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Analysis of Flood-Magnitude and Flood-Frequency Data for Streamflow-Gaging Stations in the Delaware and North Branch Susquehanna River Basins in Pennsylvania

Open-File Report 2007-1235

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

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
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)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]

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

°F=(1.8×°C)+32

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 the North American Vertical Datum of 1988 (NAVD 88).

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

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

Analysis of Flood-Magnitude and Flood-Frequency Data for Streamflow-Gaging Stations in the Delaware and North Branch Susquehanna River Basins in Pennsylvania

By Mark A. Roland and Marla H. Stuckey

Abstract

The Delaware and North Branch Susquehanna River Basins in Pennsylvania experienced severe flooding as a result of intense rainfall during June 2006. The height of the flood waters on the rivers and tributaries approached or exceeded the peak of record at many locations. Updated flood-magnitude and flood-frequency data for streamflow-gaging stations on tributaries in the Delaware and North Branch Susquehanna River Basins were analyzed using data through the 2006 water year to determine if there were any major differences in the flood-discharge data. Flood frequencies for return intervals of 2, 5, 10, 50, 100, and 500 years (Q2, Q5, Q10, Q50, Q100, and Q500) were determined from annual maximum series (AMS) data from continuous-record gaging stations (stations) and were compared to flood discharges obtained from previously published Flood Insurance Studies (FIS) and to flood frequencies using partial-duration series (PDS) data.

A Wilcoxon signed-rank test was performed to determine any statistically significant differences between flood frequencies computed from updated AMS station data and those obtained from FIS. Percentage differences between flood frequencies computed from updated AMS station data and those obtained from FIS also were determined for the 10, 50, 100, and 500 return intervals. A Mann-Kendall trend test was performed to determine statistically significant trends in the updated AMS peak-flow data for the period of record at the 41 stations. In addition to AMS station data, PDS data were used to determine flood-frequency discharges. The AMS and PDS flood-frequency data were compared to determine any differences between the two data sets. An analysis also was performed on AMS-derived flood frequencies for four stations to evaluate the possible effects of flood-control reservoirs on peak flows. Additionally, flood frequencies for three stations were evaluated to determine possible effects of urbanization on peak flows.

The results of the Wilcoxon signed-rank test showed a significant difference at the 95-percent confidence level between the Q100 computed from AMS station data and the Q100 determined from previously published FIS for 97 sites. The flood-frequency discharges computed from AMS station data were consistently larger than the flood discharges from the FIS; mean percentage difference between the two data sets ranged from 14 percent for the Q100 to 20 percent for the Q50. The results of the Mann-Kendall test showed that 8 stations exhibited a positive trend (i.e., increasing annual maximum peaks over time) over their respective periods of record at the 95-percent confidence level, and an additional 7 stations indicated a positive trend, for a total of 15 stations, at a confidence level of greater than or equal to 90 percent. The Q2, Q5, Q10, Q50, and Q100 determined from AMS and PDS data for each station were compared by percentage. The flood magnitudes for the 2-year return period were 16 percent higher when partial-duration peaks were incorporated into the analyses, as opposed to using only the annual maximum peaks. The discharges then tended to converge around the 5-year return period, with a mean collective difference of only 1 percent. At the 10-, 50-, and 100-year return periods, the flood magnitudes based on annual maximum peaks were, on average, 6 percent higher compared to corresponding flood magnitudes based on partial-duration peaks.

Possible effects on flood peaks from flood-control reservoirs and urban development within the basin also were examined. Annual maximum peak-flow data from four stations were divided into pre- and post-regulation periods. Comparisons were made between the Q100 determined from AMS station data for the periods of record pre- and post regulation. Two stations showed a nearly 60- and 20-percent reduction in the 100-year discharges; the other two stations showed negligible differences in discharges. Three stations within urban basins were compared to 38 stations without significant urbanization. The Q100 was determined for each station and subsequently divided by its respective drainage area, producing a yield (cubic feet per second per square mile) for each station. The mean yield for the three urban sites was 365 $(ft^3/s)/mi^2$ compared to 174 $(ft^3/s)/mi^2$ for the non-urban sites.

Introduction

As a result of intense rainfall from June 23 through June 29, 2006, the Delaware and North Branch Susquehanna River Basins in Pennsylvania experienced severe flooding. The height of the flood waters on the rivers and tributaries approached or exceeded the peak of record at many locations, prompting a Presidential disaster declaration on June 30, 2006. This was the third major flood along the Delaware River in 22 months. In response to this flooding, the Department of Homeland Security, Federal Emergency Management Agency (FEMA) Region III, and the U.S. Geological Survey (USGS) Pennsylvania Water Science Center began a study to analyze flood-magnitude and flood-frequency data for streamflow-gaging stations (stations) on tributaries within the Delaware and North Branch Susquehanna River Basins in Pennsylvania.

This study updates and compares flood frequencies determined from annual maximum series (AMS) data from continuous-record stations to flood discharges obtained from previously published Flood Insurance Studies (FIS) to determine whether there were any major differences in the flood-discharge data. The study also computes flood frequencies using partial-duration series (PDS) data to determine how the use of this PDS data may affect the flood frequencies compared to those determined using the AMS data. The potential effects of regulation and urbanization also were included in the study.

Purpose and Scope

This report presents the results of (1) a comparison of updated AMS-derived flood-frequency discharges and flood discharges from previously published FIS, (2) a comparison of flood-frequency discharges computed using updated AMS and PDS peak-flow data, and (3) an analysis of the potential effects of regulation and urbanization on updated AMS-derived flood frequencies in the Delaware and North Branch Susquehanna River Basins. A flood-frequency analysis with recurrence intervals of 2, 5, 10, 50, 100, and 500 years (Q2, Q5, Q10, Q50, Q100, and Q500, respectively) was performed for 41 stations in the Delaware and North Branch Susquehanna River Basins in Pennsylvania (fig. 1) (appendix 1). Thirty-six of the 41 stations had 30 or more years of continuous record; the other 5 stations had 25 or more years of record.

A Wilcoxon signed-rank test was performed to determine any statistically significant differences between flood frequencies computed from updated AMS station data and flood frequencies obtained from FIS. Percentage differences between flood frequencies computed from updated AMS station data and those flood frequencies obtained from FIS also were calculated for the 10-, 50-, 100-, and 500-year return intervals. A Mann-Kendall trend test was performed to determine any statistically significant trends in the updated AMS peak-flow data for the period of record at the 41 stations. In addition to AMS station data, PDS data were used to determine flood-frequency discharges. The AMS and PDS flood-frequency data were compared to determine any differences between the two data sets. An analysis was performed on AMS-derived flood frequencies for four stations to evaluate the possible effects of flood-control reservoirs on peak flows. Additionally, flood frequencies for three stations were evaluated to determine possible effects of urbanization on peak flows.

Previous Studies

Bulletin 17B of the Interagency Advisory Committee on Water Data (Water Resources Council, Hydrology Committee, 1981) outlines procedures for performing flood-frequency analysis of annual maximum peaks. Flood Insurance Study Reports have been developed for many communities in the Commonwealth and are available from the Federal Emergency Management Agency (2006).

Methodology Used in Analysis

A USGS computer program, PeakFQ, utilizing the LP3 frequency distribution, was used to determine flood-frequency discharges (Kathleen Flynn, U.S. Geological Survey, written commun., 2005) at 41 streamflow-gaging stations within the Delaware and North Branch Susquehanna River Basins in Pennsylvania. This program performs statistical flood-frequency analyses of AMS data following procedures recommended in Bulletin 17B (Water Resources Council, Hydrology Committee, 1981). The flood-frequency analysis is sensitive to the number of annual maximum peaks used in the analysis, and the resulting flood-frequency discharge can be skewed either high or low by dominant wet or dry periods, respectively. Stations having a minimum of 30 years of record through the 2006 water year[1] were used to limit the effect of possible bias associated with shorter periods of record. The exceptions were five stations having a minimum of 25 years record; four of these stations are subject to flood-control regulation and the period of record after regulation was used to reflect current conditions, the remaining station had a non-continuous period of record (with a collective total of 25 years). These stations along with their respective periods of record are identified in appendix 1. The peak-flow data from water year 2006 was provisional at the time of the analysis and is subject to change; however, it was used in the analysis to include the June 2006 flooding in the Delaware and North Branch Susquehanna River Basins.

To compare flood frequencies derived from AMS station data to those compiled from FIS, an initial list of 117 sites from FIS within a 10-mi radius of any of the 41 streamflow-gaging stations was compiled by FEMA Region III (Dana Moses, Federal Emergency Management Agency Region III, written commun., 2006). Four streamflow-gaging stations did not have any associated FIS data and were removed from the analysis. Flood-frequency discharges were computed for the remaining 37 sta-

[1] A water year is the 12-month period from October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 2006, is called the "2006 water year."

Figure 1. Streamflow-gaging stations used in the analysis of flood-magnitude and flood-frequency data in the Delaware and North Branch Susquehanna River Basins, Pennsylvania.

tions using recommended procedures (Water Resources Council, Hydrology Committee, 1981). The flood frequencies were then transferred from the 37 streamflow-gaging stations to the 117 sites from the FIS using drainage-area ratios. Twenty of these sites were removed from the analysis because they were outside the recommended range of 0.5 to 1.5 times the drainage area of the station for drainage-area ratio transfers (Stuckey and Reed, 2000). A total of 97 sites from 37 station-based FIS were used in the analysis. From these 97 sites, FEMA Region III identified 59 sites where flood frequencies were determined using station data, labeled as Log-Pearson Type III (LP3) or Bulletin 17B. The remaining 38 sites either utilized other methods to compute flood frequencies or the method used was unknown.

