Hydrologic Analysis Technical Support Data Notebook

Task Order HSFE02-10-J-0001 for Ashokan Reservoir Watershed Hydrologic Study, New York

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TECHNICAL SUPPORT DATA NOTEBOOK (TSDN)

for

Ashokan Reservoir Watershed (Part of Esopus Creek Watershed)

HYDROLOGIC ANALYSIS TSDN

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A. INTRODUCTION

This report presents background, methodology, and results of hydrologic analyses developed for Ashokan Reservoir Watershed (Upper Esopus Creek Watershed), New York. These analyses were conducted as part of a flood study initiated by New York City Department of Environmental Protection (NYCDEP) and Department of Homeland Security's Federal Emergency Management Agency (FEMA). The purpose of this flood study is to develop new and updated hydrologic analyses for use in the development of hydraulic analyses and other flood hazard products for selected flooding sources in the Ashokan Reservoir Watershed. The Ashokan Reservoir Watershed includes areas upstream of Ashokan Reservoir outlet, covering approximately 255 square miles (sq. mi). The study area includes selected flooding sources in the catchment area along Esopus Creek, starting from its origin in the headwaters in Catskills Mountains down to the outlet of Ashokan Reservoir. The reservoir is located 14 miles west of Kingston, New York.

The scope for this project includes 32 streams and 2 reservoir/lakes. The general locations of the flooding sources studied in this project are shown in Figure 1. Figure 2 through Figure 5 provide detailed view of the scoped flooding sources, labeled with their names. Table 1 provides the list of all study flooding sources grouped by sub-watersheds, their study types, location spans, sub-basin areas and mileage. In terms of mileage, the scope includes about 97.8 miles of streams and 13.5 miles of the reservoir's lake shoreline. It should be noted that the areas provided in the table correspond to the accumulated drainage areas at the outlets of the major tributaries and the sub-basin areas for Esopus Creek and Ashokan Reservoir. For Esopus Creek, the area provided includes the total contributing area to its outlet into Ashokan Reservoir, minus the drainage areas of the major tributaries. The area provided for Ashokan Reservoir includes the remaining contributing area below the outlets of Esopus Creek and Bush Kill. The level of analysis (study type) to be conducted for each of the flooding sources was identified prior to the initiation of this project, under the discovery (scoping) phase. Five different study types have been utilized for this project, which include approximate (A), detailed (D), backwater (B), limited detailed (LD), and lake (L). Distribution of scope miles among various study types is provided in Table 2.

The scoped flooding sources for this project span six communities located in two counties in New York. The two counties affected by this study are Greene and Ulster. Out of the six communities, four are located in Ulster and two are located in Greene. The communities located in Greene County are the Towns of Hunter and Lexington, and the communities located in Ulster County are the Towns of Hurley, Olive, Shandaken, and Woodstock. The distribution of scope miles between the counties is provided in Table 3. The analyses developed for this project are consistent with FEMA's *Guidelines and Specifications for Flood Mapping Partners*. These analyses resulted in the computation of peak flow discharges at the critical locations identified along the study stream reaches and lake elevations for five scoped flood frequencies, 10-Year, 25-year, 50-Year, 100-Year, and 500-Year.

Table 1: Summary of Flooding Sources

Sub-Basin	Area (Sq.mi)	Stream Name	Study Type	Miles	Stream Order	County(s)	Community(s)
AshokanReservoir (excluding major tributaries)	13	AshokanReservoir	L	12.8	1	Ulster	Olive, Hurley
		KenoziaLake	LD	0.7	2	Ulster	Hurley
BeaverKill	25.2	BeaverKill	D	6.4	2	Ulster	Shandaken, Woodstock
		MinkHollowStream	D	3.6	3	Ulster	Shandaken
		WagnerCreek	D	1.7	3	Ulster	Shandaken
BirchCreek	12.8	AltonCreek	D	2.1	3	Ulster	Shandaken
		AltonCreek_t1	D	1.6	4	Ulster	Shandaken
		BirchCreek_s1	D	2.5	2	Ulster	Shandaken
		BirchCreek_s2	D	1.0	2	Ulster	Shandaken
		BirchCreek_s3	LD	2.9	2	Ulster	Shandaken
		GiggleHollow	A	0.2	3	Ulster	Shandaken
		PineHillLake	D	0.2	2	Ulster	Shandaken
BroadStreetHollow	9.2	BroadStreetHollow	D	3.0	2	Green, Ulster	Lexington, Shandaken
		JayHandHollow	A	2.4	3	Greene	Lexington
BushKill	19.7	BushKill	D	4.7	2	Ulster	Olive
		DryBrook	D	3.2	3	Ulster	Olive
		KanapeBrook	A	1.9	3	Ulster	Olive
		MaltbyHollowBrook	D	2.1	3	Ulster	Olive
		SouthHollowBrook	A	0.9	3	Ulster	Olive
BushnellsvilleCreek	11.1	BushnellsvilleCreek	D	4.0	2	Greene,Ulster	Lexington, Shandaken
Esopus Creek (excluding Tributaries)	94.7	EsopusCreek	D	22.0	1	Ulster	Olive, Shandaken
		EsopusCreek_t7	A	0.3	2	Ulster	Shandaken
		TraverHollow	A	1.1	2	Ulster	Shandaken
		EsopusCreek	A	1.1	1	Ulster	Shandaken
		Hatchery Hollow	LD	0.6	2	Ulster	Shandaken
		Lost Clove	LD	0.1	2	Ulster	Shandaken
		Mckinley Hollow	LD	0.2	2	Ulster	Shandaken
		PeckHollow	A	0.2	2	Ulster	Shandaken
		FoxHollow	D	2.0	2	Ulster	Shandaken
LittleBeaverKill	16.7	LittleBeaverKill	D	0.7	2	Ulster	Olive, Shandaken
		LittleBeaverKill	LD	5.7	2	Ulster	Olive, Woodstock
StonyCloveCreek	32.5	HollowTreeBrook	D	1.5	3	Greene	Hunter
		StonyCloveCreek	D	8.6	2	Greene, Ulster	Hunter, Shandaken
		WarnerCreek_s1	D	1.9	3	Ulster	Shandaken
WoodlandCreek	20.6	CrossMountainHollow	B	0.1	2	Ulster	Shandaken
		MuddyBrook	B	0.1	3	Ulster	Shandaken
		PantherKill	A	3.3	3	Ulster	Shandaken
		WoodlandCreek_s1	D	3.5	2	Ulster	Shandaken
		WoodlandCreek_s2	A	0.6	2	Ulster	Shandaken
		WoodlandCreek_t3	B	0.1	3	Ulster	Shandaken
Total Drainage Area at Ashokan Reservoir Outlet	**255.5**	**Total Miles**		**111.3**			

Table 2: Summary of Scoped Mileage and Study Type

Study Type	Mileage
Approximate (A)	12.0
Backwater (B)	0.4
Detailed (D)	76.0
Lake (L)	12.8
Limited Detailed (LD)	10.2
Total	**111.3**

Table 3: Summary of Scoped Mileage, Study Type and Counties

County	Study Type	Mileage
Greene	Approximate (A)	2.4
	Detailed (D)	8.6
Ulster	Approximate (A)	9.6
	Backwater (B)	0.4
	Detailed (D)	67.4
	Lake (L)	12.8
	Limited Detailed (LD)	10.2
Total		**111.3**

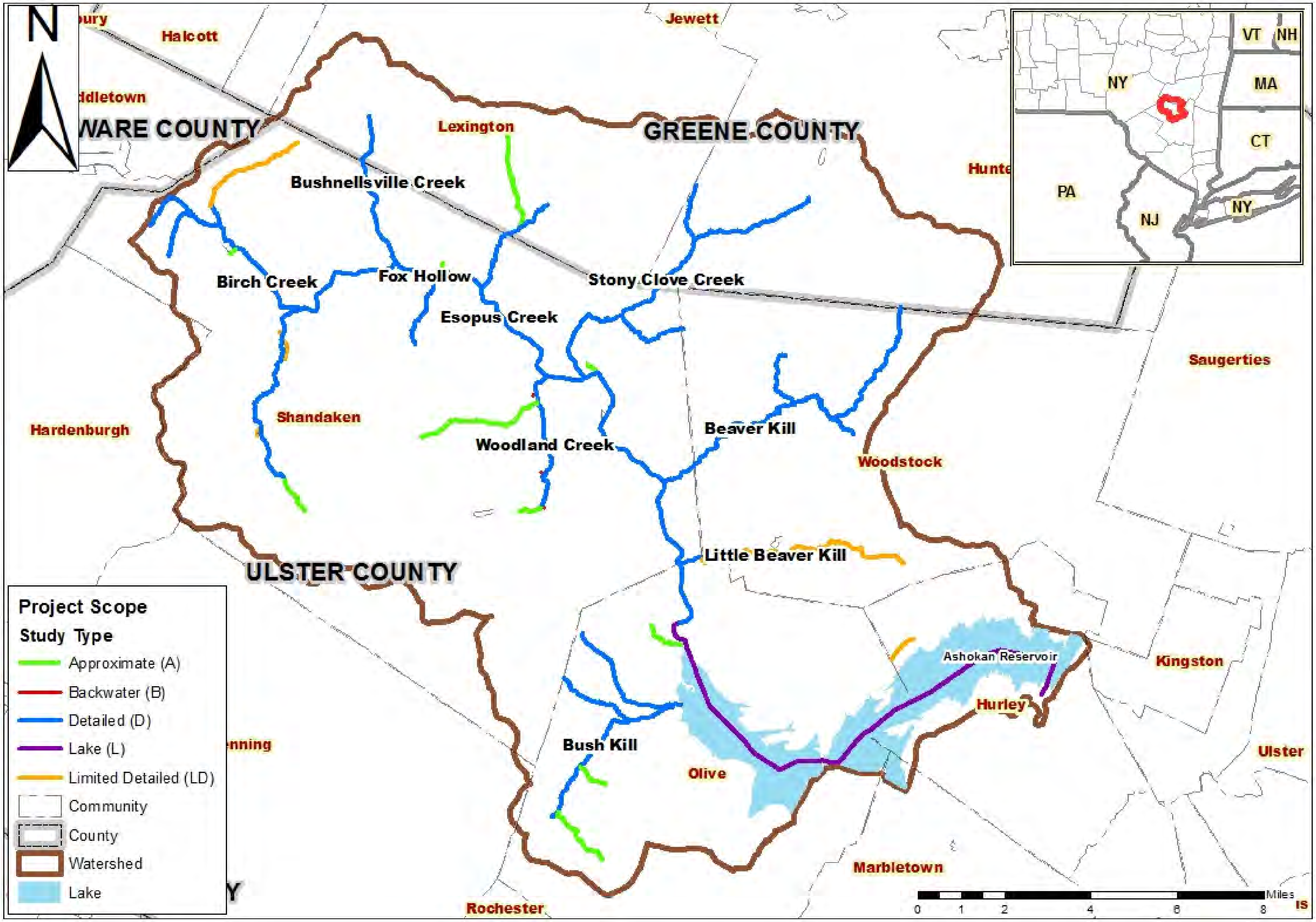

Figure 1: Ashokan Reservoir Watershed (Upper Esopus Watershed) Study Flooding Sources and Watershed

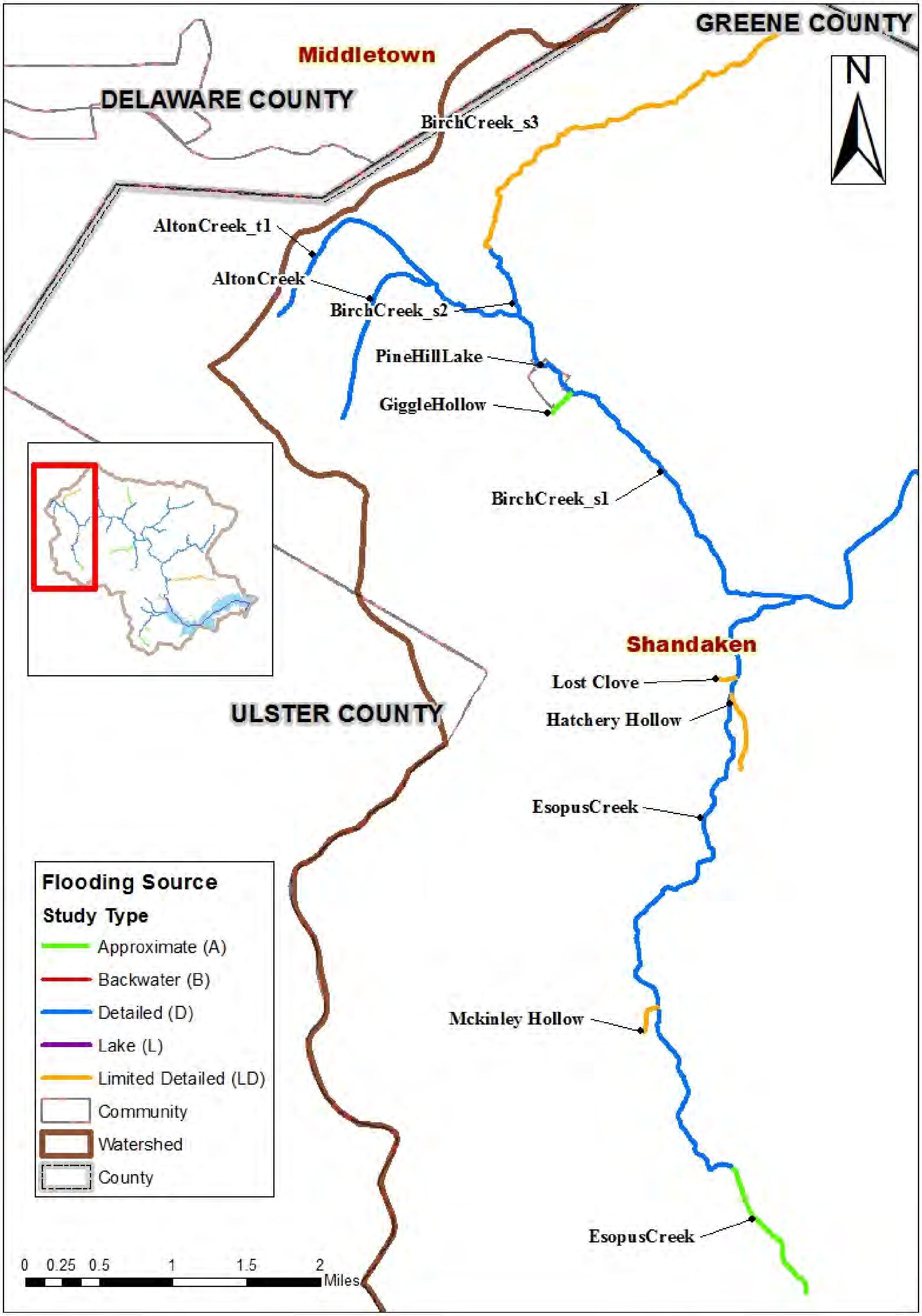

Figure 2: Scoped Flooding Sources – Part1

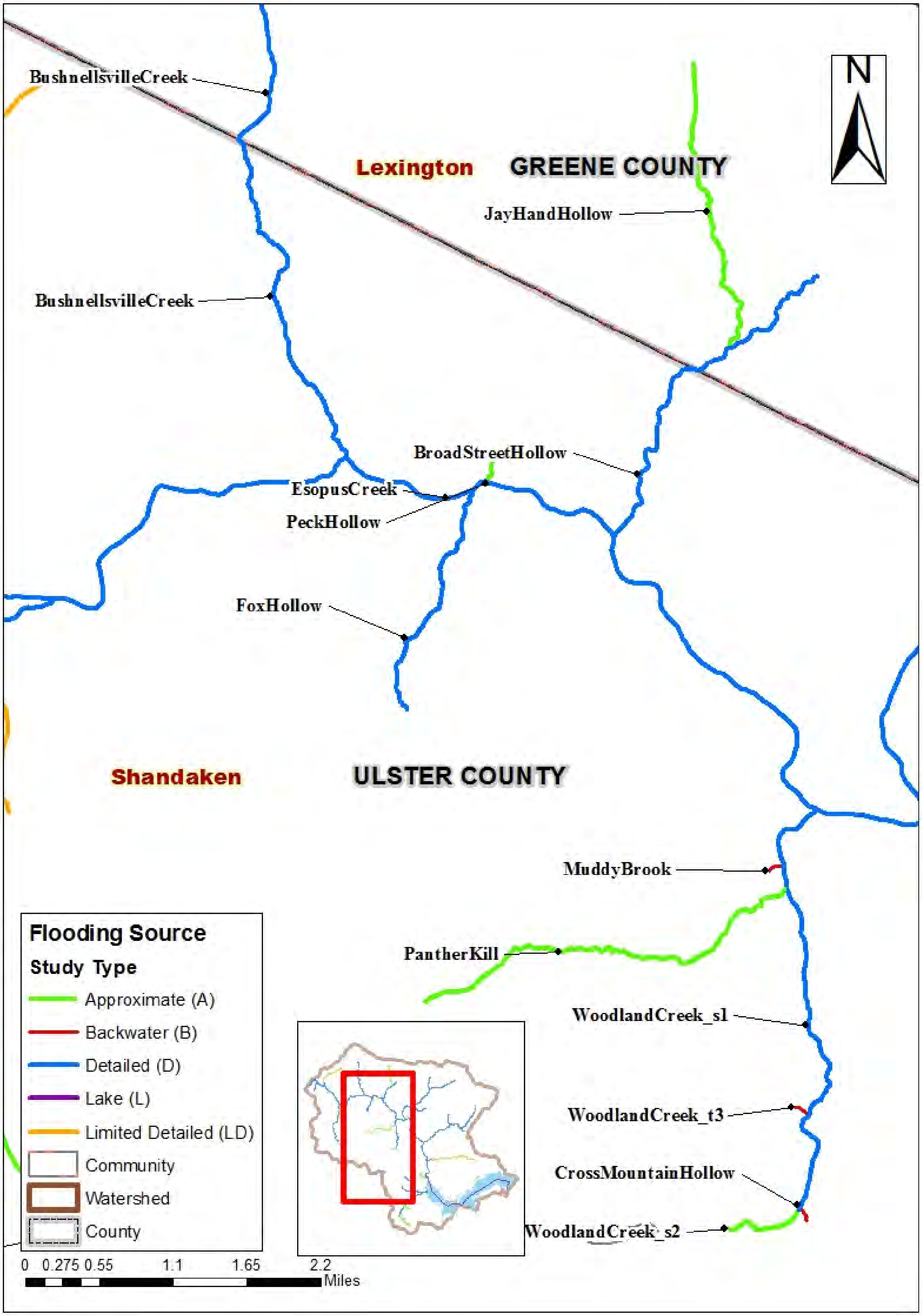

Figure 3: Scoped Flooding Sources – Part2

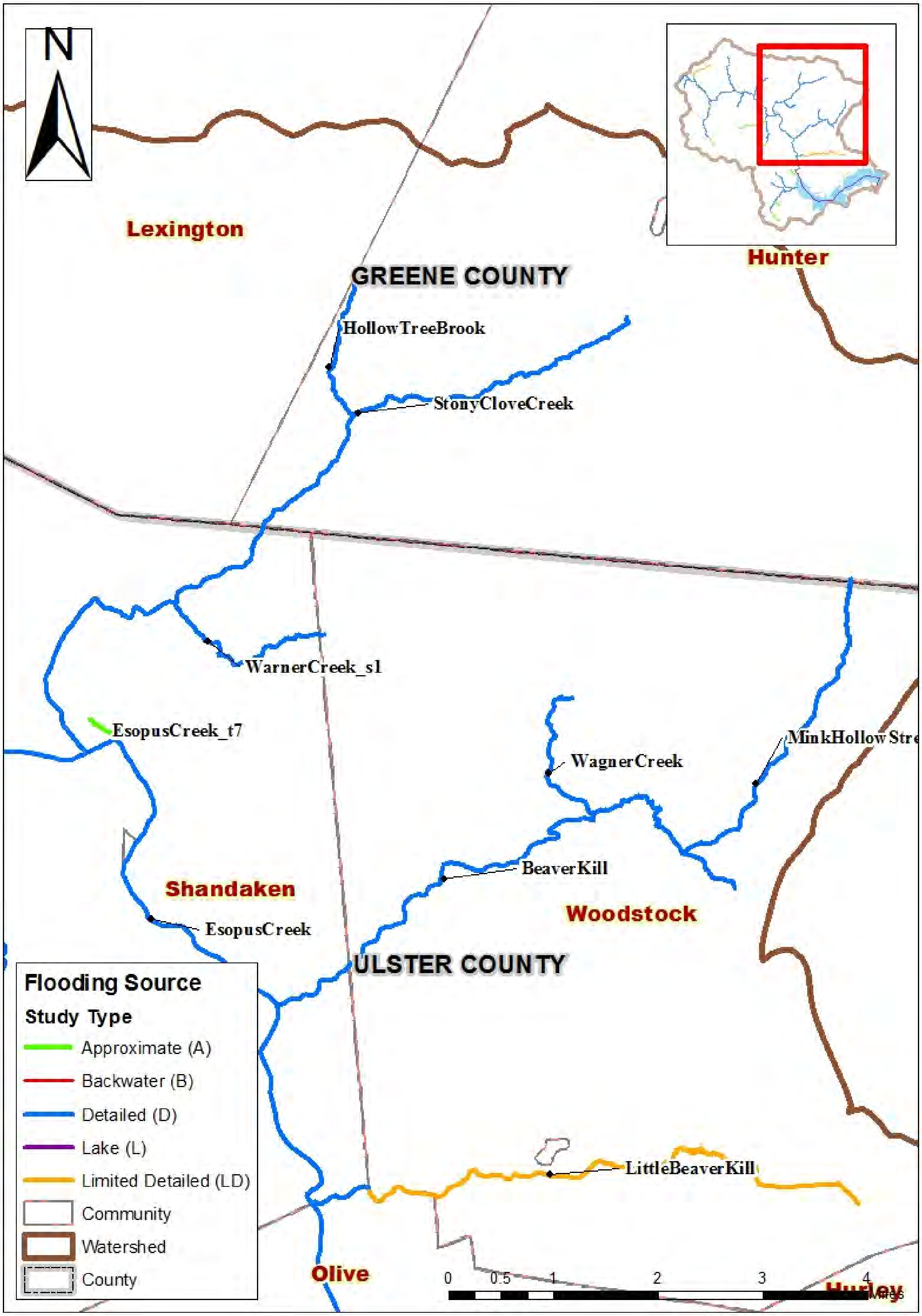

Figure 4: Scoped Flooding Sources – Part3

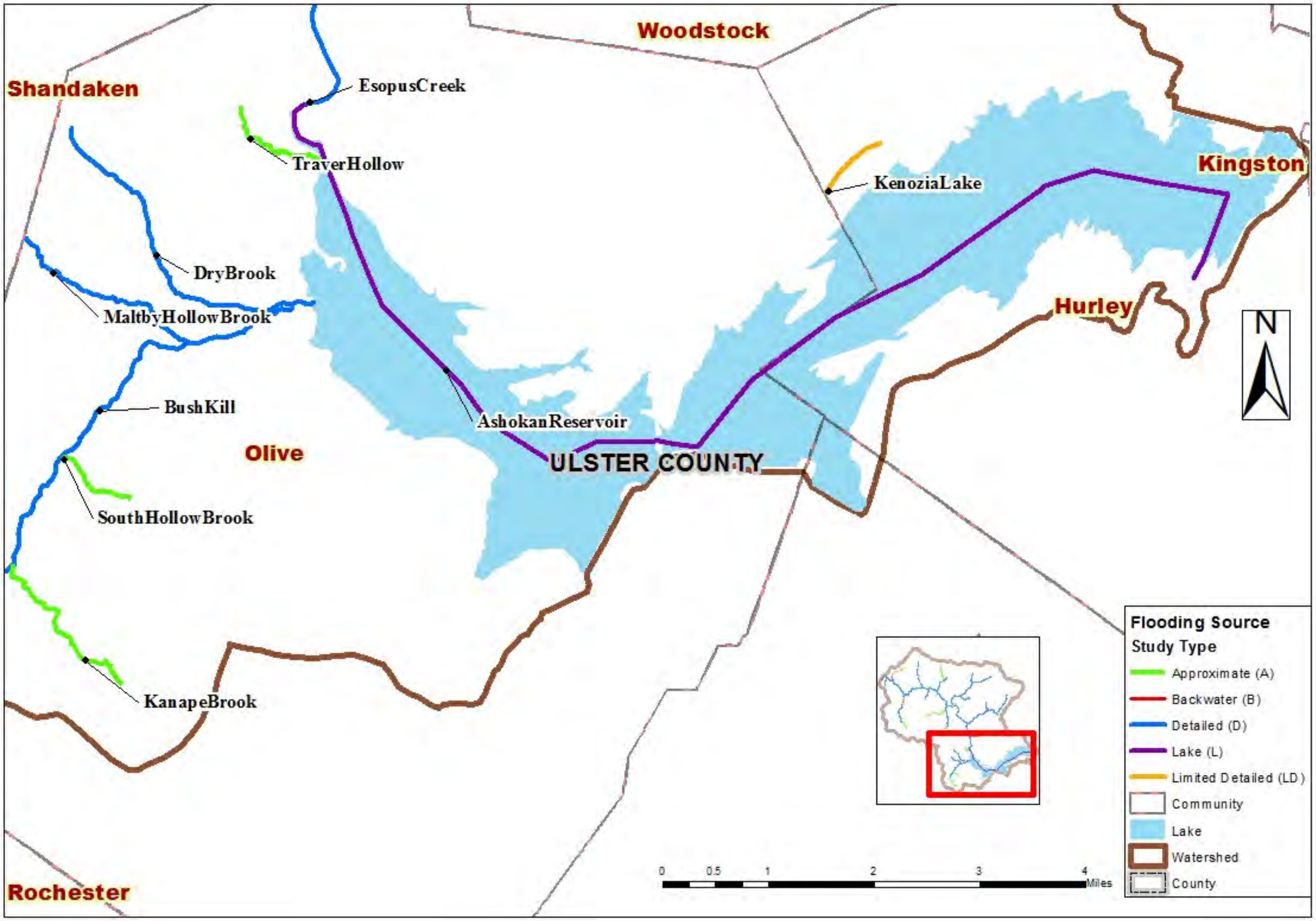

Figure 5: Scoped Flooding Sources – Part4

A.1 Study Area

Ashokan Reservoir Watershed is part of one of the three water supply systems that supply water for New York City (NYC). The watershed belongs to the Catskill water supply system; the other two are the Delaware System and Croton System. Key components of the Catskills system include Ashokan Reservoir, Schoharie Reservoir, Shandaken Tunnel, and Catskills Aqueduct. The drainage network of the watershed includes a number of streams, with Esopus Creek being the main stream feeding the reservoir. Figure 6, obtained from NYCDEP online maps repository, provides a schematic diagram of the NYC water supply system and its key components. The Catskill system satisfies approximately 40% of the city's water supply demand (NYCDEP 2007).

