Magnitude and Frequency of Floods on Nontidal Streams in Delaware

By Kernell G. Ries III and Jonathan J.A. Dillow

Prepared in cooperation with the
Delaware Department of Transportation
and the
Delaware Geological Survey

Scientific Investigations Report 2006-5146

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2006

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Ries, K.G., III, and Dillow, J.J.A., 2006, Magnitude and frequency of floods on nontidal streams in Delaware: U.S. Geological Survey Scientific Investigations Report 2006-5146, 59 p.

Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Magnitude and Frequency of Floods on Nontidal Streams in Delaware

By Kernell G. Ries III and Jonathan J.A. Dillow

Abstract

Reliable estimates of the magnitude and frequency of annual peak flows are required for the economical and safe design of transportation and water-conveyance structures. This report, done in cooperation with the Delaware Department of Transportation (DelDOT) and the Delaware Geological Survey (DGS), presents methods for estimating the magnitude and frequency of floods on nontidal streams in Delaware at locations where streamgaging stations monitor streamflow continuously and at ungaged sites. Methods are presented for estimating the magnitude of floods for return frequencies ranging from 2 through 500 years. These methods are applicable to watersheds exhibiting a full range of urban development conditions. The report also describes StreamStats, a web application that makes it easy to obtain flood-frequency estimates for user-selected locations on Delaware streams.

Flood-frequency estimates for ungaged sites are obtained through a process known as regionalization, using statistical regression analysis, where information determined for a group of streamgaging stations within a region forms the basis for estimates for ungaged sites within the region. One hundred and sixteen streamgaging stations in and near Delaware with at least 10 years of non-regulated annual peak-flow data available were used in the regional analysis. Estimates for gaged sites are obtained by combining the station peak-flow statistics (mean, standard deviation, and skew) and peak-flow estimates with regional estimates of skew and flood-frequency magnitudes. Example flood-frequency estimate calculations using the methods presented in the report are given for: (1) ungaged sites, (2) gaged locations, (3) sites upstream or downstream from a gaged location, and (4) sites between gaged locations.

Regional regression equations applicable to ungaged sites in the Piedmont and Coastal Plain Physiographic Provinces of Delaware are presented. The equations incorporate drainage area, forest cover, impervious area, basin storage, housing density, soil type A, and mean basin slope as explanatory variables, and have average standard errors of prediction ranging from 28 to 72 percent. Additional regression equations that incorporate drainage area and housing density as explanatory variables are presented for use in defining the effects of urbanization on peak-flow estimates throughout Delaware for the 2-year through 500-year recurrence intervals, along with suggestions for their appropriate use in predicting development-affected peak flows.

Additional topics associated with the analyses performed during the study are also discussed, including: (1) the availability and description of more than 30 basin and climatic characteristics considered during the development of the regional regression equations; (2) the treatment of increasing trends in the annual peak-flow series identified at 18 gaged sites, with respect to their relations with maximum 24-hour precipitation and housing density, and their use in the regional analysis; (3) calculation of the 90-percent confidence interval associated with peak-flow estimates from the regional regression equations; and (4) a comparison of flood-frequency estimates at gages used in a previous study, highlighting the effects of various improved analytical techniques.

Introduction

Reliable estimates of the magnitude and frequency of annual peak flows, generally referred to as flood-frequency estimates, are required for the economical design of transportation and water-conveyance structures such as roads, bridges, culverts, storm sewers, dams, and levees. These estimates are also needed for the effective planning and management of land use and water resources, to protect lives and property in flood-prone areas, and to determine flood-insurance rates.

Flood-frequency estimates are needed at locations where streamgaging stations monitor streamflow continuously and at ungaged sites, where no streamflow information is available for use as a basis for determining the estimates. Estimates for ungaged sites usually are achieved through a process known as regionalization, where flood-frequency information determined for a group of streamgaging stations within a region forms the basis for estimates for ungaged sites within the region.

Methods for determining flood-frequency estimates for nontidal streams in Delaware have been provided previously in reports by: Tice (1968), Cushing, Kantrowitz, and Taylor (1973), Simmons and Carpenter (1978), and Dillow (1996). The regionalization methods described in those reports relied on fewer stations and shorter periods of record than the methods described in this report. An additional 14 years of record and improved regionalization techniques have become available since the analysis was done for the previous report by Dillow (1996).

The purpose of this report, done in cooperation with the Delaware Department of Transportation (DelDOT) and the Delaware Geological Survey (DGS), is to present methods for estimating the magnitude and frequency of floods on nontidal streams in Delaware. The report (1) describes methods used to estimate the magnitude and frequency of floods for streamgaging stations; (2) presents estimates of the magnitude of floods at the 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year recurrence intervals determined for 116 streamgaging stations in and near Delaware; (3) describes methods used to develop regression equations for use in estimating the magnitude of floods at the same recurrence intervals for ungaged sites in Delaware; (4) describes the accuracy and limitations of the equations; (5) presents example applications of the methods; and (6) describes the StreamStats web application so that estimates can be easily obtained when needed.

Physical Setting

The study area, comprised of the State of Delaware, is in the Mid-Atlantic coastal region of the United States. The State lies between 38°27´ and 39°51´ north latitude and 75°04´ and 75°48´ west longitude, and is bordered on the north by the State of Pennsylvania, on the west and south by the State of Maryland, and on the east by Delaware Bay (Dillow, 1996) (fig. 1). The State of New Jersey is on the eastern shore of Delaware River and Delaware Bay. Delaware has a land area of 1,954 mi^2 (square miles) and a 2003 population of about 817,000 (FedStats, 2005).

The climate in the study area is temperate. The mean annual temperature is about 54° F (degrees Fahrenheit), with monthly averages ranging from 31° F in January to 76° F in July (National Oceanographic and Atmospheric Administration, 2005). Mean annual precipitation is about 44 inches (Carpenter and Hayes, 1996). The precipitation is distributed fairly evenly throughout the year. Annual peak flows in the State arise from a mix of frontal storms with rain and melting snow in the spring, thunderstorms in the summer, and tropical storms and hurricanes in the summer and fall.

The study area is in two major physiographic provinces, the Coastal Plain and the Piedmont (Fenneman, 1938). The Fall Line, which crosses from the northeast corner of Delaware through about 5 mi (miles) south of the northwest corner of the State, forms the divide between the two provinces. The Piedmont Province, northwest of the Fall Line, consists of gently rolling landscape with maximum elevations generally less than 400 ft (feet) above sea level. Delaware streams in this province have fairly steep gradients, and drain to the Delaware River and Delaware Bay (Dillow, 1996). The Coastal Plain Province, southeast of the Fall Line, consists of an area of low relief adjacent to the Chesapeake and Delaware Bays, with elevations ranging from sea level to less than 100 ft. Streams in the Coastal Plain are often affected by tides for substantial distances above their mouths. The Fall Line is named as such because numerous waterfalls occur where rivers drop from the Piedmont onto the Coastal Plain.