Flood frequencies and data were compared and analyzed using the Wilcoxon signed-rank test, percentage differences, and the Mann-Kendall test. The Wilcoxon signed-rank test is a nonparametric test that was used to determine whether the flood frequencies computed from AMS station data and those from the FIS were significantly different (Helsel and Hirsch, 1992). Percentage differences between flood frequencies determined from AMS station data and the FIS were determined for Q10, Q50, Q100, and Q500. However, there were instances when only the FIS Q100 was available for comparison to the corresponding AMS-derived flood frequency. The Mann-Kendall test is a nonparametric test used to detect trends within data sets (Helsel and Hirsch, 1992). It was performed on the annual maximum peaks for each of the 41 stations to determine if a positive trend existed, increasing annual peak flows over the period of record. The Wilcoxon signed-rank and Mann-Kendall tests were performed using a 95-percent confidence interval to provide a reasonable balance between maximizing the probability of finding significant differences between the data sets and minimizing the probability of failing to find any significant differences that exist.

In addition to AMS station data, PDS data were used to determine flood magnitudes and frequencies. PDS data include all peaks above a base discharge. The base discharge at each station is selected such that, on average, three independent peak discharges, including the annual maximum, exceed the base discharge each water year (Langbein and Iseri, 1960).

The partial-duration peak discharges for 41 stations in the Delaware and North Branch Susquehanna River Basins were compiled and examined. Five stations were removed from the analyses because of an insufficient number of partial-duration peaks.

Flood frequencies using PDS data were determined using the PeakFQ software and modifying the results. Because the PeakFQ program was designed to process AMS data, it has certain inherent characteristics that make it more difficult for PDS analysis. One such processing characteristic is that the number of peaks per station can not exceed 180. While this limitation was not an issue with the AMS data sets, there were some instances when the number of partial-duration peaks for an individual station exceeded this value. Although other methods may exist regarding the processing of PDS data by PeakFQ, the method implemented in this study consisted of PDS data-set reduction based on peak-flow distribution. Beginning with the lowest peaks within a PDS data set, duplicated values were removed until the data set was reduced to 180. The distribution of flows within a partial-duration peak data set tends to be skewed toward the lower end, where relatively smaller flows are more numerous, are closer in value, and are more likely to be duplicated. A sensitivity analysis was not performed to analyze the potential implications of a reduced PDS data set on the PeakFQ results.

After the necessary data sets were reduced to 180 values, the partial-duration peaks were processed by PeakFQ to determine flood magnitudes and frequencies. The Bulletin 17B procedures treat the occurrence of flooding at a site as a sequence of annual random events or trials (Kathleen Flynn, U.S. Geological Survey, written commun., 2005). Because each PDS year had more than one peak, the results needed to be normalized on the basis of the average number of peaks per year (r-value) for each station. For instance, if a station has observed flow for 61 years during which 166 partial-duration peaks were recorded, its resulting r-value would be 166/61 = 2.72. The application of this value to the PeakFQ results consisted of dividing the return periods (for example; 2, 5, and 10) by the r-value; resulting in adjusted return periods (for example; 0.74, 1.84, and 3.68, respectively) being estimated for designated discharges. After the adjusted return periods were obtained, the desired return periods and associated discharges were calculated by interpolation. The following example shows the steps involved with the normalizing process for one station:

Example:

1. Station: 01451500, Lehigh River at Walnutport, Pa.
2. Period of record: 1946–2006 (61 years)
3. Number of partial-duration peaks: 166
4. r-value = number of partial-duration peaks/number of years of record

   r-value = 166/61

   r-value = 2.72

Example of PeakFQ results with adjusted return periods for streamflow-gaging station 01451500 with 61 years of record and 166 partial-duration peaks.

Annual exceedence probability	Return period	Adjusted return period (Return Period / r-value)	Discharge (cubic feet per second)
0.995	1.005	0.37	250
.99	1.010	.37	272
.95	1.053	.39	360
.9	1.111	.41	431
.8	1.250	.46	553
.5	2	.74	987
.2	5	1.84	2,040
.1	10	3.68	3,180
.04	25	9.19	5,360
.02	50	18.4	7,710
.01	100	36.8	10,900
.005	200	73.5	15,200
.002	500	184	23,300

5. Calculate the desired return periods and associated discharges by interpolation for comparison to the AMS PeakFQ results for the 2-, 5-, 10-, 50-, and 100-year return periods.

Example of interpolated return periods and discharges for streamflow-gaging station 01451500 with 61 years of record and 166 partial-duration peaks.

Desired Return Period	Discharge (cubic feet per second)
2	2,140
5	3,700
10	5,560
50	12,500
100	17,200

Four stations (three in the North Branch Susquehanna River Basin and one in the Delaware River Basin) were effected by flood-control reservoirs. Annual maximum peak-flow data from these four stations were divided into pre- and post-regulation periods to analyze the effects of flood-control reservoirs on flood peaks. A minimum of 10 percent of the watershed subjected to regulation was used as a threshold to divide the period of record.

Land-use data at the 41 stations in the North Branch Susquehanna and Delaware River Basins were compiled and examined. Only three of the stations had urban land use greater than 50 percent. To explore the effects of urban development on peak discharges, the 3 stations with urban land use greater than 50 percent were compared to the 38 stations with lower percentages of urbanization.

Analysis of Flood Magnitudes and Flood Frequencies

Annual Maximum Peak Discharges

The results of the Wilcoxon signed-rank test (p-value = 0.00) on data from 97 sites showed a significant difference at the 95-percent confidence level between the transferred Q100 computed from AMS station data and the Q100 determined from previously published FIS. The Wilcoxon signed-rank test also was done on the 59 sites identified by FEMA Region III as using station data to determine Q100, and again, the results (p-value = 0.00) showed a significant difference between the two data sets.

For the 97 sites used in the comparison, the flood-frequency discharges computed from AMS station data were consistently larger than the flood discharges from the FIS. The mean percentage difference between the two data sets ranged from 14 percent for the Q100 to 20 percent for the Q50 (table 1). Twenty of the 97 sites did not have Q10, Q50, and Q500 flood discharges available in the FIS. The complete comparison between the data sets is shown in appendix 2. The relation between the Q100 from the FIS and the transferred Q100 determined from AMS station data is shown in figure 2. As the discharge magnitudes increase, the transferred Q100 determined from AMS station data consistently is greater than the Q100 from the FIS (fig. 2).

Of the 97 sites, 59 sites were identified by FEMA Region III as having flood frequencies determined using station data. Mean values were computed for the Q10, Q50, Q100, and Q500 and were compared to corresponding mean values determined from AMS station data. The mean percentage difference between the two data sets ranged from 16 percent for the Q100 to 21 percent for the Q10 (table 1). Fourteen of the 59 sites did not have Q10, Q50, and Q500 data available in the FIS. A possible explanation for the higher flood-frequency discharges associated with the AMS station data could be the inclusion of recent peak-flow data; flood-insurance studies completed prior to the recent flood events would not have incorporated these data into their flood-frequency estimates.

Table 1. Mean percentage difference between flood-peak discharge estimates determined from annual maximum series station data[1] and Flood Insurance Studies[2], Delaware and North Branch Susquehanna River Basins, Pennsylvania.

Summary Statistic	Recurrence Interval			
	10-year	50-year	100-year	500-year
All methods[3]				
Mean	17	20	14	19
Count	77	77	97	77
Gaging-station methods[4]				
Mean	21	20	16	18
Count	45	45	59	45

[1]Flood-frequency magnitudes computed from gaging-station data based on Log-Pearson Type III distribution of annual maximum peaks and transferred to sites using drainage-area ratios.

[2]Flood-frequency magnitudes from Flood Insurance Studies compiled by Dana Moses (Federal Emergency Management Agency, written commun., 2005).

[3]All methods refers to any method for determining flood-frequency magnitudes from the compiled Flood Insurance Studies.

[4]Gaging-station methods refers to methods for determining flood-frequency magnitudes from the compiled Flood Insurance Studies as Log Pearson Type III or Bulletin 17B, which are based on gaging-station data.

