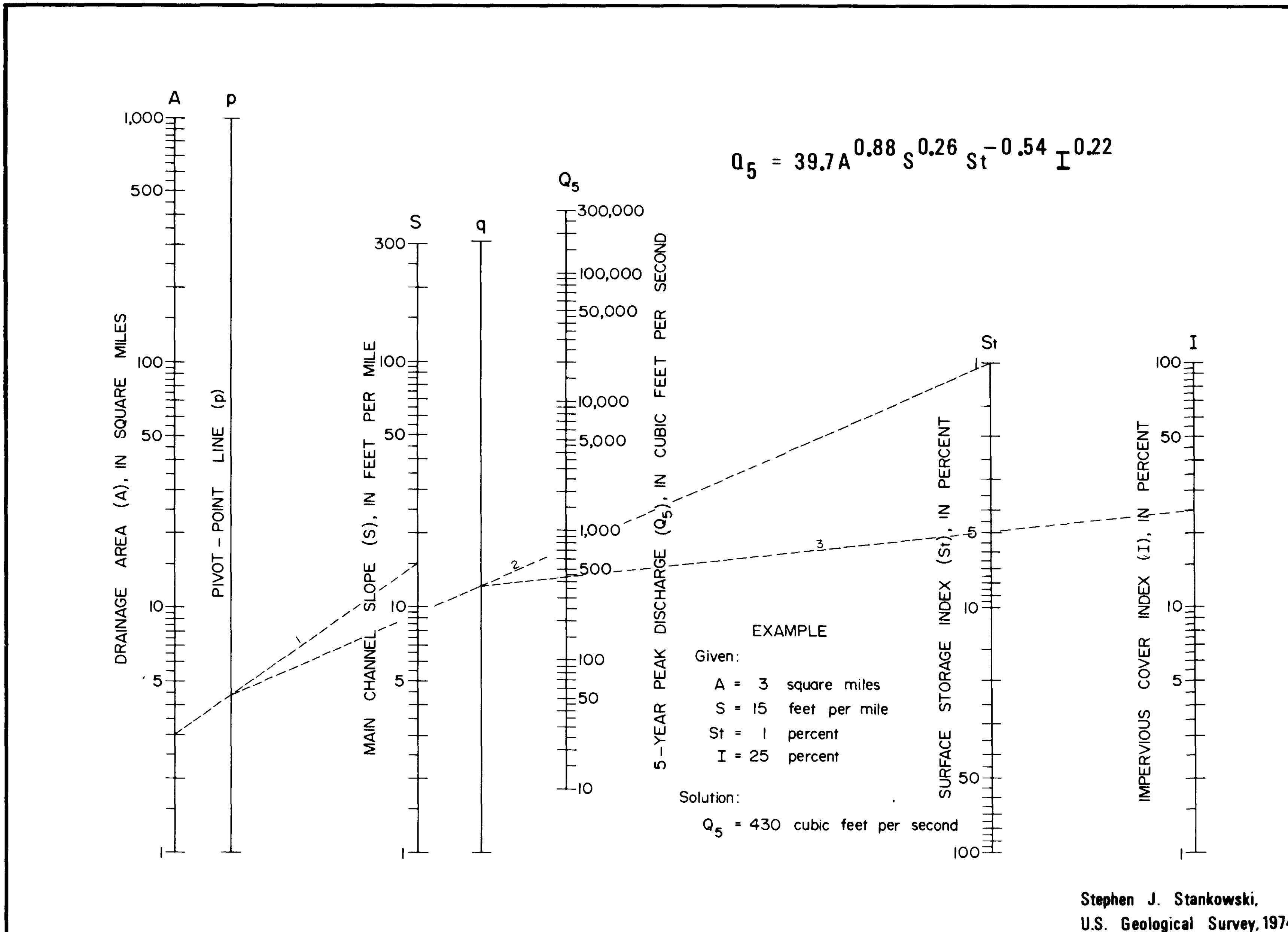

Figure 11.—Nomograph for estimating 5-year flood-peak discharge.