Methods for Estimating the Magnitude and Frequency of Floods

This report describes separate methods for estimating the magnitude and frequency of floods, hereafter referred to as flood-frequency estimates, for streamgaging stations and for ungaged sites. The general process normally followed to determine flood-frequency estimates for ungaged sites in a given region requires:

1. Selecting a group of streamgaging stations in and around the region with at least 10 years of annual peak-flow data and streamflow conditions that are generally representative of the area as a whole;
2. Computing initial flood-frequency estimates by weighting the station skews with generalized-skew values taken from "Guidelines For Determining Flood Flow Frequency" (Bulletin 17B) by the Interagency Advisory Committee on Water Data (IACWD, 1982);
3. Computing physical and climatic characteristics, hereafter termed basin characteristics, that have a conceptual relation to the generation of flood peaks for the drainage basins associated with the stations;
4. Analyzing the initial station-skew coefficients to determine new generalized-skew values for the region;
5. Re-computing the flood-frequency estimates for the stations by weighting the station skews with the new generalized-skew values;
6. Analyzing to determine if relations between flood-frequency estimates and basin characteristics are homogenous throughout the region or if the region should be divided into sub-regions;

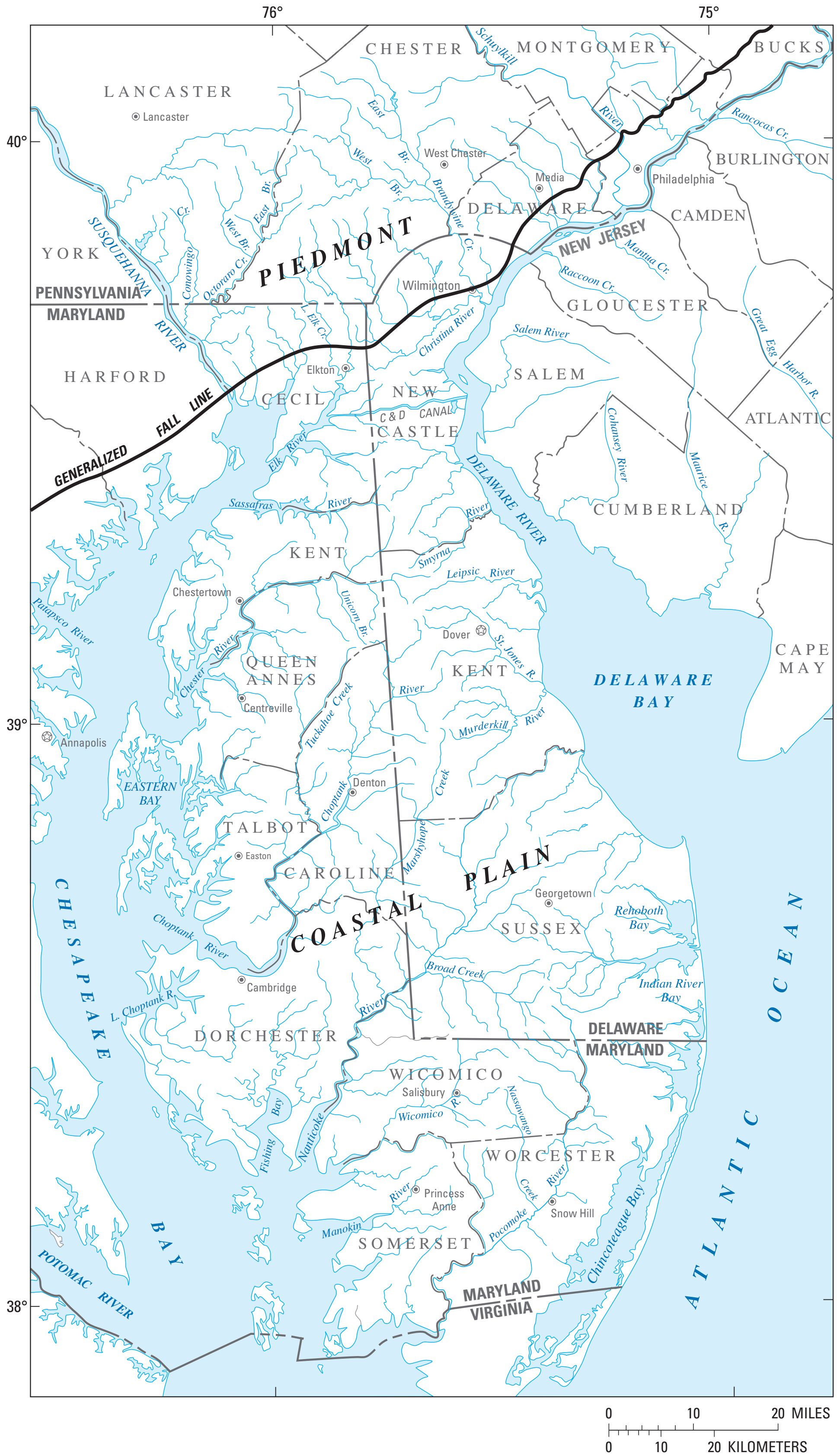

Figure 1. Study area and physiographic provinces in Delaware and surrounding states.

7. Using regression analysis to develop equations for use in estimating flood frequencies at ungaged sites in the region or sub-regions; and

8. Assessing and describing the accuracy associated with estimating flood frequencies for ungaged sites.

Streamgaging stations in Delaware and stations in adjacent states having drainage-basin centroids within 25 mi of the Delaware border were investigated for possible use in the regional analysis. Stations within this region were not used in the analysis if less than 10 years of annual peak-flow data were available, or if peak flows at the stations were substantially affected by dam regulations or flood-retarding reservoirs. Use of these criteria resulted in the initial selection of 116 stations for inclusion in the regional analysis (fig. 2, table 1).

The number of stations within the region was insufficient to develop separate regression equations for rural and urban basins. In addition, DelDOT was specifically interested in understanding how development can affect flood-frequency estimates. As a result, the stations were not screened based on the degree of urbanization.

Flood-Frequency Analysis at Streamgaging Stations

Flood-frequency estimates provided later in this report for 116 unregulated streamgaging stations in the study area were computed from annual series of peak-flow data for the stations according to methods recommended in Bulletin 17B. The estimates are reported as T-year discharges, where T is a recurrence interval that indicates the average number of years between occurrences of peak discharges of the same or greater magnitude. Flood-frequency estimates can also be expressed as exceedance probabilities, which are the reciprocal of the recurrence interval. In other words, the probability that the T-year flood will be exceeded is 1/T in every year. For example, the 100-year flood has a 1 in 100 (1 percent) chance of being equaled or exceeded in any given year.

The IACWD recommends fitting the logarithms of the annual peak flows to a log-Pearson, Type III frequency distribution. Fitting the distribution requires calculating the logarithms of the mean, standard deviation, and skew coefficient of the annual peak-flow series, which describe the mid-point, slope, and curvature of the peak-flow frequency curve, respectively. Estimates of the T-year flood peaks are computed by inserting the three statistics of the frequency distribution into the equation:

$$Q_T = X + KS \tag{1}$$

where

Q_T is the logarithm of the magnitude of the T-year recurrence interval discharge, in ft^3/s (cubic feet per second);

X is the mean of the logarithms of the annual peak streamflows;

K is a factor based on the skew coefficient and the given recurrence interval, which can be obtained from a table in Bulletin 17B; and

S is the standard deviation of the logarithms of the annual peak streamflows, which is a measure of the degree of variation of the annual values about the mean value.