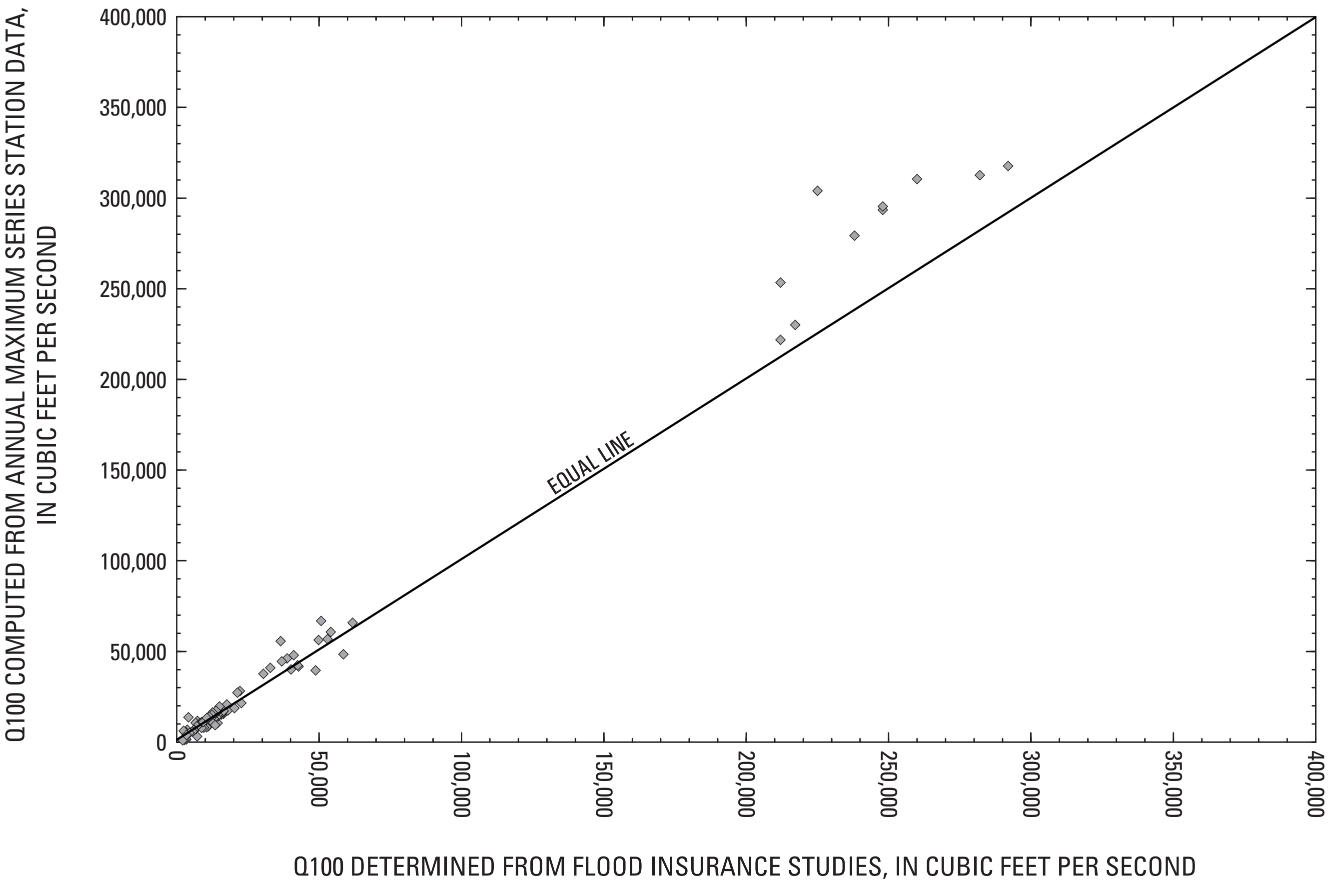

Figure 2. Relation between the 100-year recurrence interval flood-peak discharges from Flood Insurance Studies and from U.S. Geological Survey streamflow-gaging-station data, Delaware and North Branch Susquehanna River Basins, Pennsylvania.

The results of the Mann-Kendall test showed that eight stations exhibited a positive trend (increasing annual maximum peaks over time over their respective periods of record at the 95-percent confidence level) (table 2). It is worth noting that the analyses for an additional seven stations indicated a positive trend, for a total of 15 stations, at a confidence level of greater than or equal to 90 percent. This positive trend could be attributed to a number of different factors, including increased intensity short-term rainfall, increased impervious surface, or urbanization, within the basin.

Table 2. Stations with significant positive trends in annual maximum peak flows over period of record, Delaware and North Branch Susquehanna River Basins, Pennsylvania.

U.S. Geological Survey station identification number	Station name	Period of record	Level of significance (p-value)
95-percent confidence level			
01438300	Vandermark Creek at Milford, Pa.	1962-2006	0.03
01439500	Bush Kill at Shoemakers, Pa.	1909-2006	.01
01440300	Mill Creek at Mountainhome, Pa.	1961-2006	.01
01447720	Tobyhanna Creek near Blakeslee, Pa.	1962-2006	.03
01451500	Little Lehigh Creek near Allentown, Pa.	1946-2006	.00
01452000	Jordan Creek at Allentown, Pa.	1945-2006	.04
01471980	Manatawny Creek near Pottstown, Pa.	1975-2006	.01
01473900	Wissahickon Creek at Fort Washington, Pa.	1962-2006	.00
90-percent confidence level			
01442500	Brodhead Creek at Minisink Hills, Pa.	1970-2006	.10
01447680	Tunkhannock Creek near Long Pond, Pa.	1966-2006	.08
01452500	Monocacy Creek at Bethlehem, Pa.	1945-2006	.07
01516500	Corey Creek near Mainesburg, Pa.	1955-2006	.08
01531500	Susquehanna River at Towanda, Pa.	1980-2006	.10
01532000	Towanda Creek near Monroeton, Pa.	1914-2006	.06
01540500	Susquehanna River at Danville, Pa.	1980-2006	.06

Partial-Duration Peak Discharges

The partial-duration peak discharges for 41 stations in the Delaware and North Branch Susquehanna River Basins were compiled and examined. Five stations were removed from the analyses because of an insufficient number of partial-duration peaks. Hydrologic data from stations with regulated flow were divided into pre- and post-regulation periods. Because a focus of this study was primarily on current conditions, two stations were analyzed only on the basis of their post-regulated discharge period: 01531500 Susquehanna River at Towanda, Pa. (1980-2006), and 01536500 Susquehanna River at Wilkes-Barre, Pa. (1980-2006).

The Q2, Q5, Q10, Q50, and Q100 determined from AMS and PDS data for each station, along with their respective percentage differences, are shown in appendix 3. The mean values of the collective percentage differences for the various flood frequencies are shown in table 3. The flood magnitudes for the 2-year return period are 16 percent higher when partial-duration peaks are incorporated into the analyses, as opposed to using only the annual maximum peaks. The discharges tend to converge around the 5-year return period; the mean collective difference was only -1 percent for the 5-year return period. At the 10-year return period, the discharges associated with the PDS data are slightly lower (-5 percent) than when the AMS data are used. This trend continues for the 50- and 100-year return periods, where the differences between the PDS and AMS data are -7 and -6 percent, respectively.

Table 3. Mean percentage difference between flood-frequency magnitudes determined from partial-duration and annual maximum series peak flow data, Delaware and North Branch Susquehanna River Basins, Pennsylvania.

Number of stations used in analysis	Recurrence interval				
	2-year	5-year	10-year	50-year	100-year
36	16	-1	-5	-7	-6

The relation of the results appears to be attributed to the larger number of lower magnitude peaks that are included in the partial-duration peak-flow data sets. Typically, recurrence intervals based on PDS and AMS data sets tend to converge after about 10 years. In ordinary hydrologic analysis, a 5 percent difference may be considered tolerable (Chow, 1964). Taking into consideration the 5-percent tolerance, the results of this analysis generally appear to support the conclusion that although differences may exist between the PDS and AMS flood-peak discharges for the lower return periods, the effect is not as significant at the higher return periods.

Possible Effects of Regulation and Urbanization

In an attempt to analyze the effects of flood-control reservoirs upstream of stations on the flood peaks, annual maximum peak-flow data from three stations on the Susquehanna River (01531500, 01536500, and 01540500) and one station on Tulpehocken Creek (01471000), a tributary to the Schuylkill River, were divided into pre- and post-regulation periods. A minimum of 10 percent of the watershed subjected to regulation was used as a threshold to divide the periods of record for the stations. Reservoir operating procedures were not taken into consideration. Comparisons were made between the Q100 determined from AMS station data for the pre- and post-regulation periods of record. The results for station 01471000 Tulpehocken Creek near Reading and station 01531500 Susquehanna River at Towanda showed a nearly 60- and 20-percent reduction in the 100-year discharges, respectively. The results for station 01536500 Susquehanna River at Wilkes-Barre and station 01540500 Susquehanna River at Danville showed negligible differences in discharges.

This variability in results of the pre- and post-regulation comparison may be attributed to the length of respective periods of record and the percentage of basin previously influenced by regulation. For instance, the three Susquehanna River stations all had significantly longer periods of record associated with pre-regulation than with post-regulation. A shorter period of record is more likely to be influenced by either a dominant wet or dry period, which could bias the associated discharges. Secondly, with regard to percentage of basin previously influenced by flow regulation, a station is not categorized as a flow-regulated site until the percentage regulation is equal to or greater than 10 percent of the drainage area. Flows from each of the three Susquehanna River stations had previously been influenced by the effect of flow regulation (to varying degrees) prior to reaching the threshold of 10 percent. As a result, a station that had been subjected to increasing percentages of flow regulation over time may have experienced a resulting attenuation in flow discharge. This appears to be the case with stations 01536500 and 01540500, which had experienced higher degrees of flow regulation compared to station 01531500. This attenuation could have affected the pre-regulated Q100 to the degree that once the station was classified as regulated, the post-regulated Q100 discharge may not be noticeably different.

The drainage basins of each of the 41 stations included in this study have a percentage urban of less than 50 percent except for the basins of three stations in the Philadelphia area: 01465798 Poquessing Creek at Grant Ave. at Philadelphia, 01467048 Pennypack Creek at Lower Rhawn St. Bridge, Philadelphia, and 01473900 Wissahickon Creek at Fort Washington, which have percentages urban of 76, 74, and 54, respectively. The analyses of urban flood characteristics associated with these sites consisted of a comparison of the urban to non-urban Q100 yield and a hydrograph comparison for the June 2006 peak-flow event.