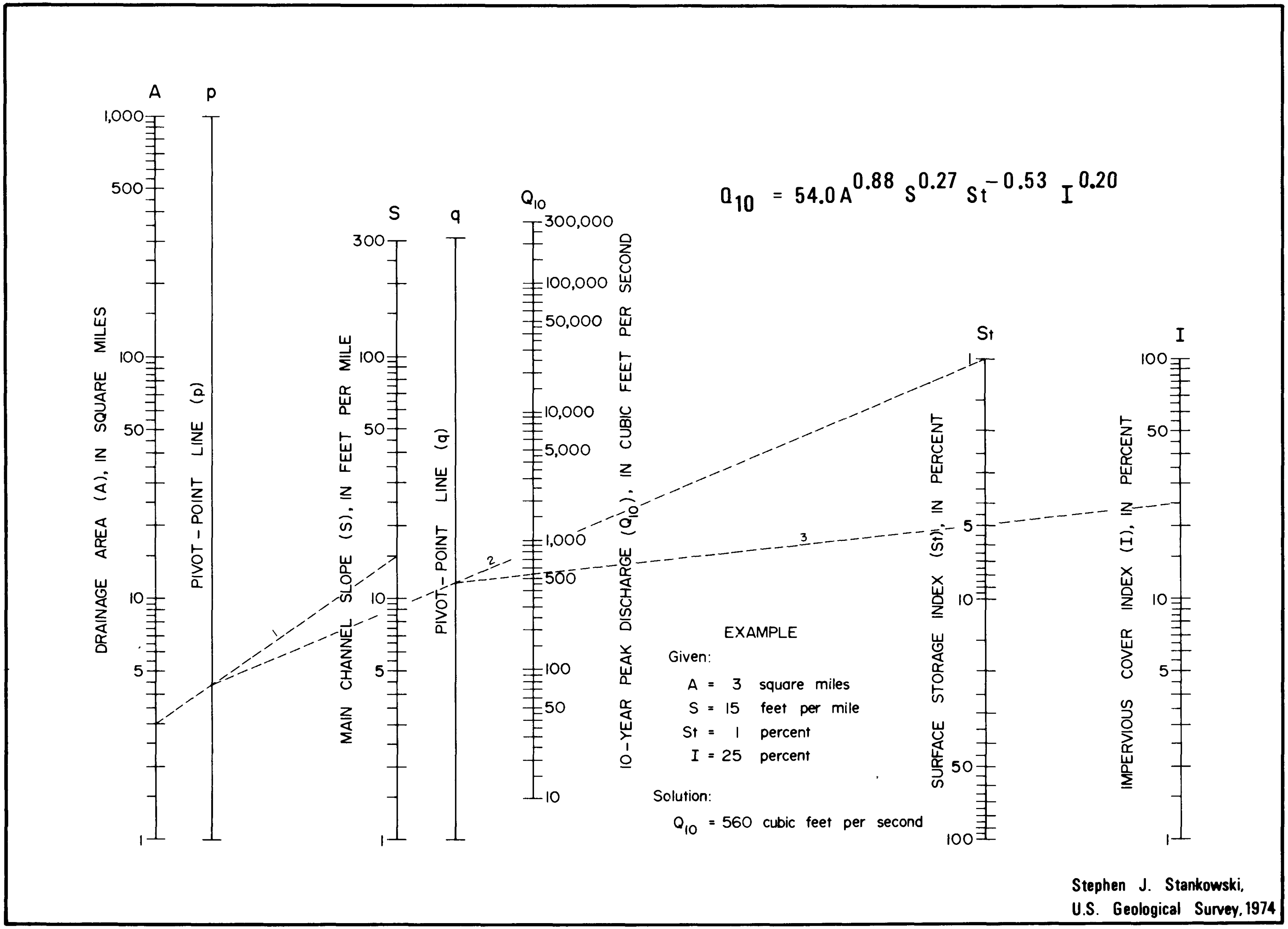

Figure 12.--Nomograph for estimating 10-year flood-peak discharge.

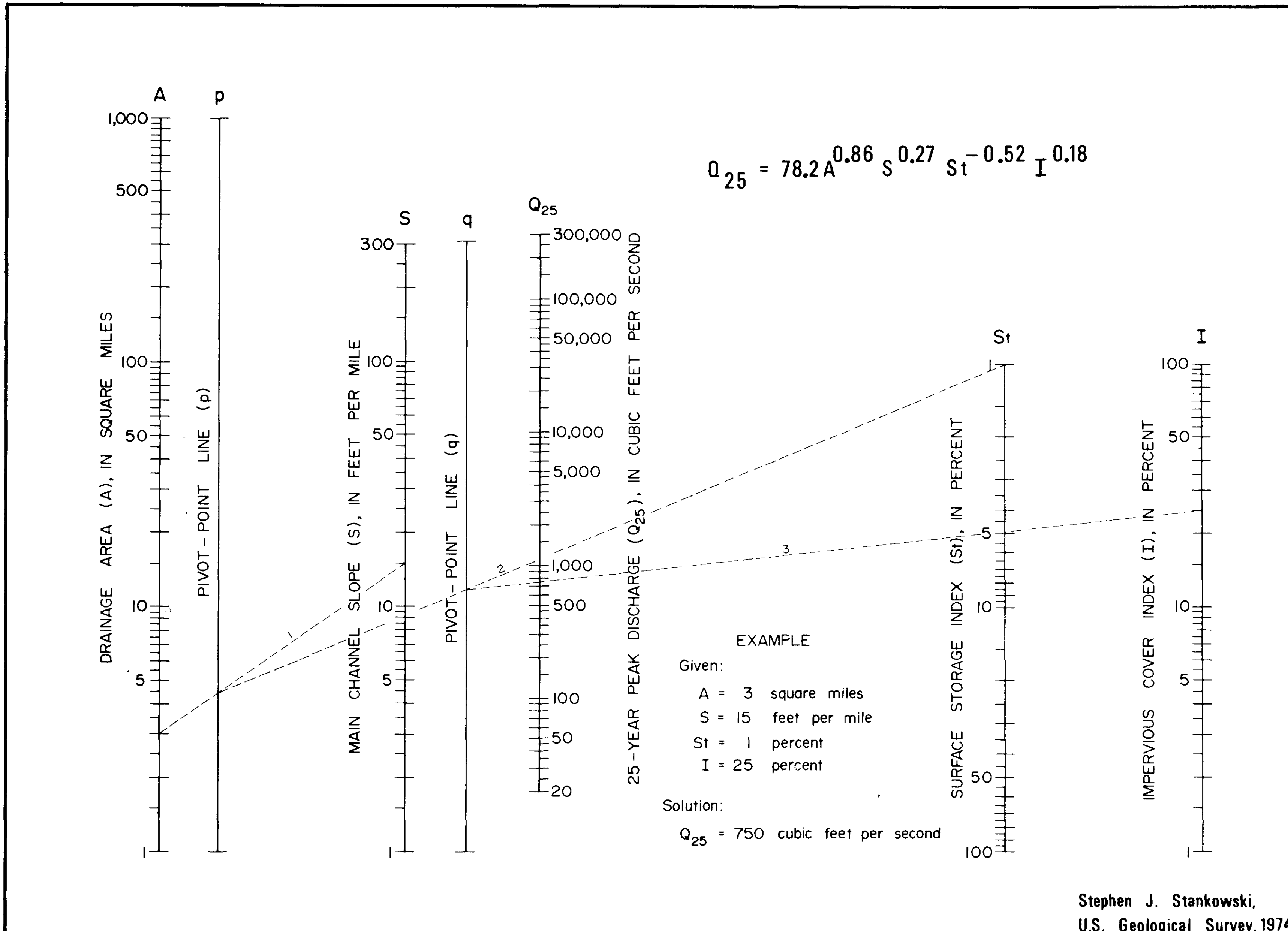

Figure 13.--Nomograph for estimating 25-year flood-peak discharge.