Esopus Creek originates at Winnisook Lake in the Slide Mountain, travels in a southeasterly clockwise direction for about 26 miles before emptying into the Ashokan Reservoir. Below the reservoir, the stream continues on its course and empties into the Hudson River. The total contributing area at the mouth of the reservoir is about 255 sq. mi. The watershed is located in USGS (United States Geological Survey) 8-digit hydrologic unit code (HUC8) 02020006. Esopus Creek and its tributaries drain about 330 miles of stream (NYCDEP 2007). Some of the major tributaries to Esopus Creek include Birch Creek, Bushnellsville Creek, Stony Clove Creek, Fox Hollow, Broad Street Hollow, Woodland Creek, Beaver Kill, Little Beaver Kill, and Bush Kill. The watershed spans across two counties, Ulster and Greene, with the majority of the area in Ulster County. The portion of the watershed in Ulster County accounts for about 82% of the total watershed area. Esopus Creek is subject to inter-basin flow due to diversion of flows from Schoharie Reservoir to Esopus Creek. The Shandaken tunnel, an 18-mile aqueduct built between Schoharie Reservoir and its outfall into Esopus Creek, facilitates the inter-basin transfer. The tunnel's outfall is located just above the confluence of Esopus Creek and Broad Street Hollow. Ashokan Reservoir is located at the downstream portion of the study area.

Figure 6: New York City Water Supply System (Source: NYCDEP 2011)

A.2 Purpose and Type of Study

The purpose of this study is development of flood hazard analyses for the flooding sources identified as part of the project scope. Included as part of the flood study are development of hydrologic analyses to compute discharges for streams and elevations for the lakes, for the five frequencies. The results of the hydrologic analyses form the basis for hydraulic analyses, which ultimately become the basis for RiskMAP products such as flood maps and other risk-based products. This report focuses on the hydrologic analyses part of the project. The study methods used for developing hydrologic analyses follow guidance provided in FEMA's *Guidelines and Specifications for Flood Mapping Partners,* Appendix C (November 2009). Discharges were calculated for the 10% (10-year), 4% (25-year), 2% (50-year), 1% (100-year), and 0.2% (500-year) annual chance peak flow discharges.

A.3 Type of flooding

The entire inventory of flooding sources can be characterized as riverine without any tidal influences. The downstream limit of the study watershed, which is the outlet of Ashokan Reservoir, is about 43 miles upstream of the Hudson River.

A.4 Flooding history

Floods in the Ashokan Reservoir Watershed can occur anytime during a year. The floods that occur in summer and fall are caused mainly by heavy rainfall produced by hurricanes and tropical storms. Floods that occur in winter or spring are primarily from snowmelt caused by rising temperatures and/or the mixing of rain with snow. The largest storm on record occurred as a result of Hurricane Irene in August 2011. The estimated peak discharge on Esopus Creek at Coldbrook is 75,800 cubic feet per second (cfs). This peak discharge is the highest on the record, beating the previous high of 65,300 cfs, which occurred in March 1980. The peak discharge records at several other gages in the basin were also broken by the damaging discharges caused by Hurricane Irene. Other notable locations include Esopus Creek at Allaben and Stony Clove Creek at Chichester.

The flood damages resulting from the March 1980 flood were estimated at 6 million dollars. A flood of similar intensity occurred on March 30, 1951. According to local and newspaper accounts, the flood resulted in a dam break on Birch Creek (FEMA 1989).

Some of the other notable floods recorded at the Coldbrook gage include the flooding events of April 2005, January 1996, April 1987, and April 1984, which rank 4th, 7th, 8th, and 11th respectively. Some of the floods that occurred before the 1980s include the flooding events of August 1933, October 1955, and December 1957. Table 4 provides a summary of discharges recorded at Coldbrook gage on Esopus Creek for the top floods.

Table 4: Historic Flood Discharges in Ashokan Reservoir Watershed

Rank	Date	Peak Discharges (cfs)
1	28-Aug-11	75800
2	21-Mar-80	65300
3	30-Mar-51	59600
4	3-Apr-05	55200
5	24-Aug-33	55000
6	15-Oct-55	54000
7	19-Jan-96	53600
8	4-Apr-87	51700
9	21-Dec-57	46900
10	12-Mar-36	38500
11	5-Apr-84	37400

A.5 Effective Flood Studies

The effective studies for the six communities affected by the current project have been reviewed in terms of methodologies adopted for hydrologic analyses. Two of the six communities are in Greene County, and the remaining four are in Ulster County. The effective studies for the communities in Ulster County were developed in the 1980s and the early part of the 1990s. Since then, there have been no additional studies for Ulster County, whereas the communities of interest in Greene County have been studied twice. The flood studies for Greene were first developed in the early part of the 1980s and restudied again under the 2008 countywide study. The 2008 study was conducted under FEMA's Map Modernization (MapMod) program. Table 5 provides the names the communities of interest for the current study and the dates of effective studies.

Of the flooding sources scoped under this project, only three, Esopus Creek, Beaver Kill, and Stony Clove Creek, were previously studied using detailed methods. The remaining flooding sources either have not been studied or were studied using approximate methods. Appendix A provides a summary of the differences between the methodologies employed in the effective studies and the current study. The effective Flood Insurance Studies (FIS) do not mention the methodologies employed for approximate streams, and, therefore, the methodologies are unknown.

Table 5: Impacted Communities and Effective FIS Dates

County	Community	FIS Date
Greene County	Town of Hunter	Aug-82
	Town of Lexington	Feb-83
	All Communities	May-08
Ulster County	Town of Shandaken	Feb-89
	Town of Woodstock	Sep-91
	Town of Olive	May-84
	Town of Hurley	Aug-82

A.5.1 Esopus Creek

In the effective studies, the reach of Esopus Creek that spans across the Towns of Shandaken and Olive was studied using detailed methods. Both communities utilized the same watershed model developed by NYSDEC and U.S.Army Corps of Engineers (USACE). The watershed model was developed in 1980 using HEC-1 and calibrated to the flood that occurred in March 1980. The frequency storms were developed using National Oceanic and Atmospheric Administration's (NOAA) Technical Memorandum HYDRO-35 and Technical Paper-40. The constant loss rate of rainfall was adjusted in order to match the model peak flow discharges with the peak discharges computed at the Coldbrook Gage (Gage ID: 01382500) using gage analyses (FEMA 1984, FEMA 1989)

A.5.2 Beaver Kill

Beaver Kill is completely within Ulster County, stretching across the Towns of Woodstock and Shandaken. In the effective studies, the reach within the Town of Woodstock has been studied using detailed methods, and the reach within the Town of Shandaken using approximate methods. The methodology used for approximate studies in Shandaken is unknown. The reach of Beaver Kill within the Town of Woodstock utilized regression equations developed by USGS (FEMA 1991).

A.5.3 Stony Clove Creek

Stony Clove Creek spans across the Town of Hunter, Greene County, and the Town of Shandaken in Ulster County. The reach of Stony Clove within Greene County was studied twice using detailed methods, whereas the reach in Ulster County was studied once using approximate methods. The methodology utilized for detailed studies is known, whereas the methodology for the approximate study reach is unknown. In the first of the two studies conducted for Stony Clove in the early part of the 1980s, a watershed model was developed using the TR-20 model, whereas in the second study conducted for the 2008 countywide FIS, a regression methodology was used.

A.5.4 Other Streams

The methodology employed in the effective studies for the streams that were studied using approximate methods is unknown.

A.6 Other Studies

A.6.1 Dam break study done using USACE's 1980 HEC-1 model

NYCDEP contracted GZA in 1998 to conduct hydrologic and hydraulic evaluation of Olive Bridge Dam and Dikes of Ashokan Reservoir. The objective was to assess the hydraulic adequacy of the spillway to pass the Spillway Design Flood (SDF). Inundation maps were prepared as part of the effort, which were incorporated into the Emergency Action Plan (EAP). The study included evaluation and use of an existing FEMA/USACE watershed model (HEC-1), which is referred to in the Esopus Creek effective model section above (FEMA 1984, FEMA 1989). The HEC-1 model was regenerated and necessary revisions were performed. The model configurations were re-adjusted for the purposes of calibration and verification at the two gages on Esopus Creek, at Allaben and Coldbrook. It should be noted that the original FEMA/COE watershed model was calibrated to only the Coldbrook gage, but the GZA/NYCDEP study calibrated the model to a second gage on Esopus Creek at Allaben. The study also utilized the bathymetric data for the reservoir and the spillway rating curves provided by NYCDEP (NYCDEP 2000). The models were not calibrated to other gages in the watershed probably because they did not exist at the time the study was performed or because of a lack of data.

A.6.2 Stream Management Studies conducted by NYCDEP

In 2004, NYCDEP collaborated with Cornell University and USACE to develop a management plan focused on a comprehensive approach to address multiple water resources-related objectives such as flooding, erosion, water quality, eco-systems, recreation, and stakeholder coordination. To develop strategies to tackle the objectives laid out, an assessment of the current hydrologic conditions in the watershed was conducted. Hydrologic analyses utilized gage analysis for gage streams with sufficient periods of record; for the ungaged streams, regression estimates were developed using 1991 equations (Lumina 1991). Some of the background information utilized in the current study was obtained from the stream management study.

B. STUDY AREA CHARACTERISTICS

This section of the report discusses the general features of the watersheds, including topography, sub-watershed configuration, land use characteristics, soil types, and precipitation. Also discussed in this section are the USGS stream gages and the Ashokan Reservoir. Detailed discussions about the datasets used to characterize the watershed in the hydrologic models can be found in Section C.

B.1 Topography

The Ashokan Reservoir watershed is located in the eastern portion of the Alleghany Plateau physiographic province, which is the northern portion of the Appalachian Plateaus that extend from southern New York to central Alabama (NYCDEP 2007). The watershed contains steep slopes due to the wide range of elevations within short distances. The watershed contains 21 peaks higher than 3,000 feet above sea level, with Slide Mountain, at an elevation of 4,180 feet, being the highest peak (NYCDEP, Vol III, 2007). Ashokan Reservoir, which is at the outlet of the basin, is at an elevation is 255 feet (Gesch 2002). The slopes along Esopus Creek vary from 13% in the headwater reaches to about 3%-0.5% in the lower reaches, with an average of 1.5%. Any stream with an average slope greater than 0.2% is classified as mountain stream (NYCDEP, Vol. III, 2007). The result of steep streams is conveyance flows at high velocities causing erosion and sedimentation problems. Figure 7 below shows the topography of the watershed.

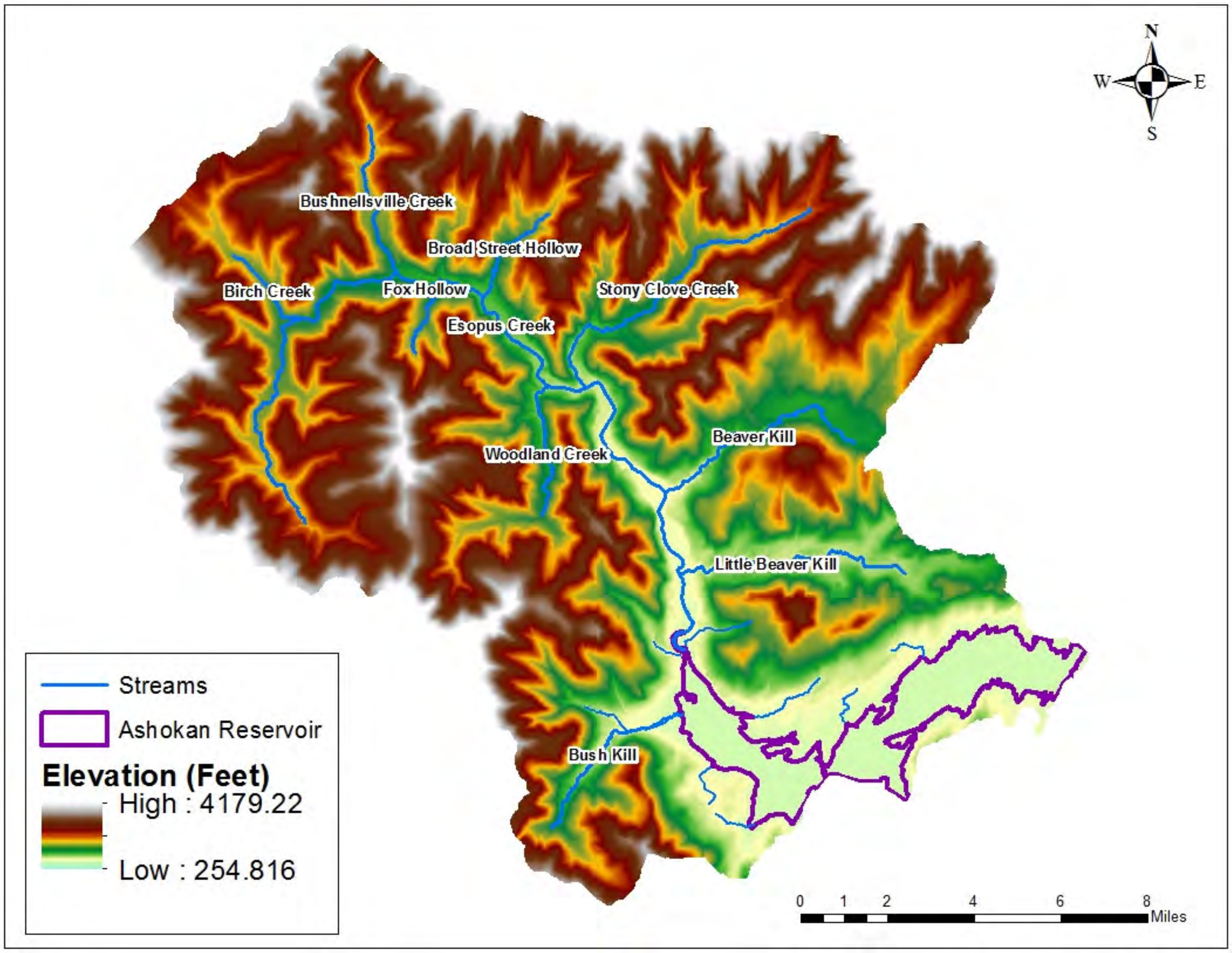

Figure 7: Topography of Upper Esopus Watershed

B.2 Watershed and Stream Network

The total drainage area of Esopus Creek watershed at the mouth of Ashokan Reservoir is about 255 sq. mi. The reservoir itself is about 13 sq. mi, and Esopus Creek and tributaries contribute the remaining area of 232 sq. mi. The drainage areas of the major sub-watersheds are shown in Table 6 below. Along with the several streams that drain into Esopus Creek, Shandaken Tunnel diverts water from Schoharie Reservoir into Esopus Creek. The outfall of the tunnel is located near the confluence of Esopus Creek and Broad Street Hollow. The tunnel was built as part of the NYC Water Supply System. During flood events, the impacts of discharge releases from the tunnel into Esopus Creek are negligible. At its full capacity of 900 cfs, during a 10-year flood, the increase in water surface elevation for the first 2 miles downstream of the tunnel is about 3 inches and about 2 inches thereafter. The impacts diminish with increased flow and distance (NYCDEP 2007).

Table 6: Sub-watershed Configuration for Ashokan Reservoir Watershed

Sub-Watershed	Area (Sq.Miles)
Beaver Kill	25.2
Birch Creek	12.8
Broadstreet Hollow	9.2
Bush Kill	19.7
Bushnellsville Creek	11.1
Little Beaver Kill	16.7
Stony Clove Creek	32.5
Woodland Creek	20.6
Ashokan Reservoir	13
Esopus Creek and other tributaries	94.7
Total	**255.5**

B.3 Land Use and Soils Characteristics

The Upper Esopus Watershed can be characterized as one with uniform land use and soil properties. The watershed is dominated by forest cover, which accounts for about 89.4% of the watershed area. Other types of land use such as open water (7.3%), medium residential (2.4%), and agriculture (0.4%) are also prevalent in the lower valley areas of the watershed (Figure 8). Land use analyses were based on USGS's National Land Cover Dataset (NLCD, 2001).

SSURGO soils data was utilized to determine the hydrologic groupings for the model sub-basins. Overall, the watershed is dominated by soil types C and D, which generally have high runoff potential and low infiltration rates. Combined, these soil types account for about 92% of the total area. They are more prevalent in the upper parts of the watershed. The higher and moderate infiltration type soils, such as A and B, account for the remaining 8% of total area and are prevalent along the stream corridors and storage areas such as lakes (Figure 9).

Figure 8: Land Use Distribution in Upper Esopus Watershed

B.4 Precipitation Characteristics

Mean annual precipitation for the watershed ranges from about 52 inches at Ashokan Reservoir to about 63.5 inches at Slide Mountain. In winters, the mountains are covered with snowpack. Snow melts during the spring and summer when the temperature rises above the freezing points, resulting in flood. Snowmelts could also result from a combination of higher temperatures and spring rains. The watershed is also subjected to heavy rainfall due to tropical storm events that can result in flooding during summer and fall (NYCDEP 2007).

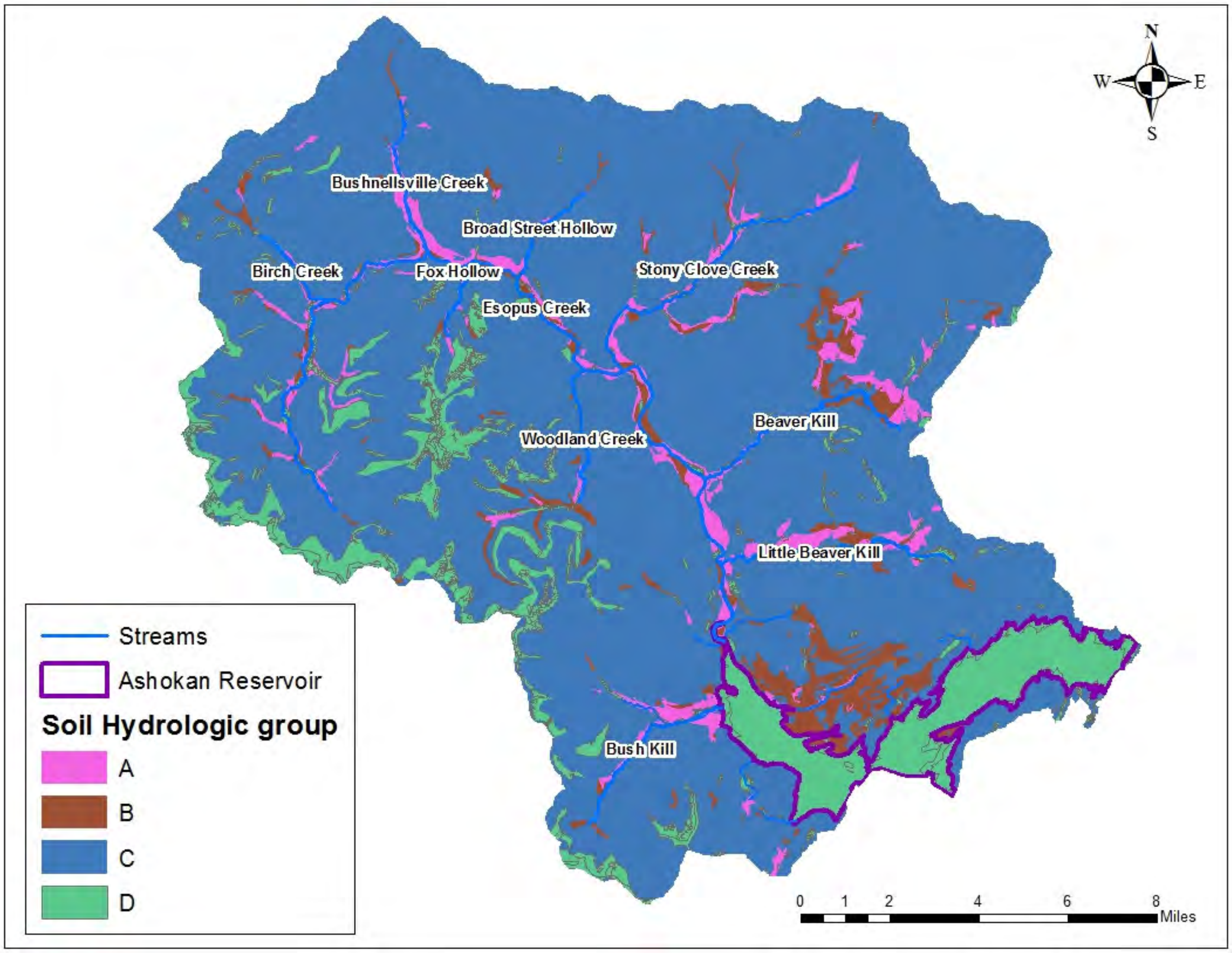

Figure 9: Soil Hydrologic Groupings in Upper Esopus Watershed

B.5 Ashokan Reservoir

Ashokan reservoir was formed by a series of dams, weirs, and dikes between the hills of the Catskills region along Esopus Creek, 14 miles west of Kingston, New York. The main dam of the reservoir is called Olive Bridge Dam. The reservoir is divided into two basins: West and East Basins. The two basins are separated by a weir, called "Dividing Weir." The spillway crests for West (Dividing Weir) and East basins (primary spillway) are 590 feet (ft) and 587 ft. The spillway elevations presented here are referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Figure 10 shows Ashokan Reservoir and related outlet structures. The usable capacity of the west basin is 47,180 million gallons between a minimum operating level of 495.5 ft and the crest of the spillway to the east basin at an elevation of 590 ft. The dead storage below minimum operating level is 2,237 million gallons. The east basin operates at a minimum level of 500 ft to the spillway crest at an elevation of 587 ft, with a usable capacity of 80,678 million gallons and no dead storage. The water from the reservoir is diverted for NYC water supply via a 92-mile aqueduct (FEMA August 1982).

The reservoir divides Esopus Creek into two main reaches: Upper Esopus and Lower Esopus. The Upper Esopus reach extends upstream of the reservoir to the headwaters. The Lower Esopus reach extends downstream of the reservoir exit to its confluence with the Hudson River. Lower Esopus Creek exits the Ashokan Reservoir under the Main Dam of the West Basin, joined later by the Spillway channel that comes from the overflow of reservoir water from the East Basin of the Ashokan (NYCDEP 2007).