The skew coefficient measures the symmetry of the frequency distribution and is strongly influenced by the presence of high or low outliers, annual peaks that are substantially higher or lower than other peaks in the series. The skew is positive when the mean of the annual series exceeds the median and negative when the mean is less than the median. Large positive skews are typically the result of high outliers, and large negative skews are typically the result of low outliers.

The U.S. Geological Survey (USGS) computer program PEAKFQ was used to compute the flood-frequency statistics for streamgaging stations presented in this report. PEAKFQ automates many of the analysis procedures recommended in Bulletin 17B, including identifying and adjusting for high and low outliers and historical periods, weighting of station skews with a generalized skew based on the skews of other stations within the region, and fitting a log-Pearson, Type III distribution to the streamflow data. The PEAKFQ program and associated documentation can be downloaded from the web free of charge at http://water.usgs.gov/software/peakfq.html. In conjunction with PEAKFQ, the USGS software programs ANNIE, IOWDM (Flynn and others, 1995), and SWSTAT were used for binary database management, for input and output of data to the database, and for testing annual peak-flow series for trends, respectively. The ANNIE program and accompanying documentation can be downloaded at http://water.usgs.gov/software/annie.html. The IOWDM program and accompanying documentation can be downloaded at http://water.usgs.gov/software/iowdm.html. The SWSTAT program and accompanying documentation can be downloaded at http://water.usgs.gov/software/swstat.html.

The process generally followed when computing flood-frequency estimates for streamgaging stations consisted of the following steps:

1. Retrieve the annual time series of peak flows for the station from the USGS NWIS-Web on-line database at http://nwis.waterdata.usgs.gov/usa/nwis/peak;

2. Compare the time series for the station to time series for upstream and downstream stations, and for stations in adjacent basins to determine if the records for the other stations can be used as the basis for a historical adjustment;

3. Consult the USGS data-collection manager for the State in which the station is located, do a literature search, or both, to obtain any information that can be used as the basis for historical adjustments;

Figure 2. Location of streamgaging stations in Delaware and surrounding states for which flood-frequency estimates were computed.

Table 1. Summary of streamgaging stations in and near Delaware for which streamflow statistics were computed.

[USGS, U.S. Geological Survey, CP, Coastal Plain Physiographic Province; PD, Piedmont Coastal Plain Physiographic Province; ° ´ ˝, degrees, minutes, seconds; N, years of record]

USGS station number	Name	Latitude ° ′ ″	Longitude ° ′ ″	Region	Peak-flow period	N
01411456	Little Ease Run near Clayton, NJ	39 39 32	75 04 03	CP	1988-2004	17
01411500	Maurice River at Norma, NJ	39 29 44	75 04 37	CP	1933-2004[h]	72
01412500	West Branch Cohansey River at Seeley, NJ	39 29 06	75 15 32	CP	1952-73, 1974-79, 1980-2004	51
01412800	Cohansey River at Seeley NJ	39 28 21	75 15 20	CP	1978-95, 2003-4	20
01467043	Stream ‘A’ at Philadelphia, PA	40 05 27	75 03 50	PD	1965-80	16
01467045	Pennypack Creek below Veree Road at Philadelphia, PA	40 05 04	75 03 34	PD	1964-80	18
01467081	South Branch Pennsauken Creek at Cherry Hill, NJ	39 56 30	75 00 04	CP	1968-76, 1978-2004	36
01467086	Tacony Creek at County Line, Philadelphia, PA	40 02 47	75 06 40	PD	1966-86	21
01467087	Frankford Creek at Castor Ave., Philadelphia, PA	40 00 57	75 05 50	PD	1966-2004[a]	39
01467089	Frankford Creek at Torresdale Ave., Philadelphia, PA	40 00 25	75 05 33	PD	1966-81[b]	16
01467130	Cooper River at Kirkwood, NJ	39 50 11	75 00 05	CP	1963-80, 2004	18
01467150	Cooper River at Haddonfield, NJ	39 54 11	75 01 17	CP	1963-2003[h]	41
01467160	North Branch Cooper River near Marlton, NJ	39 53 20	74 58 07	CP	1964-78, 2004[bh]	26
01467180	North Branch Cooper River at Ellisburg, NJ	39 54 27	75 00 41	CP	1964-75, 2004	13
01467305	Newton Creek at Collingswood, NJ	39 54 30	75 03 12	CP	1964-75, 1977-2004	40
01467317	South Branch Newton Creek at Haddon Heights, NJ	39 52 45	75 04 25	CP	1964-2004[c]	41
01467330	South Branch Big Timber Creek at Blackwood, NJ	39 48 17	75 04 32	CP	1964-84[h]	21
01467351	North Branch Big Timber Creek at Laurel Rd, Laurel Springs, NJ	39 49 07	75 00 55	CP	1975-88	14
01472157	French Creek near Phoenixville, PA	40 09 05	75 36 06	PD	1969-2004	36
01472174	Pickering Creek near Chester Springs, PA	40 05 22	75 37 50	PD	1967-83	17
01473169	Valley Creek at PA Turnpike Bridge near Valley Forge, PA	40 04 45	75 27 40	PD	1983-2004[ch]	22
01473470	Stony Creek at Sterigere Street at Norristown, PA	40 07 38	75 20 43	PD	1971, 1975-94	21
01474000	Wissahickon Creek at mouth, Philadelphia, PA	40 00 55	75 12 26	PD	1966-2004[h]	39
01475000	Mantua Creek at Pitman, NJ	39 44 13	75 06 48	CP	1940, 1942-94, 1999, 2003-4[ch]	57
01475019	Mantua Creek at Salina, NJ	39 46 13	75 07 58	CP	1975-1988	14

Table 1. Summary of streamgaging stations in and near Delaware for which streamflow statistics were computed.—Continued

[USGS, U.S. Geological Survey, CP, Coastal Plain Physiographic Province; PD, Piedmont Coastal Plain Physiographic Province; ° ´ ˝, degrees, minutes, seconds; N, years of record]