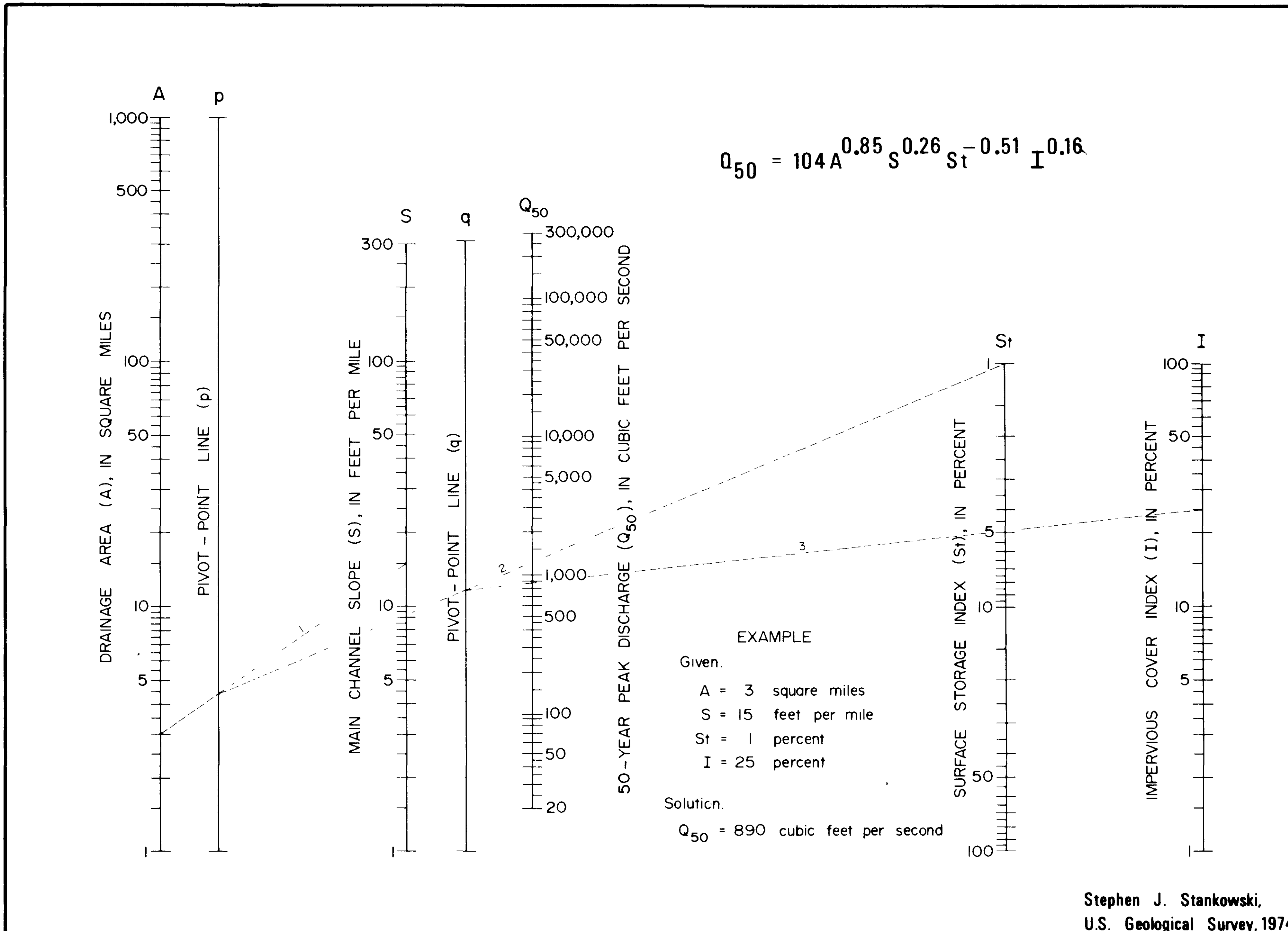

Figure 14.--Nomograph for estimating 50-year flood-peak discharge.

