Attachment 02.04.03-08X
TVA letter dated February 2, 2010
RAI Response

ASSOCIATED ATTACHMENTS/ENCLOSURES:

Attachment 02.04.03-8X: Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation

(98 Pages including Cover Sheet)

NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV A EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58 090422 001	calculations(nuclear)	L58 091230 033

Calc Title: Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080056	0	1	Entire calc ☒ Selected pages ☐
NEW								

ACTION	NEW ☐ REVISION ☒	DELETE ☐ RENAME ☐	SUPERSEDE ☐ DUPLICATE ☐	CCRIS UPDATE ONLY ☐ (Verifier Approval Signatures Not Required)	No CCRIS Changes ☐ (For calc revision, CCRIS been reviewed and no CCRIS changes required)

UNITS	SYSTEMS	UNIDS
N/A	N/A	N/A

DCN,EDC,N/A	APPLICABLE DESIGN DOCUMENT(S)	CLASSIFICATION
* See Below	N/A	"E"

QUALITY RELATED?	SAFETY RELATED? (If yes, QR = yes)	UNVERIFIED ASSUMPTION	SPECIAL REQUIREMENTS AND/OR LIMITING CONDITIONS?	DESIGN OUTPUT ATTACHMENT?	SAR/TS and/or ISFSI SAR/CoC AFFECTED
Yes ☒ No ☐	Yes ☒ No ☐	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒

PREPARER ID	PREPARER PHONE NO	PREPARING ORG (BRANCH)	VERIFICATION METHOD	NEW METHOD OF ANALYSIS
clstokes	615-252-4343	CEB	See Page 10	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Carrie L. Stokes Carrie Stokes	12/11/09	Mark Crisp Mark Crisp	12/11/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Mark Crisp Mark Crisp	12/11/09	K.R. Spates K. R. Spates	12/23/09

STATEMENT OF PROBLEM/ABSTRACT

12/11/09

Validate existing unit hydrographs for the subbasins of the Douglas Dam watershed (Subbasins 1 through 6) using several recent floods.

* EDCN 22404A(SQN), EDCN 54018A(WBN), Later (BFN)

This calculation contains electronic attachments and must be stored in EDMS as an Adobe .pdf file to maintain the ability to retrieve the electronic attachments.

MICROFICHE/EFICHE Yes ☐ No ☒ FICHE NUMBER(S)

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NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV A EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58 090422 001	calculations(nuclear)	N/A

Calc Title: Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC						Entire calc ☐ Selected pages ☐
NEW	CN	NUC	GEN	CEB	CDQ000020080056	N/A	0	

ACTION	NEW ☒ REVISION ☐	DELETE ☐ RENAME ☐	SUPERSEDE ☐ DUPLICATE ☐	CCRIS UPDATE ONLY ☐ (Verifier Approval Signatures Not Required)	No CCRIS Changes ☐ (For calc revision, CCRIS been reviewed and no CCRIS changes required)

UNITS	SYSTEMS	UNIDS
N/A	N/A	N/A

DCN,EDC,N/A	APPLICABLE DESIGN DOCUMENT(S)	CLASSIFICATION
N/A	N/A	"E"

QUALITY RELATED?	SAFETY RELATED? (If yes, QR = yes)	UNVERIFIED ASSUMPTION	SPECIAL REQUIREMENTS AND/OR LIMITING CONDITIONS?	DESIGN OUTPUT ATTACHMENT?	SAR/TS and/or ISFSI SAR/CoC AFFECTED
Yes ☒ No ☐	Yes ☒ No ☐	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒

PREPARER ID	PREPARER PHONE NO	PREPARING ORG (BRANCH)	VERIFICATION METHOD	NEW METHOD OF ANALYSIS
THJACKSO	(301) 228-8323	Bechtel (CEB)	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Thomas H. Jackson	4-13-09	Matthew C. Carney	4/13/2009
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Robert E. Swain	4/13/2009	CJT 4/17/09 K.R. Spates	4/17/09

STATEMENT OF PROBLEM/ABSTRACT

Validate existing unit hydrographs for the subbasins of the Douglas Dam watershed (Subbasins 1 through 6) using several recent floods.

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MICROFICHE/EFICHE Yes ☐ No ☒ FICHE NUMBER(S)

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NPG CALCULATION COVERSHEET/CCRIS UPDATE

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	REV
	CN	NUC	GEN	CEB	CDQ000020080056	1

ALTERNATE CALCULATION IDENTIFICATION

BLDG	ROOM	ELEV	COORD/AZIM	FIRM BWSC	Print Report Yes ☐

CATEGORIES NA

KEY NOUNS (A-add, D-delete)

ACTION (A/D)	KEY NOUN	A/D	KEY NOUN

CROSS-REFERENCES (A-add, C-change, D-delete)

ACTION (A/C/D)	XREF CODE	XREF TYPE	XREF PLANT	XREF BRANCH	XREF NUMBER	XREF REV
A	P	EN	WBN	CEB	54018	
A	P	EN	SQN	CEB	22404	
A	P	CO	GEN	CEB	UNITGRPH Version 1.0	
A	P	CO	GEN	CEB	FLDHYDRO Version 1.0	

CCRIS ONLY UPDATES:
Following are required only when making keyword/cross reference CCRIS updates and page 1 of form NEDP-2-1 is not included:

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
PREPARER PHONE NO.	EDMS ACCESSION NO.		

NPG CALCULATION RECORD OF REVISION

CALCULATION IDENTIFIER CDQ000020080056

Title Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation

Revision No.	DESCRIPTION OF REVISION
0	Initial issue 96 pages
1	This calculation was revised to address the following: • PER 203951- The verification of the original calculation was completed by personnel who had not completed the required NEDP-7 Job Performance Record (JPR). A verification JPR is now in place for all personnel engaged in verification tasks. Checking includes only changes made in this revision as the checking of the calculation was not impacted by PER 203951. The verification is inclusive of work completed prior to this revision. • PER 203872- replace NEDP-2 forms on Pages 2 through 7 with the forms from the NEDP-2 Revision in effect at the time of calculations issuance. Significant changes in Revision 1 are noted with a right margin revision bar. Administrative changes and typos are excluded. Pages Added: 1a & 10a Pages Replaced: 1-10 & 12 Total pages of calculation hard copy for Revision 1= 97

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Attachments: See the list of electronic attachments on the following page.

NPG COMPUTER INPUT FILE STORAGE INFORMATION SHEET

Document	CDQ000020080056	Rev. 1	Plant: GEN

Subject: Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation

☐ Electronic storage of the input files for this calculation is not required. Comments:

☒ Input files for this calculation have been stored electronically and sufficient identifying information is provided below for each input file. (Any retrieved file requires re-verification of its contents before use.)

See listing of electronically attached spreadsheets and input/output files on the two following pages.

☐ Microfiche/eFiche

ELECTRONIC FILE ATTACHMENTS			
Document: CDQ000020080056	Rev. 1	Plant: GEN	
Subject: Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation			