To explore the potential effects of urban development on peak discharges, the 3 stations with higher percentages of urbanization were compared to the 38 stations without significant urbanization. The Q100 was determined for each station and subsequently divided by its respective drainage area, producing a yield (cubic feet per second per square mile) for each station. The Q100 yields for the urban sites ranged from 290 to 460 $(ft^3/s)/mi^2$, compared to a range of 28 to 426 $(ft^3/s)/mi^2$ for the non-urban sites. Mean yields were then calculated for the urban and non-urban sites. The mean yield for the three urban sites was 365 $(ft^3/s)/mi^2$ compared to 174 $(ft^3/s)/mi^2$ for the non-urban sites, a difference of almost 110 percent.

The hydrologic response of a watershed affected by urban development may differ from that of a drainage basin relatively unaffected by anthropogenic influences. This hydrologic response is likely to be most noticeable under peak-flow conditions through higher peaks with larger flood volumes. To examine this, hydrographs were developed for an urban station (01473900) and a non-urban station (01471980) for the June 28, 2006, peak-flow event (fig. 3). The stations selected were comparable in drainage area and geographic location, and the June 2006 flood ranked in the top five flood events of record at both. Urban development for these two basins comprises approximately 50 percent for the urban station and 2 percent for the non-urban station of their respective drainage areas. As evidenced from figure 3, the hydrographs differ in the sense that flow in the urban setting (station 01473900 Wissahickon Creek at Fort Washington) reached a higher peak than the non-urban station (01471980 Manatawny Creek near Pottstown).

The analyses presented may not be solely a function of urbanization. Other factors, such as period of record, geology, rainfall intensity, or base-flow characteristics, also may have contributed to the observed effects. Further analyses with additional stations would be needed to more adequately define the effects of urbanization.

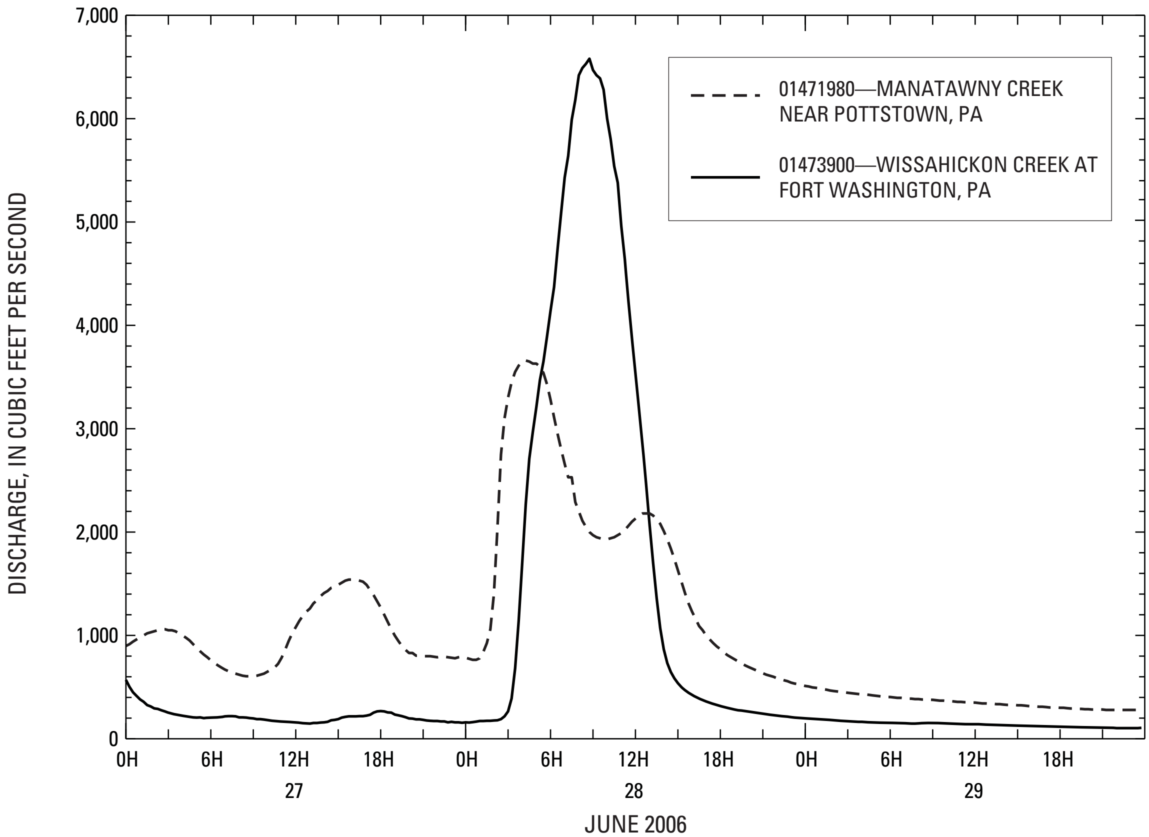

Figure 3. Hydrograph of June 28, 2006, flood for streamflow-gaging stations 01473900 Wissahickon Creek at Fort Washington and 01471980 Manatawny Creek near Pottstown, Pennsylvania.

Summary

The Delaware and North Branch Susquehanna River Basins in Pennsylvania experienced severe flooding as a result of intense rainfall occurring June 23, 2006, through June 29, 2006. The height of the flood waters on the rivers and tributaries approached or exceeded the peak of record at many locations. Updated flood-magnitude and flood-frequency data for streamflow-gaging stations (stations) were analyzed using data through the 2006 water year on tributaries within the Delaware and North Branch Susquehanna River Basins in Pennsylvania. Flood frequencies determined from annual maximum series (AMS) data from continuous-record stations were compared to flood discharges obtained from previously published Flood Insurance Studies (FIS) to determine whether there were any major differences in the flood-discharge data. The flood frequencies were compared using the Wilcoxon signed-rank test and percentage differences. The Mann-Kendall test was used to analyze trends in the AMS station data. Flood frequencies were computed using partial-duration series (PDS) data to determine how the use of PDS data may affect the flood frequencies compared to those determined using AMS data. The potential effects of regulation and urbanization also were included in the study.

The results of the Wilcoxon signed-rank test on data from 97 sites showed a significant difference between the Q100 computed from the AMS station data through the 2006 water year and the Q100 determined from previously published FIS. Flood-frequency magnitudes computed from updated station data were consistently larger than the flood-frequency discharges previously published in the FIS. The mean percentage difference between the two data sets ranged from 14 percent for the Q100 to 20 percent for the Q50.

The results of the Mann-Kendall test showed that eight stations exhibited a positive trend (an increase in annual maximum peaks) over the period of record at the 95-percent confidence level. An additional 7 stations indicated a positive trend, for a total of 15 stations, at a confidence level of greater than or equal to 90 percent. This positive trend could be attributed to a number of different factors, including increased intensity short-term rainfall, increased impervious surface, or urbanization, within the basin.

The mean flood-frequency magnitude determined using PDS station data for the 2-year return period was approximately 16 percent higher than when using only the AMS station data. The flood-frequency discharges tend to converge around the 5-year return period; the mean collective difference for the 5-year return period was only -1 percent. At the 10-year return period, the discharges associated with annual maximums are slightly higher (approximately 5 percent) than the partial-duration peak discharges. This trend continues for the 50- and 100-year return periods where the mean collective differences between the PDS and AMS data are -7 and -6 percent, respectively. The relation of the results appears to be attributed to the larger number of lower magnitude peaks that are included in the PDS data sets.

To examine potential effects of flow-regulated sites, comparisons were made at four stations between the Q100 determined for the pre-regulation period and the Q100 determined for the post-regulation period using updated AMS station data. The results for two stations showed a nearly 60- and 20-percent reduction in the 100-year discharges. The results for the other two stations showed negligible differences in discharges. This variability in results may be attributed to the length of respective periods of record and percentage of basin previously influenced by regulation.

Three stations with urbanization were compared to 38 stations without significant urbanization in order to explore the potential effects of urbanization on peak discharges. The AMS-derived Q100 was determined for each station and subsequently divided by its respective drainage area, producing a yield (cubic feet per second per square mile) for each station. The mean Q100 yield for the three urban sites was 365 cubic feet per second per square mile compared to 174 cubic feet per second per square mile for the non-urban sites, a difference of almost 110 percent. The results of the analyses may not be solely a function of urbanization. Other factors, such as period of record, geology, rainfall intensity, or base-flow characteristics, also may have contributed to the observed effects.

Acknowledgments

Special thanks are extended to David Soong of the USGS Illinois Water Science Center for his expertise and assistance in the evaluation of PDS data. Thanks also are due the USGS Pennsylvania Water Science Center data section for their compilation and meticulous review of station data that ultimately was used to determine flood frequencies. Critical reviews and suggestions were provided by Kirk White and David Soong, both with the USGS, and Kim Dunn with Dewberry, Inc.

Selected References

Chow, V.T., 1964, ed., Handbook of applied hydrology: New York, McGraw-Hill, p. 8-20 – 8-23.

Federal Emergency Management Agency, 2006, Flood insurance studies: Washington, D.C., accessed July 16, 2007, at *http://www.fema.gov/hazard/map/fis.shtm*.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier Science Publishing Co., Inc., 522 p.