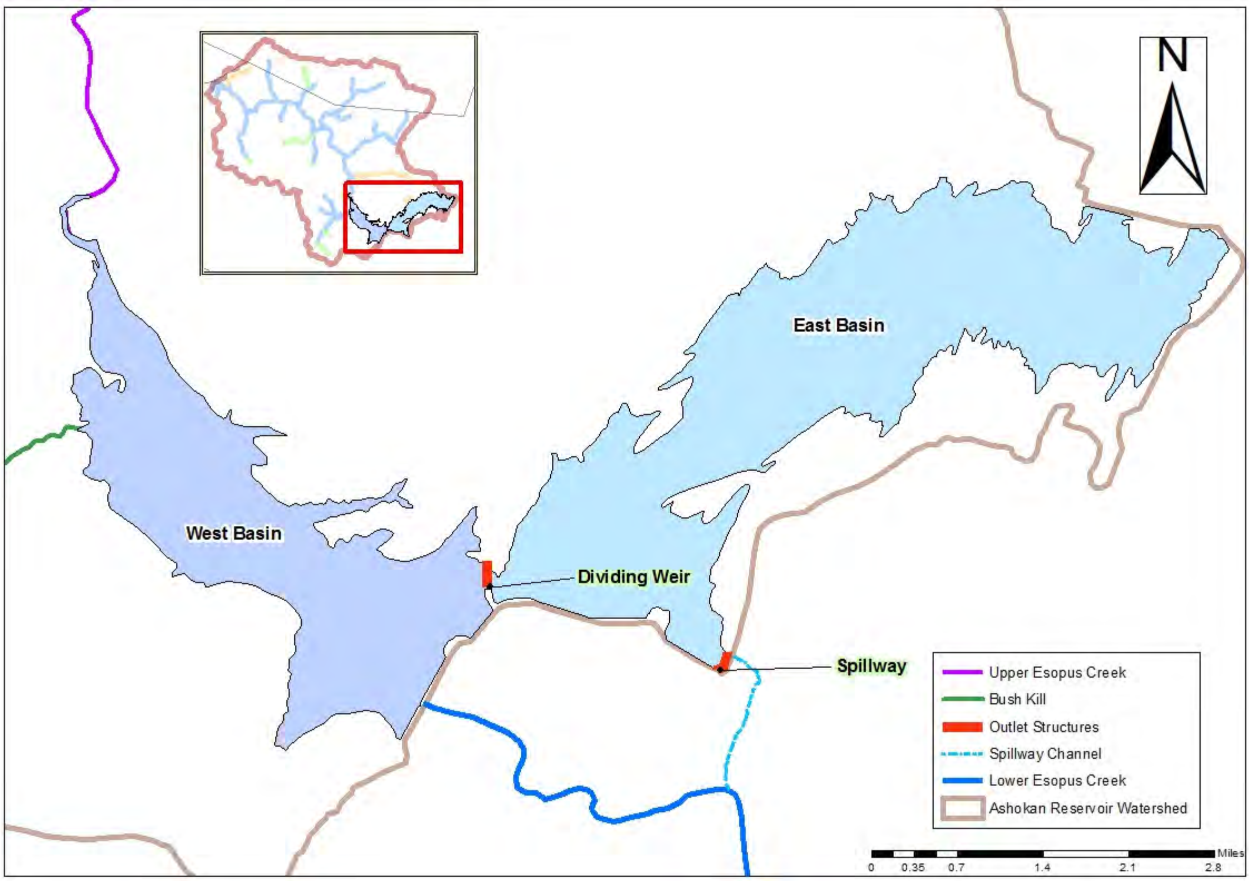

Figure 10: Ashokan Reservoir and its Outlet Structures

B.6 Shandaken Tunnel – Inter Basin Flow

The Shandaken Tunnel is an 18-mile long manmade aqueduct that connects the Schoharie Reservoir to Upper Esopus Creek. The water from the Schoharie reservoir flows naturally down the tunnel by means of gravity. The tunnel has seven shafts that are open to the air along the way; they serve to keep oxygen in the water throughout its 18-mile journey to Upper Esopus

Creek. Once delivered, Esopus Creek carries the Schoharie Reservoir water an additional 12 miles southeast into Ashokan Reservoir. From Ashokan, water is transported to New York City via the Catskill Aqueduct (NYCDEP 2007).

The operation of the tunnel in terms of releases into Upper Esopus Creek is subject to NYSDEC regulation part 670. The maximum amount of capacity of the Shandaken Tunnel is approximately 620 million gallons per day (MGD), which is equivalent to about 960 cfs. According to NYCDEP's stream management study, the tunnel flows were found to have little impact on the flooding downstream of its outlet (NYCDEP 2007). Computer models developed under the NYCDEP study indicated that the during a 10-year flood, the Shandaken Tunnel operating at its full capacity of 900 cfs caused the water surface elevation of the channel downstream to increase by 3 inches for the first two miles and about 2 inches thereafter (NYCDEP 2007). Therefore, the Shandaken tunnel's flow contribution is not reflected in the hydrologic analyses under the current study.

B.7 USGS Stream Gages

There are 10 active stream gages in the study watershed above Ashokan Reservoir that are operated by USGS and NYCDEP (Figure 11). The stream gages are spread across different streams in the watershed with varying periods of record and stream order. Out of the 10 gages, 2 are located on the main stem of Esopus Creek (stream order =1), 6 are located on the immediate tributaries (stream order =2) of Esopus Creek and the remaining 2 are located on tributaries (stream order =3 or higher) to tributaries of Esopus Creek. The streams with order 2 that have gages, include Birch Creek, Bushnellsville Creek, Bush Kill, Little Beaver Kill, Stony Clove Creek, and Woodland Creek. Streams with order greater than two, which have gages, include Hollow Tree Brook (stream order 3), a tributary to Stony Clove Creek, and an unnamed tributary (stream order 4) to Mink Hollow Brook, which is a tributary of Beaver Kill. In terms of period of record, most gages were instituted within the last 16 years. The gages with some of the highest periods of records are located at Allaben (01362200) and Coldbrook (01362500) on Esopus Creek, and at Shandaken on Bushnellsville Creek (01362197), with periods of record of 80 years, 49 years, and 33 years, respectively. Table 7 lists the gages in the Ashokan Reservoir watershed, their drainage areas, and years of operation. For model calibrations and verification, the 2 gages on the small streams were excluded. The remaining 8 gages were utilized for calibration purposes.

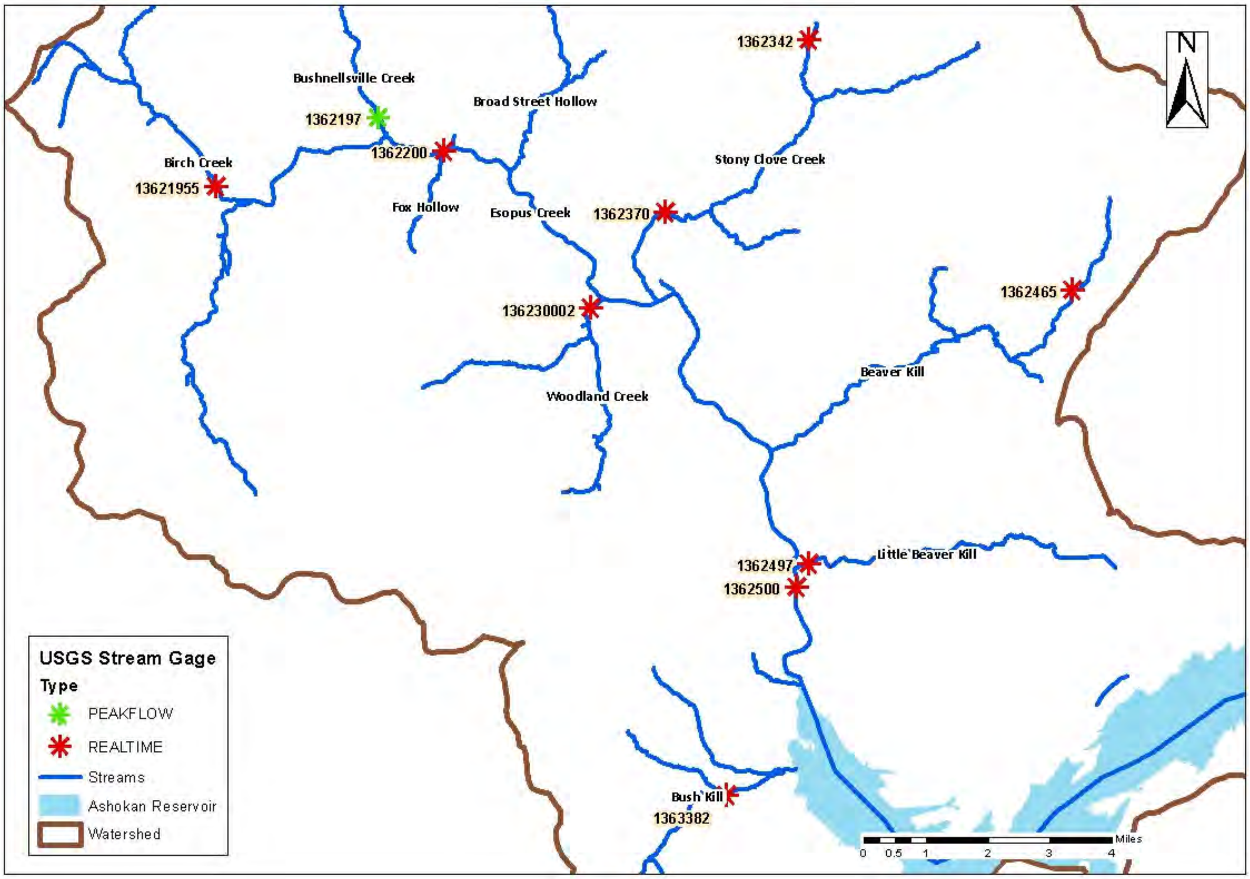

Figure 11: USGS Stream Gages in Ashokan Reservoir Watershed

Table 7: USGS Stream Gages in Ashokan Reservoir Watershed

GageID	Location Name	Gage Type	Drainage Area (Sq.Mile)	Years of Operation
01362465	BEAVER KILL TRIB ABOVE LAKE HILL NY	REALTIME	0.98	11
013621955	BIRCH CREEK AT BIG INDIAN NY	REALTIME	12.5	13
01363382	BUSH KILL BLW MALTBY HOLLOW BK AT WEST SHOKAN NY	REALTIME	16.2	11
01362197	BUSHNELLSVILLE CR AT SHANDAKEN NY	PEAKFLOW	11.4	33
01362200	ESOPUS CREEK AT ALLABEN NY	REALTIME	63.7	49
01362500	ESOPUS CREEK AT COLDBROOK NY	REALTIME	192	80
01362342	HOLLOW TREE BROOK AT LANESVILLE NY	REALTIME	1.95	14
01362497	LITTLE BEAVER KILL @ BEECHFORD NR MT TREMPER NY	REALTIME	16.5	14
01362370	STONY CLOVE CREEK BLW OX CLOVE AT CHICHESTER NY	REALTIME	30.9	15
0136230002	WOODLAND CREEK ABOVE MOUTH AT PHOENICIA NY	REALTIME	20.6	9

C. APPROACH AND METHODOLOGY

This section discusses the methods employed for developing hydrologic analyses for this project. Three different methods are commonly used for flood studies. These are the rainfall-runoff model (also referred to as watershed model), flood frequency analysis (also referred to as gage analyses), and regression analyses.

The rainfall-runoff model was selected to develop discharges for the streams studied. Reasons for model selections are discussed in section C.1. Wherever available, discharges developed by the rainfall-runoff models were compared with those developed using stream gage data and NY regression equations. Desktop and web-based hydrology software programs were utilized to facilitate the hydrologic analyses for this project. HEC-HMS 3.5 program developed by USACE was used for watershed modeling (USACE 2010). USGS's PeakFQWin program was used for developing gage analyses and USGS's StreamStats web application was used for developing regression analyses. Supplemental hydraulic models were developed using HEC-RAS 4.1 to assist in the computations of stream-based model parameters, required for HEC-HMS model.

C.1 Model Selection Criteria

The effective studies used detailed methods for only three flooding sources and approximate methods for the remaining streams that were studied. The effective FIS provides methodology information for only the detailed studies; therefore, the hydrology methods/models used for only the three flooding sources are known. The three flooding sources studied using detailed methods are Esopus Creek, Stony Clove Creek (Greene County reach), and Beaver Kill.

Based on the effective FIS, a HEC-1 watershed model was used to develop peak discharges for Esopus Creek (FEMA 1982). The reach of Stony Clove Creek in Greene County was studied twice in the past using detailed methods. The first study was developed during the early 1980s and the second (latest) study was conducted for the 2008 countywide study. The 1980s study utilized TR-20 watershed model (FEMA 1983), whereas the newer study utilized regression analyses (FEMA 2008). The reach in Ulster County was studied only once using approximate methods, and the model used is unknown. The method adopted by the 2008 Greene study (regression) is inferior than the one adopted by the 1980s study (watershed model), which is contrary to FEMA's guidelines on method selection. Based on the FEMA guidelines for method selection, the newer study methodology should be either similar or superior. Because the study done for the 2008 FIS is a newer study but used an inferior methodology than its predecessor, the current study seeks to correct this error in model selection as well as update the analyses for Ulster reach using a watershed model. Beaver Kill, which was the third stream studied using detail methods in the effective studies, was based on regression analyses (FEMA 1991).

Approximate methods and models employed in the effective studies for developing lake levels for Ashokan Reservoir are unknown. The current study utilizes the watershed model for developing lake levels for the five flood frequencies. The current study takes advantage of reservoir data, such as rating curves developed for NYCDEP's dam break analysis study. As with Stony Clove and Esopus Creek, the lake levels for the flood frequencies were developed using the HEC-HMS developed for the study watershed.

The effective FIS used a watershed model to develop Qs for Esopus Creek and Stony Clove Creek. Coincident peaking conditions are likely to exist at various confluences. In addition, the storage effects of the Ashokan Reservoir needed to be reflected to determine the 1%-chance lake level for this reservoir. Therefore, watershed modeling using HEC-HMS was selected as the appropriate method to study the rainfall/runoff characteristics of Esopus river watershed up to the Ashokan Reservoir's downstream dam. The watershed model was also calibrated and validated to flows measured during a few flooding events at the stream gages.

Regression and gage analyses were also developed to supplement the watershed model. Regression estimates were developed for all the streams scoped in this project using USGS StreamStats web-based GIS application, and gage analyses were developed for all the stream gages within the study watershed that had enough period of record using PeakFQ program. The results of the regression analyses and gage analyses are provided in Appendix B and C, respectively. Regression and gage analyses results were used to compare the results from the frequency storm runs of HEC-HMS.

C.2 Rainfall-Runoff modeling

HEC-HMS version 3.5 software program developed by USACE was utilized for developing watershed model for this project. Development of model parameters and configuration was done using ArcGIS and a pre-processing extension called HEC-GeoHMS, which was also developed by USACE.

C.2.1 Watershed Delineations

Watershed/sub-watershed boundary delineations and stream/channel delineations were developed using topographic datasets. Relevant properties of the watersheds/streams (also called morphological parameters) such as stream lengths, slopes, longest flow paths, basin centroid, and centroid elevations use USGS 10-meter Digital Elevation Model (DEM) data and HEC-GeoHMS extension for ArcGIS software published by the USACE. The longest flow path is the basis for calculation of the lengths and slopes for upland and channel flow paths. The DEMs used in this study were obtained from the USGS web site http://seamless.usgs.gov/website/seamless/viewer.htm referenced to a Geographic Coordinate System (GCS), and with elevations in meters above North American Vertical Datum of 1988 (NAVD88). For the purpose of this project, the DEMs were re-projected into New York State Plane East (FIPS 3101) with the elevation converted to feet.

Basin delineations were delineated using HEC-GeoHMS and considered basin size, land use, stream drainage features, stream gage locations, and municipal boundaries. In total 106 sub-basins were delineated for the model, at an average area of 2.4 sq. mi per sub-basin, totaling to 255 sq. mi (Figure 12).

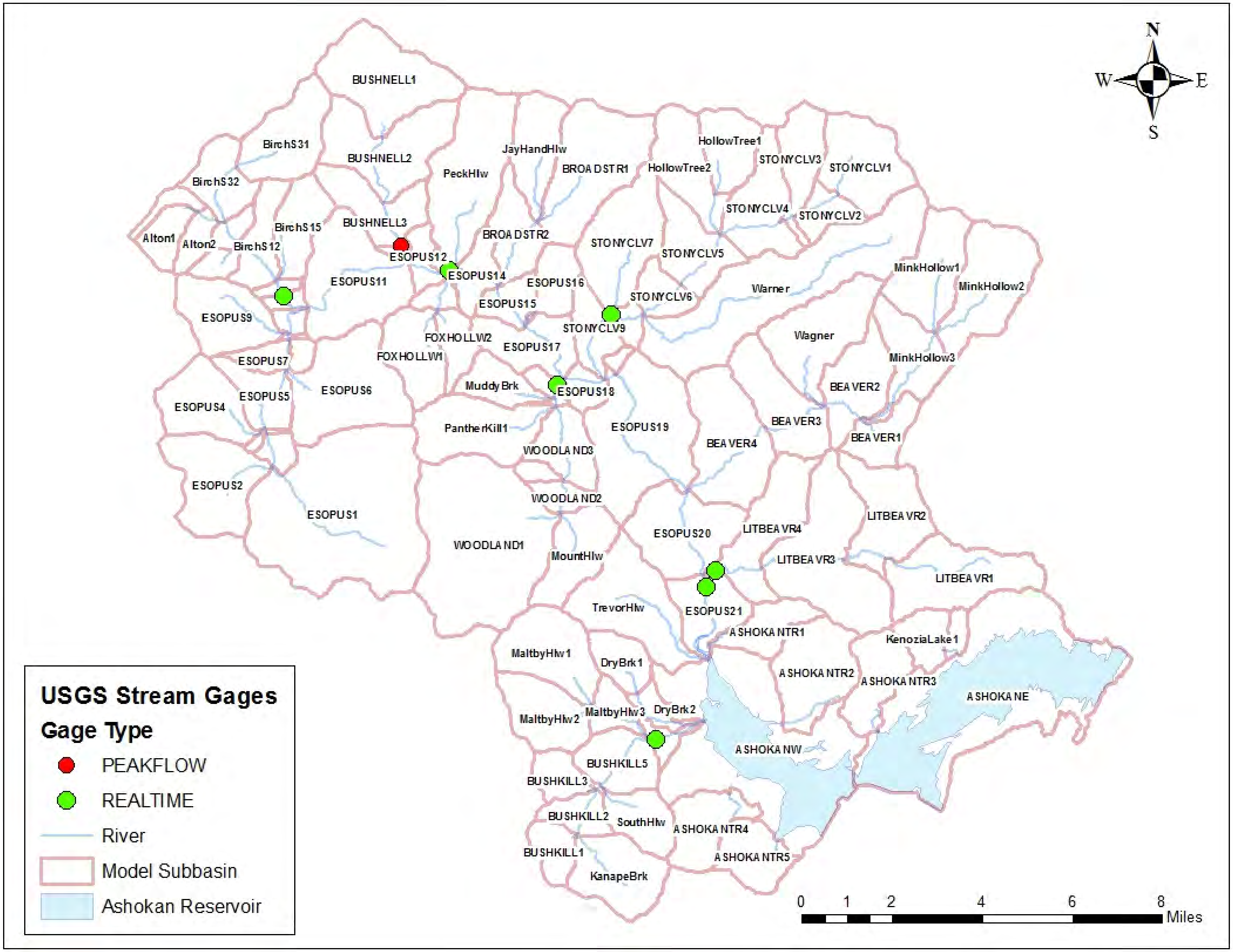

Figure 12: HEC-HMS Model Sub-Basins

C.2.2 Infiltration/Loss Method

This study uses Natural Resources Conservation Services (NRCS) curve number method (CN) to determine infiltration and losses. The initial runoff curve numbers were developed based on hydrologic soil group, land use, and hydrology condition. The curve number calculations were based on NLCD 2001 land use map and SSURGO soil datasets. The land use dataset was obtained from USGS, and the soils dataset was obtained from NRCS. Table 8 provides the distribution of land use. Table 9 provides the distribution of soil hydrologic groupings, and Table 10 provides distribution of Land use-Soil combination distribution. HEC-GeoHMS was used to develop the weighted curve number for each model's sub-basins, based on the land use – soil combinations for average antecedent moisture conditions (AMC-2). Table 11 provides the lookup table utilized for developing curve numbers. The AMC-2 initial CN estimates for model sub-basins ranged from 56 to 89 (Figure 13). The average CN of the study watershed is about 70, and most of the individual sub-basin CN values are around the average, except for the 2 sub-basins of Ashokan Reservoir, which are in 80s. The high CN values for the Ashokan Reservoir sub-basins result primarily from the large area of occupancy of the reservoir's lakes, whose CN value is generally close to 100. These initial CN estimates were refined during the model calibration. Discussion of parameter value adjustments for model calibration is provided in the subsequent sections.

Table 8: Land Use Distribution for Ashokan Reservoir Watershed

Land Use	Area (Sq.Miles)	Percent Area
Agricultural	2.4	0.9%
Forest	228.4	89.4%
Medium Residential	6.0	2.4%
Water	18.7	7.3%

Table 9: Soil Hydrologic Grouping Distribution for Ashokan Reservoir Watershed

Soil Type	Area (Sq.Miles)	Percent Area
A	9.8	3.8%
B	10.8	4.2%
C	202.0	79.0%
D	32.9	12.9%

Table 10: Land Use - Soil Type Combination Distribution

Land Use	Soil Type	Area (Sq.Miles)	Percent Area
Agricultural	A	0.8	0.3%
Agricultural	B	0.5	0.2%
Agricultural	C	1.0	0.4%
Agricultural	D	0.1	0.0%
Forest	A	6.5	2.5%
Forest	B	8.2	3.2%
Forest	C	195.8	76.6%
Forest	D	17.9	7.0%
Medium Residential	A	1.6	0.6%
Medium Residential	B	1.0	0.4%
Medium Residential	C	2.7	1.1%
Medium Residential	D	0.7	0.3%
Water	A	0.9	0.4%
Water	B	1.2	0.5%
Water	C	2.5	1.0%
Water	D	14.2	5.6%

Table 11: Curve Number Lookup Table for AMC-2 conditions

Land Use	A	B	C	D
Water	100	100	100	100
Forest	31	58	71	78
Agriculture	67	77	83	87
Medium Residential	57	72	81	86

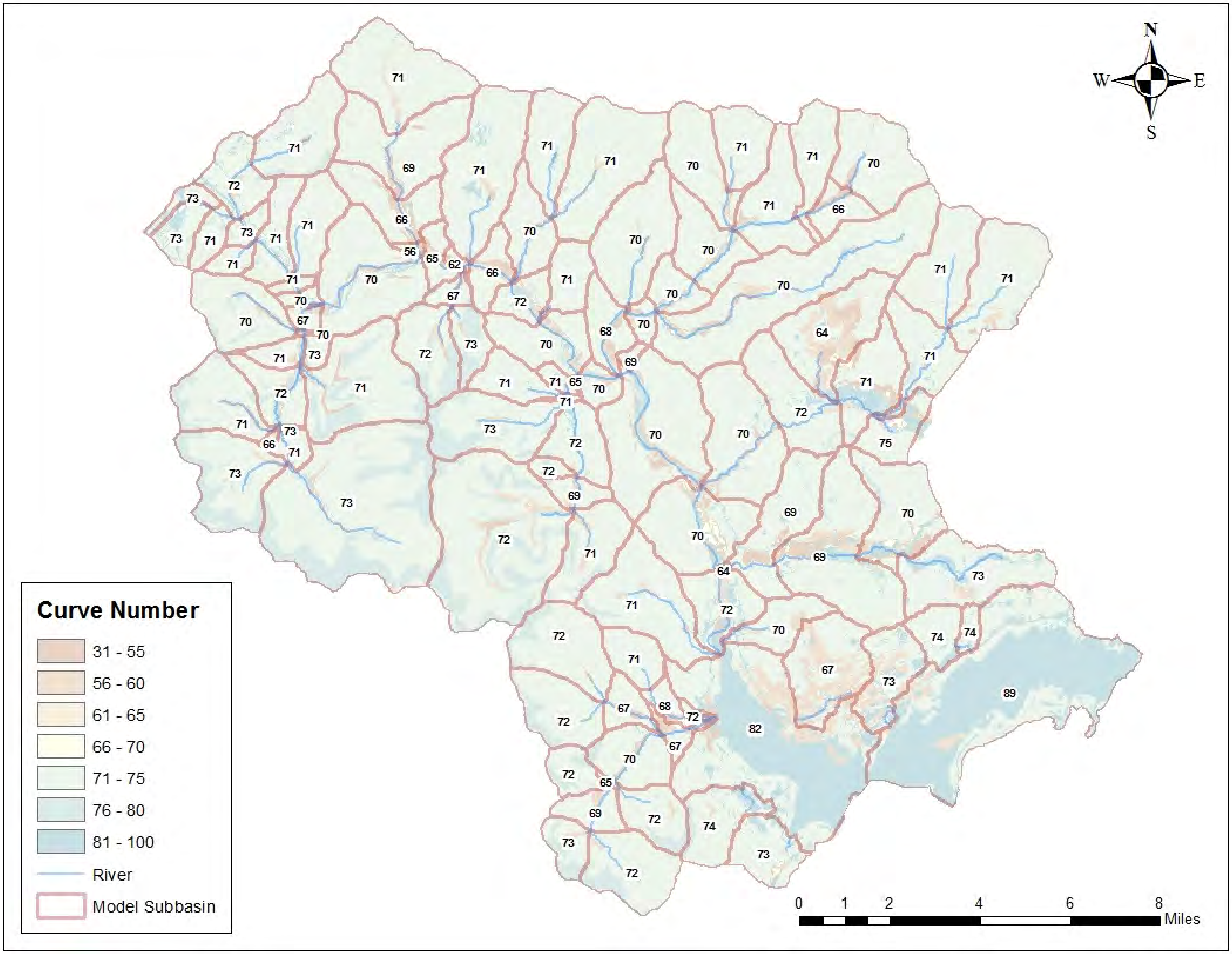

Figure 13: Curve Number Initial Estimates for AMC-2 Conditions

C.2.3 Transformation of Excess Rainfall to Runoff

The NRCS unit hydrograph method was used for excess rainfall transformation. This method requires an estimate of Lag Time (t_{lag}) for each model sub-basin. Lag time is defined as 0.6 times time of concentration (t_c). The time of concentration calculations were based on the procedures outlined by NRCS in Urban Hydrology for Small Watersheds (USDA 1986) and the National Engineering Handbook (NRCS).