USGS station number	Name	Latitude ° ′ ″	Longitude ° ′ ″	Region	Peak-flow period	N
01475300	Darby Creek at Waterloo Mills near Devon, PA	40 01 21	75 25 20	PD	1972-97, 1999[h]	27
01475510	Darby Creek near Darby, PA	39 55 44	75 16 22	PD	1964-90	27
01475530	Cobbs Creek at U.S. Highway No. 1 at Philadelphia, PA	39 58 29	75 16 49	PD	1965-81[h]	17
01475550	Cobbs Creek at Darby, PA	39 55 02	75 14 52	PD	1964-90	27
01475850	Crum Creek near Newtown Square, PA	39 58 35	75 26 13	PD	1977-2004	28
01476000	Crum Creek at Woodlyn, PA	39 52 45	75 21 00	PD	1932-37, 1975-86	18
01476435	Ridley Creek at Dutton Mill near West Chester, PA	39 58 50	75 31 00	PD	1975-86	12
01476480	Ridley Creek at Media, PA	39 54 58	75 24 13	PD	1932-55, 1978-2004[d]	48
01476500	Ridley Creek at Moylan, PA	39 54 10	75 23 35	PD	1932-55, 1978-80, 1984-85[bh]	31
01477000	Chester Creek near Chester, PA	39 52 08	75 24 31	PD	1932-2004	73
01477110	Raccoon Creek at Mullica Hill, NJ	39 44 10	75 13 29	CP	1940, 1978-95, 1999[h]	20
01477120	Raccoon Creek near Swedesboro, NJ	39 44 26	75 15 33	CP	1967-2004[h]	38
01477480	Oldmans Creek near Harrisonville, NJ	39 41 20	75 18 37	CP	1975-95	21
01477500	Oldmans Creek near Woodstown, NJ	39 41 27	75 19 04	CP	1932-40,1967[h]	10
01477800	Shellpot Creek at Wilmington, DE	39 45 39.5	75 31 07.3	PD	1945-2004[ch]	60
01478000	Christina River at Coochs Bridge, DE	39 38 14.6	75 43 40.4	PD	1943-2004	62
01478040	Christina River near Bear, DE	39 38 12	75 40 53	PD	1979-83, 1985-91[h]	12
01478200	Middle Branch White Clay Creek near Landenberg, PA	39 46 54	75 48 03	PD	1960-1991, 1995	32
01478500	White Clay Creek above Newark, DE	39 42 50	75 45 35	PD	1953-59, 1963-80, 1989, 1994-2004[ceh]	37
01478650	White Clay Creek at Newark, DE	39 41 21.2	75 44 55.5	PD	1994-2003b	10
01479000	White Clay Creek near Newark, DE	39 41 57.2	75 40 30.1	PD	1932-36, 1943-57, 1960-2004[h]	65
01479200	Mill Creek at Hockessin, DE	39 46 31	75 41 26	PD	1966-75	10

Table 1. Summary of streamgaging stations in and near Delaware for which streamflow statistics were computed.—Continued

[USGS, U.S. Geological Survey, CP, Coastal Plain Physiographic Province; PD, Piedmont Coastal Plain Physiographic Province; ° ′ ″, degrees, minutes, seconds; N, years of record]

USGS station number	Name	Latitude ° ′ ″	Longitude ° ′ ″	Region	Peak-flow period	N
01479820	Red Clay Creek near Kennett Square, PA	39 49 00	75 41 31	PD	1988-2004[h]	17
01479950	Red Clay Creek Tributary near Yorklyn, DE	39 47 50	75 39 33	PD	1966-75	10
01480000	Red Clay Creek at Wooddale, DE	39 45 46.1	75 38 11.4	PD	1943-2004[h]	62
01480015	Red Clay Creek near Stanton, DE	39 42 56.7	75 38 23.8	PD	1989-2004[h]	16
01480100	Little Mill Creek at Elsmere, DE	39 44 05	75 35 14	PD	1964-80,1989	18
01480300	West Branch Brandywine Creek near Honey Brook, PA	40 04 22	75 51 40	PD	1960-2004	45
01480500	West Branch Brandywine Creek at Coatesville, PA	39 59 08	75 49 40	PD	1942,1944-50, 1970-2004[h]	44
01480610	Sucker Run near Coatesville, PA	39 58 20	75 51 03	PD	1964-2004	41
01480617	West Branch Brandywine Creek at Modena, PA	39 57 42	75 48 06	PD	1970-2004[b]	35
01480675	Marsh Creek near Glenmoore, PA	40 05 52	75 44 31	PD	1967-2004[b]	38
01480680	Marsh Creek near Lyndell, PA	40 03 58	75 43 38	PD	1960-71[b]	12
01480700	East Branch Brandywine Creek near Downingtown, PA	40 02 05	75 42 32	PD	1966-2004[h]	39
01480800	East Branch Brandywine Creek at Downingtown, PA	40 00 20	75 42 20	PD	1942, 1958-68[bh]	12
01480870	East Branch Brandywine Creek below Downingtown, PA	39 58 07	75 40 25	PD	1972-2004[fh]	33
01481000	Brandywine Creek at Chadds Ford, PA	39 52 11	75 35 37	PD	1912-53, 1954-5, 1963-2004[bh]	85
01481200	Brandywine Creek tributary near Centerville, DE	39 50 08	75 35 57	PD	1966-75	10
01481450	Willow Run at Rockland, DE	39 47 32	75 33 16	PD	1966-75	10
01481500	Brandywine Creek at Wilmington, DE	39 46 09.9	75 34 25.0	PD	1912-2004[g]	93
01482310	Doll Run at Red Lion, DE	39 35 53	75 39 43	CP	1966-75[b]	10
01482500	Salem River at Woodstown, NJ	39 38 36	75 19 51	CP	1940-95, 2003-4[h]	58
01483000	Alloway Creek at Alloway, NJ	39 33 56	75 21 38	CP	1953-72	20
01483200	Blackbird Creek at Blackbird, DE	39 21 58.6	75 40 09.8	CP	1952-2004	52
01483290	Paw Paw Branch tributary near Clayton, DE	39 18 41	75 40 08	CP	1966-75[h]	10
01483400	Sawmill Branch tributary near Blackbird, DE	39 20 57	75 38 31	CP	1966-75	10
01483500	Leipsic River near Cheswold, DE	39 13 58	75 37 57	CP	1943-75	33
01483700	St. Jones River at Dover, DE	39 09 49.4	75 31 08.7	CP	1958-2004	47
01483720	Puncheon Branch at Dover, DE	39 08 25	75 32 20	CP	1966-75	10

Table 1. Summary of streamgaging stations in and near Delaware for which streamflow statistics were computed.—Continued

[USGS, U.S. Geological Survey, CP, Coastal Plain Physiographic Province; PD, Piedmont Coastal Plain Physiographic Province; ° ´ ˝, degrees, minutes, seconds; N, years of record.]