Electronic Attachment	Name of File or Folder	File Location
Supporting Spreadsheets		
Attachment 1-1	CheckUHVolumes.xls	Attached to PDF
Attachment 1-2	DirectROCalcs2002.xls	Attached to PDF
Attachment 1-3	DirectROCalcs2003.xls	Attached to PDF
Attachment 1-4	DirectROCalcs2004.xls	Attached to PDF
Attachment 1-5	DirectROCalcsSB2-1994&6.xls	Attached to PDF
Attachment 1-6	Douglas Dam RRR 2003.xls	Attached to PDF
Attachment 1-7	Douglas Dam RRR 2004.xls	Attached to PDF
Attachment 1-8	DouglasDamQ&H.xls	Attached to PDF
Attachment 1-9	EffectivePPTcalcSB2-1994&6.xls	Attached to PDF
Attachment 1-10	EffectivePPTcalcSB3-1996.xls	Attached to PDF
Attachment 1-11	FLDHYDRO processing.xls	Attached to PDF
Attachment 1-12	French Broad Basin.xls	Attached to PDF
Attachment 1-13	FrenchBroadAtAsheville.xls	Attached to PDF
Attachment 1-14	FrenchBroadNrNewport.xls	Attached to PDF
Attachment 1-15	GriddedPrecipitationDataAllSubbasins2002.xls	Attached to PDF
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Attachment 1-22	Precipitation Data Processing 2002.xls	Attached to PDF
Attachment 1-23	Precipitation Data Processing 2003.xls	Attached to PDF
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Attachment 1-25	Routing&HydrographSeparationSB21994&6.xls	Attached to PDF
Attachment 1-26	RRRhydrograph smoothing.xls	Attached to PDF
Attachment 1-27	Subbasin 3 New UH development.xls	Attached to PDF
Attachment 1-28	Test Basin 4 UH Run.xls	Attached to PDF
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Attachment 1-30	TVArain1996.xls	Attached to PDF
Attachment 1-31	Validated UH Ordinates & Routing Parameters.xls	Attached to PDF
FLDHYDRO Files		
Attachment 2-1	Basin01ppt2003.dat	Attached to PDF
Attachment 2-2	Basin01ppt2004.dat	Attached to PDF
Attachment 2-3	Basin03pptPartA2003.dat	Attached to PDF
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Attachment 2-5	Basin04pptNov2003.dat	Attached to PDF
Attachment 2-6	Basin04ppt2004.dat	Attached to PDF
Attachment 2-7	Basin05ppt2002.dat	Attached to PDF
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Attachment 2-11	Basin01ppt2003.out	Attached to PDF
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Attachment 2-15	Basin04pptNov2003.out	Attached to PDF
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Attachment 2-19	Basin06ppt2003.out	Attached to PDF
Attachment 2-20	Basin06ppt2004.out	Attached to PDF

ELECTRONIC FILE ATTACHMENTS			
Document: CDQ000020080056	Rev. 1	Plant: GEN	
Subject: Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation			

Electronic Attachment	Name of File or Folder	File Location
UNITGRPH Files		
Attachment 2-21	UGBasin2.dat	Attached to PDF
Attachment 2-22	UGBasin2.prn	Attached to PDF
Attachment 2-23	UGBasin3.dat	Attached to PDF
Attachment 2-24	UGBasin3.prn	Attached to PDF
Attachment 2-25	UGBasin4.dat	Attached to PDF
Attachment 2-26	UGBasin4.prn	Attached to PDF
Attachment 2-27	UGBasin6.dat	Attached to PDF
Attachment 2-28	UGBasin6.prn	Attached to PDF

HEC-HMS File Folders		
Attachment 3-1	Basin 01.zip (HEC-HMS project files)	Filekeeper No. 311834
Attachment 3-2	Basin 02.zip (HEC-HMS project files)	Filekeeper No. 311835
Attachment 3-3	Basin 03.zip (HEC-HMS project files)	Filekeeper No. 311836
Attachment 3-4	Basin 04.zip (HEC-HMS project files)	Filekeeper No. 311837
Attachment 3-5	Basin 05.zip (HEC-HMS project files)	Filekeeper No. 311838
Attachment 3-6	Basin 06.zip (HEC-HMS project files)	Filekeeper No. 311839

NPG CALCULATION VERIFICATION FORM

Calculation Identifier CDQ000020080056 Revision 0

Method of verification used:

1. Design Review ☒
2. Alternate Calculation ☐ Verifier Bob Swain Date 3/17/2009
3. Qualification Test ☐

Comments:

The calculation entitled, "Douglas Dam Watershed (Subbasins 1 through 6) Unit Hydrograph Validation" was verified by an independent design review. The process involved a critical review of the calculation to ensure that it is correct and complete, uses appropriate methodologies, and achieves its intended purpose. Backup files and documents were consulted as necessary to verify data and analysis details found in the calculation. Detailed comments and editorial suggestions were transmitted to the author and reviewer by email along with a marked up copy of the calculation.

Several issues were discussed and resolved during the verification process. Almost all of the editorial suggestions were adopted in the final document. The following discussion briefly describes the most important issues and the resolution process.

1. In the initial draft calculation, several simulated peak discharges were more than 20 percent different from the observed flood peaks. As a result, new unit hydrographs were produced for Subbasins 2 and 3. For Subbasin 2, the 1973 and 2004 floods were used for unit hydrograph development, and the 1994 and 1996 floods were used for validation. For Subbasin 3, the 1994 and 2004 floods were used for unit hydrograph development, and the 1996 and 2003 floods were used for validation.

2. Much discussion and effort was devoted to developing observed local flood hydrographs for Subbasins 5 and 6 for comparison with the simulated local flood hydrographs. However, in this case, local flood hydrographs, determined by subtracting routed upstream flows from reservoir inflows determined by reverse reservoir routing, were judged unreliable. Therefore, "operational validations" were used to validate the unit hydrographs for Subbasins 5 and 6, which means flood hydrographs were reproduced at the basin outlet rather than reproducing the local flood hydrographs for the individual subbasin. Because it was possible to reproduce flows at the outlet of the subbasins, the unit hydrographs for Subbasins 5 and 6 were validated operationally and are considered suitable for use in the probable maximum flood studies for Bellefonte Nuclear Power Plant.

The calculation supports the conclusion that the unit hydrographs developed by the TVA for the Douglas Dam watershed (Subbasins 1 through 6) have been validated against two recent floods.

1 Purpose

The Tennessee Valley Authority's (TVA) Water Management Group has adapted computer codes and data sets developed from flood studies carried out over the past 40 years to develop a dynamic hydrologic model (Reference 22) of the Tennessee River upstream of the Guntersville Dam for use in the Probable Maximum Flood (PMF) and dam break analysis for the Sequoyah, Watts Bar, and planned Bellefonte Nuclear plant sites (note that this calculation will also be used in a similar future PMF and dam break analysis for the Browns Ferry Nuclear Power plant).

Inputs to the dynamic model include hydrographs for 47 subbasins developed from design rainfall inputs convoluted with unit hydrographs (UH) developed specifically for each subbasin. These unit hydrographs were developed by the TVA in previous studies, mostly in the 1960s, 1970s, and early 1980s, utilizing observed rainfall and stream flow and reservoir headwater and discharge data, and are being validated by checking their performance in reproducing recent floods.

This calculation presents the validation of the unit hydrographs (UH) developed by the TVA for the six subbasins within the Douglas Dam watershed, Subbasins 1 through 6, located within the Tennessee River watershed upstream of Guntersville, Alabama, as shown in Figure 1.

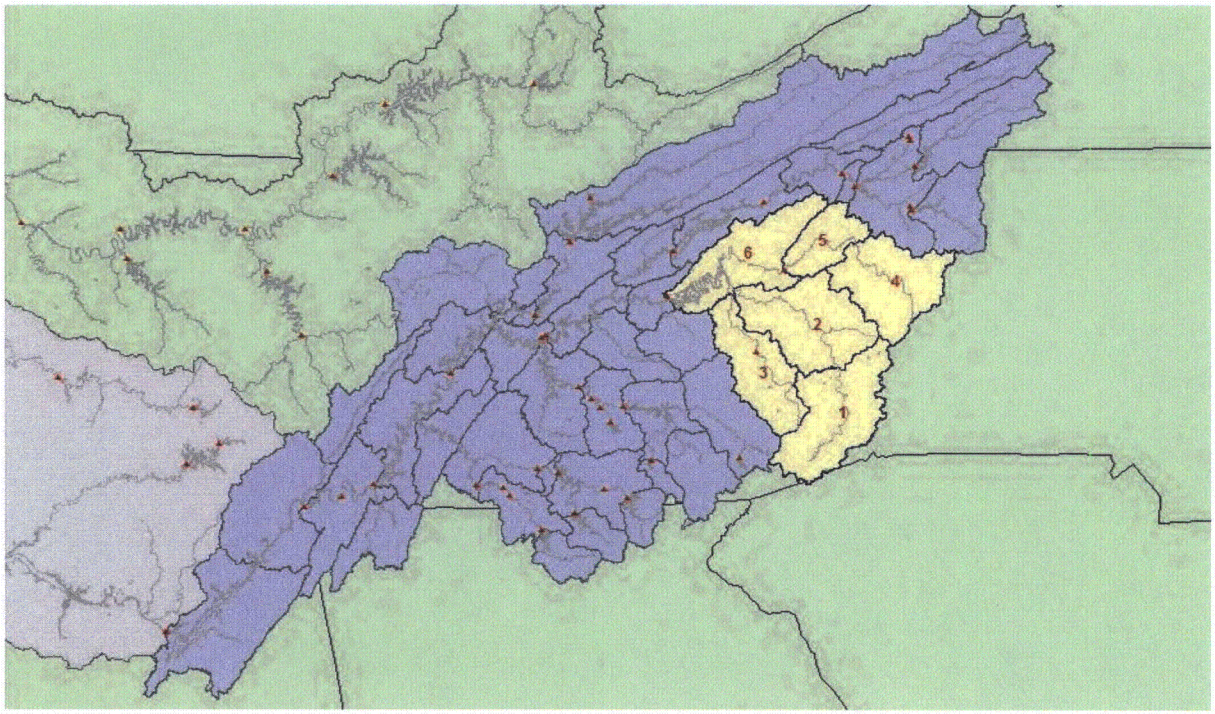

Figure 1: Location of the Six Douglas Dam Subbasins within the Tennessee River Watershed