The procedures require development of longest flow paths and break points between the three flow path components called sheet flow, shallow concentrated flow, and channel flow. Longest flow paths and preliminary lengths for the three flow components were developed using HEC-GeoHMS. The flow paths and lengths obtained by the automated process were re-adjusted manually based using the USGS topographic maps. The transitions from sheet flow, to shallow concentrated, to channel flows were determined from USGS 1:24,000 based visible channel mapping (USGS Quad blue lined streams). For channel flow, the average channel velocities were computed using channel bank-full equations developed by the USGS for the state of New York (USGS 2009). The travel time through reservoirs was determined from the method published in Chapter 15 of the National Engineering Handbook. The velocities for shallow concentrated flows were determined from graphs found in Chapter 15 of the National Engineering Handbook. The initial lag time estimates developed by the procedures were refined during a subsequent calibration and validation process as discussed later in this report.

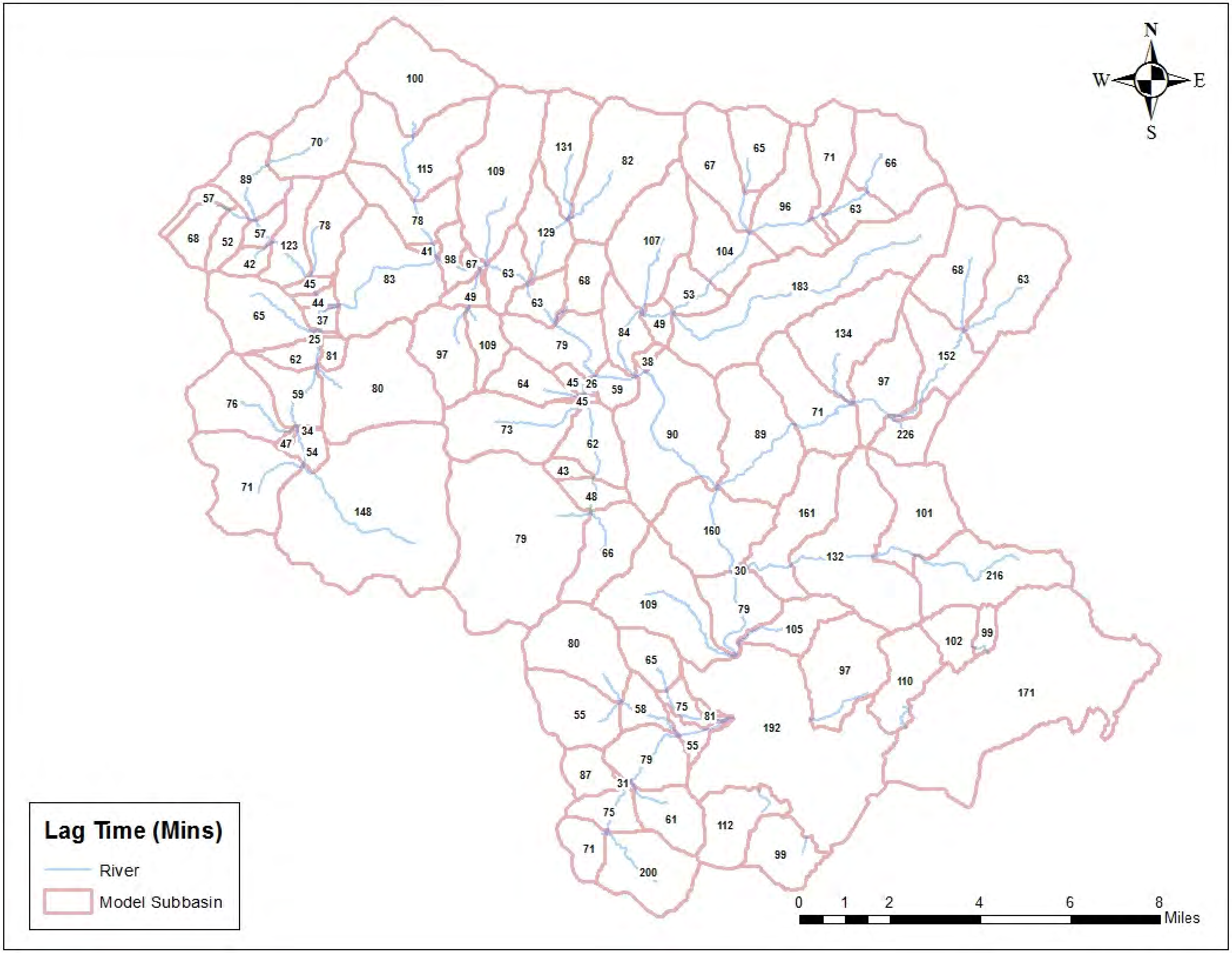

Figure 14: Lag Time Initial Estimates

C.2.4 Channel & Reservoir Routing

A Muskingum-Cunge 8-point cross-section configuration was used for simulating channel flow for 53 of the 54 reaches in the Ashokan Reservoir Watershed model. The Modified-Puls method was used for the remaining reach, which is in Beaver Kill watershed, because of the method's suitability for modeling significant overbank storage. The 8-point cross sections were developed using a LiDAR dataset (NYCDEP 2007) and HEC-RAS version 4.1. HECRAS was also utilized for developing the storage-discharge relationship required for Modified-Puls method. HEC-GeoRAS was used for generating the geometry file for the hydraulic model.

The reservoir routing option provided in HEC-HMS was used for modeling reservoirs in the watershed. The outflow discharge and stage hydrographs were generated by routing the inflow hydrographs from upstream sub-basins into the Ashokan Reservoir using rating curves and the reservoir routing method option. The parameterization of the reservoir routing model was based on information provided in the reservoir dam break analysis report (NYCDEP 2000). In the HEC-HMS model, the two basins (West Basin and East Basin) of the Ashokan Reservoir were treated as reservoirs in series, separated by a weir (Dividing Weir). The flow hydrographs were routed from the west basin into the east basin using storage-discharge-elevation relationship provided in the dam break analysis report (Table 12). Spills from the east basin downstream into Esopus Creek were also based on the storage-discharge-elevation relationships provided for the main spillway (Table 12). During flood conditions, possibility of submergence of the Dividing Weir exists. Therefore, the rating curves developed by the dam break study reflect the submergence conditions at high flows. Figure 15 and Figure 16 provide graphical representations of the Storage-Discharge-Elevation relationships for the west basin and east basin respectively. Detailed information about the characteristics of the reservoirs is also provided in the previous section.

Apart from Ashokan Reservoir, other lakes/reservoirs in the watershed include Yankee Town Pond, which is located along Little Beaver Kill, and Kenozia Pond, which is located on a small tributary that empties directly into Ashokan Reservoir. Though these two lakes are relatively small compared to Ashokan Reservoir, the model included them in order to provide assessment of impact in their local vicinity. Stage-Storage relationships developed using HEC-GeoRAS and USGS 10m DEM were used in combination with outflow structure functionality provided in

HEC-HMS to model these two lakes. The outflow structure details coded into the model were developed using the field survey data captured as part of this watershed study.

Table 12: Storage-Elevation-Discharge Relationship for Ashokan Reservoir (Source NYCDEP 2000)

West Basin (Dividing Weir)		
Storage(AcFt)	Discharge(cfs)	Elevation(Ft)*
10183	0	510
15812	0	520
23486	0	530
34421	0	540
48639	0	550
66736	0	560
88636	0	570
113930	0	580
141920	0	590
143442	1056	590.5
144965	2988	591
148009	8450	592
154237	23901	594
160605	43909	596
167116	67602	598
173768	94476	600
187529	156500	604
201920	228156	608
216954	308289	612

* Elevations are referenced to NGVD29 datum

East Basin (Main Spillway Routing)		
Storage(AcFt)	Discharge(cfs)	Elevation(ft)*
107760	0	556
111350	0	557
118700	0	559
130100	0	562
141900	0	565
149980	0	567
193700	0	577
242410	0	587
244954	1040	587.5
247497	3040	588
252624	8870	589
257791	16800	590
262998	27400	591
268245	40400	592
273533	53100	593
284231	81700	595
295094	114200	597
306120	150100	599
311697	209700	602
365000	398198	610

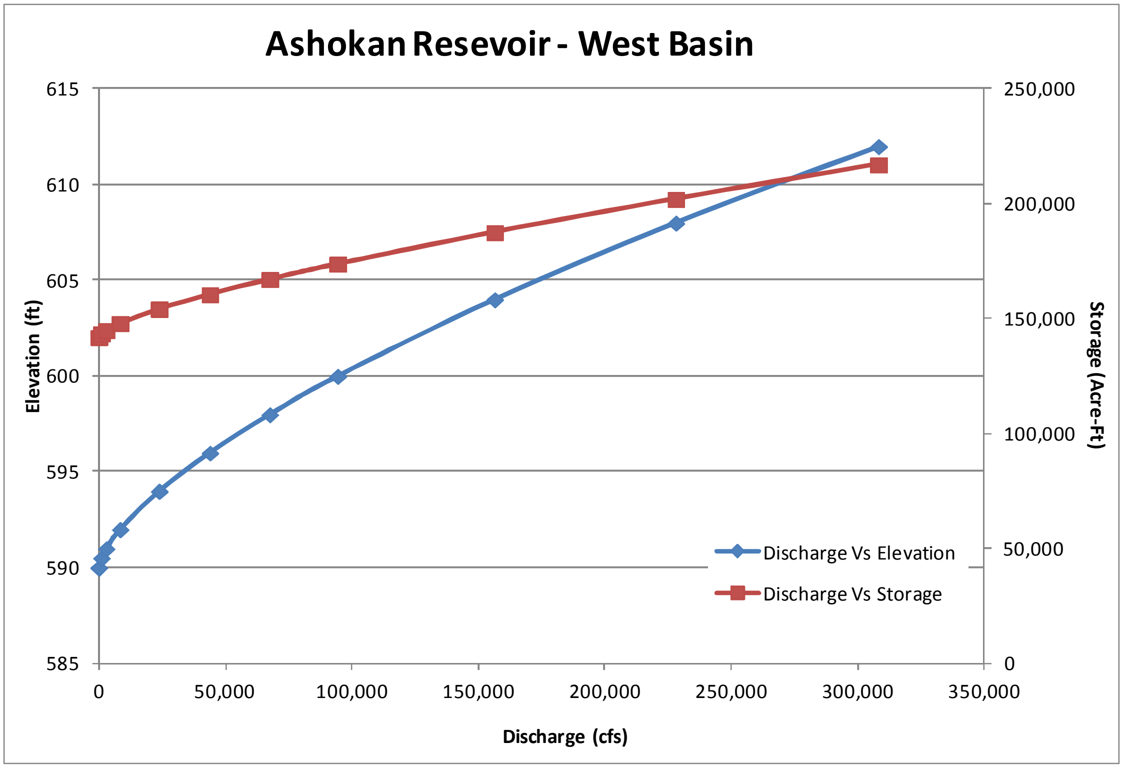

Figure 15: Storage-Discharge-Elevation for West Basin

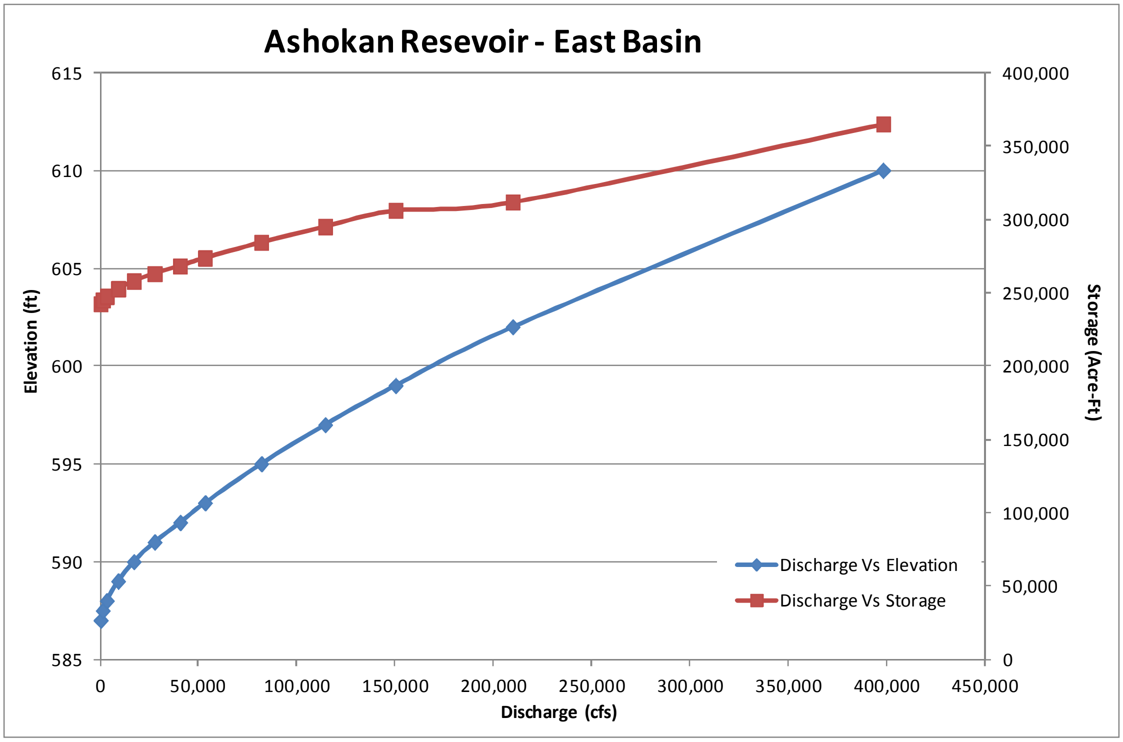

Figure 16: Storage-Discharge-Elevation for East Basin

C.2.5 Recession Baseflow

Recession baseflow was simulated for the model sub-basins. These sub-basins consisted primarily of forest cover with steep slopes where interflow could be expected. The parameter set-up for these simulations was based on guidance provided in the HEC-HMS Technical Reference and on a review of the observed hydrographs during the calibration process. The values for the baseflow parameters are discussed in more detail under the calibration sections.

C.2.6 Event Precipitation Data

A final set of calibrated values to be used for simulating the frequency storms was developed by adjusting the raw parameter estimates so that simulated results compared reasonably well with the observed flow data for known flooding events of the past. In order to simulate the flooding events accurately, observed rainfall with good spatial and temporal (time) resolution is required. The National Oceanic and Atmospheric Administration's (NOAA's) gridded rainfall product, called Multi-sensor precipitation estimate (MPE), provided the resolution needed to represent the distribution of rainfall. MPE data is a product developed by NOAA's North East River Forecasting Center (NERFC) using Next-Generation Radar (NEXRAD) rainfall and data collected at the rain gauges. The purpose of the rain gauge data is calibration of NEXRAD raw data to produce MPE. MPE has a temporal resolution of 1 hour and a spatial resolution of 4 kilometers. MPE data was translated into grids in HEC-HMS system using a supplemental program called HEC-GridUtil, developed by USACE. HEC-GridUtil helps in converting the MPE files, which are in a custom format called XMRG, into gridded data in HEC-DSS database. HEC-DSS is a database that acts as a central repository for inputs and outputs from a variety of HEC software programs such as HEC-HMS, HEC-RAS, etc. In terms of gridded rainfall data, the model HEC-DSS contains one grid dataset per time step. Thus, MPE rainfall product facilitated the use of the gridded rainfall option in HEC-HMS.

Hourly precipitation data collected by NYCDEP rain gauge at Winnisook Lake (DNM148) was used for the comparison for amount and timing of rainfall captured by MPE. The selected period of comparison is from August 27, 2011, 13:00 to August 28, 2011, 24:00. The accumulated amount of rainfall captured by MPE during the selected period is 10.28 compared to 11.57 collected by NYCDEP rain gauge. The rain data collected by both the sources match closely;

because the MPE data provided the spatial variability required to accurately represent the rainfall distribution, it was chosen over the gauge data (Figure 17).

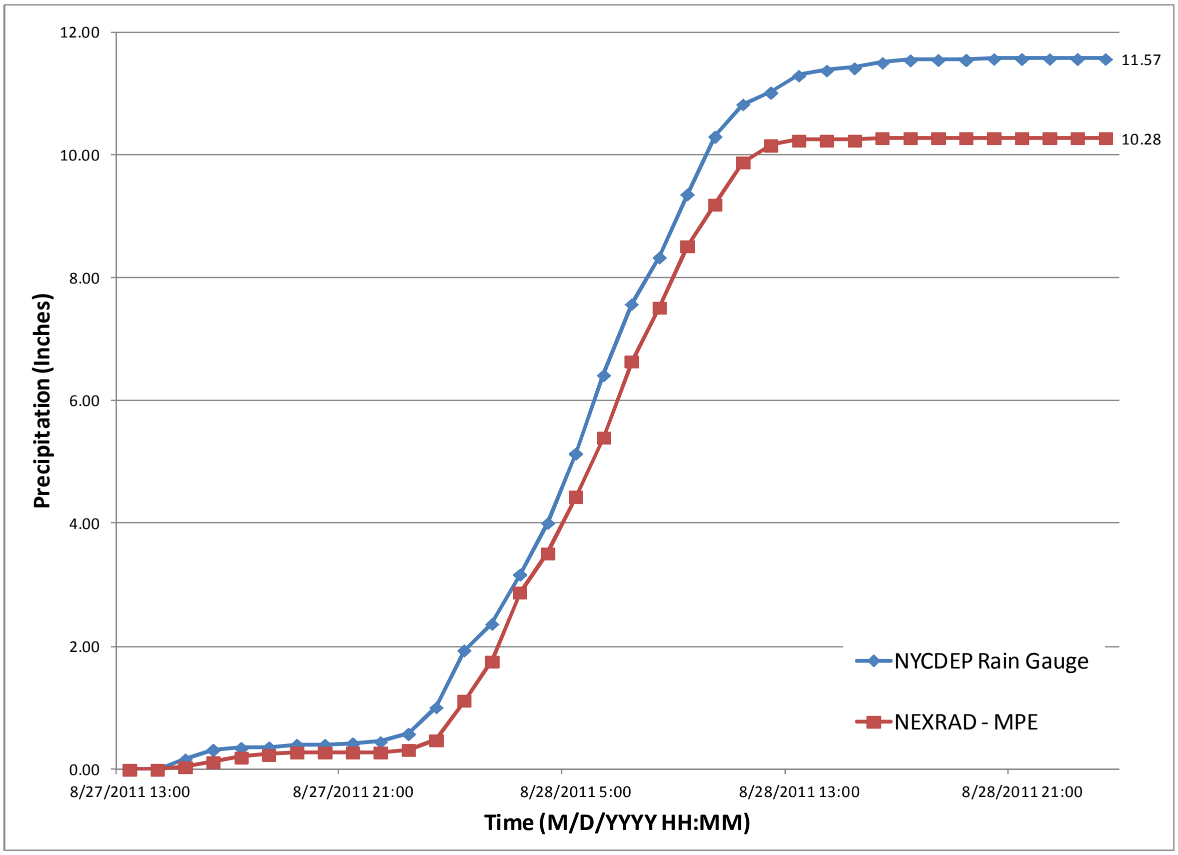

Figure 17: Comparison of Cumulative Precipitation Reported by NYCDEP Rain Gauge at Slide Mountain and the Corresponding MPE Grid Cell

D. APPLICATION AND RESULTS

D.1 Model Calibration and Verification

There are 10 gages in the watershed, 2 of which were not considered useful for model calibration because the gages had small contributing areas and were streams with order greater than 2. The excluded gages are Beaver Kill tributary above Lake Hill, New York (01362465) and Hollow Tree Brook at Lanesville, New York (01362342). The drainage areas at these gage locations are 0.98 sq. mi and 1.95 sq. mi. For 7 of the remaining 8 gages, 15-min hydrographs were available, and for the other gage, which is located on Bushnellsville Creek Gage at Shandaken, New York, only annual peak flows were available (01362197).

Calibration of the HEC-HMS model was performed by adjusting the model parameters until a reasonable match was achieved between the model-simulated hydrographs and the observed hydrographs at the stream gages for known storm events that caused flooding in the past. Selections of storm events were based on the return period of the flood discharges recorded at Coldbrook Gage on Esopus Creek and the availability of precipitation and discharge data. Most of the gages in the watershed are relatively new (10 to 15 years old), and the MPE rainfall data was roughly available for last 10-12 years. Therefore, the events selected for calibration and validation were the ones that occurred in the last 10 years. In the recent past, back-to-back storms devastated the watershed during the last week of August and first week of September in 2011. Hurricane Irene, which was one of the worst flood events ever faced by the watershed, occurred during the last part of August 2011. Hurricane Irene formed in the Atlantic Ocean and moved north along the Northeast corridor. Heavy rains associated with damaging winds started mid-day on August 27th and continued pouring almost all of August 28th. Discharges resulting from this event broke the previous records at most of the gages in the watershed. The frequency of the discharge (75,800 cfs) recorded at Coldbrook Gage on Esopus Creek had a return interval of more than 50 years. Since Hurricane Irene caused the worst flooding in the watershed, it was chosen as a candidate event for model calibration. Well before the effects of Hurricane Irene had subsided, the watershed was faced with yet another storm that was caused by the remnants of Tropical Storm Lee, which occurred in the first week of September 2011. When Lee made landfall the soil was already saturated from Irene, and therefore as expected most of whatever fell on the ground ran off. Tropical Storm Lee was used as a candidate storm event for model verification. In addition to Lee, model verification was also performed for a storm that occurred in October 2005.

D.1.1 Hurricane Irene (August 2011) – Calibration Event

During the process of calibration the initial model parameter values computed for curve number (CN), lag time, and baseflow were adjusted. The initial CN values were computed based on average Antecedent Moisture Conditions (AMC-2). The AMC conditions for Hurricane Irene were assumed to be at average saturation conditions. During the calibration, the model was first run with the initial estimates to test the resulting hydrographs with observed hydrographs. In the subsequent runs, the CN lag times parameters were adjusted to obtain closer match. In the process of parameter adjustment, the CN values changed from the original estimates by an average of 4%, and the lag times were modified by an average of 14%. Baseflow parameters, which include initial discharge per unit area, recession constant, and ratio to peak were calculated based on the rising and falling limb information from the observed hydrographs. The list of parameter values developed from the calibration effort is provided in Table 13. CN values ranged from 59 to 89, with an average of 68. The lag times varied from 20 minutes to 302 minutes. Initial baseflow (cfs/sq.mile) varied from 1.27 sq. mi. to 2.9 sq. mi., with a basin-wide average of 2.1 sq. mi.