USGS station number	Name	Latitude ° ′ ″	Longitude ° ′ ″	Region	Peak-flow period	N
01484000	Murderkill River near Felton, DE	38 58 33	75 34 03	CP	1932-3, 1960-85, 1997-99[h]	31
01484002	Murderkill River tributary near Felton, DE	38 58 19	75 33 31	CP	1966-75[h]	10
01484050	Pratt Branch near Felton, DE	39 00 37	75 31 46	CP	1966-75[h]	10
01484100	Beaverdam Branch at Houston, DE	38 54 20.8	75 30 45.9	CP	1958-2004	47
01484270	Beaverdam Creek near Milton, DE	38 45 41	75 16 03	CP	1966-80, 2002-3[bh]	18
01484300	Sowbridge Branch near Milton, DE	38 48 51	75 19 39	CP	1957-78	22
01484500	Stockley Branch at Stockley, DE	38 38 19.9	75 20 31.1	CP	1943-2004[c]	62
01484525	Millsboro Pond outlet at Millsboro, DE	38 35 40.4	75 17 27.7	CP	1987-8, 1992-2004	15
01484550	Pepper Creek at Dagsboro, DE	38 32 50	75 14 40	CP	1960-75[b]	16
01485000	Pocomoke River near Willards, MD	38 23 20.0	75 19 28.0	CP	1950-2004[ch]	55
01485500	Nassawango Creek near Snow Hill, MD	38 13 44.1	75 28 17.2	CP	1950-2004[c]	55
01486000	Manokin Branch near Princess Anne, MD	38 12 50.0	75 40 17.0	CP	1951-71, 1975-2004	50
01486100	Andrews Branch near Delmar, MD	38 26 15	75 31 46	CP	1967-76	10
01486980	Toms Dam Branch near Greenwood, DE	38 48 04	75 33 28	CP	1966-75	10
01487000	Nanticoke River near Bridgeville, DE	38 43 42.0	75 33 42.7	CP	1943-2004[ch]	62
01487500	Trap Pond outlet near Laurel, DE	38 31 40.4	75 28 56.7	CP	1952-75, 2001-4	27
01488000	Holly Ditch near Laurel, DE	38 32 20	75 35 55	CP	1951-56, 1959-61, 1967-75	18
01488500	Marshyhope Creek near Adamsville, DE	38 50 58.9	75 40 23.2	CP	1943-68, 1973-2003[ch]	59
01489000	Faulkner Branch at Federalsburg, MD	38 42 44	75 47 34	CP	1950-91[bh]	42
01490000	Chicamacomico River near Salem, MD	38 30 42.0	75 52 47.7	CP	1951-80, 2003[h]	31
01490600	Meredith Branch near Sandtown, DE	39 02 23	75 41 52	CP	1966-75[h]	10
01490800	Oldtown Branch at Goldsboro, MD	39 01 23	75 47 16	CP	1967-76[h]	10
01491000	Choptank River near Greensboro, MD	38 59 49.9	75 47 08.9	CP	1948-2004[h]	57
01491010	Sangston Prong near Whiteleysburg, DE	38 58 25	75 43 32	CP	1966-75[h]	10
01491050	Spring Branch near Greensboro, MD	38 56 34	75 47 25	CP	1967-76[h]	10

Table 1. Summary of streamgaging stations in and near Delaware for which streamflow statistics were computed.—Continued

[USGS, U.S. Geological Survey, CP, Coastal Plain Physiographic Province; PD, Piedmont Coastal Plain Physiographic Province; ° ´ ˝, degrees, minutes, seconds; N, years of record]

USGS station number	Name	Latitude ° ′ ″	Longitude ° ′ ″	Region	Peak-flow period	N
01492000	Beaverdam Branch at Matthews, MD	38 48 41	75 58 15	CP	1950-81[h]	32
01492050	Gravel Run at Beulah, MD	38 40 54	75 53 53	CP	1966-76[h]	11
01492500	Sallie Harris Creek near Carmichael, MD	38 57 53.6	76 06 31.8	CP	1952-81, 2001-4	34
01492550	Mill Creek near Skipton, MD	38 55 00	76 03 42	CP	1966-76[h]	11
01493000	Unicorn Branch near Millington, MD	39 14 58.9	75 51 40.7	CP	1948-2003[c]	56
01493500	Morgan Creek near Kennedyville, MD	39 16 48.1	76 00 52.4	CP	1951-2004[h]	54
01494000	Southeast Creek at Church Hill, MD	39 07 57	75 58 51	CP	1952-59, 1961-65	13
01495000	Big Elk Creek at Elk Mills, MD	39 39 25.4	75 49 20.5	PD	1884, 1932-2004[h]	73
01495500	Little Elk Creek at Childs, MD	39 38 30	75 52 00	PD	1949-58, 1989,1999	12
01496000	Northeast Creek at Leslie, MD	39 37 40	75 56 40	PD	1949-84, 1999[h]	37
01496080	Northeast River tributary near Charlestown, MD	39 35 53	75 58 37	PD	1967-75	10
01496200	Principio Creek near Principio Furnace, MD	39 37 34	76 02 27	PD	1967-92, 1999[h]	27
01578200	Conowingo Creek near Buck, PA	39 50 35	76 11 45	PD	1963-89, 1991-2004	41
01578400	Bowery Run near Quarryville, PA	39 53 41	76 06 50	PD	1963-81	19
01578500	Octoraro Creek near Rising Sun, MD	39 41 24	76 07 43	PD	1884,1918, 1932-58, 1963, 1965-77, 1999[h]	44
01578800	Basin Run at West Nottingham, MD	39 39 23	76 04 30	PD	1967-76	10
01579000	Basin Run at Liberty Grove, MD	39 39 30	76 06 10	PD	1949-76, 1999[bh]	23

[a] 1966-1981 estimated based on record for station 01467089.

[b] Station not used in regression analysis.

[c] Peak-flow record adjusted for trends.

[d] 1932-55,1978-80,1984-85 estimated based on record for station 01476480.

[e] 1994-2004 estimated based on records for stations 01478245, 01478650, and 01479000.

[f] 1958-68 estimated based on records for station 01480800, 1969-71 estimated based on records for stations 01480800 and 01481000, historical period based on records for station 01481500.

[g] 1912-46 estimated based on records from station 01481000.

[h] Peak-flow record adjusted for historical period.

4. Plot the annual time series to look for unusual observations that will require further investigation and to visually detect monotonic or step trends;

5. Run SWSTAT to perform a Kendall's tau test on the time series to determine if monotonic trends are statistically significant (Helsel and Hirsch, 1992);

6. If necessary, adjust the time series for trends or eliminate the station from further analysis;

7. Run PEAKFQ, applying any necessary historical adjustments, to obtain initial flood-frequency estimates for the station, using the default generalized-skew values provided by the program, which are derived from the Bulletin 17B skew map;

8. Plot the initial flood-frequency curve to determine if it adequately fits the data or if low- or high-outlier thresholds or other adjustments need to be made for the curve to better fit the data (fig. 2); and

9. If necessary, re-run PEAKFQ to apply any adjustments to obtain a satisfactory flood-frequency curve.

Completion of the steps described above resulted in flood-frequency estimates that were based on weighting of the station skew and the Bulletin 17B generalized skew. The station skews from these initial analyses were used to develop an improved method for computing generalized-skew values for the stations used in the study. PEAKFQ was then rerun for each station with the new generalized-skew values replacing the Bulletin 17B skew values to obtain the final flood-frequency estimates for the stations. The following two sections describe methods for handling stations with trends and developing new generalized-skew values, respectively.