2 References

1. American Nuclear Society, American National Standard for Determining Design Basis Flooding at Power Reactor Sites, ANSI/ANS-2.8-1992, 1992.
2. Chow, V.T., D.R. Maidment, and L.W. Mays, *Applied Hydrology*, McGraw-Hill Book Company, 1988.
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3 Assumptions

3.1 General Assumptions

None

3.2 Unverified Assumptions

None

4 Background

The unit hydrograph is used to predict the runoff response at the outlet of a watershed, or subbasin, to the input of one inch of excess rainfall applied over a given duration of time. Runoff from other depths of excess rainfall can be obtained by scaling (References 2 and 4).

The direct runoff (stream flow minus base flow) hydrograph can be calculated from a series of M excess rainfall inputs of any depth and the K ordinates of the unit hydrograph using the process of "convolution." The N = K + M -1 ordinates of the direct runoff hydrograph are given by the discrete convolution equation, which states that the direct runoff Q_n at a given time n is obtained from the excess runoff P_m and the unit hydrograph ordinate U_{n-m+1} (where $U_i = 0$ for all $i = n - m + 1 > K$) as follows (Reference 2):

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1} \tag{1}$$

The reverse process, called deconvolution, can be used to derive the ordinates of the unit hydrograph (U), from excess rainfall (P) and direct runoff (Q) derived from observed data.

Unit hydrograph theory is applicable under the following conditions (References 2 and 4):

1. Excess rainfall has a constant intensity within the effective duration.
2. Excess rainfall is uniformly distributed over the entire subbasin.
3. The duration of direct runoff resulting from a unit of excess rainfall is constant.
4. The ordinates of the unit hydrograph are directly proportional to the total amount of direct runoff (linear response).
5. The surface runoff hydrograph reflects all the unique physical characteristics and runoff processes in the drainage basin in a given "epoch."

5 Methodology

The methodology used for unit hydrograph validation follows that described in ANSI/ANS-2.8-1992 (Reference 1). This document is included as a reference in the NRC's Standard Review Plan for Section 2.4.3, Probable Maximum Flood on Streams and Rivers (Reference 26). With regard to verifying runoff models, ANSI/ANS-2.8-1992 indicates the following:

"Deterministic simulation models including unit hydrographs should be verified or calibrated by comparing results of the simulation with the highest two or more floods for which suitable precipitation data are available."

For the purpose of validating the unit hydrographs for the six subbasins within the Douglas Dam watershed, the period of record from which the highest two or more floods were selected extended from 1997 through 2007. This period was targeted because high resolution, radar-based, hourly precipitation data are available for this period as is described in Section 6.6. Where suitable floods could not be found within that period, data from as far back as 1985 was considered. Furthermore, since the original unit hydrographs were developed from floods that occurred between 1940 and1973 (see Section 6.2.1 through 6.2.6), it was necessary to use recent rainfall and stream flow data to evaluate the possibility that changes in watershed characteristics over the intervening years might have altered the rainfall-runoff response of the watershed to such an extent as to invalidate the original TVA unit hydrograph.

In general, the methodology used for unit hydrograph validation includes the following steps:

1. Screen historical stream flow data to identify significant floods that occurred subsequent to those used to develop the subbasin unit hydrograph. These more recent floods are used for unit hydrograph validation.
2. Obtain the observed hydrograph data for the more recent floods and transfer the flow series to the subbasin outlet using established hydrologic procedures as necessary (e.g. reverse reservoir routing or stream flow routing and hydrograph separation) to develop the local basin hydrograph.
3. Separate base flow from the local basin hydrograph to obtain the "observed" direct runoff hydrograph for the basin, and calculate the volume of direct runoff based on hydrograph ordinates.
4. Obtain observed rainfall data for the selected floods and calculate the basin average precipitation for the adopted time step.
5. Convert the observed rainfall series to an effective rainfall series using the TVA's API-RI method as implemented in FLDHYDRO (Reference 6). This includes inputting the observed runoff volume obtained in Step 3 to ensure that the effective rainfall volume calculated by FLDHYDRO equals the observed runoff volume.
6. Run HEC-HMS (References 23 and 24) utilizing the TVA unit hydrograph and the effective rainfall series as input and compare the resulting simulated hydrograph with the observed direct runoff hydrograph in terms of total volume, and the timing and magnitude of peak discharge. Since HEC-HMS is not TVA-validated software, the program output was validated for this calculation by independent replication of the results of hydrograph convolution for a representative subbasin (Subbasin 4) using an Excel spreadsheet, "Test Basin 4 UH Run.xls," (Attachment 1-28).

Where observed flow at the outlet to a subbasin is not available and the time distribution of local runoff cannot be reliably estimated with simple lag routing, as for Subbasins 5 and 6, approximate methods must be utilized. For this calculation the total volume of local runoff was estimated as the difference in the volume of direct runoff calculated for the up- and downstream observed hydrographs, as described in Sections 7.2.5 and 7.2.6. This total volume was used in FLDHYDRO to compute the effective rainfall hyetograph. The local flood hydrograph generated by convolution of this excess runoff hyetograph with the TVA unit hydrograph developed for the subbasin was validated by comparing the simulated in-stream hydrograph with the observed hydrograph at the downstream basin outlet.

6 Design Input Data

The input data necessary for validating the unit hydrographs for the six subbasins within the Douglas Dam watershed includes:

- Unit hydrograph ordinates and durations
- Flood routing parameters for applicable river reaches
- Observed discharge records from stream flow gages located at/near subbasin outlets
- Observed outflows from Douglas Dam and from Nolichucky Dam and the corresponding headwater elevations
- The stage-volume relationships for the Douglas and Nolichucky reservoirs
- Observed rainfall data associated with selected recent floods

Each of these inputs is described in more detail in the following subsections.

6.1 Subbasin Areas

The Douglas Dam closes an upstream watershed with an area of approximately 4,543 square miles, which is divided by the TVA into six subbasins for hydrologic modeling as shown in the key map presented as Figure 2, and as summarized in Table 1. The original unit hydrograph calculations are based on the areas shown in the column of Table 1 labeled "Reference." The difference between the reference areas and the areas recently calculated by the TVA using Geographic Information System (GIS) software (which are used in this calculation) differ by less than 0.5% in all cases and by less than 0.1 % for the basin total.