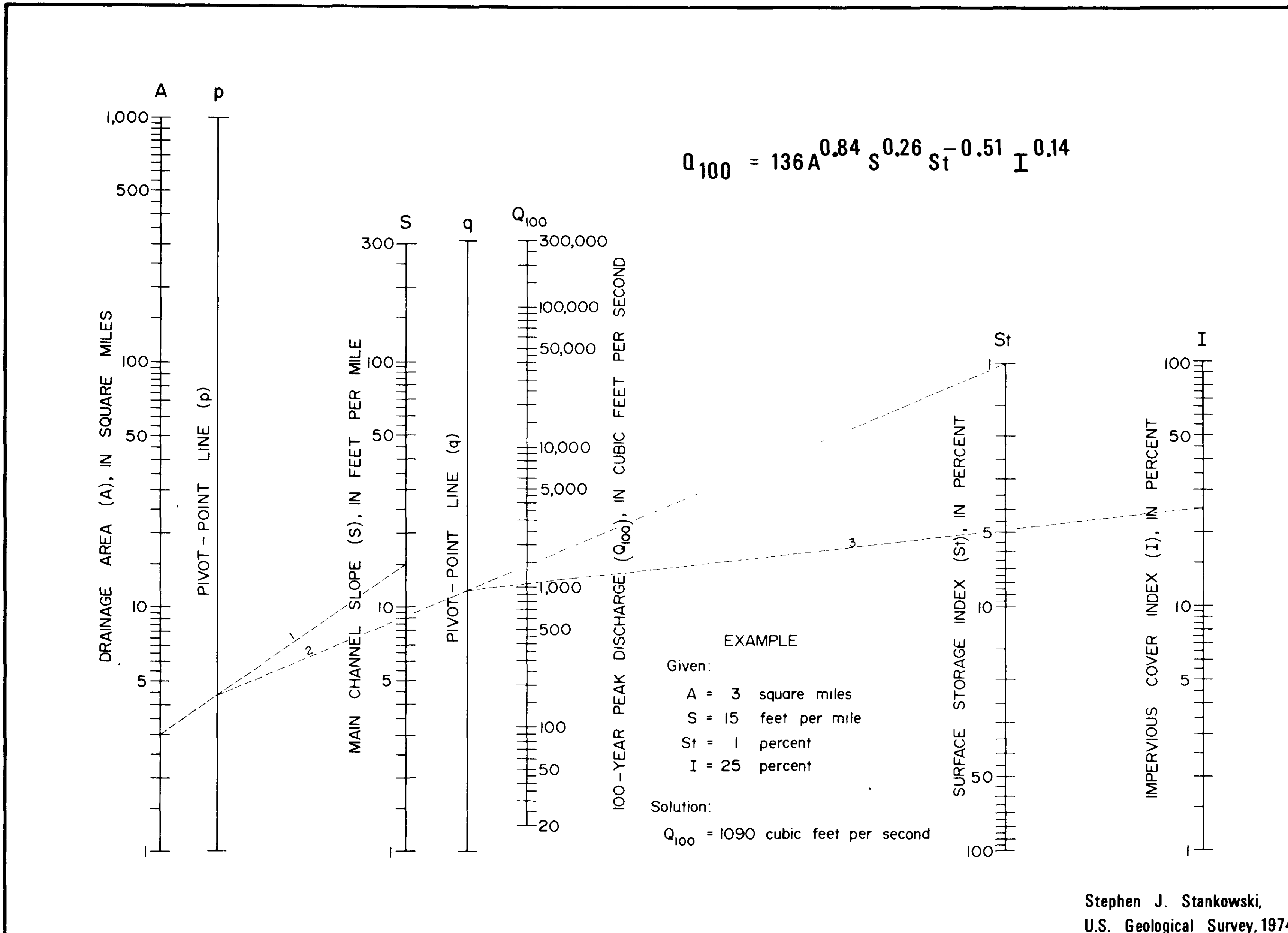

Figure 15.—Nomograph for estimating 100-year flood-peak discharge.

A gazetteer containing values for different points on most New Jersey streams will be published later. The fourth variable is the index of manmade impervious cover, which can be determined from existing population data, but in actual practice will usually be estimated for future developed conditions based on population projections. In doing this, however, it would be desirable to consider whether the future development will also include changes in drainage area, main-channel slope, and the amount of surface storage. If such changes are likely to occur they can be accounted for in the computations by using the anticipated values of area, slope, and storage rather than the existing values. Drainage area and slope are seldom significantly changed except in small drainage areas, but surface storage can either be increased or decreased by building reservoirs or filling in swamps.

The following example illustrates the application of the method and nomographs in figures 9 through 15. If a digital computer or adequate desk or pocket calculator is available, the formulas given in table 3 may, of course, be solved directly by inserting proper values for the four variables. Suppose it is desired to estimate the 100-year flood-peak discharge at a known location in New Jersey for an expected future development with a population density of 3,700 persons per square mile with no anticipated changes in contributing drainage area, main-channel slope, and surface storage:

1. Ascertain that the selected site is nontidal and not significantly affected by upstream reservoir operation.

2. Determine the size of the contributing drainage area from a topographic map. For this example, assume the drainage area (A) is 3.00 square miles.

3. Compute the main-channel slope (S) from a topographic map as follows: (a) Measure the river length from the selected site to the basin divide. If the stream forks, follow the fork with the greater drainage area. (b) Determine elevations at points that are 10 percent and 85 percent of the total stream length above the site being studied. (c) Determine the difference between these elevations and divide by the distance, in miles, between the points. For this example, assume the total river-mile distance from the known location to the basin divide is 2.4 miles; the elevation at the 10 percent point (0.24 mile) is 200 feet, as determined from contours on map or detailed surveys, and the elevation at the 85 percent point (2.04 miles) is 227 feet. The average slope is:

$$S = \frac{227 \text{ feet} - 200 \text{ feet}}{2.04 \text{ miles} - 0.24 \text{ mile}} = 15.0 \text{ feet per mile.}$$

4. Determine the area of lakes and swamps from a topographic map. Compute the surface storage index as the percentage of total drainage area occupied by lakes and swamps or other bodies of water plus 1.0 percent. For this example, assume the lake and swamp area is zero; therefore the surface storage index (St) is 1.0 percent.

5. Determine manmade-impervious-cover index for expected population density by nomograph from figure 9. In this example, the population density (D) is 3,700 persons per square mile; therefore the manmade-impervious-cover index (I) is 25 percent.

6. Determine 100-year flood-peak discharge by nomograph from figure 15. Plot the values of A (step 2), S (step 3), St (step 4), and I (step 5) on those respective scales. Connect the plotted points on the A and S scales with a straight line (dashed line 1) to determine pivot point on the p scale. Connect the pivot point on the p scale and the plotted point on the St scale with a straight line (dashed line 2) to determine pivot point on the q scale. Connect the pivot point on the q scale and the plotted point on the I scale with a straight line (dashed line 3) and read the 100-year flood-peak discharge, Q_{100} = 1,090 cubic feet per second, on the Q_{100} scale.

A complete recurrence-interval array can be compiled for this hypothetical location by repeating step 6 for several recurrence intervals using nomographs in figures 10 through 14.