Simmons and Carpenter (1978) previously determined flood-frequency statistics for 21 of the stations used in this study by weighting estimates determined from the systematic records for the stations with estimates determined from a rainfall-runoff model. The rainfall-runoff model simulated a longer period of record than the one actually available for the stations. The weighted flood-frequency estimates were also used in the previous regression analysis done by Dillow (1996). Although none of the stations had additional record since either of the two previous reports were published, the weighted flood-frequency estimates were not used in this

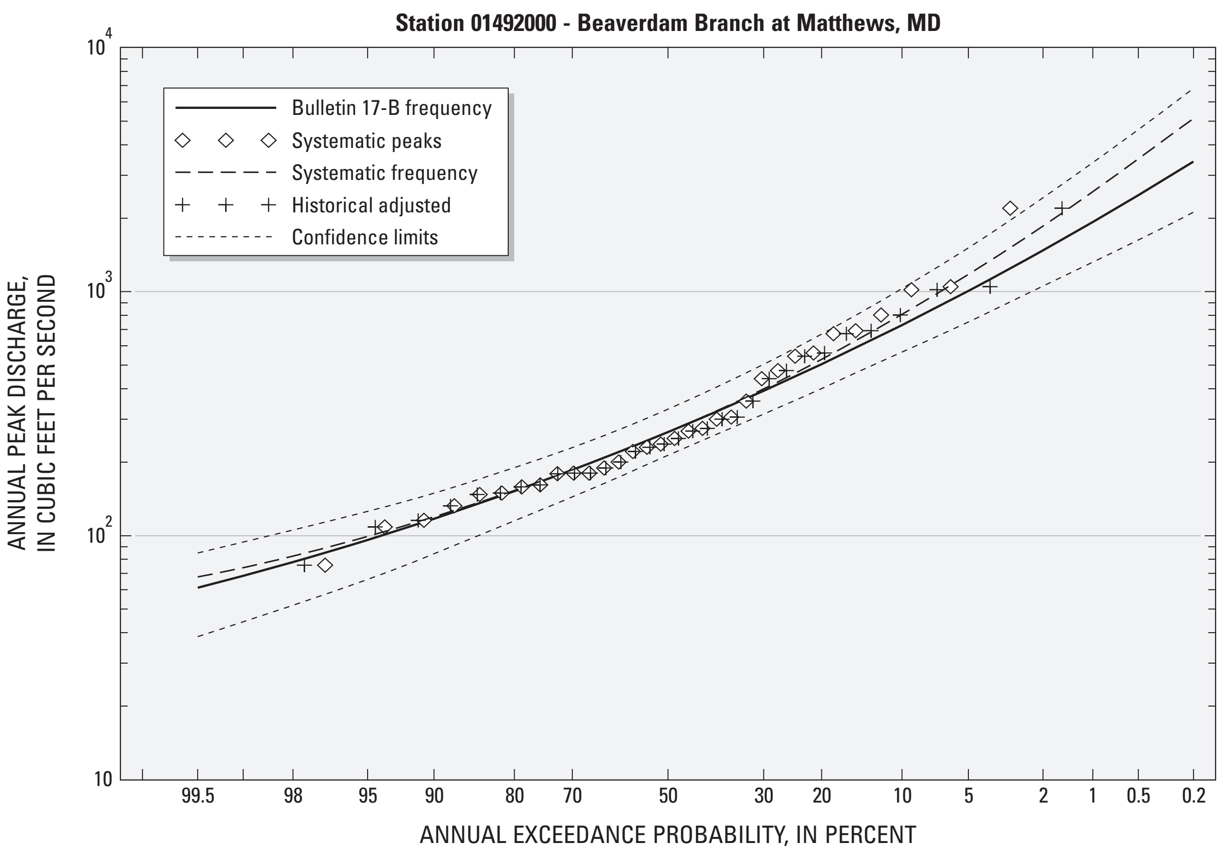

Figure 3. Example flood-frequency curve produced by the PEAKFQ program for Beaverdam Branch at Matthews, Maryland.

analysis because the previous estimates were not determined using the revised generalized-skew values determined for this report.

Analysis of and Adjustments for Trends in Annual Peak-Flow Time Series

Trends in the annual peak flows at a station can affect the reliability and interpretation of the flood-frequency estimates. Plots of the peak-flow time series for a station can show evidence of (1) gradual upward or downward trends, known as monotonic trends; (2) sudden jumps from one condition to another, known as step trends; or (3) trends with more complex patterns. Visual inspection of the plots indicated no stations with step trends or obvious complex patterns, but monotonic trends were evident for several stations.

Kendall's tau tests for monotonic trends (Helsel and Hirsch, 1992) were done on the annual series of peak flows for all stations considered for use in this study. The two primary outputs from the test are the tau value and the probability (p-value) associated with accepting the null hypothesis that there is no trend when, in fact, a trend exists. The tau value measures the strength of the correlation between the annual peak-flow values and time. Positive values of tau indicate increasing trends and negative values indicate decreasing trends. Trends are considered to be significant when the p-value is less than or equal to 0.05. At this p-value, there is a 5-percent likelihood that the test will detect a significant trend when there is no actual trend present.

Usually only a small percentage of stations considered for use in similar regional flood-frequency studies are found to have trends. Because of this, any stations with trends usually are excluded from further analysis to avoid the effort required to treat the trends and to avoid confusion over how to interpret the resulting de-trended statistics. Usually, there are plenty of stations left over to use for regression analyses after the stations with trends are excluded.

The trend tests done for this study identified 18 stations with statistically significant trends (p-values <= 0.05). All stations with significant trends had positive tau values, indicating that peak flows were increasing with time. About half of the trend-affected stations were in and around southern Delaware. The remaining trend-affected stations were distributed throughout the region of study. Removal of the stations with trends from the regional analysis would leave an inadequate dataset to define regional peak-flow frequencies in southern Delaware. As a result, the annual-peak-flow records for stations with trends were further analyzed to determine if climate, land use, or other data could be used as the basis for de-trending the peak-flow data.

First, relations between annual series of peak flows and maximum 24-hour precipitation were examined for the trend-affected stations. Annual series of maximum 24-hour precipitation were obtained for 11 precipitation stations in and around Delaware from the National Oceanic and Atmospheric Administration web site at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_series.html (Bonnin and others, 2004), and Kendall's tau trend tests were performed using these data. Tau values for 9 of the 11 precipitation stations were negative, in contrast to the positive tau values for the trend-affected streamgaging stations during the same time period, but no precipitation trends were statistically significant. From this analysis, it was concluded that the increasing trends in the streamflow data were not related to similar increasing trends in maximum 24-hour rainfall.

Second, relations between annual series of peak flows and housing density were examined for the trend-affected streamgaging stations. Geographic Information System (GIS) coverages of housing-density data for 1960, 1970, 1980, 1990, and 2000 were obtained from The Nature Conservancy (Theobald, 2001). These data were derived from U.S. Census Bureau (2001) data. Average housing density, in homes per acre, was determined for each station for each decadal sample by using GIS to overlay drainage boundaries for the stations on the housing data. Linear interpolation between years of known housing density was then used to estimate average housing density for each year between 1960 and 2000 for each station. Values for 2001 through 2004 were extrapolated based on the rate of change between 1990 and 2000. The annual series of average housing density was related to the annual series of peak flows for each of the 18 streamgaging stations with significant trends in the peak-flow series using scatterplots and regression analyses. The regression analyses indicated statistically significant relations between the two time series for 8 of the 18 trend-affected stations.

As further described in the Explanatory Variable Selection and Measurement section, several GIS datasets were available to indicate the degree of urbanization in the study area. Housing density and population data were the only data that were readily available in 10-year snapshots, enabling interpolation to annual time series and relation to the annual peak-flow time series. The housing density data were considered superior to the population data for use as an indicator of urbanization in Delaware because of the large concentration of vacation homes in coastal areas. Housing density was considered more likely to reflect the existence of these vacation homes and their effect on peak flows than population density, which was not measured for this study. The housing density data are strongly related to the percentage of impervious surfaces, as determined from the impervious cover dataset developed by the USGS as part of the 2001 National Land Cover Dataset (NLCD) (Yang and others, 2003). The impervious data can be downloaded from the web at http://gisdata.usgs.net/website/MRLC/.