Table 1: Subbasins within the Douglas Dam Watershed

Basin ID	Subbasin Name	Area, mi^2		% difference
		GIS-basis	Reference	
1	French Broad River at Asheville	944.4	945.0	0.06%
2	French Broad River at Newport	913.1	913.0	-0.01%
3	Pigeon River at Newport	667.1	666.0	-0.17%
4	Nolichucky River at Embreesville	804.8	805.0	0.02%
5	Nolichucky Dam Local Inflow	378.7	378.0	-0.19%
6	Douglas Dam Local Inflow	835.0	832.0	-0.36%
	Total watershed	4543.1	4539.0	-0.09%

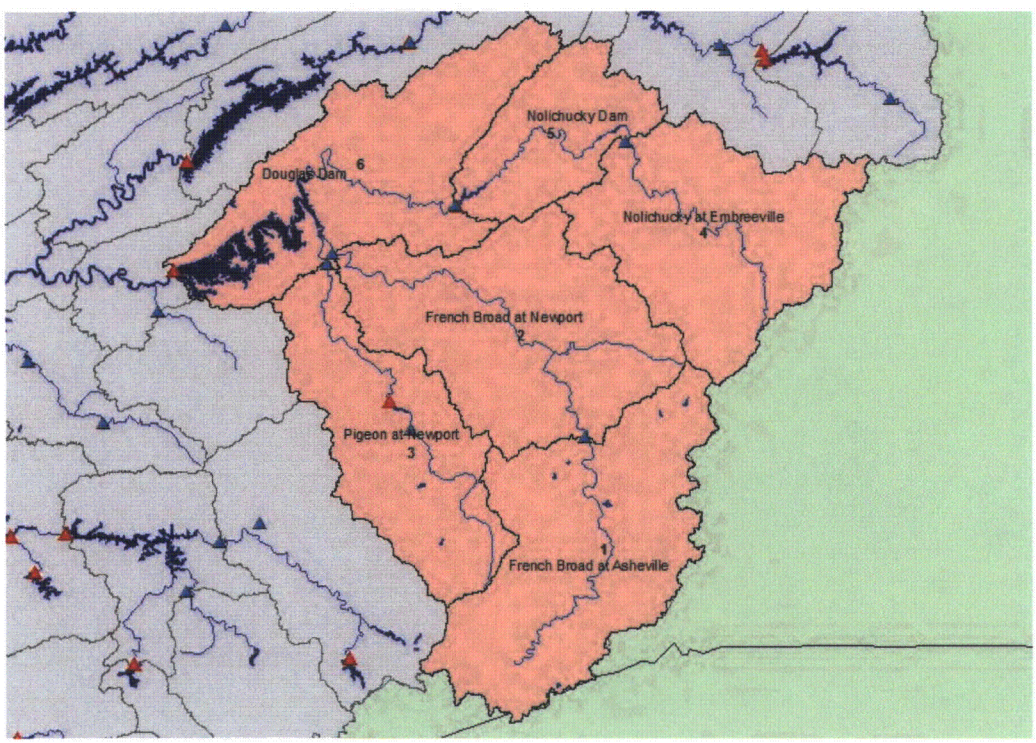


Figure 2: Douglas Dam Watershed Subbasin Map

6.2 Unit Hydrographs

The response of a watershed to one inch of rainfall is simulated with a unit hydrograph, as described in Section 4. Unit hydrographs were developed by the TVA for each of the subbasins within the Douglas Dam watershed, mostly in the 1960s and 70s, using the methodology proposed by Newton and Vinyard (Reference 5) as implemented in the UNITGRPH computer program (Reference 6). Use of this methodology allows consideration of possible adjustments in the initial estimate of the time distribution of precipitation excess, and adjustment of the timing and depth of excess precipitation ordinates in the development of the unit hydrograph.

The TVA inputs for the UNITGRPH program for Subbasins 2, 3, 4, and 6 were obtained from References 8, 9, 10, and 12. These input files were re-run using the revised 2008 version of the UNITGRPH program to verify the existing TVA unit hydrographs. The TVA's original unit hydrographs for Subbasins 1, 4, 5, and 6 were used in the analyses presented in this calculation. New unit hydrographs were developed for Subbasins 2 and 3, as discussed in Sections 6.2.2 and 6.2.3; the new input files were also rerun with the revised 2008 version of UNITGRPH. Input and output files for the new runs for Subbasins 2, 3, 4, and 6 are provided as Attachments 2-21 to 2-28.

Key parameters associated with each of the original TVA unit hydrographs are presented in Table 2. As shown in the final column of the table, the volume of runoff is approximately one inch for each unit hydrograph as required by theory. The calculation is based on the calculation of area under the unit hydrograph, determined from the ordinates developed by the TVA, as shown in the spreadsheet CheckUHVolumes.xls, provided as an electronic file as Attachment No. 1-1.

Table 2: TVA Unit Hydrograph Parameters for the Subbasins of the Douglas Dam Watershed (Subbasins 2, 3, 4, and 6 regenerated with revised 2008 version of UNITGRPH)

Subbasin	Effective Duration, hrs	Number of ordinates	Qpeak, cfs	Peak Time, hours	Area, sq. mi.	Volume, acft	Volume inches
1	6	29	14,000	12	944.4	50,355	1.000
2	6	19	34,807	12	913.1	48,698	1.000
3	6	14	26,516	12	667.1	35,575	1.000
4	4	21	33,275	12	804.8	42,934	1.000
5	6	16	11,740	12	378.7	20,226	1.001
6	6	11	47,207	6	835.0	44,533	1.000

A summary of the procedures used by the TVA for the development of the unit hydrograph for each subbasin is presented in the following six subsections.

6.2.1 Subbasin 1 Unit Hydrograph

A unit hydrograph for the French Broad River at Asheville was developed by the TVA from stream flow and rainfall data from the three following floods (Reference 7):

- August 14, 1940
- August 30, 1940
- April 5, 1957

The three floods were used by the TVA to develop a composite unit hydrograph. A unit hydrograph developed earlier by the TVA river forecasting organization, which had been used with satisfactory results, was adopted by the TVA because it closely agreed with the composite unit hydrograph (Reference 7). The Subbasin 1 unit hydrograph is shown in Figure 3 and Table 3.

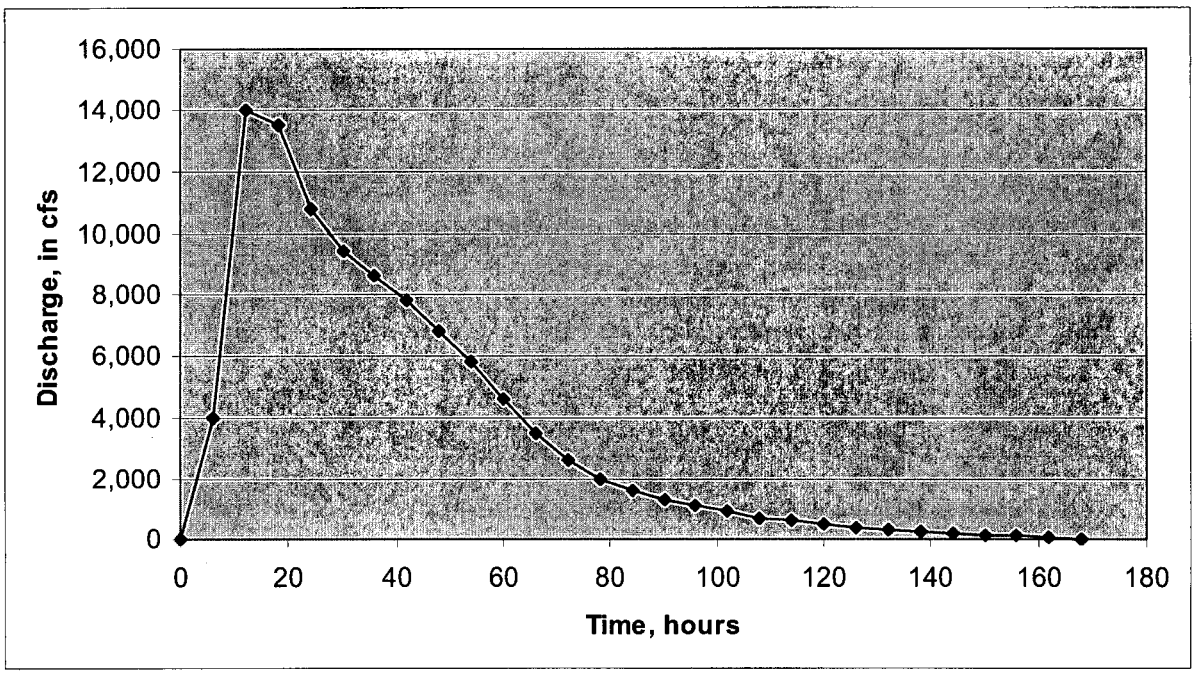


Figure 3: Six-hour Unit Hydrograph for Subbasin 1 (French Broad River at Asheville)

Table 3: Six-hour Unit Hydrograph for Subbasin 1 (French Broad River at Asheville)

t, hours	Q, cfs
0	0
6	4,000
12	14,000
18	13,500
24	10,800
30	9,400
36	8,600
42	7,800
48	6,800
54	5,800
60	4,600
66	3,500
72	2,600
78	2,000
84	1,600
90	1,300
96	1,100
102	900
108	700
114	600
120	500
126	400
132	300
138	250
144	200
150	150
156	100
162	50
168	0

The unit hydrograph for Subbasin 1 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4 and comparing the basin outlet hydrograph with observed stream flow on the French Broad River at Asheville.