As another example of the use of the nomographs, assume that it is desired to determine at what stage of development the 100-year recurrence interval flood will exceed the channel capacity at this same hypothetical location. Assume that detailed hydraulic studies show that the existing channel capacity is 840 cubic feet per second. Using the nomograph from figure 15, plot the channel capacity on the Q_{100} scale. Connect the pivot point (same as in above example) on the q scale and the plotted point on the Q_{100} scale with a straight line extended to the I scale. The value of 4 percent is read on the impervious-cover-index scale. By nomograph from figure 9, this corresponds to an average basin population density of 150 persons per square mile. When development increases beyond that point, adequate drainage at the 100-year recurrence interval will no longer exist.

APPLICABILITY AND LIMITATIONS

The regional flood-frequency equations developed in this study permit estimates of flood magnitude and frequency at open-channel sites on any nontidal New Jersey stream where flood flow is not significantly affected by regulation or diversion. The equations are recommended for use, however, only for drainage basins from 1.0 to 1,000 square miles in area because of constraints imposed by the drainage area sizes of the 103 gaging stations used in the regression analyses.

The method of prediction is dependent on two relationships. One transforms the existing or projected basin population density to an index of manmade impervious cover (I). The other relates the flood-peak discharge to the size of drainage area (A), the main-channel slope (S), the surface storage index (St), and the index of manmade impervious cover (I). Table 5 lists these basin characteristics for each of the 103 gaging stations used in the analysis. The manmade-impervious-cover indexes listed in table 5 are the average values for the period of streamflow record for each basin. The range, median, and mean of these basin characteristics are given in table 6.

Multiple regression results in empirical equations that serve to sum up all the evidence of a large number of observations in a single statement that expresses in condensed form the extent to which average differences in the dependent variable (peak discharge for a selected recurrence interval) tend to be associated with the average differences in each of the independent variables (basin characteristics). Regression analyses define relations that are most accurate for the average of the sample data; therefore, flood-peak discharge estimates should be most accurate for basins with characteristics near the average of the sample basins.

Useful flood-peak discharge predictions should be obtained in most cases; however, results should be studied carefully to determine whether the computed flood magnitude is reasonable. For example, the relations are based on the assumption that urban development, whatever the stage, can be described by the index of manmade impervious cover as determined from concomitant population density data. Some small basins may be highly developed industrially and commercially with little or no residential population to reflect the degree of development. The user should be familiar with the basin being studied so as to recognize and make allowances for a severe anomaly; in this case, the user should determine an index of manmade impervious cover directly from land-use data or projections. However, because this method deviates from that used for determining the index of manmade impervious cover as applied to the development of the flood magnitude and frequency equations, the degree of error associated with the computed discharge is indeterminate.

Table 5.--Characteristics of drainage basins used in developing flood magnitude and frequency estimating equations

USGS station number	Stream and location	Period of record	A (sq mi)	S (ft/mi)	St (%)	I (%)
	HUDSON RIVER BASIN					
01368000	Wallkill River near Unionville, N.Y.	1938-40, 1945-71	140.	16.5	5.3	3.5
	HACKENSACK RIVER BASIN					
01377000	Hackensack River at Rivervale, N.J.	1942-56	58.0	4.38	5.1	9.4
01377475	Musquapsink Brook near Westwood, N.J.	1965-69, 1971	2.16	70.5	3.3	27.0
01377490	Musquapsink Brook at Westwood, N.J.	1966-72	6.53	48.5	6.5	22.0
01377500	Pascack Brook at Westwood, N.J.	1935-71	29.6	36.2	3.7	14.0
01378350	Tenakill Brook at Cresskill, N.J.	1965-72	3.01	9.7	1.0	25.0
01378385	Tenakill Brook at Closter, N.J.	1965-71	8.56	3.98	1.0	24.0
01378500	Hackensack River at New Milford, N.J.	1922-71	113.	4.10	5.1	8.8
01378590	Metzler Brook at Englewood, N.J.	1965-72	1.54	31.6	1.0	38.0
01378615	Wolf Creek at Ridgefield, N.J.	1965-67, 1969-71	1.18	81.0	1.0	46.0
	PASSAIC RIVER BASIN					
01379000	Passaic River near Millington, N.J.	1904-06, 1922-71	55.4	30.3	19.1	7.8
01379500	Passaic River near Chatham, N.J.	1904-11, 1938-71	100.	11.4	12.2	8.6
01380500	Rockaway River above reservoir, at Boonton, N.J.	1938-71	116.	11.9	7.7	7.6
01381500	Whippany River at Morristown, N.J.	1922-71	29.4	49.0	2.0	12.0
01381900	Passaic River at Pine Brook, N.J.	1966-72	349.	2.78	10.1	13.0
01384500	Ringwood Creek near Wanaque, N.J.	1936-71	16.9	59.9	8.1	1.0
01385000	Cupsaw Brook near Wanaque, N.J.	1936-58	4.38	96.6	7.8	1.2
01386000	West Brook near Wanaque, N.J.	1936-71	11.8	179.	4.4	2.7
01386500	Blue Mine Brook near Wanaque, N.J.	1936-58	1.71	275.	1.1	4.1
01387500	Ramapo River near Mahwah, N.J.	1904-14, 1923-71	118.	17.4	5.6	4.3
01388000	Ramapo River at Pompton Lakes, N.J.	1922-62, 1964-71	160.	12.9	5.8	5.1
01388500	Pompton River at Pompton Plains, N.J.	1941-71	355.	12.1	7.4	5.2
01389500	Passaic River at Little Falls, N.J.	1898-1971	762.	1.83	9.6	7.7
01389900	Fleischer Brook at Market Street, at East Paterson, N.J.	1967-72	1.37	19.0	1.2	37.0

Table 5.--Characteristics of drainage basins used in developing flood magnitude and frequency estimating equations--Continued