The relation between 2000 housing density and 2001 impervious area percentage determined for the streamgaging stations used in this study is shown in figure 4. A polynomial equation fit through the data has an R^2 value of 0.9144. The dependent y variable in the equation in figure 4 is 2000 housing density in homes per acre, and the explanatory x variable is 2001 impervious percentage. The R^2 value, known as the

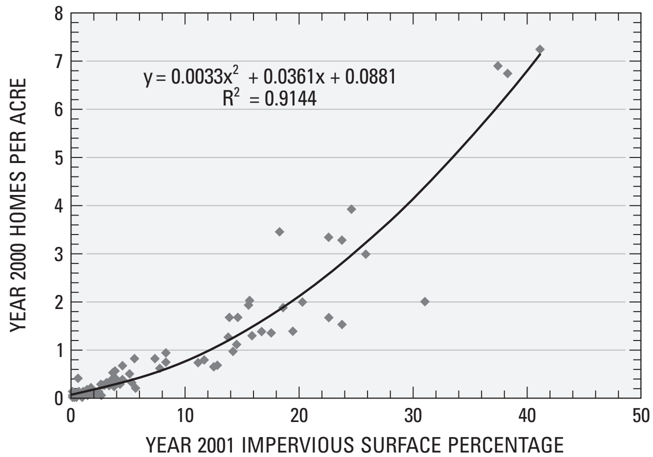

Figure 4. Relation between 2000 housing density and 2001 impervious surface percentage for streamgaging stations in and within 25 miles of Delaware.

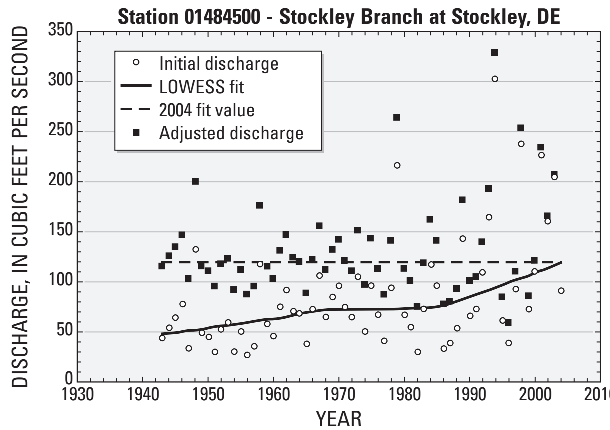

Figure 5. Time-series plot showing adjustment of annual-peak flows for Stockley Branch at Stockley, Delaware for an increasing trend with time.

coefficient of determination, indicates the proportion of the variation in the dependent variable that is explained by the explanatory variable. The standard error of estimate of this relation is 0.38 homes per acre, meaning that two thirds of the estimated homes per acre determined from the equation for stations used in the analysis were within the given standard error of the measured homes per acre for the stations.

Use of the relations between the annual series of peak flows and housing density to de-trend the peak-flow time series would give unsatisfactory results for the stations where the relations were not significant. Although it was not tried, it is also possible that use of only the housing density data to de-trend the peak-flow data would not result in complete removal of the peak-flow trends for these stations. Resources to further investigate other possible physical or climatic mechanisms for the trends were not available.

The peak-flow time series for 11 of the trend-affected stations were adjusted on the basis of time alone. Trend-adjusted peaks were determined for each year by (1) fitting a curve through the actual annual values by use of a LOWESS, or Locally-Weighted Scatterplot Smoothing, algorithm (Helsel and Hirsch, 1992), (2) computing the differences between the actual peaks and the corresponding values from the curve, and (3) subtracting the difference for each year from the 2004 value from the smoothed curve. The adjusted values were then subjected to the standard Bulletin 17B flood-frequency analysis to obtain de-trended estimates of flood frequencies and magnitudes for the trend-affected stations.

An example scatterplot that illustrates the treatment of trends for station 01484500 is shown in figure 5. The original annual time series of peak-flow values are shown as open circles. A solid line is fit through the data by use of the LOWESS algorithm. The trend-adjusted peaks are shown as black squares, with a dashed baseline equal to the 2004 value from the smoothed trend curve.

Information for stations that were affected by trends is provided in table 2. For the 11 stations that were treated for trends, table 2 provides the 2- through 500-year flood-frequency estimates, means, standard deviations, and skew values of the logarithms of the annual peak flows before and after the time series for the stations were treated for trends. In addition, the table provides the change per year for the last 10 years of the trend, in cubic feet per second and in percent, the base discharge used in the analysis, and the percentage change in housing density during the period of record at the station or from 1960 to the end of record for stations with record that precedes 1960. The base discharge is the 2004 value from the smoothed curve through the annual peak-flow values for all stations except station 01488500, where record ended in 2002. The change-per-year values were determined by fitting a regression line through the last 10 values of the time series. These values are useful for evaluating the future reliability of the flood-frequency estimates for the trend-adjusted stations. The time series for 7 of the 18 stations with trends were not adjusted for various reasons. A description of how the seven stations that were not adjusted for trends were treated is also provided in table 2. Asterisks in front of the period-of-record housing density change percentages for 8 of the 18 stations indicate that the relation between the unadjusted annual peak flows and housing density is statistically significant at the 95-percent probability (p-value <= 0.05) for those stations.

In all 11 cases where the time series were adjusted for trends, the adjustments resulted in larger means and smaller standard deviations of the logarithms of the annual-peak flows. The skews were smaller in absolute value for 4 of the

Table 2. Description of treatment of stations with annual peak-flow time series that were affected by trends.

[Recurrence intervals, changes per year, and base discharges are in cubic feet per second; station statistics are in logarithms, base 10; std. dev. is standard deviation; base discharge is trend line value for 2004 except 01488500, which is value for 2002; POR HD change is period-of-record housing density change, in percent; * development-related trend]