6.2.2 Subbasin 2 Unit Hydrograph

The unit hydrograph for local inflow to the French Broad River from Asheville to Newport was developed from stream flow and rainfall data from the four following floods (Reference 8):

- August 30, 1940
- April 5, 1957
- March 13, 1963
- March 26, 1965

The flood hydrographs for the local area between Newport and Asheville used to develop the unit hydrograph were computed by routing the observed flows on the French Broad River at Asheville downstream to Newport and subtracting the routed flows from the stream flow observed at Newport.

The four floods were used to develop the composite unit hydrograph used by the TVA to model local runoff from Subbasin 2. Evaluation of the originally derived unit hydrograph for this calculation indicated unsatisfactory results in simulating recent floods. A new unit hydrograph was developed for Subbasin 2 using the storms of March 1973 and September 2004. The original and new hydrographs are compared in Figure 4 and Table 4.

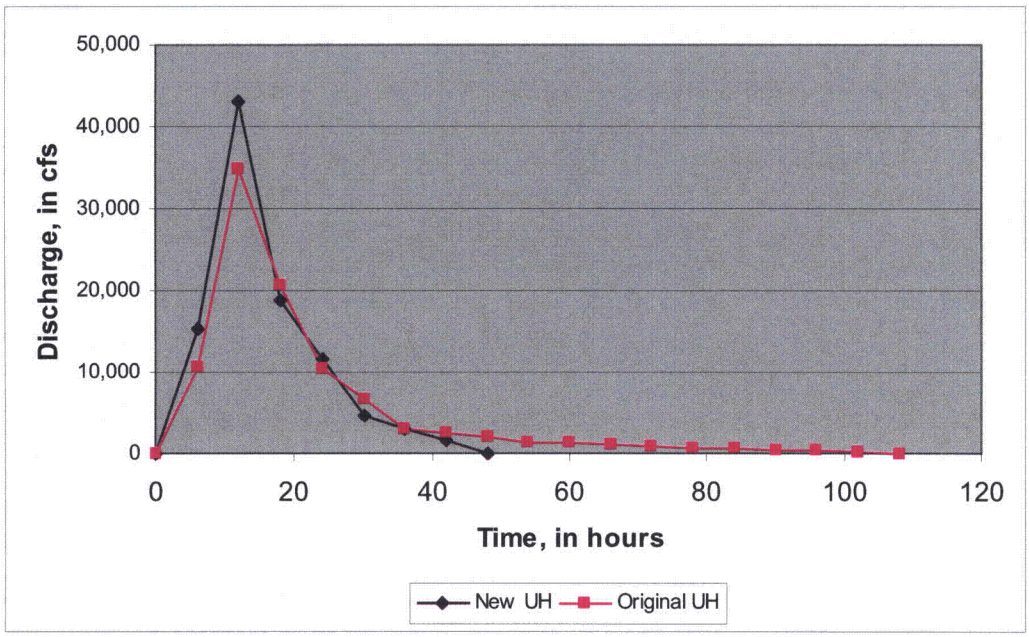


Figure 4: 6-hour Unit Hydrographs for Subbasin 2 (French Broad River near Newport)

Table 4: Six-hour Unit Hydrograph for Subbasin 2 (French Broad River near Newport)

t, hrs	Unit graph ordinates, cfs	
	Original	New
0	0	0
6	10,731	15,374
12	34,807	43,114
18	20,624	18,839
24	10,519	11,712
30	6,764	4,585
36	3,009	3,057
42	2,506	1,528
48	2,003	0
54	1,500	
60	1,301	
66	1,103	
72	904	
78	705	
84	595	
90	486	
96	376	
102	266	
108	0	

The unit hydrograph for Subbasin 2 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, and comparing the simulated local flood hydrograph with the observed local stream flow originating on the French Broad River between Newport and Asheville, after hydrograph separation.

6.2.3 Subbasin 3 Unit Hydrograph

The unit hydrograph for the Pigeon River at Newport was developed from stream flow and rainfall data from the four following floods (Reference 9):

- June 17, 1949
- February 1, 1957
- March 12, 1963
- March 26, 1965

The four floods were used to develop the composite unit hydrograph used by the TVA to model runoff in Subbasin 3. Evaluation of the originally derived unit hydrograph used by the TVA for this calculation indicated unsatisfactory results in simulating recent floods. A new unit hydrograph was developed for Subbasin 3 using the March 1994 and September 2004 floods (see spreadsheet "Subbasin 3 New UH development.xls" provided as Attachment 1-27 and the UNITGRPH files provided as Attachment 2-23 and 2-24). The original and new hydrographs are compared in Figure 5 and Table 5.

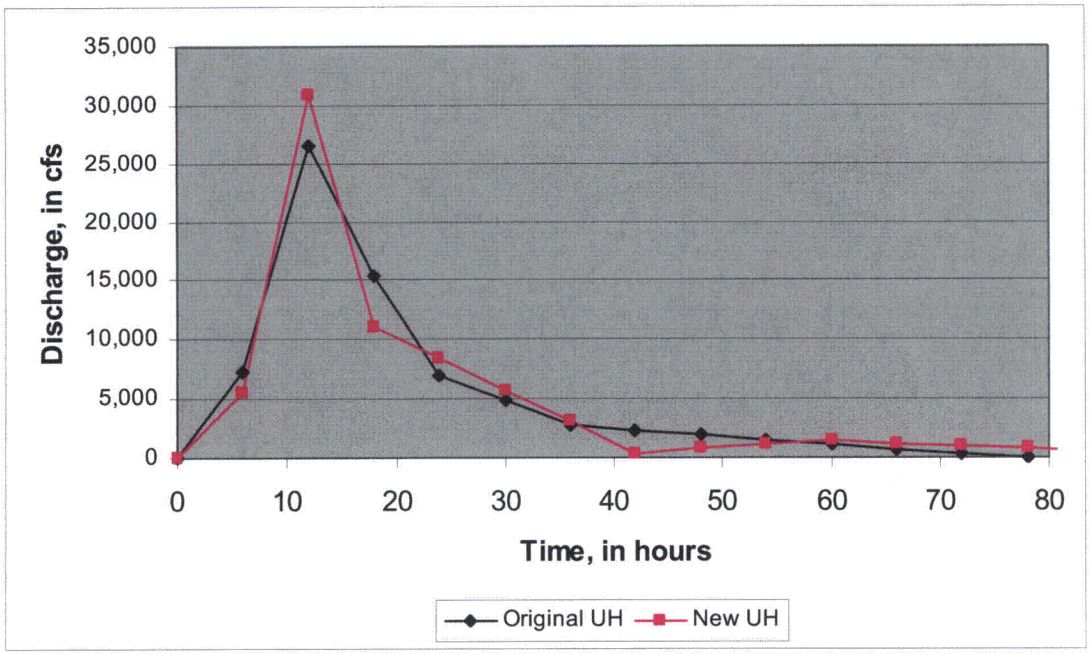


Figure 5: 6-hour Unit Hydrograph for Subbasin 3 (Pigeon River at Newport)

Table 5: Six-hour Unit Hydrograph for Subbasin 3 (Pigeon River at Newport)

t, hrs	Unit graph ordinates, cfs	
	Original	New
0	0	0
6	7,299	5,543
12	26,516	30,910
18	15,421	11,024
24	6,978	8,367
30	4,837	5,710
36	2,697	3,053
42	2,303	396
48	1,910	746
54	1,516	1,097
60	1,118	1,448
66	719	1,213
72	320	979
78	0	744
84		510
90		0

The unit hydrograph for Subbasin 3 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4, and comparing the simulated hydrograph with observed stream flow on the Pigeon River at Newport.