Langbein, W.B., and Iseri, K.T., 1960, General introduction and hydrologic definitions—Manual of hydrology—Part 1. General surface-water techniques: U.S. Geological Survey Water-Supply Paper 1541-A, 29 p.

Soong, D.T., Ishii, A.L., Sharpe, J.B., and Avery, C.F., 2004, Estimating flood-peak discharge magnitudes and frequencies for rural streams in Illinois: U.S. Geological Survey Water-Resources Investigations Report 04-5103, 147 p.

Stuckey, M.H., and Reed, L.A., 2000, Techniques for estimating magnitude and frequency of peak flows for Pennsylvania streams: U.S. Geological Survey Water-Resources Investigations Report 00-4189, 43 p.

Water Resources Council, Hydrology Committee, 1981, Guidelines for determining flood flow frequencies: Washington, D.C., Bulletin 17B, variously paged.

Appendixes

Appendix 1. Station summary data for streamflow-gaging stations in the Delaware and North Branch Susquehanna River Basins, Pennsylvania.

[mi^2, square miles]

U.S. Geological Survey station identification number	Station name	Drainage area (mi^2)	Period of record	Percent urban[1]
01428750	West Branch Lackawaxen River near Aldenville, PA	40.6	1975 - 2006	0.28
01438300	Vandermark Creek at Milford, Pa.[2]	5.4	1962 - 2006	4.06
01439500	Bush Kill at Shoemakers, Pa.	117	1909 - 2006	3.65
01440300	Mill Creek at Mountainhome, Pa.[2]	5.8	1961 - 2006	12.80
01440400	Brodhead Creek near Analomink, Pa.	65.9	1958 - 2006	3.70
01442500	Brodhead Creek at Minisink Hills, Pa.	259	1951 - 2006	8.29
01447500	Lehigh River at Stoddartsville, Pa.	91.7	1942 - 2006	7.47
01447680	Tunkhannock Creek near Long Pond, Pa.	20	1966 - 2006	.74
01447720	Tobyhanna Creek near Blakeslee, Pa.	118	1962 - 2006	9.90
01449360	Pohopoco Creek at Kresgeville, Pa.	49.9	1967 - 2006	7.30
01450500	Aquashicola Creek at Palmerton, Pa.	76.7	1940 - 2006	2.03
01451500	Little Lehigh Creek near Allentown, Pa.	80.8	1946 - 2006	13.02
01451800	Jordan Creek near Schnecksville, Pa.	53	1967 - 2006	1.79
01452000	Jordan Creek at Allentown, Pa.	75.8	1945 - 2006	4.96
01452500	Monocacy Creek at Bethlehem, Pa.	44.5	1945 - 2006	12.76
01465500	Neshaminy Creek near Langhorne, Pa.	210	1933 - 2006	26.78
01465798	Poquessing Creek at Grant Ave. at Philadelphia, Pa.	21.4	1966 - 2006	76.27
01467048	PennyPack Cr at Lower Rhawn St Bdg, Phila., Pa.	49.8	1966 - 2006	74.41
01468500	Schuylkill River at Landingville, Pa.	133	1948 - 2006[3]	8.61
01469500	Little Schuylkill River at Tamaqua, Pa.	42.9	1920 - 2006	3.96
01470500	Schuylkill River at Berne, Pa.	355	1942 - 2006	5.74
01470779	Tulpehocken Creek near Bernville, Pa.	66.5	1972 - 2006	4.51
01471000	Tulpehocken Creek near Reading, Pa.	211	1951 - 1978[4], 1979 - 2006[5]	3.94
01471980	Manatawny Creek near Pottstown, Pa.	85.5	1975 - 2006	2.22
01472157	French Creek near Phoenixville, Pa.	59.1	1969 - 2006	1.76
01473900	Wissahickon Creek at Fort Washington, Pa.	40.8	1962 - 2006[3]	53.55
01477000	Chester Creek near Chester, Pa.	61.1	1932 - 2006	38.06
01480300	West Branch Brandywine Creek near Honey Brook, Pa.	18.7	1960 - 2006	2.61
01480500	West Branch Brandywine Creek at Coatesville, Pa.	45.8	1944 - 2006[3]	4.33
01480617	West Branch Brandywine Creek at Modena, Pa.	55	1970 - 2006	10.54
01480675	Marsh Creek near Glenmoore, Pa.	8.6	1967 - 2006	1.49
01481000	Brandywine Creek at Chadds Ford, Pa.	287	1912 - 2006[3]	11.72
01516500	Corey Creek near Mainesburg, Pa.	12.2	1955 - 2006	.06
01531500	Susquehanna River at Towanda, Pa.	7,797	1913 - 1979[4], 1980 - 2006[5]	2.17
01532000	Towanda Creek near Monroeton, Pa.	215	1914 - 2006	.57
01533400	Susquehanna River at Meshoppen, Pa.	8,720	1977 - 2006	2.02
01534000	Tunkhannock Creek near Tunkhannock, Pa.	383	1914 - 2006	3.06

Appendix 1. Station summary data for streamflow-gaging stations in the Delaware and North Branch Susquehanna River Basins, Pennsylvania.—Continued

[mi^2, square miles]

U.S. Geological Survey station identification number	Station name	Drainage area (mi^2)	Period of record	Percent urban[1]
01536500	Susquehanna River at Wilkes-Barre, Pa.	9,960	1899 - 1979[4], 1980 - 2006[5]	2.62
01538000	Wapwallopen Creek near Wapwallopen, Pa.	43.8	1920 - 2006	11.14
01539000	Fishing Creek near Bloomsburg, Pa.	274	1936 - 2006	.30
01540500	Susquehanna River at Danville, Pa.	11220	1900 - 1979[4], 1980 - 2006[5]	3.11

[1]Percent urban area is defined by low-intensity residential, high-intensity residential, commercial/industrial/transportation, residential with trees, and residential without trees in the basin, determined by the National Land Cover Dataset, enhanced.

[2]Partial-record crest-stage gage. Only the maximum discharge for each water year is published.

[3]Period of record not continuous.

[4]Pre-flow regulated period (less than 10 percent of drainage area subjected to flow regulation).

[5]Post-flow regulated period (greater than or equal to 10 percent of drainage area subjected to flow regulation).

Appendix 2. Flood frequencies determined by Flood Insurance Studies (FIS) and from annual maximum streamflow-gaging-station data.

[mi^2, square miles; ft^3/s, cubic feet per second; –, no data]

Description	Drainage area (mi^2)	FIS community	FIS date	Method[1]	FIS flood frequencies (ft^3/s)				Nearby station	Transferred station flood frequencies[2] (ft^3/s)				Percent difference			
					10-yr	50-yr	100-yr	500-yr		10-yr	50-yr	100-yr	500-yr	10-yr	50-yr	100-yr	500-yr
Bush Kill Creek	117.0	Middle Smithfield Twp	–	1	–	–	14,400	–	01439500	4,430	8,240	10,500	18,000	–	–	-27	–
Bush Kill Creek	88.6	Middle Smithfield Twp	–	1	–	–	11,000	–	01439500	3,620	6,730	8,600	14,700	–	–	-22	–
Mill Creek	5.3	Barrett Twp	–	1	–	–	2,770	–	01440300	879	1,570	1,930	2,940	–	–	-30	–
Broadhead Creek	68.9	Price Twp	–	1	–	–	16,400	–	01440400	7,300	12,700	15,600	23,500	–	–	-5	–
Broadhead Creek	66.8	Price Twp	–	1	–	–	15,700	–	01440400	7,140	12,500	15,200	23,000	–	–	-3	–
Broadhead Creek	61.2	Price Twp	–	1	–	–	14,600	–	01440400	6,700	11,700	14,300	21,600	–	–	-2	–
Broadhead Creek	57.8	Price Twp	–	1	–	–	13,800	–	01440400	6,430	11,200	13,700	20,700	–	–	-1	–
Broadhead Creek	46.9	Price Twp	–	1	–	–	11,300	–	01440400	5,520	9,640	11,800	17,800	–	–	4	–
Broadhead Creek	287.0	Smithfield Twp	3/2/88	1	21,200	42,900	54,100	105,000	01442500	23,900	46,800	60,700	107,000	13	9	12	2
Brodhead Creek	259.0	Smithfield Twp	3/1/88	1	19,500	39,500	49,800	96,300	01442500	22,100	43,400	56,300	99,300	13	10	13	3
Broad Head Creek	255.0	Borough of Stroudsburg	1/1/76	1	14,500	28,000	36,500	69,000	01442500	21,900	42,900	55,700	98,100	51	53	53	42
Lehigh River	91.7	Buck Twp	12/1/88	1	7,310	16,600	22,700	44,200	01447500	7,230	15,900	21,500	41,200	-1	-4	-5	-7
Upper Tunkhannock Creek	24.2	Tobyhanna Twp	12/1/88	2	–	–	3,400	–	01447680	831	1,270	1,480	2,040	–	–	-56	–
Upper Tunkhannock Creek	19.6	Tobyhanna Twp	12/2/88	2	–	–	2,760	–	01447680	713	1,090	1,270	1,750	–	–	-54	–
Upper Tunkhannock Creek	15.0	Tobyhanna Twp	12/3/88	2	–	–	2,130	–	01447680	587	896	1,050	1,440	–	–	-51	–
Tobyhanna Creek	118.0	Tobyhanna Twp	12/1/88	1	–	–	18,000	–	01447720	7,960	14,200	17,500	26,900	–	–	-3	–
Tobyhanna Creek	86.0	Tobyhanna Twp	12/2/88	1	–	–	11,800	–	01447720	6,320	11,300	13,900	21,400	–	–	18	–
Pohopoco Creek	52.0	Polk Twp	9/1/87	2	–	–	7,200	–	01449360	2,010	2,820	3,180	4,030	–	–	-56	–
Aquashicola Creek	77.8	Borough of Palmerton	3/1/78	1	4,550	7,930	9,790	15,300	01450500	5,370	9,550	11,800	18,700	18	20	21	22
Aquashicola Creek	71.0	Lower Towamensing Twp	11/1/89	1	–	–	9,700	–	01450500	5,020	8,930	11,100	17,500	–	–	14	–
Aquashicola Creek	69.2	Borough of Palmerton	3/1/78	1	4,130	7,250	8,960	14,100	01450500	4,930	8,770	10,900	17,100	19	21	22	21
Little Lehigh Cr	97.6	Lehigh Co	12/2/81	2	5,510	12,900	17,600	34,000	01451500	6,570	15,300	20,900	39,600	19	19	19	16
Little Lehigh Cr	80.8	Lehigh Co	11/1/01	1	4,800	11,400	15,600	30,400	01451500	5,730	13,300	18,200	34,500	19	17	17	13