During calibration, runoff volume, time of peak, and peak flow intensities resulting from the model were compared to observed data. The results compared well for 4 out the 8 gages. The gage locations where the modeled and measured hydrographs compared well include Esopus Creek at Allaben (01362200), Stony Clove Creek at Chichester (01362370), Esopus Creek at Coldbrook (01362500), and Bushkill at West Ashokan (01363382). Table 14 summarizes the modeled and observed runoff volumes, runoff coefficients, peak flows, and peak times. Figure 18 through Figure 25 provide graphical comparisons of modeled and observed hydrographs.

For Birch Creek gage, USGS has revised the rating curve based on the post Hurricane Irene survey. The model simulated hydrograph at the gage has been compared with the observed hydrographs developed using both the pre and post Irene rating curves. Simulated hydrographs matched with the observed well when pre-Irene rating is used. These observed discrepancies related to discharges between the pre- and post Irene have been communicated to the USGS.

The Woodland Creek gage appeared to have malfunctioned during the Irene flood event. The simulated hydrograph captures the rising limb well. The model results have been communicated to the USGS.

The simulated hydrograph for Little Beaver Kill predicted higher peak discharges and larger outflow volume than observed. Is it unclear why the yield from this watershed is much lower than other neighboring basins. Since the validation event simulation compared well with the observed event, the basin parameters appear to be suitable.

The average cumulative precipitation depth during Hurricane Irene in the watershed is about 8.6 inches and the average depths for the gage sub-watersheds varied from about 7.5 inches to 10 inches. Since the watershed is expected to have similar antecedent moisture conditions (AMC-2) before the storm arrived and since the runoff conditions are similar, it can be expected that the runoff coefficients measured at the gages are similar. In examining the observed data, some discrepancies were found between runoff coefficients measured at the gages. While the gages that calibrated well had runoff coefficients between 58% and 88%, the gages that did not calibrate well in terms of runoff had coefficients between 17% and 40%. Based on the discrepancies, it can be concluded that the gages whose runoff coefficients were not reasonable were malfunctioning. In order to further test the validity and sensitivity of the calibrated parameters, model verifications were performed for two different events, which are discussed in later sub-sections.

Table 13: Calibrated Parameter Values (Hurricane Irene - August 2011)

SUBBASIN	HMS Basin	Initial Estimates			Calibrated Values				
		DA (Sq.Mi)	CN	LAG	CN	LAG	Init Q (CFS/MI2)	Recession Constant	Ratio to Peak
Little Beaver	LITBEAVR1	4.04	73	216	69	302	1.27	0.25	0.25
	LITBEAVR2	3.39	70	101	67	142	1.27	0.25	0.25
	LITBEAVR3	5.95	69	132	66	185	1.27	0.25	0.25
	LITBEAVR4	3.30	69	161	66	226	1.27	0.25	0.25
	LITBEAVR5	0.05	64	30	61	42	1.27	0.25	0.25
Stony Clove Creek	HollowTree1	1.96	71	65	67	58	2.26	0.25	0.25
	HollowTree2	2.66	70	67	67	60	2.26	0.25	0.25
	STONYCLV1	3.30	70	66	67	59	2.26	0.25	0.25
	STONYCLV2	1.07	66	63	63	57	2.26	0.25	0.25
	STONYCLV3	2.00	71	71	67	64	2.26	0.25	0.25
	STONYCLV4	2.88	71	96	67	87	2.26	0.25	0.25

SUBBASIN	HMS Basin	Initial Estimates			Calibrated Values				
		DA (Sq.Mi)	CN	LAG	CN	LAG	Init Q (CFS/MI2)	Recession Constant	Ratio to Peak
	STONYCLV5	2.47	70	104	67	94	2.26	0.25	0.25
	STONYCLV6	1.17	70	53	67	48	2.26	0.25	0.25
	STONYCLV7	3.88	70	107	67	96	2.26	0.25	0.25
	STONYCLV8	0.51	70	49	67	44	2.26	0.25	0.25
	Warner	9.04	70	183	67	165	2.26	0.25	0.25
	STONYCLV9	1.5	68	84	65	76	2.26	0.25	0.25
Bushnellsville Creek	BUSHNELL1	4.43	71	100	71	100	1.92	0.25	0.25
	BUSHNELL2	4.16	69	115	69	115	1.92	0.25	0.25
	BUSHNELL3	2.38	66	78	66	78	1.92	0.25	0.25
	BUSHNELL4	0.15	56	41	56	41	1.92	0.25	0.25
Birch Creek	Alton1	1.08	73	68	69	88	1.92	0.25	0.25
	Alton2	0.81	71	52	67	68	1.92	0.25	0.25
	AltonTr1	0.54	73	57	69	74	1.92	0.25	0.25
	BirchS11	0.57	73	57	69	74	1.92	0.25	0.25
	BirchS12	1.71	71	123	67	160	1.92	0.25	0.25
	BirchS13	0.31	71	45	67	59	1.92	0.25	0.25
	BirchS15	1.97	71	78	67	101	1.92	0.25	0.25
	BirchS31	3.05	71	70	67	91	1.92	0.25	0.25
	BirchS32	1.91	72	89	68	116	1.92	0.25	0.25
	GiggleHlw	0.57	71	42	67	55	1.92	0.25	0.25
	BirchS14	0.34	70	44	67	57	1.92	0.25	0.25
Esopus Creek At Allaben Gage	ESOPUS1	11.80	73	148	73	118	1.4	0.25	0.25
	ESOPUS10	0.37	67	37	67	29	1.4	0.25	0.25
	ESOPUS11	4.76	70	83	70	67	1.4	0.25	0.25
	ESOPUS12	0.80	65	98	65	79	1.4	0.25	0.25
	ESOPUS2	3.71	73	71	73	57	1.4	0.25	0.25
	ESOPUS3	0.58	71	54	71	43	1.4	0.25	0.25
	ESOPUS3b	0.05	73	34	73	27	1.4	0.25	0.25
	ESOPUS4	2.77	71	76	71	61	1.4	0.25	0.25
	ESOPUS5	1.64	72	59	72	47	1.4	0.25	0.25
	ESOPUS6	4.86	71	80	71	64	1.4	0.25	0.25
	ESOPUS7	0.70	71	62	71	50	1.4	0.25	0.25
	ESOPUS8	0.06	70	25	70	20	1.4	0.25	0.25
	ESOPUS9	2.92	70	65	70	52	1.4	0.25	0.25
	FOXHOLLW1	2.36	72	97	72	78	1.4	0.25	0.25
	FOXHOLLW2	1.13	73	109	73	87	1.4	0.25	0.25
	FOXHOLLW3	0.53	67	49	67	40	1.4	0.25	0.25
	HatcheryHlw	0.38	73	81	73	65	1.4	0.25	0.25
	McKinleyHlw	0.11	66	47	66	38	1.4	0.25	0.25
Woodland Creek	MountHlw	2.50	71	66	64	86	2.32	0.25	0.25
	MuddyBrk	1.42	71	64	64	83	2.32	0.25	0.25
	PantherKill1	3.53	73	73	66	94	2.32	0.25	0.25

SUBBASIN	HMS Basin	Initial Estimates			Calibrated Values				
		DA (Sq.Mi)	CN	LAG	CN	LAG	Init Q (CFS/MI2)	Recession Constant	Ratio to Peak
	WOODLAND1	9.63	72	79	65	103	2.32	0.25	0.25
	WOODLAND2	0.77	69	48	62	62	2.32	0.25	0.25
	WOODLAND3	1.87	72	62	65	81	2.32	0.25	0.25
	WOODLAND4	0.09	71	45	64	59	2.32	0.25	0.25
	WOODLAND5	0.35	71	45	64	58	2.32	0.25	0.25
	WOODLAND6	0.05	65	26	59	34	2.32	0.25	0.25
	WOODLANDT3	0.37	72	43	65	56	2.32	0.25	0.25
Esopus Creek At Coldbrook Gage	BEAVER1	1.45	75	226	75	271	2.36	0.25	0.25
	BEAVER2	2.68	71	97	71	116	2.36	0.25	0.25
	BEAVER3	3.12	72	71	72	85	2.36	0.25	0.25
	BEAVER4	4.48	70	89	70	107	2.36	0.25	0.25
	BROADSTR1	4.93	71	82	71	99	2.36	0.25	0.25
	BROADSTR2	1.92	70	129	70	155	2.36	0.25	0.25
	ESOPUS13	0.20	62	67	62	81	2.36	0.25	0.25
	ESOPUS14	1.21	66	63	66	75	2.36	0.25	0.25
	ESOPUS15	1.08	72	63	72	76	2.36	0.25	0.25
	ESOPUS16	1.37	71	68	71	82	2.36	0.25	0.25
	ESOPUS17	2.37	70	79	70	95	2.36	0.25	0.25
	ESOPUS18	0.74	70	59	70	71	2.36	0.25	0.25
	ESOPUS19	6.29	70	90	70	108	2.36	0.25	0.25
	ESOPUS20	3.81	70	160	70	193	2.36	0.25	0.25
	ESOPUST71	0.20	69	38	69	45	2.36	0.25	0.25
	JayHandHlw	2.36	71	131	71	157	2.36	0.25	0.25
	MinkHollow1	3.11	71	68	71	82	2.36	0.25	0.25
	MinkHollow2	3.92	71	63	71	75	2.36	0.25	0.25
	MinkHollow3	2.43	71	152	71	182	2.36	0.25	0.25
	PeckHlw	5.03	71	109	71	131	2.36	0.25	0.25
	Wagner	3.87	64	134	64	161	2.36	0.25	0.25
Bush Kill	BUSHKILL1	1.11	73	71	64	100	2.9	0.25	0.15
	BUSHKILL2	1.11	69	75	61	104	2.9	0.25	0.2
	BUSHKILL3	1.07	72	87	64	122	2.9	0.25	0.2
	BUSHKILL4	0.07	65	31	57	43	2.9	0.25	0.2
	BUSHKILL5	2.06	70	79	61	110	2.9	0.25	0.2
	KanapeBrk	2.94	72	200	63	280	2.9	0.25	0.2
	MaltbyHlw1	3.30	72	80	63	112	2.9	0.25	0.2
	MaltbyHlw2	2.57	72	55	63	77	2.9	0.25	0.2
	MaltbyHlw3	0.98	67	58	59	81	2.9	0.25	0.2
	SouthHlw	1.73	72	61	63	85	2.9	0.25	0.2
	BUSHKILL6	0.57	67	55	59	77	2.9	0.25	0.2
	BUSHKILL7	0.14	72	81	63	113	2.9	0.25	0.2
	DryBrk1	1.36	71	65	62	92	2.9	0.25	0.2
	DryBrk2	0.65	68	75	60	105	2.9	0.25	0.2

SUBBASIN	HMS Basin	Initial Estimates			Calibrated Values				
		DA (Sq.Mi)	CN	LAG	CN	LAG	Init Q (CFS/MI2)	Recession Constant	Ratio to Peak
Ashokan Reservoir	ASHOKANE	14.01	89	171	89	171	2.36	0.25	0.25
	ASHOKANTR1	1.64	70	105	70	105	2.36	0.25	0.25
	ASHOKANTR2	3.50	67	97	67	97	2.36	0.25	0.25
	ASHOKANTR3	2.24	73	110	73	110	2.36	0.25	0.25
	ASHOKANTR4	2.24	74	112	74	112	2.36	0.25	0.25
	ASHOKANTR5	1.95	73	99	73	99	2.36	0.25	0.25
	ASHOKANW	12.05	82	192	82	192	2.36	0.25	0.25
	ESOPUS21	2.17	72	79	72	79	2.36	0.25	0.25
	KenoziaLake1	1.23	74	102	74	102	2.36	0.25	0.25
	KenoziaLake2	0.45	74	99	74	99	2.36	0.25	0.25
	TrevorHlw	4.33	71	109	71	109	2.36	0.25	0.25

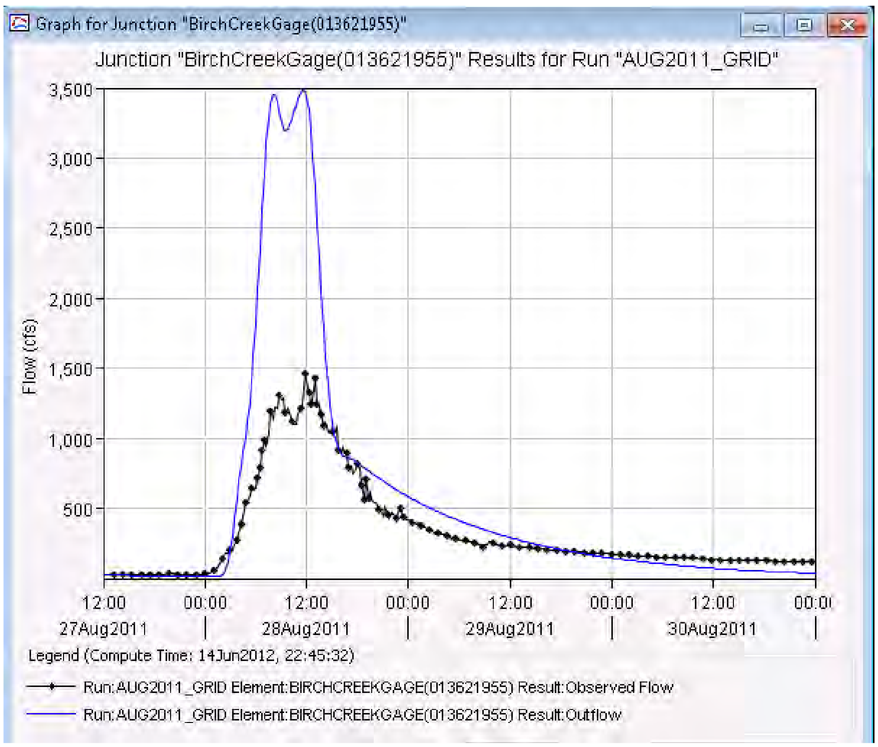

Figure 18. Modeled and Observed Flow Hydrographs at USGS 013621955 (Birch Creek) for Hurricane Irene (August 2011) Storm Event (based on post-Irene rating curve).

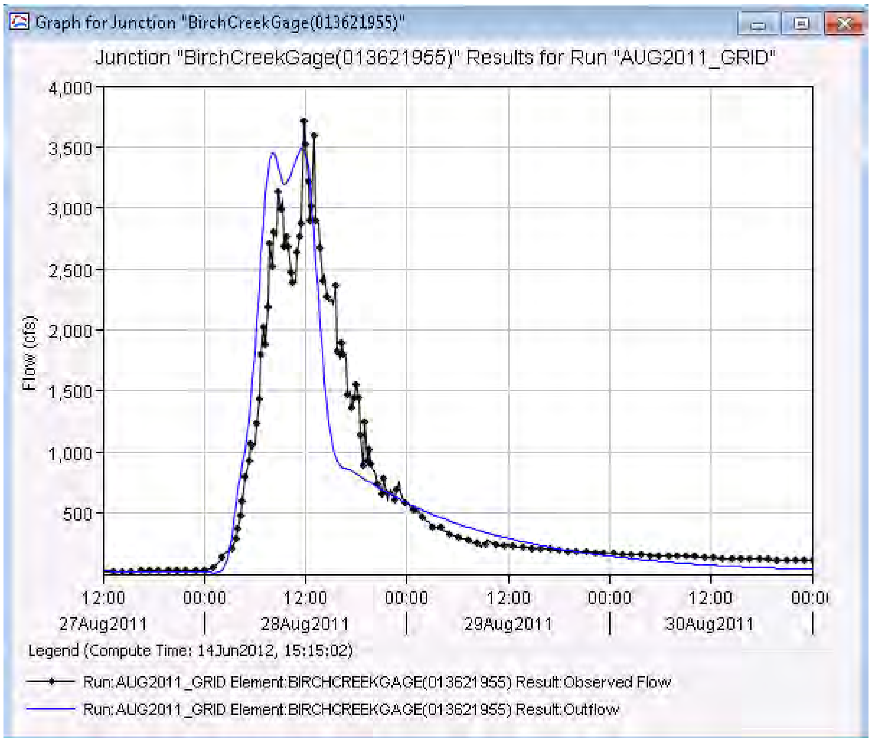

Figure 19. Modeled and Observed Flow Hydrographs at USGS 013621955 (Birch Creek) for Hurricane Irene (August 2011) Storm Event (based on pre-Irene rating curve).

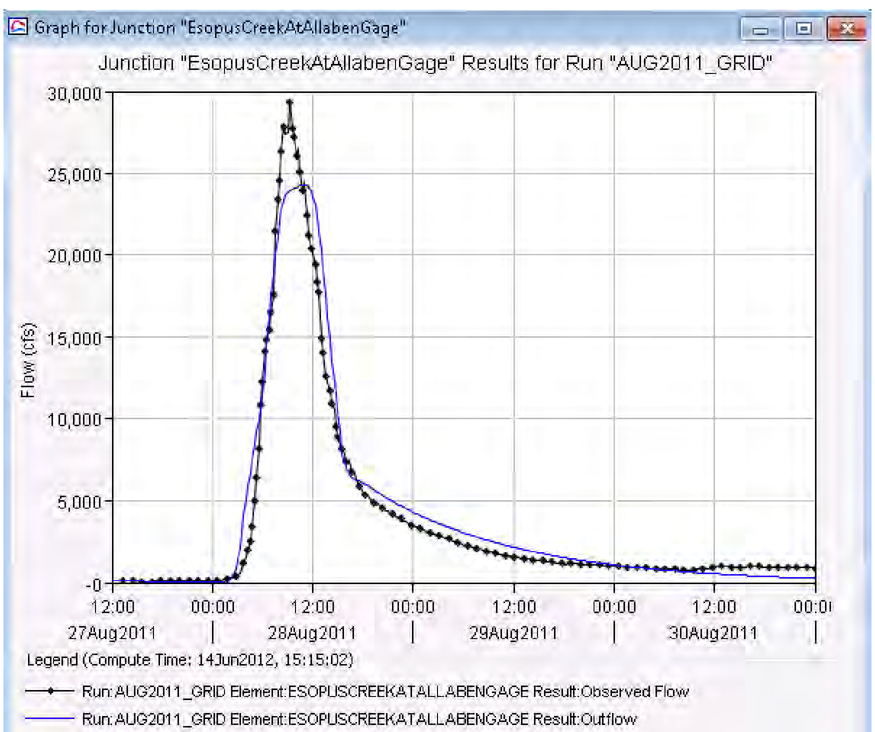

Figure 20. Modeled and Observed Flow Hydrographs at USGS 01362200 (Esopus Creek at Allaben) for Hurricane Irene (August 2011) Storm Event.

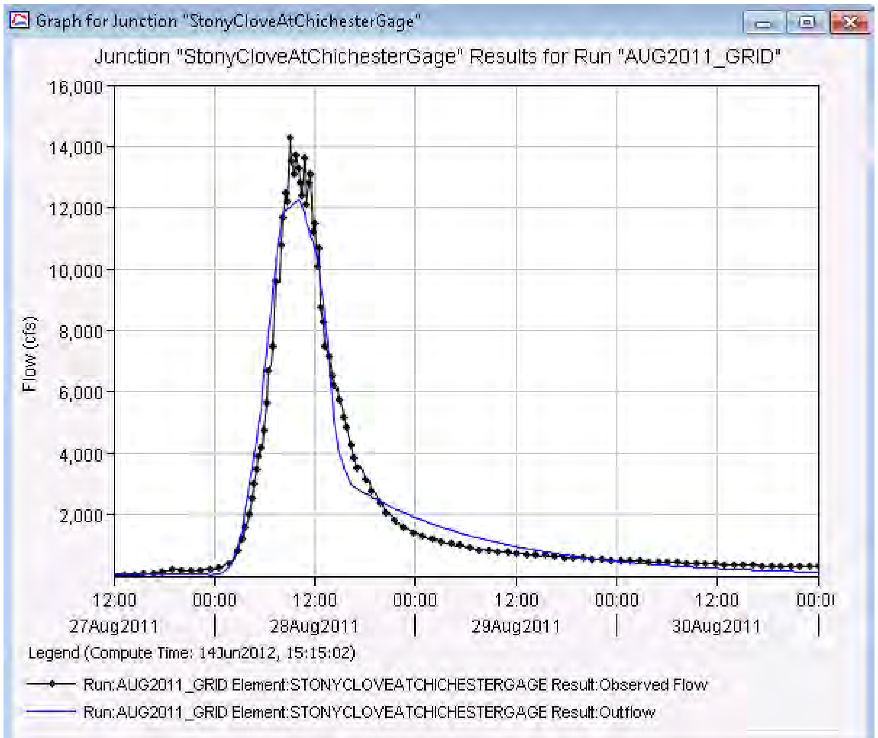

Figure 21. Modeled and Observed Flow Hydrographs at USGS 01362370 (Stony Clove Creek) for Hurricane Irene (August 2011) Storm Event.

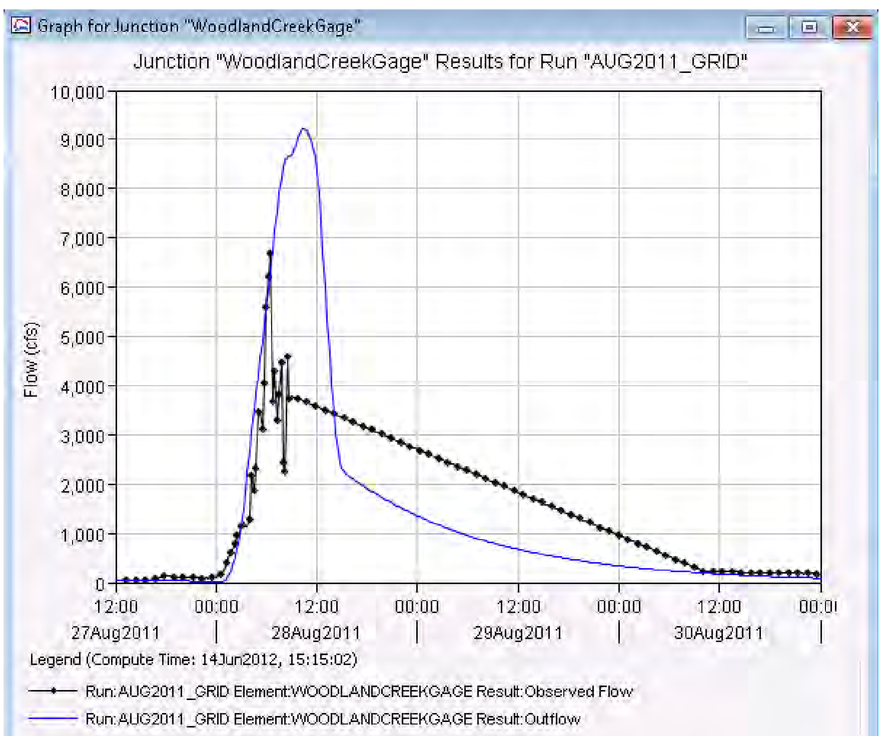

Figure 22. Modeled and Observed Flow Hydrographs at USGS 0136230002 (Woodland Creek) for Hurricane Irene (August 2011) Storm Event.

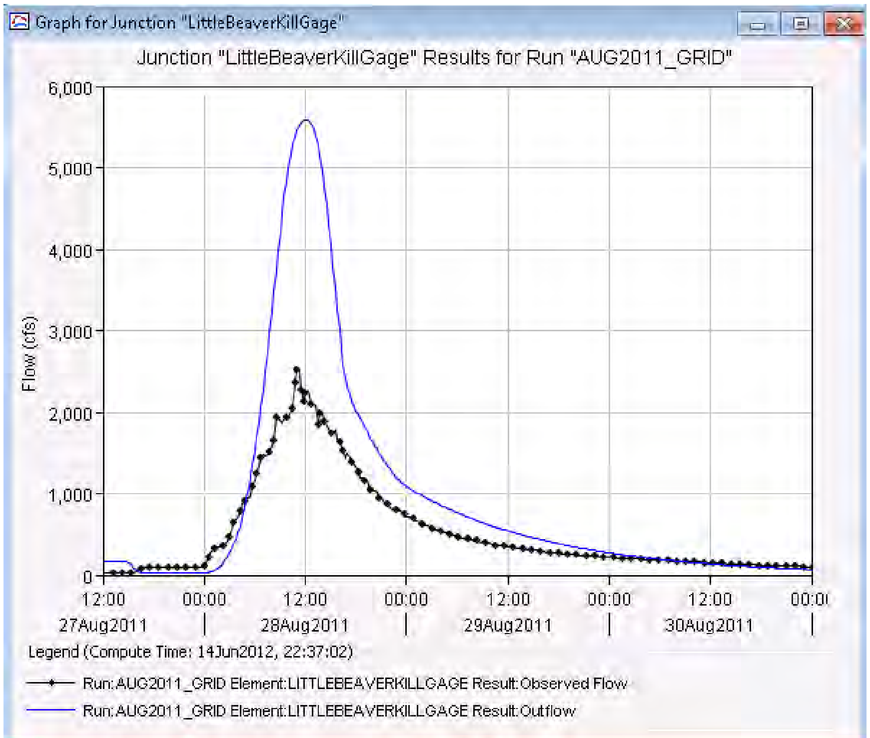

Figure 23. Modeled and Observed Flow Hydrographs at USGS 01362370 (Little Beaver Kill) for Hurricane Irene (August 2011) Storm Event.