6.2.4 Subbasin 4 Unit Hydrograph

The unit hydrograph for Nolichucky River at Embreeville was developed from stream flow and rainfall data from the four following floods (Reference 10):

- August 13, 1940
- August 30, 1940
- June 16, 1949
- March 12, 1963

The four floods were used to develop the composite unit hydrograph used by the TVA to model runoff in Subbasin 4 (see Figure 6 and Table 6).

The unit hydrograph for Subbasin 4 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4, and comparing the simulated hydrograph with observed stream flow on the Nolichucky River at Embreeville.

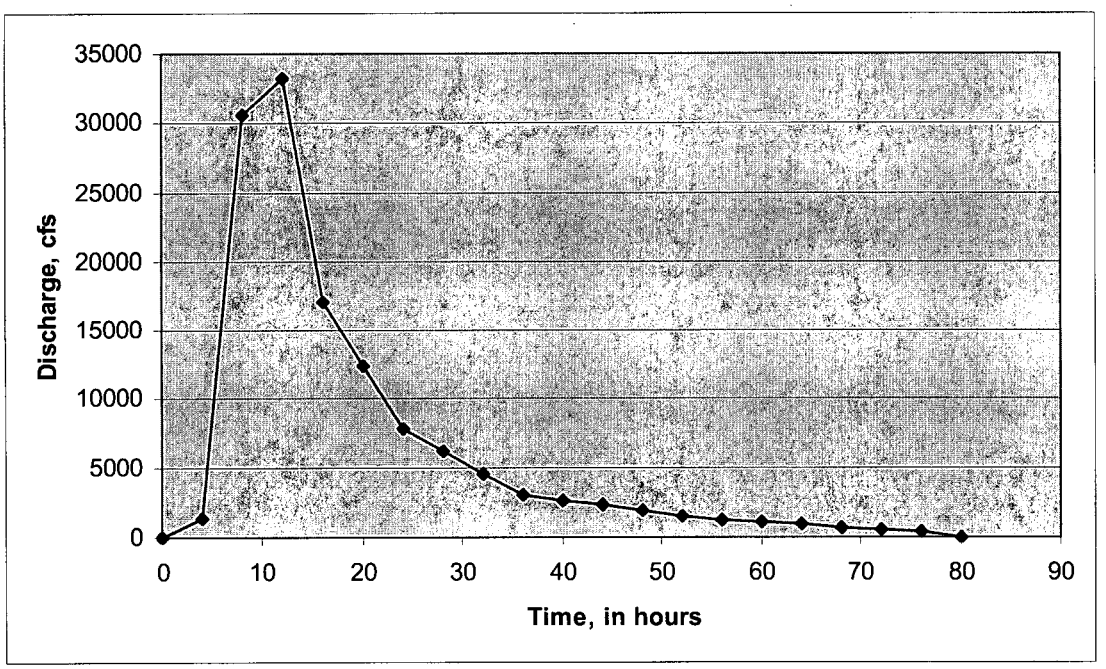


Figure 6: 4-hour Unit Hydrograph for Subbasin 4 (Nolichucky River at Embreeville)

Table 6: Four-hour Unit Hydrograph for Subbasin 4 (Nolichucky River at Embreeville)

t, hrs	Q, cfs
0	0
4	1355
8	30641
12	33275
16	17109
20	12449
24	7790
28	6203
32	4615
36	3027
40	2665
44	2304
48	1943
52	1581
56	1220
60	1060
64	900
68	740
72	580
76	419
80	0

6.2.5 Subbasin 5 Unit Hydrograph

The unit hydrograph for local inflow to the Nolichucky River between Embreeville and Nolichucky Dam is plotted in Figure 7, and the ordinates are listed in Table 7.

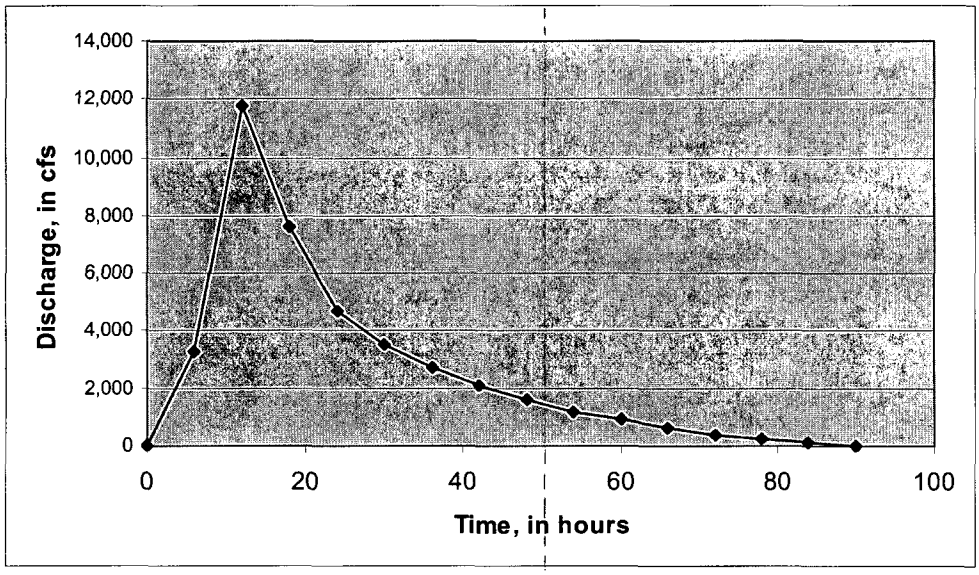


Figure 7: 6-hour Unit Hydrograph for Subbasin 5 (Nolichucky River Local Inflow from Embreeville to Nolichucky Dam)

Table 7: Six-hour Unit Hydrograph for Subbasin 5 (Nolichucky River Local Inflow from Embreeville to Nolichucky Dam)

t, hrs	Q, cfs
0	0
6	3310
12	11740
18	7630
24	4720
30	3510
36	2710
42	2110
48	1610
54	1200
60	900
66	600
72	400
78	250
84	100
90	0

The unit hydrograph was developed by the TVA's River Operations organization for use in river forecasting, but the calculations used in its development could not be recovered (Reference 11).

The unit hydrograph for Subbasin 5 was validated by the TVA by utilizing it together with the other five subbasins upstream of Douglas Dam to simulate the historic floods of March 1963 and March 1973. Since both floods were duplicated well at Douglas Dam, the use of the Subbasin 5 unit hydrograph was considered adequate for use in the runoff model (Reference 11).

The unit hydrograph for Subbasin 5 is validated in this calculation by utilizing it in a simulation of the Nolichucky Dam watershed for two recent events, using the observed flow series for the Nolichucky River at Embreeville as an upstream source. The observed flow series is routed down to the Nolichucky Dam and subtracted from the observed flow series at the site to obtain the local inflow hydrographs to compare with the simulated hydrographs.

6.2.6 Subbasin 6 Unit Hydrograph

The unit hydrograph for local inflow to the French Broad River at Douglas Dam was developed from stream flow and rainfall data from the two following floods (Reference 12):

- March 1963
- March 1973

The flow series used to develop the unit hydrograph were developed from the inflow to the Douglas Dam reservoir based on reverse reservoir routing after separation of the observed hydrographs lag-routed downstream from the French Broad River and the Pigeon River at Newport, and the Nolichucky River at Nolichucky Dam.

The two floods were used to develop the composite unit hydrograph used by the TVA to model runoff in Subbasin 6 (see Figure 8 and Table 8).

The unit hydrograph for Subbasin 6 is validated indirectly in this calculation by utilizing it in a simulation of two recent events and comparing the hydrograph with the flow into the Douglas Dam reservoir, as determined from reverse reservoir routing. Because the reservoir inflow hydrograph includes the impact of all upstream basins, the unit hydrograph for subbasin 6 is indirectly validated by this procedure.