Appendix 2. Flood frequencies determined by Flood Insurance Studies (FIS) and from annual maximum streamflow-gaging-station data.—Continued

[mi^2, square miles; ft^3/s, cubic feet per second; –, no data]

Description	Drainage area (mi^2)	FIS community	FIS date	Method[1]	FIS flood frequencies (ft^3/s)				Nearby station	Transferred station flood frequencies[2] (ft^3/s)				Percent difference			
					10-yr	50-yr	100-yr	500-yr		10-yr	50-yr	100-yr	500-yr	10-yr	50-yr	100-yr	500-yr
Little Lehigh Cr	66.2	Lehigh Co	12/3/81	2	4,150	9,990	13,700	27,000	01451500	4,960	11,500	15,700	29,900	20	15	15	11
Little Lehigh Cr	53.9	Lehigh Co	12/4/81	2	3,580	8,710	12,000	23,900	01451500	4,270	9,940	13,500	25,700	19	14	13	8
Jordan Creek	58.0	Lehigh Co	–	1	5,270	9,320	11,500	18,200	01451800	5,460	8,910	10,600	15,200	4	-4	-8	-16
Jordan Creek	53.0	Lehigh Co	–	1	4,880	8,470	10,400	16,100	01451800	5,110	8,340	9,940	14,200	5	-2	-4	-12
Jordan Creek	81.0	Lehigh Co	–	1	6,960	13,000	16,400	27,000	01452000	7,570	13,700	17,000	26,700	9	5	4	-1
Jordan Creek	75.8	Lehigh Co	12/7/81	1	6,630	12,400	15,700	26,000	01452000	7,210	13,000	16,200	25,500	9	5	3	-2
Jordan Creek	70.4	Lehigh Co	–	1	6,220	11,500	14,400	23,600	01452000	6,830	12,300	15,300	24,100	10	7	6	2
Monocacy Creek	50.0	Northampton Co	1/1/78	1	1,350	2,800	3,750	7,000	01452500	2,110	4,910	6,790	13,600	56	75	81	94
Monocacy Creek	37.1	Northampton Co	1/2/78	1	1,150	2,400	3,200	5,900	01452500	1,700	3,950	5,460	11,000	48	65	71	86
Monocacy Creek	35.7	Northampton Co	1/3/78	1	1,050	2,170	2,920	5,570	01452500	1,650	3,840	5,310	10,700	57	77	82	92
Neshaminy Creek	233.0	Bucks Co	3/2/77	1	20,700	34,100	41,100	61,000	01465500	24,100	39,700	48,000	71,600	16	16	17	17
Neshaminy Creek	221.3	Bucks Co	3/3/77	1	21,400	33,400	38,700	56,600	01465500	23,200	38,300	46,200	69,000	8	15	19	22
Neshaminy Creek	210.0	Bucks Co	3/1/77	1	20,300	31,800	36,900	53,900	01465500	22,300	36,800	44,500	66,400	10	16	21	23
Neshaminy Creek	187.8	Bucks Co	3/4/77	1	18,100	28,300	32,900	48,000	01465500	20,600	34,000	41,000	61,200	14	20	25	28
Neshaminy Creek	166.9	Bucks Co	3/5/77	1	16,800	26,200	30,400	44,400	01465500	18,900	31,200	37,600	56,200	13	19	24	27
Poquessing Cr	21.4	City of Philadelphia	2/1/92	1	5,630	8,940	10,600	15,500	01465798	5,690	8,490	9,850	13,500	1	-5	-7	-13
Pennypack Cr	47.1	City of Philadelphia	12/3/78	2	5,600	10,200	14,000	28,000	01467048	7,090	11,500	13,800	20,500	27	13	-1	-27
Pennypack Cr	42.8	City of Philadelphia	12/1/78	2	4,800	9,600	13,000	26,000	01467048	6,610	10,700	12,900	19,100	38	11	-1	-27
Pennypack Cr	37.9	City of Philadelphia	12/2/78	2	4,500	9,000	12,000	23,600	01467048	6,050	9,840	11,800	17,500	34	9	-2	-26
Schuylkill River	160.0	West Brunswick Twp	11/2/96	1	8,600	13,800	16,500	24,000	01468500	8,270	14,100	17,200	26,500	-4	2	4	10
Schuylkill River	133.0	Schuykill Haven	11/1/96	1	6,790	11,000	13,200	19,400	01468500	7,230	12,300	15,100	23,100	6	12	14	19
Little Schuylkill River	77.0	Tamaqua	12/1/89	1	–	–	13,500	–	01469500	4,890	7,900	9,320	13,000	–	–	-31	–
Schuylkill River	640.0	Berks Co	12/1/97	2	28,800	43,500	50,700	69,000	01470500	36,500	57,000	66,900	92,500	27	31	32	34
Schuylkill River	335.0	Berks Co	12/2/97	2	23,200	36,300	42,800	60,200	01470500	22,800	35,600	41,700	57,800	-2	-2	-3	-4
Tulpehocken Creek	56.4	Berks Co	8/1/88	1	–	–	7,280	–	01470779	4,890	9,300	11,700	18,700	–	–	61	–
Tulpehocken Creek	49.8	Berks Co	8/2/88	1	–	–	6,650	–	01470779	4,470	8,490	10,700	17,100	–	–	61	–
Tulpehocken Creek	70.4	Berks Co	–	1	2,100	3,500	4,100	6,400	01470779	5,750	10,900	13,700	22,000	174	211	234	244
Tulpehocken Creek	219.0	Berks Co	12/2/97	1	3,210	5,600	6,750	10,500	01471000	4,650	6,520	7,360	9,460	45	16	9	-10
Tulpehocken Creek	211.0	Berks Co	12/1/97	1	2,180	5,400	6,550	9,850	01471000	4,530	6,340	7,170	9,210	108	17	9	-6
Tulpehocken Creek	175.0	Berks Co	–	3	2,000	2,000	2,400	5,900	01471000	3,950	5,540	6,250	8,040	98	177	160	36
Manatawny Creek	61.9	Berks Co	–	2	4,700	6,900	10,500	14,900	01471980	5,000	7,260	8,280	10,800	6	5	-21	-28

Appendix 2. Flood frequencies determined by Flood Insurance Studies (FIS) and from annual maximum streamflow-gaging-station data.—Continued

[mi^2, square miles; ft^3/s, cubic feet per second; –, no data]