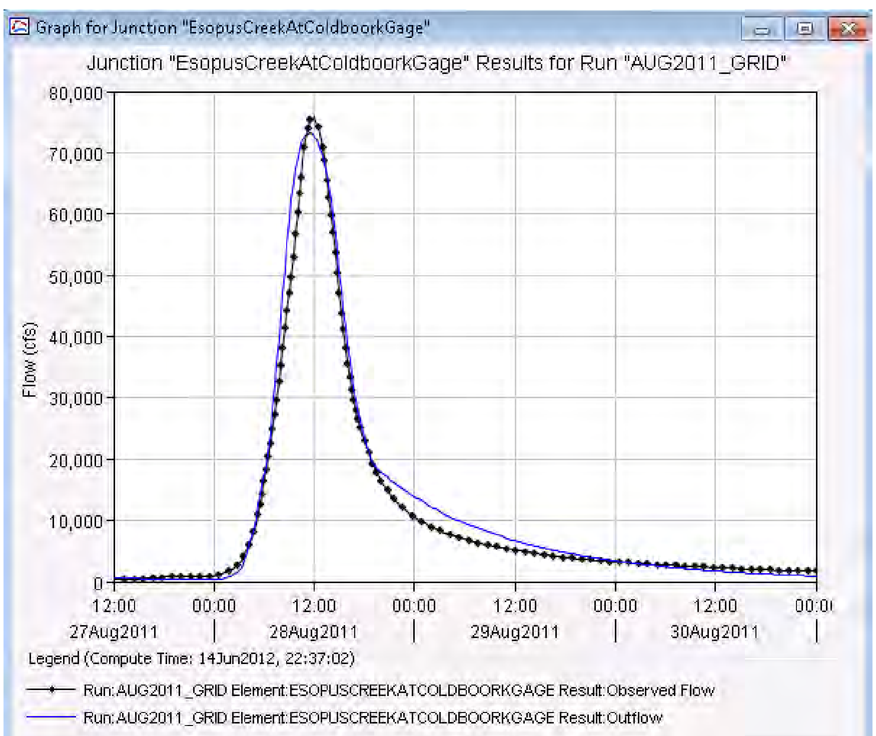

Figure 24. Modeled and Observed Flow Hydrographs at USGS 01362500 (Esopus Creek at Coldbrook) for Hurricane Irene (August 2011) Storm Event.

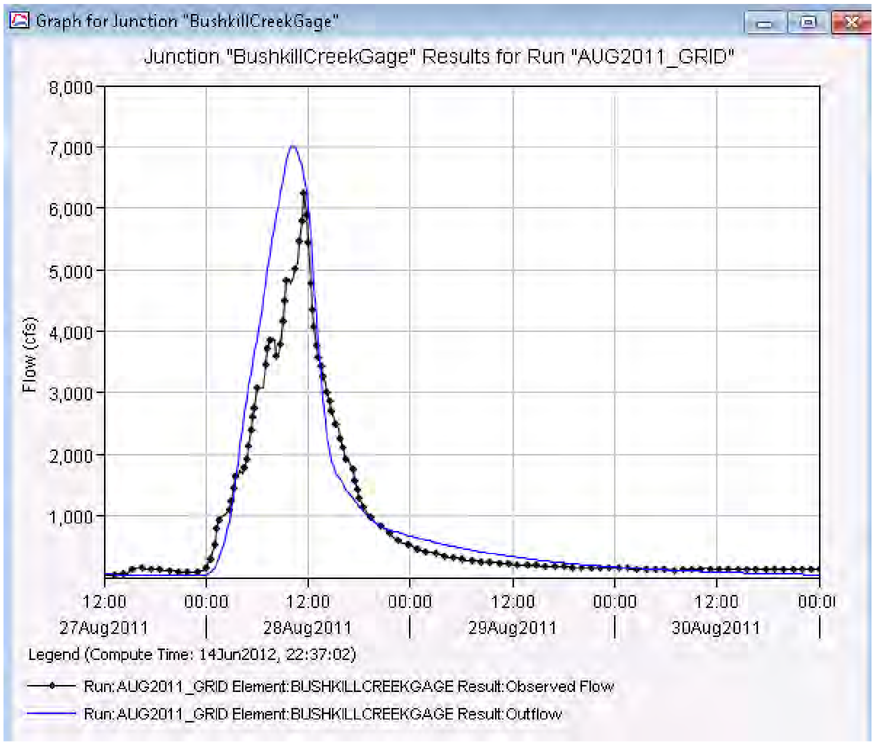

Figure 25. Modeled and Observed Flow Hydrographs at USGS 01363382 (Bushkill) for Hurricane Irene (August 2011) Storm Event.

D.1.2 October 2005 – Verification Event

Unlike Tropical Storm Lee, the October 2005 event was preceded by a long period of extensive drought. The average cumulative rainfall that fell in the watershed was about 6 inches, which is about 2 inches lower than the rainfall amounts that fell during Hurricane Irene. The rainfall amounts were close to a 25-year return period, but the translation of rainfall into flows did not exceed even a 10-year return period. Therefore, dry antecedent soil conditions (AMC-1) were prevalent in the watershed when the storm made landfall. During model simulations, CN values that correspond to AMC-1 conditions were applied. The base flow parameters were computed based on the observed hydrograph data, and lag times computed during calibration were used without further modifications. Table 14 summarizes the runoff volumes, runoff coefficients, peak flows, and peak times for modeled and observed data. CN values varied from 44 to 78, with a basin-wide average of about 52. Initial baseflow values vary from 0.11 to 5 cfs/sq. mi., with an average of 1.3 cfs/sq. mi. Figure 26 through Figure 32 provide graphical comparisons of modeled and observed hydrographs.

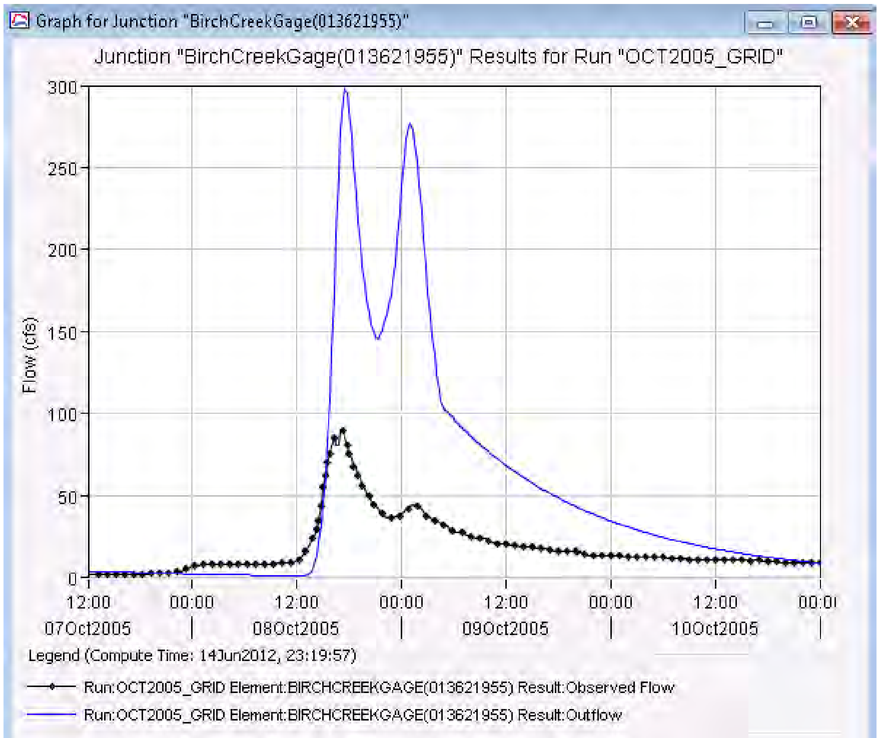

Figure 26. Modeled and Observed Flow Hydrographs at USGS 013621955 (Birch Creek) for October 2005 Storm Event.

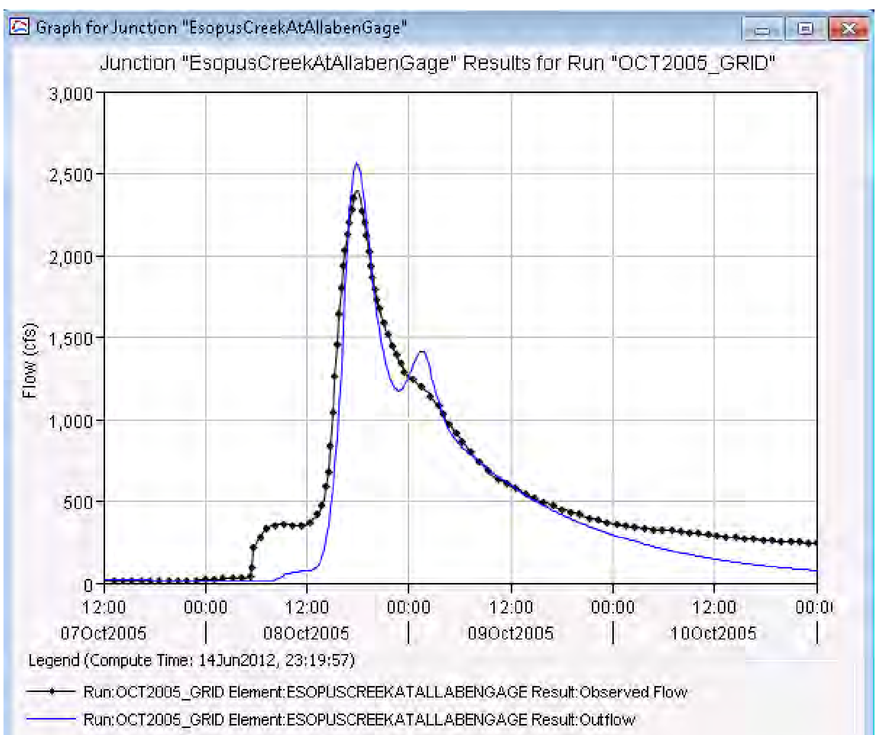

Figure 27. Modeled and Observed Flow Hydrographs at USGS 01362200 (Esopus Creek at Allaben) for October 2005 Storm Event.

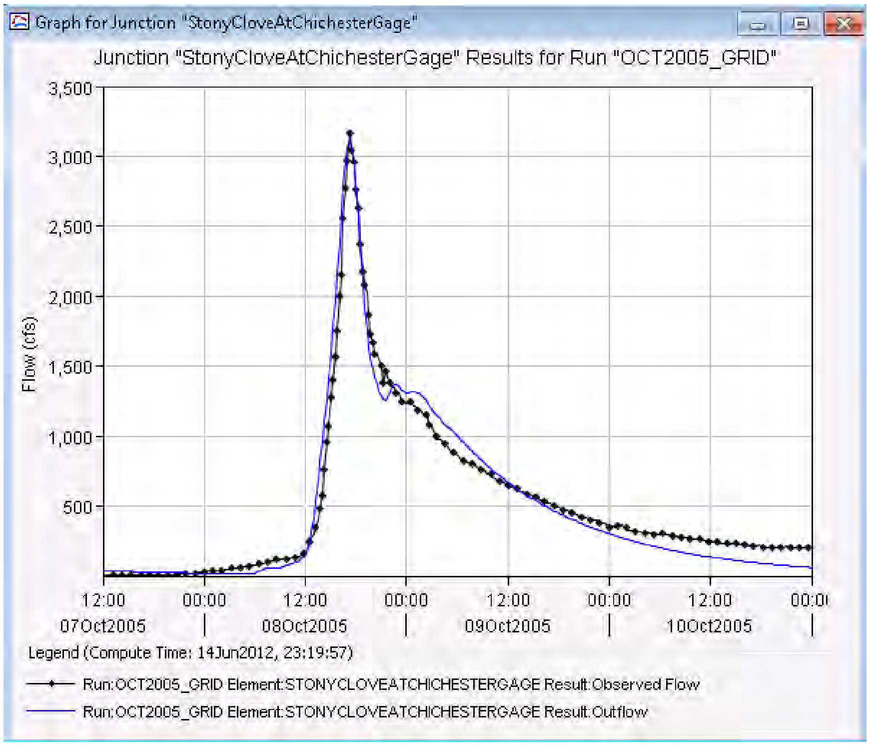

Figure 28. Modeled and Observed Flow Hydrographs at USGS 01362370 (Stony Clove Creek) for October 2005 Storm Event.

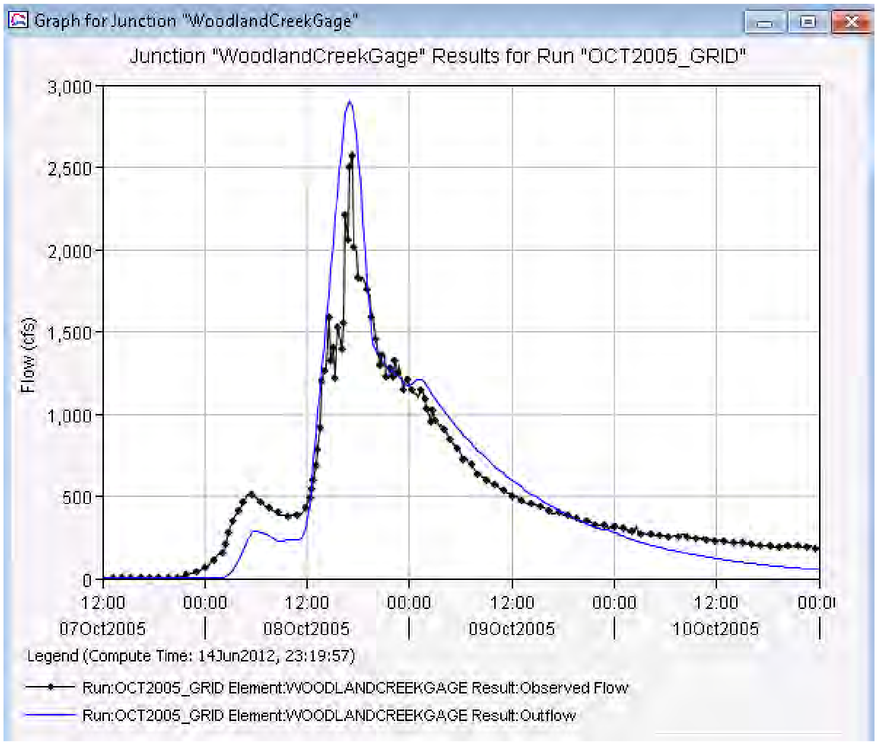

Figure 29. Modeled and Observed Flow Hydrographs at USGS 0136230002 (Woodland Creek) for October 2005 Storm Event.

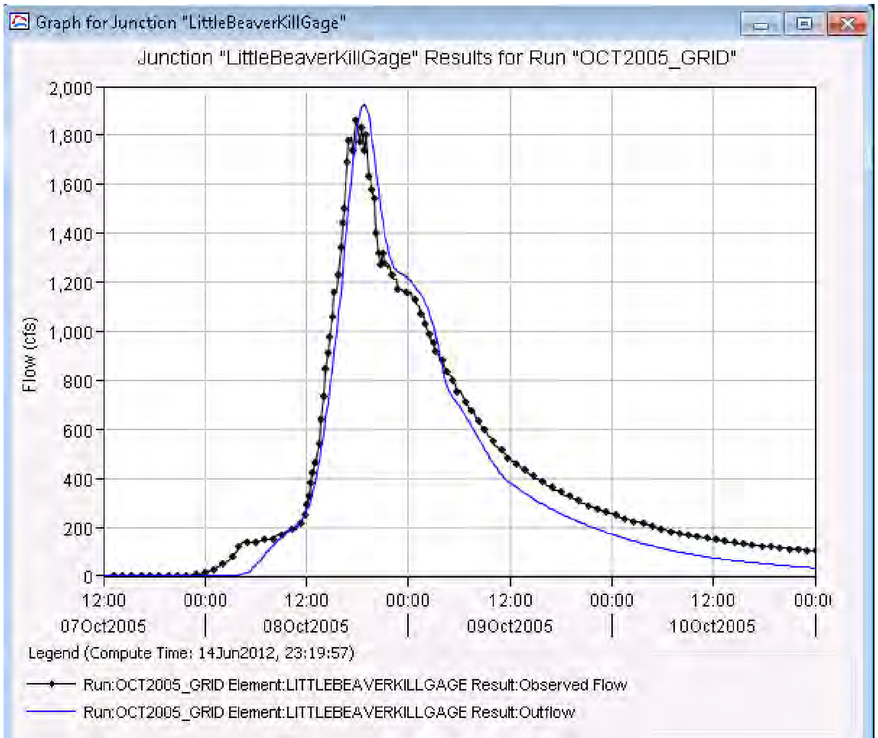

Figure 30. Modeled and Observed Flow Hydrographs at USGS 01362370 (Little Beaver Kill) for October 2005 Storm Event.

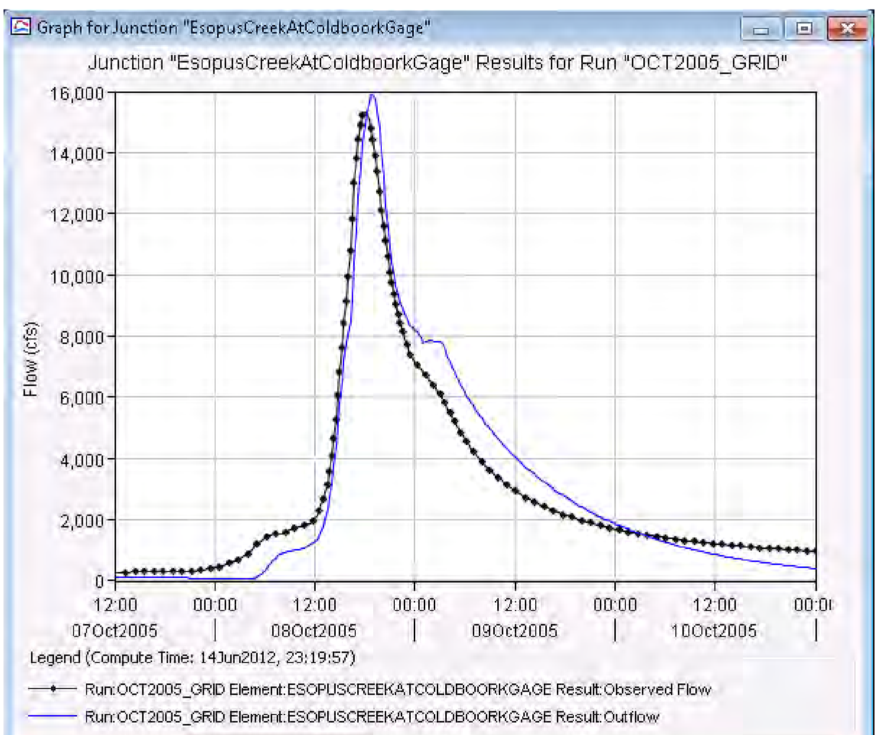

Figure 31. Modeled and Observed Flow Hydrographs at USGS 01362500 (Esopus Creek at Coldbrook) for October 2005 Storm Event.

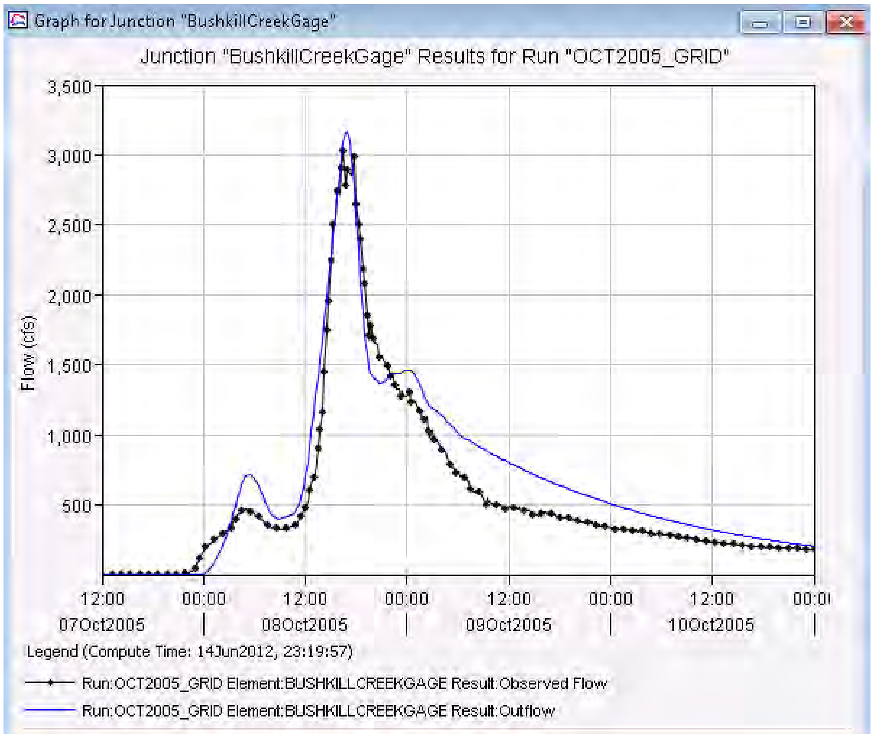

Figure 32. Modeled and Observed Flow Hydrographs at USGS 01363382 (Bushkill) for October 2005 Storm Event.

D.1.3 Tropical Storm Lee (September 2011) – Verification Event

During the verification process, CN values were adjusted to reflect the antecedent moisture conditions and the baseflow parameters were computed based on the falling and rising limbs of observed hydrographs. The lag times developed during the calibration process were used without any changes for model verification purposes. As mentioned before, the storms included for model verification are Tropical Storm Lee (September 2011) and the October 2005 storm event.

Hurricane Irene preceded Tropical Storm Lee, and, therefore, the soils were saturated before Lee made landfall in the watershed. Therefore, during model simulation, CN values that reflect AMC-3 (wet) soil conditions were utilized. Table 14 summarizes the runoff volumes, runoff coefficients, peak flows, and peak times for modeled and observed data. CN values varied from 75 to 93, with a basin-wide average of 84. Initial baseflow values vary from 7 to 15 cfs/sq.mi., with an average of 11 cfs/sq.mi. Figure 33 through Figure 39 provide graphical comparisons of modeled and observed hydrographs.

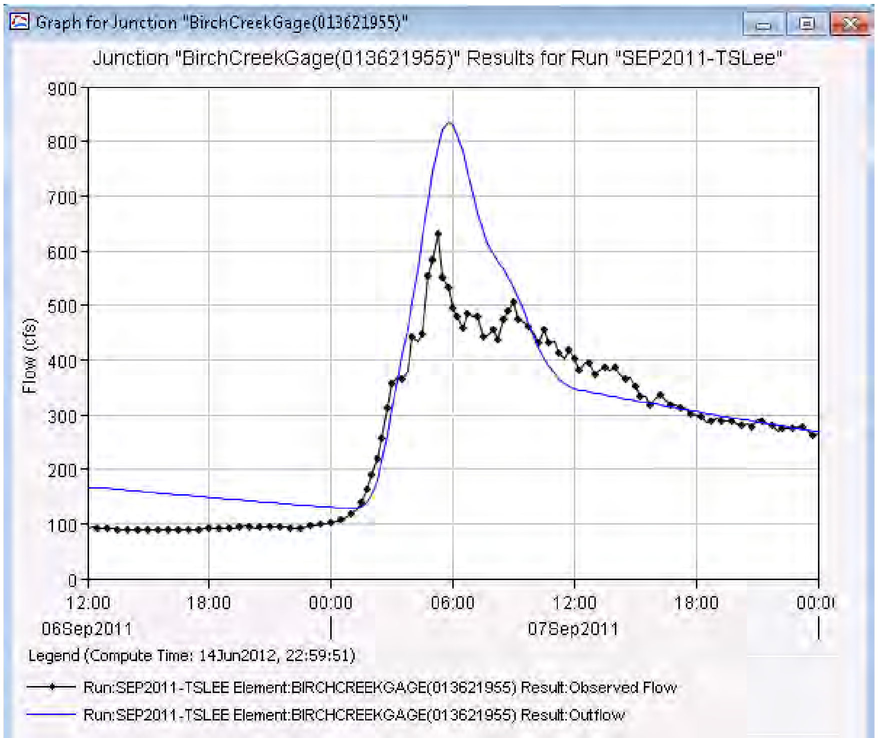

Figure 33. Modeled and Observed Flow Hydrographs at USGS 013621955 (Birch Creek) for Tropical Storm Lee (September 2011) Storm Event.