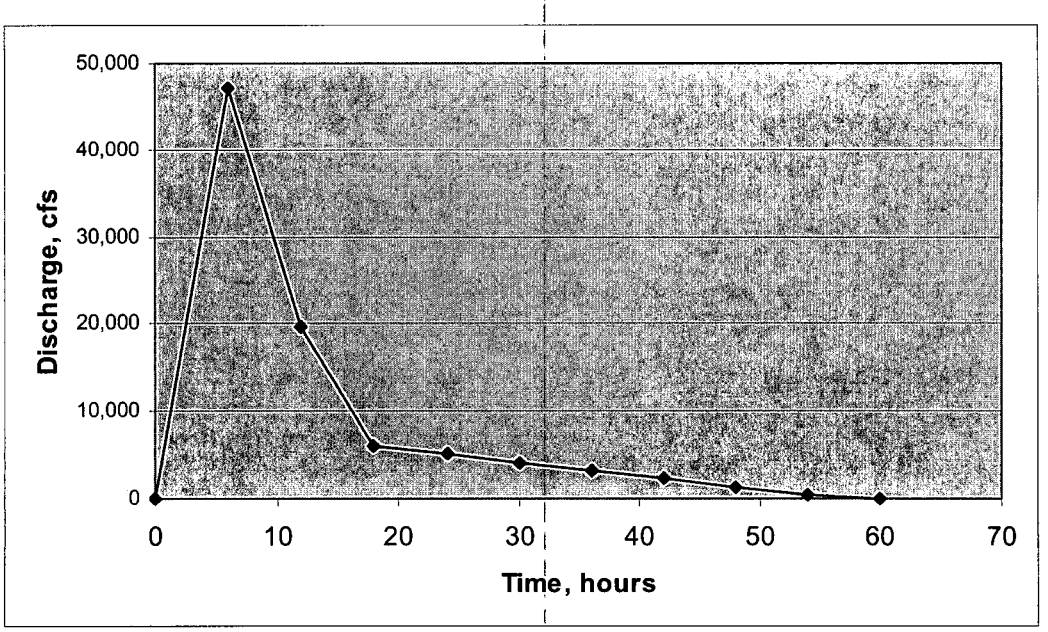


Figure 8: 6-hour Unit Hydrograph for Subbasin 6 (Douglas Dam Local Inflow)

Table 8: Six-hour Unit Hydrograph for Subbasin 6 (Douglas Dam Local Inflow)

Time, hrs	Basin 6
0	0
6	47,207
12	19,655
18	6,103
24	5,162
30	4,220
36	3,278
42	2,336
48	1,395
54	453
60	0

6.3 Observed Stream Flows

Bi-hourly observed in-channel stream flow series were obtained from the TVA for the following locations:

- French Broad River at Asheville for January 1985 to February 2008 (Reference 16)
- French Broad River at Newport for January 1985 to February 2008 (Reference 17)
- Pigeon River at Newport for January 1985 to February 2008 (Reference 18)
- Nolichucky River at Embreeville for January 1988 to February 2008 (Reference 19)
- Nolichucky River at Nolichucky Dam for January 1988 to February 2008 (Reference 20)

These time series are provided in spreadsheets by the TVA and are included with this calculation as electronic attachments. All times entered in the TVA data base are in Central Time. Note that the precipitation data used in this calculation, which is obtained from the National Weather Service, is reported in Greenwich Mean Time and is converted to Central Time for use in modeling, as described in Sections 6.6 and 7.4.

6.4 Observed Outflows and Headwater Elevations

Hourly records of outflow from Douglas Dam (including spills and turbine discharges) and hourly headwater elevations were obtained from the TVA in spreadsheet format (Reference 13) and are contained in the tabs labeled "Total Q" and "HW" of the spreadsheet "DouglasDamQ&H.xls," which is provided with this calculation as Attachment 1-8.

Observed bihourly discharge and headwater elevations for the Nolichucky River at Nolichucky Dam were obtained in spreadsheet format (Reference 20) and are contained in the tabs labeled "Stage" and "Flow" of the spreadsheet "NolichuckyDamHW.xls," provided as Attachment 1-20.

6.5 Stage-Volume Relationship

The stage-volume relationship for the Douglas Dam reservoir (Reference 14), which is used for reverse reservoir routing, was obtained in the "FrenchBroadBasin.xls," provided as Attachment 1-12. This file includes stage-volume data for all dams in the upstream watershed.

The stage-volume curve for the Douglas Dam reservoir is plotted in Figure 9.

The stage-volume relationship for the Nolichucky Dam was obtained from the TVA for use in reservoir routing to obtain inflows to the Nolichucky Dam reservoir (Reference 15), known as Davy Crockett Lake. The impact of limited storage behind Nolichucky Dam was checked and there was only a very

small attenuation in flows across the dam, so the dam can be considered as a run-of-river dam with minimal regulation. For this reason, no reverse reservoir calculations are presented for Nolichucky Dam.

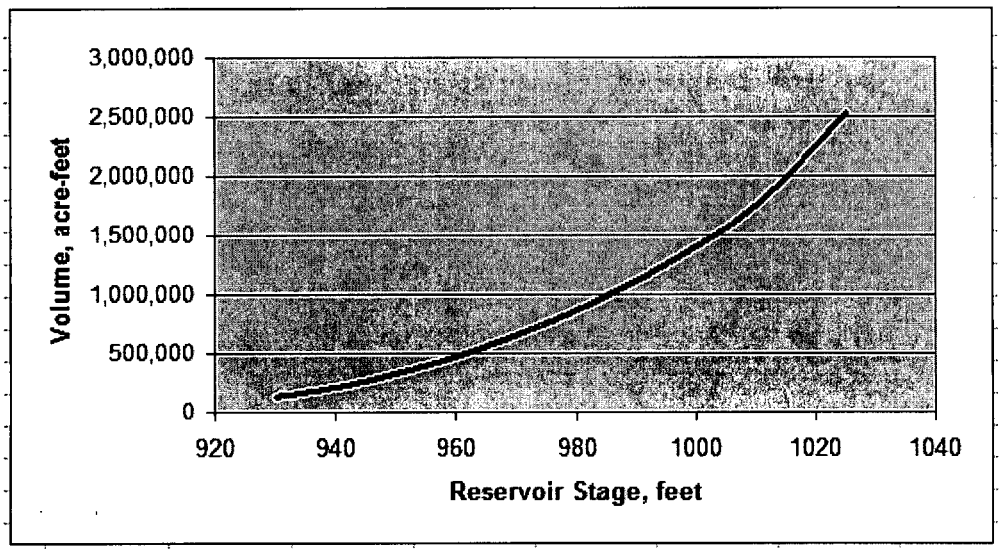


Figure 9: Stage-Storage Curve for the Douglas Dam Reservoir

6.6 Observed Rainfall

Radar-based, geospatially referenced precipitation data is extremely useful for hydrologic analysis because of its comprehensive spatial and temporal detail. Gridded daily precipitation data are available at http://water.weather.gov/ from 2005 to the present. Hourly precipitation data are not generally available without special arrangements with the National Weather Service (NWS).

NWS NEXRAD Stage III hourly precipitation data were obtained from the Lower Mississippi River Forecast Center (LMRFC) from January 1997 to April 2008 for unit hydrograph validation. A Microsoft.Net utility was developed to generate radar-based Mean Areal Precipitation (MAPX) time series for each of the subbasins (Reference 21).

The utility reads the raw hourly precipitation depth data for each 4-km square grid cell, performs necessary coordinate system and projection calculations, and then calculates the average precipitation depth within each subbasin, grouping output into a matrix of MAPX elements arrayed by subbasin and time (Greenwich Mean Time, GMT). Each column of this matrix is equivalent to an annual hyetograph for each subbasin in the TVA model.

The results are stored in an Excel spreadsheet for each year of record. Reference 21 describes the methodology used to process the precipitation data and includes resulting subbasin-averaged hourly values for the January 1997 to April 2008 period of record.