Description	Drainage area (mi^2)	FIS community	FIS date	Method[1]	FIS flood frequencies (ft^3/s)				Nearby station	Transferred station flood frequencies[2] (ft^3/s)				Percent difference			
					10-yr	50-yr	100-yr	500-yr		10-yr	50-yr	100-yr	500-yr	10-yr	50-yr	100-yr	500-yr
Manatawny Creek	59.2	Berks Co	–	3	4,300	6,300	9,500	13,100	01471980	4,840	7,030	8,020	10,500	13	12	-16	-20
Manatawny Creek	57.2	Berks Co	–	3	4,000	5,900	8,700	11,700	01471980	4,720	6,850	7,820	10,200	18	16	-10	-13
French Creek	70.2	Chester Co	–	3	9,740	13,200	14,800	18,600	01472157	7,270	13,800	17,500	29,000	-25	5	18	56
French Creek	67.1	Chester Co	–	3	9,440	12,700	14,300	18,000	01472157	7,030	13,300	16,900	28,000	-26	5	18	56
French Creek	64.1	Chester Co	–	3	9,100	12,200	13,800	17,300	01472157	6,800	12,900	16,400	27,100	-25	6	19	57
French Creek	62.6	Chester Co	–	3	8,960	12,000	13,500	17,000	01472157	6,680	12,700	16,100	26,600	-25	6	19	56
French Creek	54.9	Chester Co	–	3	7,760	10,500	12,000	15,400	01472157	6,080	11,500	14,600	24,200	-22	10	22	57
French Creek	43.7	Chester Co	–	3	5,340	8,680	10,400	13,700	01472157	5,150	9,760	12,400	20,500	-4	12	19	50
French Creek	44.8	Chester Co	–	3	–	–	10,200	–	01472157	5,240	9,940	12,600	20,900	–	–	24	–
Wissahickon Creek	64.0	City of Philadelphia	6/1/79	1	6,600	11,900	15,000	25,200	01473900	9,290	15,900	19,600	31,100	41	34	31	23
Wissahickon Creek	53.6	City of Philadelphia	6/2/79	1	6,000	10,900	13,800	24,500	01473900	8,160	14,000	17,200	27,400	36	28	25	12
Wissahickon Creek	49.8	Montgomery Co	12/1/77	2	8,300	11,200	12,600	15,700	01473900	7,740	13,200	16,300	25,900	-7	18	29	65
Wissahickon Creek	27.3	Montgomery Co	12/2/77	2	5,400	7,400	8,330	10,800	01473900	4,990	8,540	10,500	16,800	-8	15	26	56
Wissahickon Creek	24.1	Montgomery Co	12/3/77	2	4,980	6,830	7,650	9,900	01473900	4,560	7,800	9,630	15,300	-8	14	26	55
Chester Creek	61.1	Delaware Co	5/1/95	1	8,090	15,600	20,300	35,800	01477000	7,480	14,500	18,700	32,400	-8	-7	-8	-9
W Br Brandywine Creek	37.5	Chester Co	–	3	3,920	6,890	8,870	13,900	01480300	5,020	9,020	11,200	17,500	28	31	26	26
W Br Brandywine Creek	18.8	Chester Co	–	3	2,520	4,530	5,970	9,660	01480300	3,040	5,450	6,760	10,600	21	20	13	10
W Br Brandywine Creek	15.4	Chester Co	–	3	2,240	4,140	5,540	9,190	01480300	2,630	4,720	5,850	9,140	17	14	6	-1
W Br Brandywine Creek	52.0	Chester Co	–	3	5,100	8,700	10,400	15,600	01480500	5,260	9,740	12,200	19,800	3	12	17	27
W Br Brandywine Creek	45.8	Chester Co	–	3	4,500	7,700	9,300	14,000	01480500	4,800	8,880	11,200	18,000	7	15	20	29
W Br Brandywine Creek	64.4	Chester Co	–	3	5,670	9,730	12,400	19,000	01480617	7,070	12,400	15,100	22,900	25	27	22	21
W Br Brandywine Creek	57.5	Chester Co	–	3	–	–	11,500	–	01480617	6,510	11,400	13,900	21,100	–	–	21	–
W Br Brandywine Creek	54.0	Chester Co	–	3	5,200	8,900	10,600	15,800	01480617	6,220	10,900	13,300	20,100	20	22	25	27
Brandywine Creek	295.0	Delaware Co	5/2/95	1	13,100	18,600	22,200	34,000	01481000	14,700	23,600	28,200	40,900	12	27	27	20
Brandywine Creek	281.1	Delaware Co	5/1/95	1	12,500	18,000	21,300	32,500	01481000	14,100	22,800	27,200	39,400	13	27	28	21
Susquehanna River	8,196.0	Asylum Twp	2/1/80	2	144,000	197,000	217,000	275,000	01531500	158,000	208,000	230,000	282,000	10	6	6	3

Appendix 2. Flood frequencies determined by Flood Insurance Studies (FIS) and from annual maximum streamflow-gaging-station data.—Continued

[mi^2, square miles; ft^3/s, cubic feet per second; –, no data]

Description	Drainage area (mi^2)	FIS community	FIS date	Method[1]	FIS flood frequencies (ft^3/s)				Nearby station	Transferred station flood frequencies[2] (ft^3/s)				Percent difference			
					10-yr	50-yr	100-yr	500-yr		10-yr	50-yr	100-yr	500-yr	10-yr	50-yr	100-yr	500-yr
Susquehanna River	7,797.0	Wysox Twp	8/1/77	1	140,000	192,000	212,000	270,000	01531500	153,000	201,000	222,000	271,000	9	5	5	0
Susquehanna River at station 01531500	7,797.0	Windham Twp	9/1/87	1	140,000	192,000	212,000	270,000	01531500	153,000	201,000	222,000	271,000	9	5	5	0
Towanda Creek	263.6	Monroe Borough	9/2/92	1	26,800	48,900	61,800	99,700	01532000	28,200	52,200	65,900	108,000	5	7	7	8
Towanda Creek	215.0	Monroe Borough	9/1/92	1	23,000	42,000	53,000	85,600	01532000	24,300	45,000	56,800	92,900	6	7	7	9
Susquehanna River	9,539.0	Eaton Twp	11/1/79	1	160,000	221,000	248,000	324,000	01533400	195,000	263,000	293,000	367,000	22	19	18	13
Susquehanna River	8,913.0	Meshoppen Twp	8/1/79	2	154,000	212,000	238,000	308,000	01533400	185,000	250,000	279,000	350,000	20	18	17	14
Tunkhannock Creek	413.0	Tunkhannock Borough	8/1/79	1	26,300	37,600	42,500	53,900	01534000	26,200	37,500	42,300	53,800	0	0	0	0
Tunkhannock Creek at station 01534000	383.0	Tunkhannock Twp	8/1/99	1	24,800	35,500	40,100	50,900	01534000	24,800	35,500	40,100	50,900	0	0	0	0
Susquehanna River	10,215.0	Hunlock Twp	10/1/79	1	167,000	232,000	260,000	340,000	01536500	202,000	277,000	310,000	393,000	21	19	19	16
Susquehanna River	9,539.0	Ransom	10/1/79	1	160,000	221,000	248,000	324,000	01536500	192,000	263,000	295,000	374,000	20	19	19	15
Susquehanna River	9,925.0	City of Wilkes-Barre	3/1/92	2	165,000	227,000	225,000	335,000	01536500	198,000	271,000	304,000	385,000	20	19	35	15
Wapwallopen Creek	42.2	Hollenback Twp	3/1/80	1	2,350	3,770	4,490	6,470	01538000	2,550	4,190	5,020	7,300	9	11	12	13
Big Wapwallopen Creek	30.8	Dorrance Twp	2/1/80	2	1,810	2,900	3,450	4,970	01538000	2,030	3,330	3,990	5,810	12	15	16	17
Fishing Creek	385.0	Montour Twp	2/1/79	1	24,300	45,700	58,500	102,000	01539000	24,200	40,200	48,500	71,300	0	-12	-17	-30
Fishing Creek	292.0	Orange Twp	2/1/78	1	20,000	38,000	48,800	87,000	01539000	19,800	32,900	39,600	58,300	-1	-13	-19	-33
Susquehanna River	11,210.0	Montour Twp	2/1/79	1	182,000	259,000	292,000	377,000	01540500	204,000	282,000	318,000	406,000	12	9	9	8
Susquehanna River	10,963.0	Montour Twp	2/1/79	1	176,000	250,000	282,000	365,000	01540500	200,000	278,000	313,000	399,000	14	11	11	9

[1]Method refers to method listed in FIS to determine hydrology as compiled by Federal Emergency Management Agency Region 3; 1 is based on gaging-station data; 2 is based on methods other than gaging-station data; 3 is unknown.

[2]Flood frequencies were computed for stations using annual maximum streamflow-gaging-station data and transferred to nearby FIS sites using drainage-area ratios.

Appendix 3. Log-Pearson Type III flood frequencies determined from annual maximum (AMS) and partial-duration (PDS) streamflow-gaging-station data.

Station number	Station name	Drainage area (square miles)	Period of Record	r-value[1]	Type of peak flow	Flood-frequency magnitudes (cubic feet per second)				
						2-year	5-year	10-year	50-year	100-year
01428750	West Branch Lackawaxen River near Aldenville, Pa.	40.6	1975-2006		AMS	2,050	3,690	5,310	11,100	14,900
				2.13	AMS and PDS	2,330	3,620	4,820	9,240	12,000
					% Difference	14	-2	-9	-17	-19
01439500	Bush Kill at Shoemakers, Pa.	117	1909-2006		AMS	1,980	3,260	4,430	8,240	10,500
				1.84	AMS and PDS	2,360	3,470	4,360	7,500	9,300
					% Difference	19	6	-2	-9	-11
01440400	Brodhead Creek near Analomink, Pa.	65.9	1958-2006		AMS	2,910	5,190	7,070	12,300	15,100
				2.80	AMS and PDS	3,220	4,730	6,350	11,400	14,400
					% Difference	11	-9	-10	-7	-5
01442500	Brodhead Creek at Minisink Hills, Pa.	259	1951-2006		AMS	8,900	15,700	22,100	43,400	56,300
				2.96	AMS and PDS	11,000	15,900	21,100	37,900	47,800
					% Difference	24	1	-5	-13	-15
01447500	Lehigh River at Stoddartsville, Pa.	91.7	1942-2006		AMS	2,410	4,820	7,230	15,900	21,500
				2.08	AMS and PDS	3,040	4,980	6,790	13,800	18,300
					% Difference	26	3	-6	-13	-15
01447680	Tunkhannock Creek near Long Pond, Pa.	20	1966-2006		AMS	346	530	670	1,020	1,200
				1.66	AMS and PDS	360	522	639	999	1,180
					% Difference	4	-2	-5	-2	-2
01447720	Tobyhanna Creek near Blakeslee, Pa.	118	1962-2006		AMS	3,130	5,750	7,960	14,200	17,500
				2.49	AMS and PDS	4,040	5,770	7,570	12,600	15,400
					% Difference	29	0	-5	-11	-12
01449360	Pohopoco Creek at Kresgeville, Pa.	49.9	1967-2006		AMS	1,080	1,600	1,950	2,740	3,090
				2.85	AMS and PDS	1,200	1,560	1,900	2,780	3,210
					% Difference	11	-3	-3	1	4