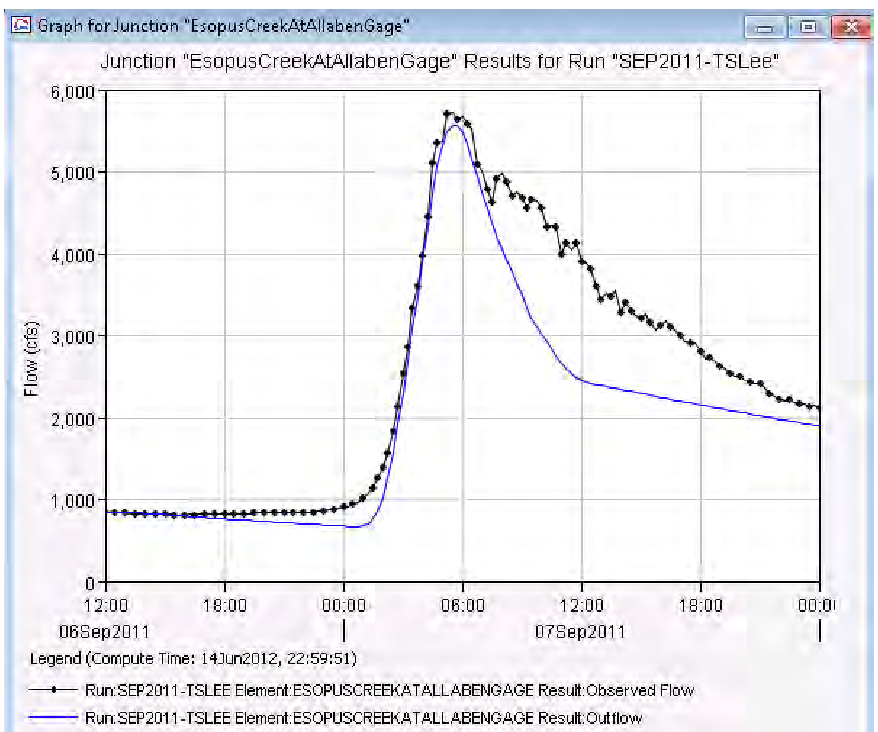

Figure 34. Modeled and Observed Flow Hydrographs at USGS 01362200 (Esopus Creek at Allaben) for Tropical Storm Lee (September 2011) Storm Event.

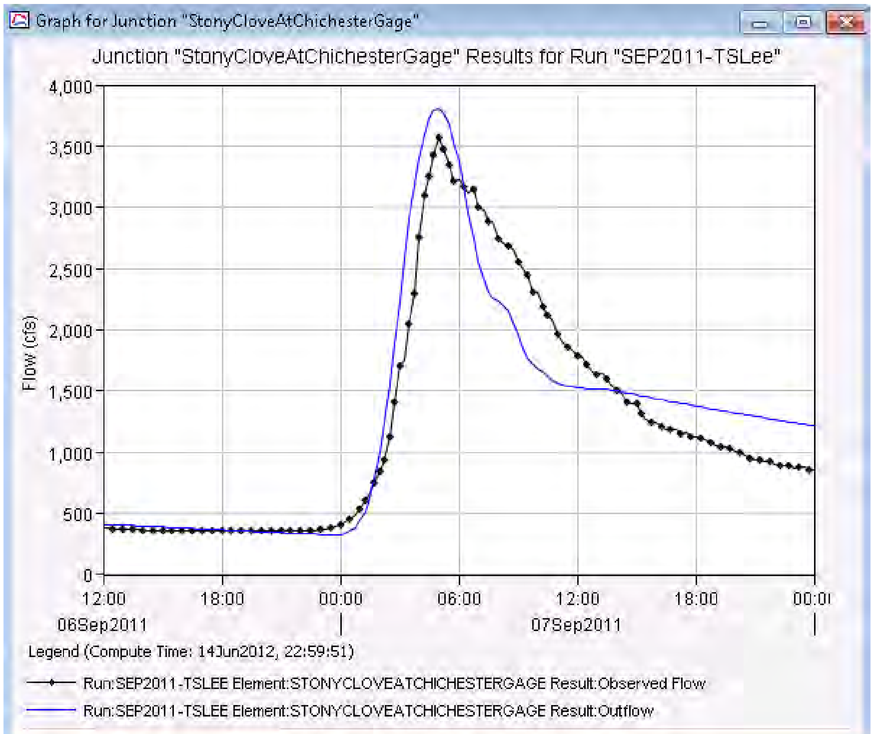

Figure 35. Modeled and Observed Flow Hydrographs at USGS 01362370 (Stony Clove Creek) for Tropical Storm Lee (September 2011) Storm Event.

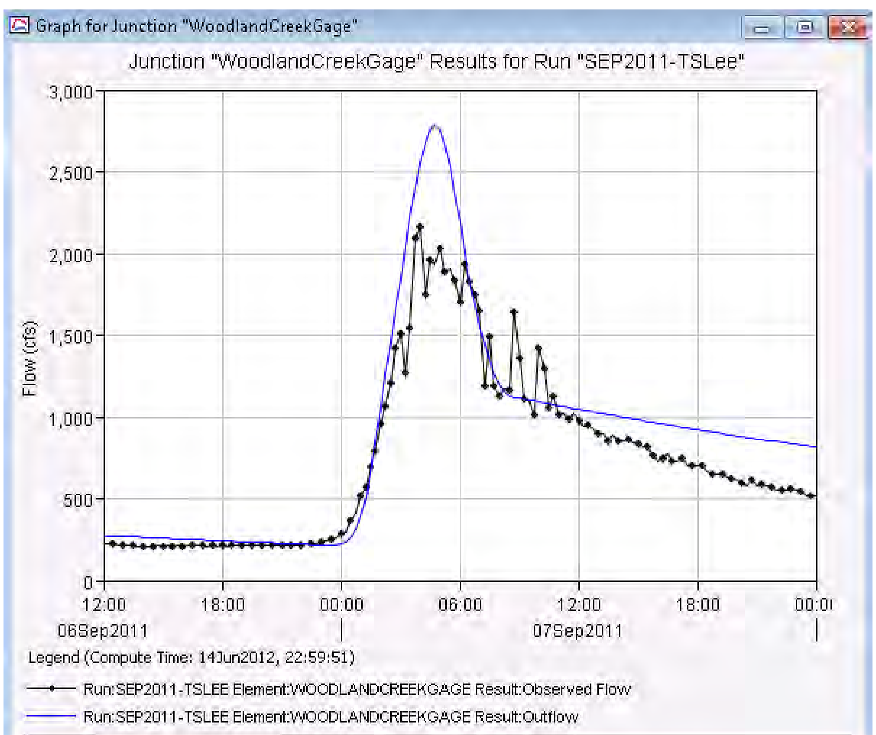

Figure 36. Modeled and Observed Flow Hydrographs at USGS 0136230002 (Woodland Creek) for Tropical Storm Lee (September 2011) Storm Event.

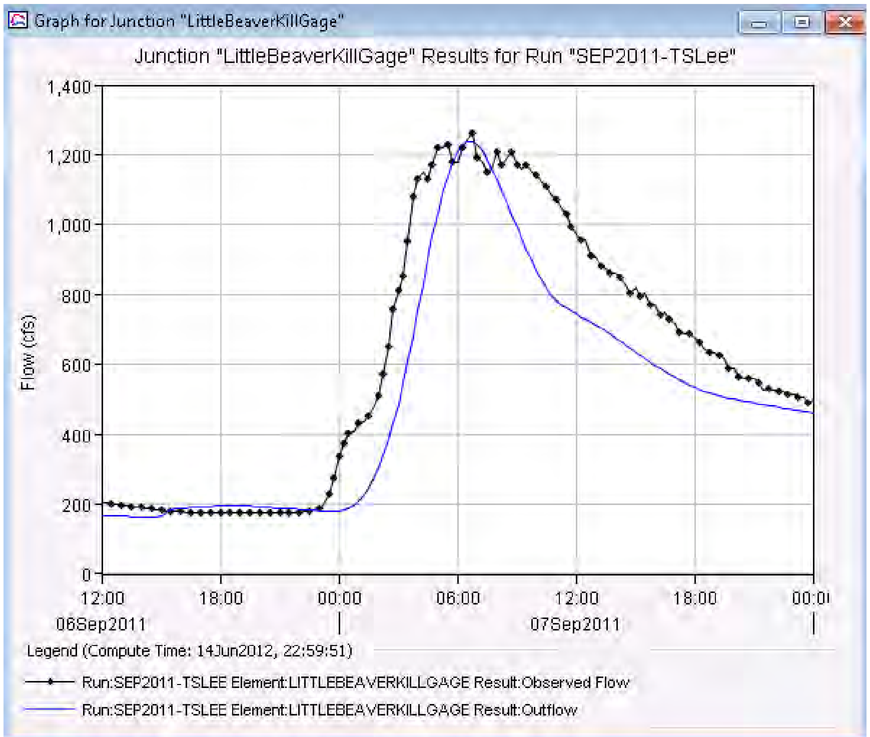

Figure 37. Modeled and Observed Flow Hydrographs at USGS 01362370 (Little Beaver Kill) for Tropical Storm Lee (September 2011) Storm Event.

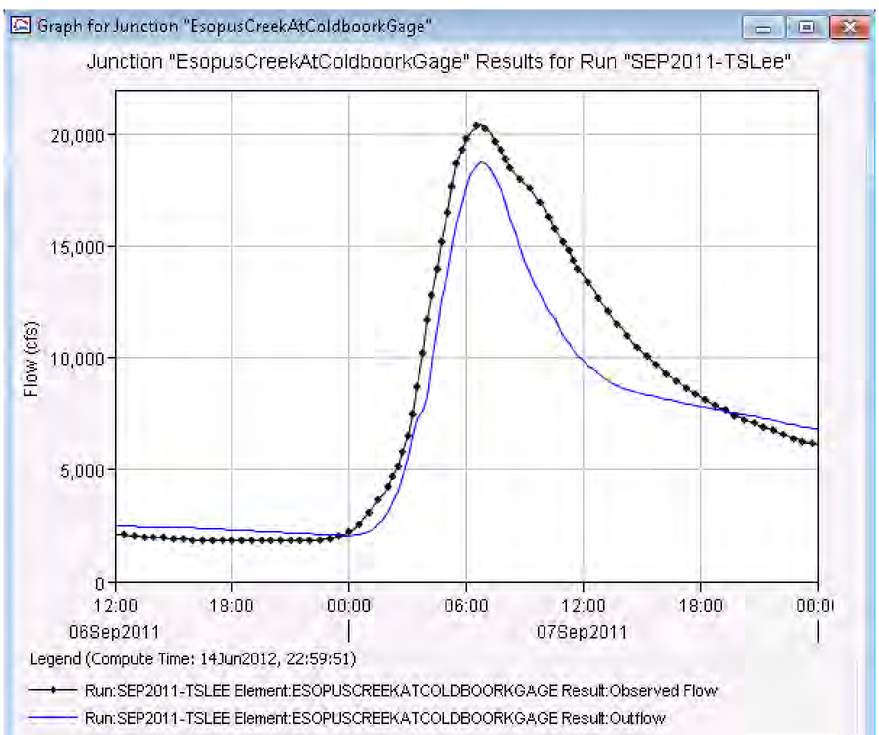

Figure 38. Modeled and Observed Flow Hydrographs at USGS 01362500 (Esopus Creek at Coldbrook) for Tropical Storm Lee (September 2011) Storm Event.

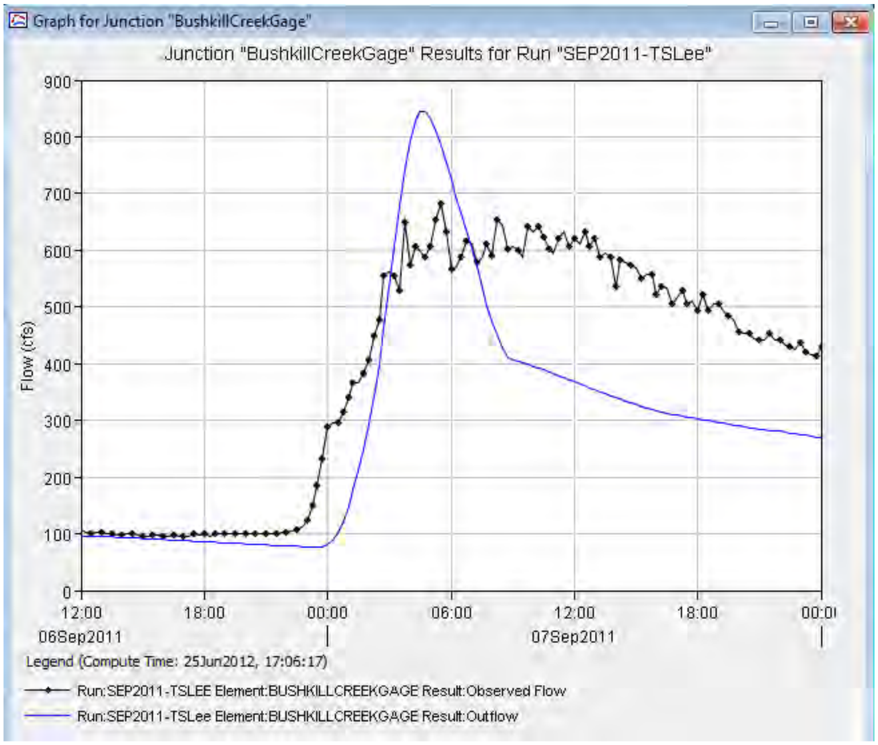

Figure 39. Modeled and Observed Flow Hydrographs at USGS 01363382 (Bushkill) for Tropical Storm Lee (September 2011) Storm Event.

Table 14: Comparison of Model Results against Observed Gage Data for Calibration and Validation Events

EVENT	Gage ID	Location	DA (Sq.Mile)	AVG. PCP (IN)	RUNOFF (IN)				PEAK FLOW (CFS)				LAG TIME (hh:mm)		
					OBSERVED		MODEL		OBS	MODEL	DIFFERNCE		OBS	MODEL	DIFFERNCE
					DEPTH	COEFFICIENT	DEPTH	COEFFICIENT			ACTUAL	PERCENT			
Aug-11	013621955	BIRCH CREEK AT BIG INDIAN NY	12.5	7.5	2.98	**40%**	5.6	74%	1,460	3,481	-2,021	-138%	11:45	11:30	0:15
	01362197	BUSHNELLSVILLE CR AT SHANDAKEN NY	11.4	7.9	N/A		6.26	80%	2,750	3,582	-832	-30%	N/A	12:00	N/A
	01362200	ESOPUS CREEK AT ALLABEN NY	63.7	8.5	6.9	81%	7.96	93%	29,300	24,325	4,975	17%	9:15	10:45	1:30
	0136230002	WOODLAND CREEK ABOVE MOUTH AT PHOENICIA NY	20.6	10.3	9.32	**91%**	8.59	84%	6,690	9,232	-2,542	-38%	6:30	10:30	4:00
	01362370	STONY CLOVE CREEK BLW OX CLOVE AT CHICHESTER NY	31.5	8.1	7.73	96%	7.72	96%	14,300	12,255	2,045	14%	9:00	10:00	1:00
	01362497	LITTLE BEAVER KILL @ BEECHFORD NR MT TREMPER NY	16.7	9.3	4.14	**44%**	7.19	77%	2,530	5,589	-3,059	-121%	11:00	12:00	1:00
	01362500	ESOPUS CREEK AT COLDBROOK NY	190.2	8.6	7.31	79%	7.93	85%	75,800	73,166	2,634	3%	12:00	11:30	0:30
	01363382	BUSH KILL BLW MALTBY HOLLOW BK AT WEST SHOKAN NY	16.2	10.0	6.05	**61%**	6.96	70%	6,240	7,027	-787	-13%	11:30	10:15	1:15
Oct-05	013621955	BIRCH CREEK AT BIG INDIAN NY	12.5	4.2	0.2	**5%**	0.55	13%	90	298	-208	-231%	17:00	17:30	0:30
	01362197	BUSHNELLSVILLE CR AT SHANDAKEN NY	11.4	4.3	N/A		0.75	17%	N/A	398	N/A	N/A	N/A	17:30	N/A
	01362200	ESOPUS CREEK AT ALLABEN NY	63.7	5.0	1.06	21%	0.88	18%	2,390	2,558	-168	-7%	17:45	17:45	0:00
	0136230002	WOODLAND CREEK ABOVE MOUTH AT PHOENICIA NY	20.6	6.6	3.11	47%	3.1	47%	2,570	2,901	-331	-13%	17:15	17:00	0:15
	01362370	STONY CLOVE CREEK BLW OX CLOVE AT CHICHESTER NY	31.5	6.5	2.13	33%	2.07	32%	3,160	3,107	53	2%	17:15	17:15	0:00
	01362497	LITTLE BEAVER KILL @ BEECHFORD NR MT TREMPER NY	16.7	6.3	3.14	50%	2.77	44%	1,860	1,926	-66	-4%	17:45	18:45	1:00
	01362500	ESOPUS CREEK AT COLDBROOK NY	190.2	5.7	1.99	35%	2.02	35%	15,300	15,893	-593	-4%	18:00	19:00	1:00
	01363382	BUSH KILL BLW MALTBY HOLLOW BK AT WEST SHOKAN NY	16.2	7.7	4.23	55%	5.1	66%	3,030	3,164	-134	-4%	16:30	17:00	0:30
Sep-11	013621955	BIRCH CREEK AT BIG INDIAN NY	12.5	2.3	1.19	**52%**	1.36	60%	631	835	-204	-32%	5:15	5:45	0:30
	01362197	BUSHNELLSVILLE CR AT SHANDAKEN NY	11.4	2.2	N/A		1.83	85%	N/A	1,007	N/A	N/A	N/A	5:30	N/A
	01362200	ESOPUS CREEK AT ALLABEN NY	63.7	2.6	2.19	84%	1.79	69%	5,730	5,574	156	3%	5:30	5:30	0:00
	0136230002	WOODLAND CREEK ABOVE MOUTH AT PHOENICIA NY	20.6	2.6	2.01	76%	2.38	90%	2,160	2,786	-626	-29%	4:00	4:45	0:45
	01362370	STONY CLOVE CREEK BLW OX CLOVE AT CHICHESTER NY	31.5	2.6	2.24	86%	2.31	89%	3,570	3,809	-239	-7%	5:00	5:00	0:00
	01362497	LITTLE BEAVER KILL @ BEECHFORD NR MT TREMPER NY	16.7	2.3	2.06	90%	1.71	74%	1,260	1,237	23	2%	6:45	6:30	0:15
	01362500	ESOPUS CREEK AT COLDBROOK NY	190.2	2.5	2.34	94%	2.07	83%	20,500	18,759	1,741	8%	6:45	6:45	0:00
	01363382	BUSH KILL BLW MALTBY HOLLOW BK AT WEST SHOKAN NY	16.2	2.2	1.28	**58%**	0.96	44%	683	846	-163	-24%	5:30	4:45	0:45

D.2 FREQUENCY STORM DATA

Hypothetical rainfall data (frequency storm) were used to develop peak flow hydrographs and lake elevations for the five return intervals scoped for the project. The frequencies considered for this study are 10-year (10%), 25-year (4%), 50-year (2%), 100-year (1%), and 500-year (0.2%). The hypothetical rainfall used in this study was based on NOAA Atlas 14 data and was obtained from the Northeast Regional Climate Center – Cornell University. The duration chosen for the frequency storm was 24-hour and the type of distribution chosen was SCS Type-2. To compute rainfall depths at the centroid of the model sub-basins, 24-hour duration grids for the five frequencies were downloaded from the Cornell website. The 100-year grid suggests that the storm depths varied within the watershed from about 7.3 inches in the areas upstream of Allaben Gage to about 8.3 inches in the areas downstream of Allaben gage. Figure 40 shows the spatial variation of 100-year, 24-hour depths across Ashokan Basin. Variation in the precipitation depths was reflected in the model by dividing the basin was into 2 areas. The first area includes the sub-basin above Esopus Creek at Allaben gage, and the second is the sub-basin below the Allaben gage.

The 24-hour precipitation depths for the five frequencies were obtained from the grids at the centroid of the two sub-basins (Table 15). In the HEC-HMS model, each frequency was composed of two basin files in HEC-HMS and the corresponding meteorological and run. The outlet of the upper sub-basin formed the source for the downstream sub-basin. Parameters obtained for the calibration run were used for the frequency runs.

Table 15: 24-Hour Duration Precipitation depths for the Five Study Flood Frequencies

Subbasin	10Yr	25Yr	50Yr	100Yr	500Yr
Above Allaben Gage	4.2	5.2	6.1	7.2	10.6
Below Allaben Gage	4.6	5.8	6.9	8.2	12.2

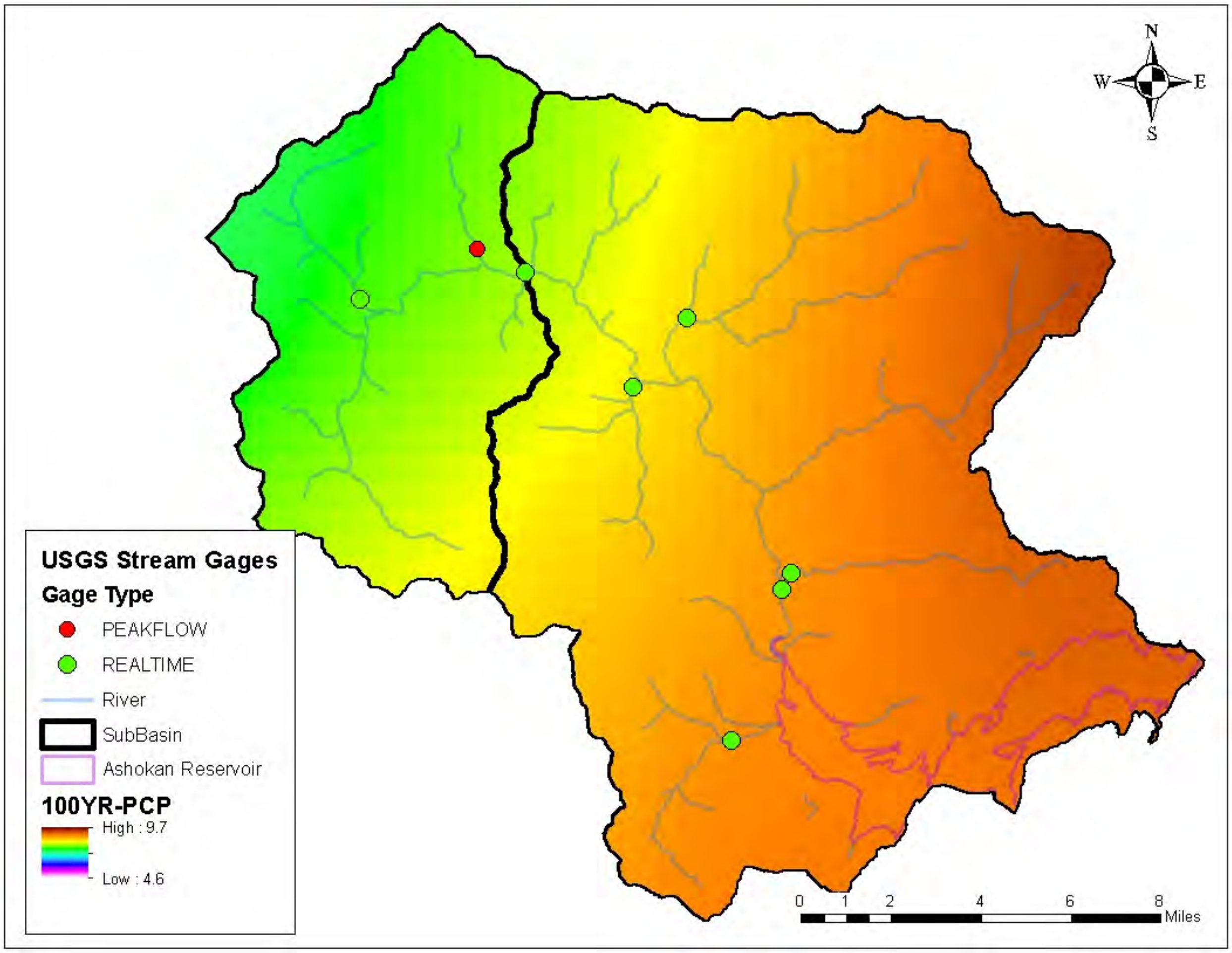

Figure 40: Spatial Distribution of 100-Year Frequency Rainfall Depths in Ashokan Basin

E. DISCUSSION OF RESULTS

This section discusses the results of the comparison of the 1% (100-year) proposed discharges at the gages to the discharges at the effective study flow change locations. Along with the gage estimates and the effective discharges, this study also provides regression estimates for these locations. In general, the proposed discharges are higher compared to the regression estimates. This study developed regression equations for the hydrologic region of the study watershed using the peak flows prior to 2000, and, therefore, the study did not include the flooding events that occurred in the past decade. Moreover, the regression equation developed by USGS included only three of the eight gages that are available within the watershed, probably because of the lack of a required period of record for the other gages. Therefore, the study relied on utilizing a watershed model for development of peak discharges for flood frequencies. Figure 41 provides the general trend of discharges between various types of hydrologic methods. Table 16 provides the comparisons between proposed 100-year discharges, gage analyses estimates, effective study discharges, and regression estimates.