USGS station number	Stream and location	Period of record	A (sq mi)	S (ft/mi)	St (%)	I (%)
	PASSAIC RIVER BASIN--Continued					
01390450	Saddle River at Upper Saddle River, N.J.	1966-70, 1972	10.9	94.1	2.9	15.0
01390500	Saddle River at Ridgewood, N.J.	1955-71	21.6	36.9	5.6	13.0
01391000	Hohokus Brook at Hohokus, N.J.	1954-71	16.4	29.6	6.5	12.0
01391110	Saddle River at Paramus, N.J.	1965, 1967-72	45.0	28.8	6.0	19.0
01391485	Sprout Brook at Rochelle Park, N.J.	1965-67, 1969-71	5.56	11.2	8.8	18.0
01391500	Saddle River at Lodi, N.J.	1924-71	54.6	16.6	5.0	16.0
01392000	Weasel Brook at Clifton, N.J.	1950-71	4.45	95.0	1.4	30.0
01392500	Second River at Belleville, N.J.	1938-71	11.6	48.5	1.9	35.0
	ELIZABETH RIVER BASIN					
01393000	Elizabeth River at Irvington, N.J.	1931-38	2.91	16.8	1.0	72.0
01393500	Elizabeth River at Elizabeth, N.J.	1922-71	18.0	19.5	1.1	45.0
	RAHWAY RIVER BASIN					
01394000	West Branch Rahway River at Millburn, N.J.	1938, 1940-50	7.10	47.1	1.2	16.0
01394500	Rahway River near Springfield, N.J.	1938-71	25.5	14.6	1.4	26.0
01395000	Rahway River at Rahway, N.J.	1922-71	40.9	8.84	1.5	24.0
01396000	Robinsons Branch Rahway River at Rahway, N.J.	1940-71	21.6	13.3	6.6	19.0
	RARITAN RIVER BASIN					
01396500	South Branch Raritan River near High Bridge, N.J.	1896, 1902, 1904, 1919-24, 1926-54, 1956-71	65.3	27.9	2.7	3.8
01397000	South Branch Raritan River at Stanton, N.J.	1904-06, 1919-71	147.	26.9	1.8	3.5
01397500	Walnut Brook near Flemington, N.J.	1937-71	2.24	159.	1.1	3.1
01398000	Neshanic River at Reaville, N.J.	1931-71	25.7	26.7	1.1	4.7
01398500	North Branch Raritan River near Far Hills, N.J.	1919, 1922-71	26.2	44.4	1.8	5.9
01399500	Lamington (Black) River near Pottersville, N.J.	1922-63, 1965-71	32.8	23.1	5.8	4.9
01400000	North Branch Raritan River near Raritan, N.J.	1924, 1926-71	190.	18.7	2.0	4.2
01400500	Raritan River at Manville, N.J.	1904-06, 1909-15, 1922-71	490.	12.1	1.7	4.4

Table 5.--Characteristics of drainage basins used in developing flood magnitude and frequency estimating equations--Continued

USGS station number	Stream and location	Period of record	A (sq mi)	S (ft/mi)	St (%)	I (%)
	RARITAN RIVER BASIN--Continued					
01400730	Millstone River at Plainsboro, N.J.	1964-71	65.8	6.45	4.5	7.0
01400850	Woodsville Brook at Woodsville, N.J.	1957, 1964-72	1.78	37.8	1.0	5.3
01400900	Stony Brook at Glenmoore, N.J.	1957-72	17.0	43.5	1.0	3.9
01400930	Baldwin Creek at Pennington, N.J.	1957, 1960-67, 1969-72	1.99	66.1	1.0	5.3
01401000	Stony Brook at Princeton, N.J.	1954-71	44.5	10.4	1.2	6.8
01401200	Duck Pond Run at Clarksville, N.J.	1966-72	5.21	13.8	10.2	4.7
01401500	Millstone River near Kingston, N.J.	1934-49	171.	4.49	3.6	4.2
01401520	Beden Brook near Hopewell, N.J.	1967-72	6.07	45.8	1.0	4.5
01401595	Rock Brook near Blawenburg, N.J.	1967-72	9.03	74.1	1.1	6.4
01401600	Beden Brook near Rocky Hill, N.J.	1967-72	27.6	17.0	1.0	5.0
01401870	Six Mile Run near Middlebush, N.J.	1966-70, 1972	10.7	14.2	2.5	12.0
01402000	Millstone River at Blackwells Mills, N.J.	1921-71	258.	3.84	2.9	4.8
01402600	Royce Brook tributary near Belle Meade, N.J.	1967-72	1.20	22.6	1.0	4.3
01403000	Raritan River at Bound Brook, N.J.	1904-09, 1936-39, 1942, 1945-71	779.	11.6	2.1	5.1
01403500	Green Brook at Plainfield, N.J.	1938-62, 1964-71	9.75	49.2	2.0	25.0
01405000	Lawrence Brook at Farrington Dam, N.J.	1927-71	34.4	5.58	6.0	5.0
01405300	Matchaponix Brook at Spotswood, N.J.	1958, 1960-67	43.9	6.30	4.7	8.0
01405500	South River at Old Bridge, N.J.	1940-71	94.6	7.90	5.1	7.6
01406000	Deep Run near Browntown, N.J.	1933-40	8.07	31.3	1.1	2.4
01406500	Tennent Brook near Browntown, N.J.	1933-41	5.25	25.3	10.9	6.0
	MATAWAN CREEK BASIN					
01407000	Matawan Creek at Matawan, N.J.	1933-47, 1949-55	6.11	22.5	3.3	7.5
	NAVESINK RIVER BASIN					
01407500	Swimming River near Red Bank, N.J.	1919, 1923-71	48.5	12.7	2.4	5.1