Station number	Scenario	Recurrence interval								Station statistics			Change per year	Percent per year	Base discharge	POR HD change
		2	5	10	25	50	100	200	500	Mean	Std. dev.	Skew				
Stations for which trends were adjusted before use in the regression analysis																
01467317	Initial	69	147	217	327	425	537	665	859	1.836	0.393	-0.193				
	Adjusted	210	259	294	342	379	419	460	520	2.329	0.115	0.115	8.67	4.09	212	*6.5
01473169	Initial	1,230	1,930	2,510	3,360	4,100	4,930	5,870	7,310	3.115	0.240	0.803				
	Adjusted	2,040	2,620	3,050	3,650	4,150	4,680	5,260	6,110	3.317	0.165	0.504	73.9	3.56	2,078	69.7
01475000	Initial	114	220	331	537	755	1,050	1,430	2,140	2.090	0.282	0.423				
	Adjusted	211	291	353	444	521	607	703	848	2.347	0.164	1.044	7.49	3.64	206	619
01477800	Initial	1,590	2,710	3,670	5,160	6,510	8,070	9,890	12,800	3.220	0.261	0.533				
	Adjusted	2,440	3,480	4,320	5,560	6,650	7,880	9,280	11,400	3.402	0.182	0.618	37.6	1.56	2,397	36.4
01478500	Initial	3,450	5,720	7,550	10,200	12,500	15,100	18,000	22,200	3.523	0.278	-0.583				
	Adjusted	4,830	6,710	8,190	10,400	12,200	14,300	16,600	20,100	3.655	0.246	-1.820	17.9	0.38	4,757	*227
01484500	Initial	70	115	151	207	256	312	375	472	1.862	0.242	0.465				
	Adjusted	120	160	190	231	264	299	338	393	2.093	0.140	0.722	2.54	2.12	120	*290
01485000	Initial	711	1,020	1,270	1,640	1,970	2,330	2,740	3,370	2.869	0.193	0.399				
	Adjusted	832	1,130	1,360	1,700	1,980	2,300	2,650	3,180	2.935	0.163	0.510	3.32	0.40	831	*200
01485500	Initial	584	966	1,250	1,640	1,960	2,290	2,640	3,130	2.763	0.262	-0.166				
	Adjusted	827	1,180	1,430	1,770	2,040	2,330	2,640	3,070	2.925	0.176	0.274	11.3	1.38	818	*340
01487000	Initial	630	1,100	1,500	2,100	2,630	3,240	3,930	4,990	2.811	0.278	0.269				
	Adjusted	1,000	1,440	1,780	2,290	2,720	3,200	3,740	4,550	3.019	0.177	0.802	21.4	2.17	989	120
01488500	Initial	1,040	1,940	2,630	3,560	4,290	5,050	5,820	6,880	2.992	0.334	-0.555				
	Adjusted	2,160	2,830	3,260	3,780	4,160	4,540	4,900	5,390	3.330	0.135	-0.251	38.7	1.82	2,131	*100
01493000	Initial	334	627	878	1,260	1,600	1,990	2,440	3,110	2.529	0.320	0.076				
	Adjusted	622	879	1,080	1,390	1,650	1,940	2,280	2,790	2.805	0.189	-0.007	18.3	2.93	625	230
Stations with trends that were not used in the regression analysis and reasons for not using them																
01467089	Combined with upstream station 01467087; 1966-80 peaks at station 01467087 estimated based on flow per unit area at station 01467089.															1.6
01467160	No record since 1988 to indicate if trend adjustment is still appropriate.															609
01482310	Development-related trend with no record since 1975 to indicate if trend adjustment is still appropriate.															97.0
01484270	Large break in record results in uncertainty in appropriateness of trend adjustment.															*345
01484550	Development-related trend with no record since 1975 to indicate if trend adjustment is still appropriate.															*35.0
01489000	No record since 1991 to indicate if trend adjustment is still appropriate.															100
01579000	Large break in record and no record since 1999 to indicate if trend adjustment is still appropriate.															113

11 stations after adjustment. The trend-adjusted flood-frequency estimates were all higher in discharge for recurrence intervals of 2 years or less and lower in discharge for the 200- and 500-year recurrence intervals than the non-trend-adjusted estimates. Trend-adjusted flood-frequency estimates for recurrence intervals between 5 and 100 years were sometimes lower and sometimes higher in discharge than those for the non-trend-adjusted estimates.

Housing density increased from 1960 to 2000 for all 116 stations considered for use in this study except for 2 stations, where housing density was constant. The average increase in housing density, over the period of record for the stations or between 1960 and the end of the period of record for stations with record prior to 1960, was 121 percent. The maximum increase was 619 percent at station 01475000, and the standard deviation was 130 percent. Interestingly, the relation between the unadjusted annual peak flows and housing density was not statistically significant at station 01475000, but the relation was statistically significant at station 01467317, which had an increase in housing density of only 6.5 percent.

Several other investigators have hypothesized a strong relation between the magnitude of peak flows and the degree of urbanization (for example, Beighley and Moglen, 2003; National Resources Conservation Service, 1986; and Sauer and others, 1983), so it is somewhat surprising that only 17 of the 116 stations considered for use in this study had statistically significant trends in annual peak flows, and that only 8 of those trends could be attributed to urbanization. Numerous other USGS peak-flow studies have found similarly small numbers of stations with trends in annual peak-flow time series, however. For instance, recent flood-frequency studies for Illinois (Soong and others, 2004), Ohio (Koltun, 2003), Vermont (Olson, 2002), and West Virginia (Wiley and others, 2000) found 50 of 288 stations, 34 of 305 stations, 0 of 138 stations, and 10 of 160 stations affected by positive trends, respectively. Although the other studies did not compare the annual peak-flow time series to annual time series of housing density or other indicators of development, the generally very small percentage of stations with trends may indicate that either better methods are needed to detect trends that are actually present or the relation between the magnitude of peak flows and the degree of urbanization needs further investigation.

Regional Skew Analysis

As mentioned previously, the skew coefficient describes the curvature of the peak-flow frequency curve used to describe the annual peak-flow series from a streamgaging station. The value of skew is highly influenced by large events, and the addition of a single large value to the annual peak-flow time series for a station with a short record length can have a large influence on the skew. Also, a localized large event can have a large influence on the skew for an individual station. This causes large variations in skew between stations. Because of this, it is advantageous to improve the accuracy of the skew coefficient for any station by considering not only data from that station, but also information from other nearby stations. For the purpose of discussion, the station skew is defined as the skew calculated using the annual peak-flow series from that station alone. The generalized skew is defined as a skew coefficient associated with a defined region, calculated using the station skews from all stations in the region. A weighted skew, calculated using the station skew and a generalized skew, is used to calculate the flood-frequency statistics used in regression analyses to produce the peak-flow estimation equations for ungaged sites presented in this report.

The calculations of the station skew and the weighted skew are performed using the peak-flow series for an individual station and the equations and methods given in Bulletin 17B. Generalized skew can also be obtained from a national map of generalized-skew values included in Bulletin 17B; however, that map was prepared at a national scale using data and methods that are now more than 30 years old. It is generally preferable for regional studies of flood frequency to include a regional analysis of station skews to either confirm the reasonableness of using the Bulletin 17B skew map or to generate more accurate generalized-skew values using the latest available station skews (Interagency Advisory Committee on Water Data, 1982, Plate 1). Bulletin 17B provides the following recommendations with regard to the data and methods to be used for a generalized-skew analysis:

1. Data from at least 40 stations, or all stations within a 100-mi radius of the study region should be used in the analysis;
2. Each station providing data for the analysis should have at least 25 years of peak-flow record;
3. The recognized analytical methods for calculating generalized skew, in order of preference, are (a) development of skew isolines, (b) development of skew prediction equations, and (c) calculation of the mean station-skew value.

A generalized-skew analysis using these guidelines was performed as part of the study. The steps followed, as well as the results, are discussed below.

From the dataset of 116 stations considered for use in this flood-frequency study, 53 of them had 25 or more years of peak-flow record and were suitable for use in the initial skew analysis. Graphical analysis indicated that the station-skew data associated with these sites is unbiased and approximately normally distributed.

The station skews for the 53 stations were plotted on a map (fig. 6), which was visually inspected for spatial patterns in the skew values. To create the map, the stations were separated into six bins based on the magnitude of the skew value. The three bins with the smallest skew values were shown on the map with circular symbols in shades of red, with the size of the circle and the intensity of the color increasing as the skew value decreased. The three bins with the largest skew values were shown on the map with circular symbols