E.1 Esopus Creek

The 1% (100-year) annual chance peak discharges computed in this study for Esopus Creek are within 10% of the estimates developed using gage analyses and are lower than the effective study discharges by 7% to 20%. The effective study, which was based on HEC-1, was calibrated only to the gage at Coldbrook on Esopus Creek, whereas the current study was calibrated to all 8 major gages in the watershed, with longer periods of record. Since the current model is based on longer periods of record and the discharges are within 10% of gage analyses estimates, the proposed discharges are suitable for hydraulic analyses.

E.2 Stony Clove Creek and its Tributaries

The 1% (100-year) annual chance peak discharges computed in this study for Stony Clove Creek and its tributaries are within 20% of the estimate developed using gage analyses and are higher than the effective study discharges by 11% to 35%. The gage on Stony Clove Creek has a record of only 15 years compared to the 2 gages on Esopus Creek, which have 49 and 80 years of record, and the effective study was an uncalibrated model. Since the proposed discharges are within the reasonable limits of gage estimates, they are suitable for utilization for hydraulic analyses.

E.3 Bushnellsville Creek and Birch Creek

The 1% (100-year) annual chance peak discharges computed in this study at gage locations on Bushnellsville Creek and Birch Creek are higher than the gage analyses estimates by 47% and 56% respectively. The discharges at these locations compare reasonably well with regression estimates. The proposed discharges are 17% and 22% more than the regression estimates.

E.4 Stony Clove Creek and its Tributaries

The proposed 100-year discharge at Little Beaver Kill gage compares reasonably well with both gage analysis estimates and regression estimates. The proposed discharge is 24% higher than the gage estimate and 27% higher than the regression estimates.

E.5 Woodland Creek

At Woodland Creek gage, the proposed 100-year discharge can be compared only with regression and it is higher by 30%. The length of gage record (8 years) is not sufficient for gage analyses. The proposed 100-year discharge is within reasonable range compared to gage analyses estimate and the regression estimate. The discharge is about 12% lower than the gage analyses estimate and 11% higher than the regression estimate. At the outlet, the proposed discharge is about 15% higher than the regression estimate.

E.6 Beaver Kill

The proposed 100-year discharges for Beaver Kill were compared to the effective study and the regression estimates. The proposed discharges are about 49% to 60% higher than the effective discharges and about 26% to 32% higher than the regression estimates. The proposed discharges provide a more reasonable match with the discharges developed using the new equations than the older equation estimates utilized by the effective study.

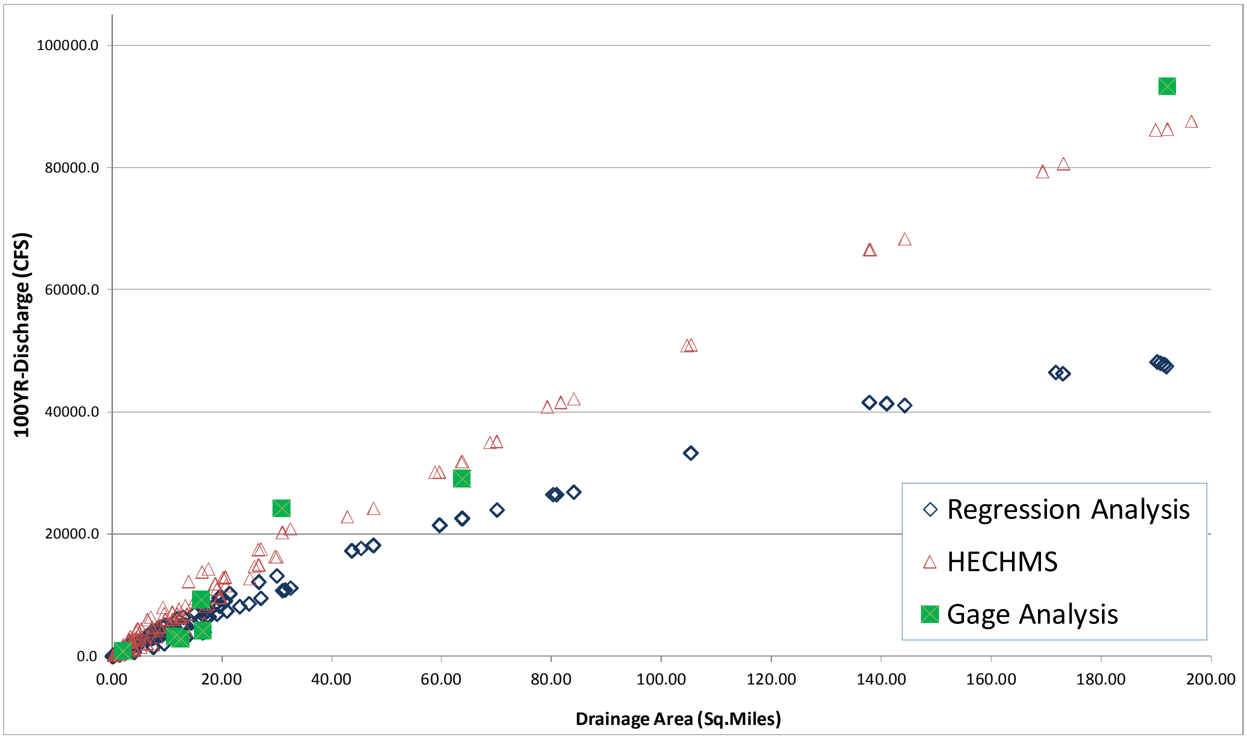

Figure 41: Comparison of Results Obtained from the Three Different Hydrologic Methods

Table 16: Comparison of Model Results, Gage Analyses, Effective Study, and Regression

Stream	Location	DA (Sq.Mi)	100 Year - Discharge (CFS)						
			Proposed-HMS	LP3	HMS-LP3	Effective	Effective-HMS	Regression	HMS-Regression
Esopus Creek	USGS Gage At Allaben (01362200)	63.7	31889	29090	9%	N/A		22600	29%
	Above Confluence With Broad Street Hollow Creek	70.0	35214	N/A	N/A	37529	-7%	24000	32%
	Above Confluence With Woodland Creek	84.0	42159	N/A	N/A	48801	-16%	26900	36%
	Above Confluence With Beaver Kill	144.3	68362	N/A	N/A	74619	-9%	41100	40%
	Above Confluence With Little Beaver Kill	173.3	80683	N/A	N/A	92599	-15%	46300	43%
	USGS Gage At Coldbrook (01362500)	190.2	86203	93260	-8%	103438	-20%	48200	44%
Stony Clove Creek	At Route 214 & Silver Hollow Road	3.3	3263	N/A	N/A	2910	11%		
	At Lanesville Bridge	9.3	8031	N/A	N/A	6100	24%	3710	54%
	GREENE - ULSTER Border	16.3	13863	N/A	N/A	9070	35%		
	USGS Gage At Chichester (01362380)	30.9	20321	24230	-19%	N/A	N/A	10900	46%
Bushnellsville Creek	USGS Gage At Shadaken NY (01362197)	11.4	6122	3253	47%	N/A	N/A	5057	17%
Birch Creek Gage	USGS Gage At Big Indian (013621955)	12.0	6522	2892	56%	N/A	N/A	5090	22%
Little Beaver Kill	USGS Gage At Beechford NR MT Tremper (01362497)	16.5	5509	4161	24%	N/A	N/A	4000	27%
Woodland Creek	USGS Gage At Phoenicia (0136230002)	20.6	13022	N/A		N/A	N/A	9120	30%
Bush Kill	USGS Gage At Maltby Hollow Bk At West Ashokan (01363382)	17.9	8274	9302	-12%	N/A	N/A	7350	11%
	At the outlet	19.6	9725	N/A	N/A	N/A	N/A	8250	15%
Beaver Kill	Above confluence with Tributary	10.91	7239.8	N/A	N/A	2873	60%		
	Above confluence with Tributary	13.59	6941.9	N/A	N/A	3341	52%	5090	27%
	Above confluence with Tributary	17.46	8609.1	N/A	N/A	4382	49%		
	Above confluence with Tributary	20.58	10108.6	N/A	N/A	4886	52%	7440	26%
	At the outlet	25.06	12763.9	N/A	N/A	5115	60%	8630	32%

F. RECOMMENDED DISCHARGES

Peak flow discharges developed in this study for Esopus Creek and its tributaries are summarized in Table 17. Peak water surface elevations developed for Ashokan Reservoir and Kenozia Lake are summarized in Table 18. The units of drainage area provided in the tables are in sq. mi., discharges are in cfs, and elevations are in feet. The discharges and elevations developed in this study include 10%, 4%, 2%, 1%, and 0.2% annual chance peak flow discharges. Lake elevations for Ashokan Reservoir are referenced to NGVD 29. The computations for all flow change locations are based on a calibrated HEC-HMS rainfall-runoff model of the watershed.

Table 17: Summary of Recommended Discharges

SUBBASIN	STREAM	LOCATION	DA	Q10	Q25	Q50	Q100	Q500
Ashokan Reservoir	Ashokan Reservoir	Ashokan Reservoir - West Basin	237.4	17984	29074	40938	57086	115202
		Ashokan Reservoir - East Basin	255.3	11884	19980	28678	40607	81509
	Kenozia Lake	Generic junction	1.2	134	172	215	274	491
Beaver Kill	Beaver Kill	Beaver Kill above Mink Hollow	1.5	234	342	448	583	1002
		Beaver Kill above Wagner Creek	13.6	2601	3876	5232	6942	12666
		Confluence of Beaver Kill and Hoyt Hollow	20.6	3683	5592	7583	10109	18446
		Beaver Kill above Esopus Creek	25.1	4613	7087	9583	12764	23147
	Mink Hollow	Mink Hollow above Unnamed Tributary	3.1	1006	1540	2069	2746	4876
		Mink Hollow above Beaver Kill	9.5	2605	3957	5314	7058	12583
	Wagner Creek	Wagner Creek above Beaver Kill	3.9	532	877	1230	1702	3249
Birch Creek	Alton Creek	Aton Creek above Alton Creek Tributary	1.1	248	390	531	698	1274
		Alton Creek above Birch Creek	2.4	563	890	1220	1615	2989
	Alton Creek Tributary	Alton Creek Tributary above Alton Creek	0.5	140	220	300	394	718
	Birch Creek	Birch Creek at intersection of Birch Creek Rd and Lower Birch Creek Rd	3.1	602	973	1348	1797	3365
		Birch Creek above Alton Creek	5.0	936	1491	2060	2738	5094
		Birch Creek above Giggle Hollow	8.0	1564	2500	3433	4570	8484
		Birch Creek above Rochester Hollow	10.2	1838	2930	4033	5390	10016
		Birch Creek above Esopus Creek	12.9	2253	3578	4937	6569	12348
	Giggle Hollow	Giggle Hollow above Birch Creek	0.6	159	254	352	471	885
Broad Street Hollow	Broad Street Hollow	Broad Street Hollow above Jay Hand Hollow	4.9	1406	2145	2869	3796	6741
		Broad Street Hollow Above Esopus Creek	7.3	1772	2715	3628	4810	8598
	Jay Hand Hollow	Jay Hand Hollow Above Broad Street Hollow	2.4	481	734	984	1304	2312

SUBBASIN	STREAM	LOCATION	DA	Q10	Q25	Q50	Q100	Q500
Bush Kill	Bush Kill	Bush Kill above Kanape Brook	1.1	215	357	503	695	1319
		Bush Kill above Mine Hollow	5.2	464	780	1110	1557	3058
		Bush Kill above South Hollow	6.3	647	1084	1537	2150	4193
		Bush Kill above Maltby Hollow Brook	10.1	1255	2132	3046	4271	8319
		Bush Kill above Dry Brook	17.5	2485	4239	6058	8484	16492
		Bush Kill Creek oulet into Ashokan Reservoir	19.7	2835	4843	6938	9725	18904
	Dry Brook	Dry Brook at near upstream end of Dry Brook Rd	1.4	244	417	600	843	1647
		Dry Brook above Bush Kill	2.0	336	579	832	1174	2310
	Kanape Brook	Kanape Brook above Bushkill	2.9	257	423	594	824	1585
	Maltby Hollow Brook	Maltby Hollow Brook above Unnamed Tributary	3.3	553	932	1321	1837	3531
		Maltby Hollow Brook above Bush Kill	6.9	1192	2033	2919	4067	7864
	South Hollow	South Hollow above Bush Kill	1.7	352	594	843	1172	2248
Bushnellsville Creek	Bushnellsville Creek	Bushnellsville Creek above Angle Creek	4.4	1038	1587	2129	2767	4944
		Bushnellsville Creek at 2000 ft Upstream of Gossoo Rd	8.6	1823	2810	3787	4944	8930
		Bushnellsville Creek above Esopus Creek	11.1	2200	3430	4654	6114	11213
Esopus Creek	Esopus Creek	Esopus Creek above Elk Bush Kill	11.8	2711	4065	5390	6943	12199
		Esopus Creek above McKinley Hollow	16.1	3539	5322	7051	9104	16133
		Esopus Creek above Hatchery Hollow	20.7	4393	6696	8919	11611	20869
		Esopus Creek above Lost Clove	26.7	5439	8431	11397	15007	27333
		Esopus Creek above Birch Creek	30.0	5886	9094	12406	16312	30206
		Esopus Creek above Bushnellsville Creek	47.6	8716	13546	18444	24287	45372
		Esopus Creek above Fox Hollow	59.5	10769	16756	22972	30211	56709
		Esopus Creek Above Peck Hollow	63.7	11390	17664	24274	31925	60210
		Esopus Creek Above Broad Street Hollow	70.0	12600	19550	26827	35214	66342
		Esopus Creek above Woodland Creek	84.0	15173	23382	31970	42159	79494
		Esopus Creek above Stony Clove Creek	105.3	18209	27904	38121	51036	97916

SUBBASIN	STREAM	LOCATION	DA	Q10	Q25	Q50	Q100	Q500
		Esopus Creek above Beaver Kill	144.2	24183	36677	50173	68362	134869
		Esopus Creek above Little Beaver Kill	173.1	28476	43429	59272	80683	158630
		Esopus Creek above Ashokan Reservoir	193.6	30440	46736	63747	86781	169597
	Esopus Creek Tributary 7	Esopus Creek Tributary 7 above Esopus Creek	0.2	88	138	186	249	446
	Hatchery Hollow	Hatchery Hollow above Esopus Creek	5.2	1683	2581	3465	4506	8050
	Lost Clove	Lost Clove above Esopus Creek	2.9	1007	1571	2128	2788	5047
	McKinley Hollow	McKinley Hollow above Esopus Creek	2.9	946	1451	1947	2532	4521
	Peck Hollow	Peck Hollow Above Esopus Creek	5.0	1170	1789	2397	3177	5634
	Trevor Hollow	Trevor Hollow above Ashokan Reservoir	4.3	1147	1751	2351	3120	5544
Fox Hollow	Fox Hollow	Fox Hollow at Herdmand Rd	2.4	691	1050	1401	1814	3216
		Fox Hollow above Esopus Creek	4.0	1089	1649	2209	2868	5114
Little Beaver Kill	Little Beaver Kill	Little Beaver Kill at Yankeetown Pond Outlet	4.0	735	735	955	1279	2261
		Little Beaver Kill at 6000 ft downstream of Coldbrook Rd	7.4	740	1010	1416	1940	3806
		Little Beaver Kill at Woodstock-Olive US Border	13.4	1455	2315	3185	4351	8361
		Little Beaver Kill above Esopus Creek	16.7	1839	2931	4038	5520	10553
Stony Clove Creek	Hollow Tree Brook	Hollow Tree Brook Gage	2.0	658	1051	1443	1950	3576
		Hollow Tree Brook above Stony Clove Creek	4.6	1517	2440	3360	4553	8362
	Stony Clove Creek	Stony Clove Creek at Route 214	3.3	1097	1756	2412	3263	5977
		Stony Clove Creek at Lanesville Bridge	4.4	1350	2206	3068	4185	7770
		Confluence of Stony Clove Creek and Unnamed Tributary	6.4	1946	3180	4420	6033	11187
		Stony Clove Creek above Hollow Tree Brook	9.3	2647	4280	5913	8031	14853
		Stony Clove Creek at Greene-Ulster Border	16.3	4634	7451	10216	13863	25736
		Stony Clove Creek above Warner Creek	17.5	4772	7682	10569	14324	26694
		Stony Clove above Ox Clove	27.1	5807	9382	12979	17606	32650

SUBBASIN	STREAM	LOCATION	DA	Q10	Q25	Q50	Q100	Q500
		Stony Clove Creek above Esopus Creek	32.4	6966	11226	15463	20895	38759
	Warner Creek	Warner Creek above Stony Clove Creek	9.0	1448	2303	3162	4281	7915
Woodland Creek	Cross Mount Hollow	Mount Hollow above Woodland Creek	2.5	537	895	1260	1740	3301
	Muddy Brook	Muddy Brook above Woodland Creek	1.4	312	518	729	1006	1926
	Panther Kill	Panther Kill above Woodland Creek	3.5	798	1290	1795	2454	4583
	Woodland Creek	Woodland Creek above Mount Hollow	9.6	1930	3176	4442	6103	11485
		Woodland Creek above Woodland Creek Tributary 3	12.9	2555	4224	5920	8143	15398
		Woodland Creek above Panther Kill	15.1	2938	4896	6868	9501	18113
		Woodland Creek above Muddy Brook	18.8	3698	6136	8598	11934	22655
		Woodland Creek above Esopus Creek	20.6	3991	6662	9352	13011	24747
	Woodland Creek Tributary 3	Woodland Creek Tributary 3 above Woodland Creek	0.4	113	184	257	353	668

Table 18: Summary of Recommended Water Surface Elevations

SUBBASIN	STREAM	LOCATION	DA	WSEL10	WSEL25	WSEL50	WSEL100	WSEL500
Ashokan Reservoir	Ashokan Reservoir	Ashokan Reservoir - West Basin*	237.4	593.2	594.5	595.7	597.1	601.3
		Ashokan Reservoir - East Basin*	255.3	589.4	590.3	591.1	592	595
	Kenozia Lake	Generic junction	1.2	693.9	694.7	695.4	696.4	699.1

*Elevations are referenced to NGVD 29

G. REFERENCES

1) Chow VT, Maidment DR, Mays LW (1988) Applied hydrology. McGraw-Hill, New York
2) Federal Emergency Management Agency, *Guidelines and Specifications for Flood Hazard Mapping Partners*, Appendix C: *Guidance for Riverine Flooding Analysis and Mapping*, November 2009.
3) Federal Emergency Management Agency (FEMA). 2008. Flood Insurance Study, Greene County, New York (All Jurisdictions)
4) Federal Emergency Management Agency (FEMA). 1983. Flood Insurance Study, Town of Hunter, Greene County, New York
5) Federal Emergency Management Agency (FEMA). February 1982. Flood Insurance Study, Town of Lexington, Greene County, New York
6) Federal Emergency Management Agency (FEMA). August 1982. Flood Insurance Study, Town of Hurley, Ulster County, New York
7) Federal Emergency Management Agency (FEMA). 1984. Flood Insurance Study, Town of Olive, Ulster County, New York
8) Federal Emergency Management Agency (FEMA). 1989. Flood Insurance Study, Town of Shandaken, Ulster County, New York
9) Federal Emergency Management Agency (FEMA). 1991. Flood Insurance Study, Town of Woodstock, Ulster County, New York
10) Gesch, D.B., 2007, The National Elevation Dataset, in Maune, D., ed., Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition: Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, p. 99-118.
11) Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D., 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, p. 5-11. http://seamless.usgs.gov/.
12) Haan C.T., H.P. Johnson, and D.L. Brakensiek. Hydrologic Modeling of Small Watersheds. Chapter 5, pp 207-214. American Society of Agricultural Engineers. 2950 Niles Road, P.O. Box 410. St. Joesph, Michigan 49085
13) Kent, M.K. 1972. National Engineering Handbook, Section 4, Hydrology, Chapter 15. Travel Time, Time of Concentration and Lag. United State Department of Agriculture, Natural Resources Conservation Service. Washington, DC 20250.

14) Linsley, Kohler, Paulhus (1975) Hydrology for Engineers

15) McCuen, R.H. 1989. Hydrologic Analysis and Design. Prentice-Hall, Inc. Englewood Cliffs, NJ

16) Natural Resources Conservation Service (NRCS). National Engineering Handbook. Section 4- Hydrology. Washington, DC.

17) New York City Department of Environmental Protection (NYCDEP) , Cornell Cooperative Extension, Ulster County, U.S. Army Engineer Research Development Center, Upper Esopus Creek Management Plan, January 2007.

18) New York City Department of Environmental Protection (NYCDEP), Prepared by GZA Buffalo, NY. Draft Hydrologic Study of Olive Bridge Dam and Dikes and Ashokan Reservoir. February 2000.

19) Ponce, V.M. and R.H. Hawkins. 1996. Journal of Hydrologic Engineering. Vol.1. No.1.

20) Kernell G. Ries III, John G. Guthrie, Alan H. Rea, Peter A. Steeves, and David W. Stewart (2008), StreamStats: A Water Resources Web Application. http://water.usgs.gov/osw/streamstats/

21) U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Weather Bureau. (1961). Technical Paper 42, Generalized Estimates of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands.

22) U.S. Army Corps of Engineers, Hydrologic Engineering Center, Hydrologic Modeling System HEC-HMS, Version: 3.5 Build: 1417 Date: 10Aug2010.

23) U.S. Army Corps of Engineers, Hydrologic Engineering Center, Hydrologic Modeling System HEC-HMS User's Manual, Version 3.3, August 2009.

24) U.S. Army Corps of Engineers, Hydrologic Engineering Center, HEC-GeoHMS Geospatial Hydrologic Modeling Extension User's Manual, Version 4.2, May 2009.

25) U.S. Army Corps of Engineers, New York District 1995. General Design Memorandum, Passaic River, Flood Damage Reduction Project, Appendix C – Hydrology & Hydraulics,

26) U.S. Army Corps of Engineers and New Jersey Department of Environmental Protection. 2004. Upper Passaic River and Tributaries, Flood Reduction and Ecosystem Restoration, Final Detailed Project Report, Appendix A – Hydrology & Hydraulics. USACE, New York District.

27) USACE, 2007. Pompton Lake Dam Post-Flood Report April 15-17, 2007 Nor'easter. USACE NY District.
28) USDA (NRCS). 1986. Urban Hydrology for Small Watersheds, TR-55. Washington, D.C.
29) USGS, 2006 Magnitude and Frequency of Floods in New York; USGS Scientific Investigations Report 2006-5112, 2006.
30) USGS, 2009 Bankfull Discharge and Channel Characteristics of Streams in New York State; Scientific Investigations Report 2009–5144.
31) U.S. Environmental Protection Agency (USEPA) and USACE, Kansas City District. 2008.
32) U.S. Environmental Protection Agency, Stormwater Management Model User's Manual, Version 4.0, August 1988.
33) U.S. Geological Survey Water-Resources Investigations Report 94-4002: Nationwide summary of U.S. Geological Survey regional regression equations for estimating magnitude and frequency of floods for ungaged sites, 1993
34) USGS. 1991. Regionalization of Flood Discharges for Rural, Unregulated Streams in New York, excluding Long Island. Water-Resources Investigations Report 90-4197. USGS, Reston, VA.
35) Viessman Jr., W., Knapp, J.W., Lewis, G.L., Harbaugh, T.E. 1977. Introduction to Hydrology, Harper and Row, New York.
36) USGS. February 2002. Annual Peak Flow Frequency Analysis, PeakFQ, Version 4.1.
37) USGS. March 1982. Water Resources Council Hydrology Subcommittee. March 1982. Guidelines for Determining Flood Flow Frequency, Bulletin 17B, Washington, D.C.