Table 5.--Characteristics of drainage basins used in developing flood magnitude and frequency estimating equations--Continued

USGS station number	Stream and location	Period of record	A (sq mi)	S (ft/mi)	St (%)	I (%)
	MANASQUAN RIVER BASIN					
01408000	Manasquan River at Squankum, N.J.	1932-71	43.4	6.46	2.2	5.0
	TOMS RIVER BASIN					
01408500	Toms River near Toms River, N.J.	1929-71	124.	7.24	14.6	2.6
	CEDAR CREEK BASIN					
01409000	Cedar Creek at Lanoka Harbor, N.J.	1933-35, 1938-44, 1952-54, 1957-58, 1971	56.0	7.70	13.3	1.1
	MULLICA RIVER BASIN					
01409400	Mullica River near Batsto, N.J.	1958-71	46.1	6.69	29.4	2.2
01410000	Oswego River at Harrisville, N.J.	1931-43, 1945-71	64.0	6.56	15.8	1.1
	GREAT EGG HARBOR RIVER BASIN					
01411000	Great Egg Harbor River at Folsom, N.J.	1926-71	56.3	3.14	14.9	4.3
	MAURICE RIVER BASIN					
01411500	Maurice River at Norma, N.J.	1933-71	113.	5.16	9.9	4.5
01412000	Manantico Creek near Millville, N.J.	1932-57, 1963, 1964	22.3	7.04	8.2	4.1
	DELAWARE RIVER BASIN					
01440000	Flat Brook near Flatbrookville, N.J.	1924-33, 1935-71	65.1	36.2	2.5	1.0
01443500	Paulins Kill at Blairstown, N.J.	1922-30, 1932-71	126.	5.79	6.9	2.9
01445000	Pequest River at Huntsville, N.J.	1940, 1942-71	31.4	10.2	5.1	2.4
01445500	Pequest River at Pequest, N.J.	1922-71	108.	8.02	6.0	2.4
01446000	Beaver Brook near Belvidere, N.J.	1923-24, 1926-71	36.2	24.2	4.0	1.8
01455200	Pohatcong Creek at New Village, N.J.	1960-64, 1966, 1968-72	33.4	38.6	1.1	5.9
01456000	Musconetcong River near Hackettstown, N.J.	1922-71	70.0	24.0	11.3	4.6
01457000	Musconetcong River near Bloomsbury, N.J.	1904-06, 1922-71	143.	18.2	6.1	4.2
01464000	Assunpink Creek at Trenton, N.J.	1924-71	89.4	4.41	3.6	11.0

Table 5.--Characteristics of drainage basins used in developing flood magnitude and frequency estimating equations--Continued

USGS station number	Stream and location	Period of record	A (sq mi)	S (ft/mi)	St (%)	I (%)
	DELAWARE RIVER BASIN--Continued					
01464500	Crosswicks Creek at Extonville, N.J.	1938, 1948-51, 1953-71	83.6	5.47	8.8	5.1
01465850	South Branch Rancocas Creek at Vincentown, N.J.	1961-71	53.3	6.63	15.3	2.9
01466000	Middle Branch Mount Misery Brook in Lebanon State Forest, N.J.	1953-72	2.73	11.4	9.6	1.3
01466500	McDonalds Branch in Lebanon State Forest, N.J.	1954-71	2.31	17.6	7.1	1.2
01467000	North Branch Rancocas Creek at Pemberton, N.J.	1922-71	111.	6.41	15.0	3.5
01467130	Cooper River at Kirkwood, N.J.	1964-72	5.14	36.9	3.3	13.0
01467150	Cooper River at Haddonfield, N.J.	1964-71	17.4	8.12	1.6	15.0
01467160	North Branch Cooper River near Marlton, N.J.	1964-72	5.33	16.6	1.2	9.4
01467180	North Branch Cooper River at Ellisburg, N.J.	1964-72	10.4	11.3	1.2	12.0
01467305	Newton Creek at Collingswood, N.J.	1966-72	1.32	48.8	1.4	33.0
01467317	South Branch Newton Creek at Haddon Heights, N.J.	1964-71	.63	57.5	1.0	38.0
01467330	South Branch Big Timber Creek at Blackwood, N.J.	1964-72	19.0	14.8	4.5	10.0
01475000	Mantua Creek at Pitman, N.J.	1940, 1942-71	6.05	24.0	4.3	9.5
01476600	Still Run near Mickleton, N.J.	1957-66	3.95	23.0	1.8	4.0
01477120	Raccoon Creek near Swedesboro, N.J.	1967-72	29.9	13.2	2.2	3.7
01477500	Oldmans Creek near Woodstown, N.J.	1931-40	19.3	13.6	1.9	1.8
01482500	Salem River at Woodstown, N.J.	1940-71	14.6	12.8	2.3	5.0
01483000	Alloway Creek at Alloway, N.J.	1953-71	21.9	14.4	4.1	2.2

Table 6.--Range, median, and mean of basin characteristics used in developing flood magnitude and frequency estimating equations; data for 103 gaging stations

Basin characteristic		Properties			
Symbol	Units	Minimum	Maximum	Median	Mean
A	sq mi	0.63	779.	26.2	67.9
S	ft/mi	1.83	275.	16.6	29.1
St	%	1.00	29.4	3.6	5.0
I	%	1.00	72.0	5.3	10.7

The estimating relations are also based on the assumption that urban development and surface storage (lakes and swamps) are homogeneous throughout the basin. Urbanization or large storage areas concentrated in the upper or lower part of a basin probably would produce different flood characteristics than those resulting from uniform urbanization or surface storage throughout; however, the degree of this effect is presently unknown.