Appendix 3. Log-Pearson Type III flood frequencies determined from annual maximum (AMS) and partial-duration (PDS) streamflow-gaging-station data.—Continued

Station number	Station name	Drainage area (square miles)	Period of Record	r-value[1]	Type of peak flow	Flood-frequency magnitudes (cubic feet per second)				
						2-year	5-year	10-year	50-year	100-year
01450500	Aquashicola Creek at Palmerton, Pa.	76.7	1940-2006		AMS	2,270	3,910	5,310	9,450	11,700
				2.69	AMS and PDS	2,660	3,790	5,000	8,630	10,800
					% Difference	17	-3	-6	-9	-8
01451500	Little Lehigh Creek near Allentown, Pa.	80.8	1946-2006		AMS	1,550	3,610	5,730	13,400	18,200
				2.72	AMS and PDS	2,140	3,700	5,560	12,500	17,200
					% Difference	38	2	-3	-7	-5
01451800	Jordan Creek near Schnecksville, Pa.	53	1967-2006		AMS	2,310	3,880	5,110	8,340	9,940
				3.93	AMS and PDS	2,530	3,660	4,780	8,450	10,400
					% Difference	10	-6	-6	1	5
01452000	Jordan Creek at Allentown, Pa.	75.8	1945-2006		AMS	2,930	5,230	7,210	13,000	16,200
				2.37	AMS and PDS	3,520	5,190	6,880	12,100	15,200
					% Difference	20	-1	-5	-7	-6
01452500	Monocacy Creek at Bethlehem, Pa.	44.5	1945-2006		AMS	596	1,250	1,920	4,440	6,120
				2.84	AMS and PDS	817	1,270	1,790	3,610	4,790
					% Difference	37	2	-7	-19	-22
01465500	Neshaminy Creek near Langhorne, Pa.	210	1933-2006		AMS	10,800	17,100	22,300	36,800	44,500
				2.47	AMS and PDS	11,400	16,000	20,700	35,100	43,500
					% Difference	6	-6	-7	-5	-2
01465798	Poquessing Creek at Grant Ave. at Philadelphia, Pa.	21.4	1966-2006		AMS	3,110	4,580	5,690	8,490	9,850
				4.39	AMS and PDS	3,550	4,680	5,660	8,310	9,620
					% Difference	14	2	-1	-2	-2
01467048	PennyPack Cr at Lower Rhawn St Bdg, Phila., Pa.	49.8	1966-2006		AMS	3,690	5,730	7,380	12,000	14,400
				4.39	AMS and PDS	4,340	5,830	7,200	11,300	13,500
					% Difference	18	2	-2	-6	-6
01468500	Schuylkill River at Landingville, Pa.	133	1948-2006		AMS	3,370	5,470	7,230	12,300	15,100
				4.19	AMS and PDS	3,850	5,320	6,750	11,300	13,900
					% Difference	14	-3	-7	-8	-8

Appendix 3. Log-Pearson Type III flood frequencies determined from annual maximum (AMS) and partial-duration (PDS) streamflow-gaging-station data.—Continued

Station number	Station name	Drainage area (square miles)	Period of Record	r-value[1]	Type of peak flow	Flood-frequency magnitudes (cubic feet per second)				
						2-year	5-year	10-year	50-year	100-year
01469500	Little Schuylkill River at Tamaqua, Pa.	42.9	1920-2006		AMS	1,400	2,410	3,190	5,160	6,090
				2.02	AMS and PDS	1,700	2,500	3,040	4,730	5,550
					% Difference	21	4	-5	-8	-9
01470500	Schuylkill River at Berne, Pa.	355	1942-2006		AMS	11,500	18,500	23,800	37,100	43,500
				3.00	AMS and PDS	12,500	17,600	22,800	38,200	46,600
					% Difference	9	-5	-4	3	7
01470779	Tulpehocken Creek near Bernville, Pa.	66.5	1972-2006		AMS	1,950	3,850	5,520	10,500	13,200
				2.06	AMS and PDS	2,390	3,770	4,870	8,600	10,700
					% Difference	23	-2	-12	-18	-19
01471980	Manatawny Creek near Pottstown, Pa.	85.5	1975-2006		AMS	3,430	5,120	6,320	9,180	10,500
				4.47	AMS and PDS	3,690	4,900	6,010	9,170	10,900
					% Difference	8	-4	-5	0	4
01472157	French Creek near Phoenixville, Pa.	59.1	1969-2006		AMS	2,480	4,550	6,410	12,200	15,400
				4.74	AMS and PDS	2,940	4,370	5,820	10,800	14,100
					% Difference	19	-4	-9	-11	-8
01473900	Wissahickon Creek at Fort Washington, Pa.	40.8	1962-2006		AMS	3,320	5,130	6,690	11,400	14,100
				3.56	AMS and PDS	3,700	5,190	6,640	10,900	13,100
					% Difference	11	1	-1	-4	-7
01477000	Chester Creek near Chester, Pa.	61.1	1932-2006		AMS	2,990	5,330	7,480	14,500	18,700
				2.40	AMS and PDS	3,670	5,340	7,070	12,600	15,900
					% Difference	23	0	-5	-13	-15
01480300	West Branch Brandywine Creek near Honey Brook, Pa.	18.7	1960-2006		AMS	1,230	2,200	3,030	5,430	6,730
				3.83	AMS and PDS	1,570	2,240	2,930	5,200	6,450
					% Difference	28	2	-3	-4	-4
01480500	West Branch Brandywine Creek at Coatesville, Pa.	45.8	1944-2006		AMS	1,910	3,450	4,800	8,880	11,200
				4.00	AMS and PDS	2,360	3,410	4,470	8,050	10,000
					% Difference	24	-1	-7	-9	-11

Appendix 3. Log-Pearson Type III flood frequencies determined from annual maximum (AMS) and partial-duration (PDS) streamflow-gaging-station data.—Continued

Station number	Station name	Drainage area (square miles)	Period of Record	r-value[1]	Type of peak flow	Flood-frequency magnitudes (cubic feet per second)				
						2-year	5-year	10-year	50-year	100-year
01480617	West Branch Brandywine Creek at Modena, Pa.	55	1970-2006		AMS	2,590	4,620	6,300	11,000	13,500
				3.73	AMS and PDS	3,110	4,480	5,880	10,400	12,900
					% Difference	20	-3	-7	-5	-4
01480675	Marsh Creek near Glenmoore, Pa.	8.6	1967-2006		AMS	247	426	572	978	1,190
				2.83	AMS and PDS	302	410	519	825	991
					% Difference	22	-4	-9	-16	-17
01516500	Corey Creek near Mainesburg, Pa.	12.2	1955-2006		AMS	810	1,480	2,090	4,050	5,200
				3.10	AMS and PDS	941	1,420	1,940	3,670	4,710
					% Difference	16	-4	-7	-9	-9
01531500	Susquehanna River at Towanda, Pa.	7797	1980-2006		AMS	98,100	131,000	153,000	20,1000	222,000
				2.00	AMS and PDS	109,000	137,000	153,000	20,1000	222,000
					% Difference	11	5	0	0	0
01532000	Towanda Creek near Monroeton, Pa.	215	1914-2006		AMS	9,890	17,500	24,300	45,000	56,800
				1.94	AMS and PDS	10,600	16,800	22,000	41,700	53,600
					% Difference	7	-4	-9	-7	-6
01533400	Susquehanna River at Meshoppen, Pa.	8720	1977-2006		AMS	113,000	154,000	182,000	246,000	275,000
				2.67	AMS and PDS	129,000	157,000	183,000	244,000	274,000
					% Difference	14	2	1	-1	0
01534000	Tunkhannock Creek near Tunkhannock, Pa.	383	1914-2006		AMS	13,200	20,100	24,800	35,500	40,100
				1.94	AMS and PDS	12,600	18,700	23,300	38,600	46,700
					% Difference	-5	-7	-6	9	16
01536500	Susquehanna River at Wilkes-Barre, Pa.	9960	1980-2006		AMS	121,000	167,000	198,000	272,000	305,000
				2.26	AMS and PDS	139,000	173,000	199,000	266,000	297,000
					% Difference	15	4	1	-2	-3

Appendix 3. Log-Pearson Type III flood frequencies determined from annual maximum (AMS) and partial-duration (PDS) streamflow-gaging-station data.—Continued

Station number	Station name	Drainage area (square miles)	Period of Record	r-value[1]	Type of peak flow	Flood-frequency magnitudes (cubic feet per second)				
						2-year	5-year	10-year	50-year	100-year
01538000	Wapwallopen Creek near Wapwallopen, Pa.	43.8	1920-2006		AMS	1,210	2,000	2,620	4,300	5,160
				2.07	AMS and PDS	1,240	1,840	2,350	4,150	5,190
					% Difference	2	-8	-10	-3	1
01539000	Fishing Creek near Bloomsburg, Pa.	274	1936-2006		AMS	8,630	14,300	18,900	31,400	37,800
				2.32	AMS and PDS	9,560	13,800	17,900	30,600	37,900
					% Difference	11	-3	-5	-3	0

[1]The r-value is the total number of partial-duration peaks divided by the number of years of continuous record for any given station.