Sensitivity

One problem of concern to the design engineer is the sensitivity of a prediction equation to the accuracy of the independent variables included in it. An evaluation of the regional equations (table 3) was conducted to investigate this potential problem. Initially, these equations were solved using the mean value of each basin characteristic obtained from the sample of 103 gaging stations used in developing the regional equations (table 6). This yields a solution of 1,860 cfs for Q_2; 2,760 cfs for Q_5; 3,760 cfs for Q_{10}; 4,850 cfs for Q_{25}; 5,790 cfs for Q_{50}; and 6,930 cfs for Q_{100}. These equations were then solved by varying the value of each basin characteristic, one at a time, by a defined percentage that represented a reasonable high error of determination on the part of the user. For example, a defined error of 5 percent in A from its mean (or a value of 64.5 sq mi) and assuming no change in the other variables yields a solution of 1,780 cfs for Q_2. Similarly, an error of 5 percent in S (or a value of 27.6 ft/mi) yields a solution of 1,840 cfs; a 10 percent error in St (or a value of 4.5 percent) yields a solution of 1,980 cfs; and a 20 percent error in I (or a value of 8.6 percent) yields a solution of 1,770 cfs. Table 7 gives the percent change in Q_2 through Q_{100} resulting from the defined percent change in the basin characteristics. The percent change in the Q_T predictions ($\Delta Q_T\%$) were determined from

$$\Delta Q_T\% = \frac{Q_T' - Q_T}{Q_T} (100)$$

in which Q_T is the "correct" prediction and Q_T' is the solution after altering the basin characteristic. Based on this illustration, the most sensitive term is the drainage area (A) because as much as 90 percent of its error can be transferred to peak flow prediction. The second most sensitive term is the surface storage index (St). Up to 64 percent of its error can be transferred to peak flow prediction. The likelihood of a measurable error in these terms is dependent on the care and accuracy with which one delineates and measures the drainage area and lake and swamp area on topographic maps.

Table 7.--Percent changes in peak discharges for selected recurrence intervals ($\Delta Q_T\%$) due to changes defined in basin characteristics ($\Delta\%$)

Basin characteristic				$\Delta Q_T\%$					
Symbol	Units	Mean	$\Delta\%$	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}
A	sq mi	67.9	-5.0	-4.3	-4.3	-4.5	-4.3	-4.1	-4.3
S	ft/mi	29.1	-5.0	-1.1	-1.4	-1.3	-1.4	-1.4	-1.4
St	%	5.0	-10	+6.4	+5.8	+5.8	+5.6	+5.5	+5.5
I	%	10.7	-20	-4.8	-4.7	-4.2	-3.9	-3.4	-3.0

The estimating relations presented in this report provide for simple techniques of obtaining design discharges that are based on the most recent hydrologic data and analytical concepts. Although these relations might be refined or improved on the basis of information subsequently obtained, as discussed in the following section, they should be useful to planners and engineers in their present form.

FUTURE STUDIES

The present investigation has led to the development of a procedure for the determination of flood-peak discharges with selected recurrence intervals ranging from 2 to 100 years for drainage basins larger than one square mile with various degrees of existing or projected urban and suburban development. Although the parameters required for use of the procedure can be readily obtained from U. S. Geological Survey 7.5-minute series topographic maps and from planning-agency census data and population projections, much of the required data will be summarized and furnished to the users in published tables for ready reference (Stankowski and others, 1976). This will take the form of a gazetteer containing values of significant basin characteristics for different points on most New Jersey streams.

The reliability of any flood-frequency estimating technique depends on the number and length of available records of precipitation and runoff and on the adequacy of the basin-characteristic data used in the analysis. No amount of mathematical manipulation of limited data will improve the results. Accordingly, when a sufficient number of years have elapsed (5 years or more) and additional data have been collected, another analysis could improve reliability. Multiple regression analysis lends itself quite readily to periodic updates of this kind.

Additional peak flow data, primarily from watersheds ranging in size from less than 1 square mile to about 5 square miles, and including a wide range of urban and suburban development conditions, should aid in future attempts to improve the regression equations. It may be possible to shorten the time period of peak flow data collection at some sites by the use of continuous-recording stage-rainfall gages. Observations of streamflow and rainfall collected at a given site over a relatively short time period can be used to define the parameters of a continuous-moisture-accounting hydrologic model. Long-term records of rainfall can then be used as input to the model to compute a long-term record of peak discharge at the given site. Based on these data, a flood-frequency relation can be developed. Floods of selected recurrence intervals along with pertinent basin characteristic data can then be used to increase sample coverage in subsequent multiple regression analyses.

The development and use of new basin characteristics which account for the location of the bulk of urban development and surface storage areas within the basin could also serve to improve the reliability of flood estimates.

Model studies of flood peaks on major regulated streams would permit the development of a frequency curve for any point on these streams.

Additional tide-gage data, collected along the coasts, bays, and estuaries, would permit improved estimates of tide heights for various recurrence intervals. At present, such estimates must be based on very few tide-gage records of significant length, although it is well recognized that tide heights vary greatly from place to place for a given storm surge.

SUMMARY

Relations have been presented for estimating future flood discharges having recurrence intervals ranging from 2 to 100 years for drainage basins larger than one square mile with various degrees of existing or projected urban and suburban development. Four parameters are required for use of the relations. They are the basin size, channel slope, and surface storage within the basin, which may be measured from topographic maps, and an index of manmade impervious cover, which can be determined for existing and future development conditions from population data and projections that are readily available from regional, State, and local planning agencies. The estimating relations were converted to nomographs for easy use.

Results of this study indicate that changing a rural basin, with a 1 percent manmade-impervious-cover index, to a highly developed urban basin, with an 80 percent manmade-impervious-cover index, will increase flood peaks up to 3 times at the 2-year recurrence interval and up to 1.8 times at the 100-year recurrence interval as statewide averages.

Information presented in this report should aid designers of bridge waterway openings and drainage structures as well as engineers and planners charged with defining flood-prone areas and with guiding future land use and development.

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