Observed average basin rainfall for the March 2002, May 2003, and September 2004 events were obtained from Reference 21. The hourly precipitation series developed from NWS gridded data for use in the calculation are provided in the following spreadsheets:

- "GriddedPrecipitationDataAllSubbasins2002.xls" (Attachment 1-15)
- "GriddedPrecipitationDataAllSubbasins2003.xls" (Attachment 1-16)
- "GriddedPrecipitationDataAllSubbasins2004.xls" (Attachment 1-17)

The conversion of the time base of the precipitation time series to Central Daylight Savings Time (CDT) for the 2003 and 2004 events and to Central Standard Time (CST) for the 2002 event, and unit conversion and reformatting required for input to FLDHYDRO (see Section 7.4) are carried out in the following spreadsheets:

- Precipitation Data Processing 2002.xls (Attachment 1-22)
- Precipitation Data Processing 2003.xls (Attachment 1-23)
- Precipitation Data Processing 2004.xls (Attachment 1-24)

It was necessary to use rainfall data for two years predating the availability of gridded data for Subbasin 2, as described below. This data was obtained from the TVA 6-hour rainfall data base in spreadsheet format, reproduced here as:

- TVArain1994.xls (Attachment 1-29)
- TVArain1996.xls (Attachment 1-30)

7 Computations and Analysis

Computations required for the development of the hydrologic models used in the validation of the TVA unit hydrographs and the analysis of modeling results are presented in the following sections.

7.1 Selection of Flood Events for Unit Hydrograph Validation

As noted in Section 5, the unit hydrographs must be verified by comparing the results of simulations with the two highest peaked floods of record for the period in which suitable precipitation data are available. Towards this end, the annual peak discharge and date of occurrence was identified for each of the years between 1985 and 2007 based on the bihourly discharge data provided by the TVA (see Section 6.3) for the stream gages located at the outlets of Subbasins 1 through 5 and from reverse reservoir routing for Subbasin 6 between 1998 and 2007. The results of this review are presented in Table 9. The years for which gridded precipitation data are available are shown in gray.

Table 9: Annual Peak Discharges in the Six Subbasins from 1985 to 2007

BASIN 1

YEAR	Date	Qp
2004	8-Sep	35,347
1995	15-Jan	27,821
1998	8-Jan	24,411
1994	17-Aug	20,960
1996	27-Jan	18,672
1990	14-Mar	18,354
1991	29-Mar	16,964
2003	6-May	14,650
1987	1-Mar	14,052
1993	27-Mar	13,022
2005	7-Jul	11,390
1992	8-May	10,949
2000	20-Mar	10,011
1997	14-Mar	9,945
1988	21-Jan	9,896
1989	16-Nov	9,846
2007	8-Jan	9,427
1986	26-Nov	8,704
2006	31-Dec	8,198
2002	24-Dec	7,691
1985	17-Aug	7,647
1999	26-Nov	5,921
2001	30-Mar	5,595

BASIN 2

YEAR	Date	Qp
2004	17-Sep	63,385
1991	30-Mar	60,484
1994	28-Mar	60,484
1990	14-Mar	56,998
1996	27-Jan	55,133
1995	15-Jan	49,881
2003	6-May	43,354
1998	8-Jan	41,130
2002	17-Mar	33,579
1987	1-Mar	29,754
1997	28-Feb	25,678
1993	24-Mar	22,911
2001	29-Jul	19,545
1992	8-May	17,856
2006	22-Apr	17,214
2000	4-Apr	16,706
1989	22-Sep	16,017
2005	8-Jul	15,115
2007	1-Jan	14,065
1999	26-Nov	13,892
1985	1-Feb	13,492
1986	27-Nov	10,261
1988	20-Jan	9,957

BASIN 3

YEAR	Date	Qp
1994	28-Mar	51,151
2004	17-Sep	48,021
1990	17-Mar	43,422
2003	6-May	42,240
1996	27-Jan	38,448
1998	8-Jan	27,187
1991	29-Mar	25,266
1995	5-Oct	24,658
1997	3-Mar	18,018
2002	17-Mar	15,446
1985	1-Feb	14,700
1989	22-Sep	13,400
2000	4-Apr	10,424
1992	20-Dec	10,146
2006	18-Jan	9,383
1993	27-Mar	9,310
2005	29-Nov	8,859
2001	29-Jul	7,373
1988	20-Jan	5,410
1999	26-Nov	5,391
2007	1-Jan	4,504
1986	13-Mar	3,640
1987	27-Dec	2,350

BASIN 4

YEAR	Date	Qp
1995	15-Jan	63,642
2004	17-Sep	61,333
1998	8-Jan	50,298
1994	17-Aug	40,211
1996	19-Jan	34,100
2003	19-Nov	32,427
1991	29-Mar	29,963
1989	22-Sep	28,582
1992	21-Apr	26,780
1990	14-Mar	26,336
1985	22-Feb	23,360
1987	1-Mar	21,308
1993	24-Mar	18,412
2001	13-Aug	16,694
2005	30-Aug	15,518
2002	17-Mar	14,979
1999	26-Nov	14,449
2006	18-Jan	12,852
2000	20-Mar	12,178
1997	3-Mar	10,984
2007	1-Jan	9,013
1988	4-Feb	5,119
1986	18-Feb	4,477

BASIN 5 *

YEAR	Date	Qp
1995	15-Jan	60,500
2004	18-Sep	48,802
2001	4-Aug	42,506
1994	28-Mar	42,025
1987	5-Jul	41,602
1998	8-Jan	37,064
2003	20-Nov	33,949
1991	30-Mar	30,915
1990	14-Mar	29,684
1996	27-Jan	29,172
1989	23-Sep	20,841
1992	21-Apr	19,253
2002	18-Mar	18,806
1993	24-Mar	17,824
2006	23-Apr	12,486
1997	4-Mar	12,236
2000	21-Mar	10,922
1999	27-Nov	9,219
2005	30-Nov	9,073
1988	5-Feb	7,872
2007	1-Jan	7,440
1986	25-Dec	5,330
1985	N/A	0

BASIN 6 **

YEAR	Date	Qp
2004	17-Sep	104,405
2003	7-May	84,957
2002	18-Mar	72,603
1998	9-Jan	71,157
1999	28-Jun	51,151
2001	4-Aug	44,367
2006	22-Apr	36,707
2000	4-Apr	34,875
2005	3-Apr	26,320
2007	1-Jan	22,489
1985		N/C
1986		N/C
1987		N/C
1988		N/C
1989		N/C
1990		N/C
1991		N/C
1992		N/C
1993		N/C
1994		N/C
1995		N/C
1996		N/C
1997		N/C

* Gage is downstream of Nolichucky Dam, which has minimal impact on discharge due to very small storage

** Qp is inflow to the Douglas Dam reservoir obtained from reverse reservoir routing

The selection of the observed flow series for the validation of each of the unit hydrographs, limited as possible to the years for which gridded data were available, was guided by the rankings shown in Table 9. Based on these criteria, the May 2003 and September 2004 floods were selected for the majority of the validation runs (the 1998 data set was not used because of incomplete stream flow and precipitation data). For Subbasins 2 and 3, the 2004 flood was used for developing new unit hydrographs and there were no other suitable storms from within the period for which gridded data are available, so 6-hour rainfall data were utilized.

The storms selected for each basin and the reasons for the rejection of any higher-ranked events are summarized in Table 10. Additional considerations with respect to storm selection for individual basins are presented in later sections of this calculation.

Table 10: Selection Criteria for Storms Used in Validation Runs for Each Subbasin

	YEAR	Date	Qp, cfs	Comment
Basin 1	2,004	17-Sep	29,899	Selected for validation run, rejecting peak storm of 8-Sep (see Table 9) due to incomplete discharge data set
	1995	15-Jan	27,821	Gridded precipitation data not available
	1998	8-Jan	24,411	Gridded precipitation data set not complete for this year
	1994	17-Aug	20,960	Gridded precipitation data not available
	1996	27-Jan	18,672	Gridded precipitation data not available
	1990	14-Mar	18,354	Gridded precipitation data not available
	1991	29-Mar	16,964	Gridded precipitation data not available
	2003	6-May	14,650	Selected for validation run
Basin 2	2004	17-Sep	63,385	Not available for validation (used for development of new UH)
	1991	30-Mar	60,484	6-hr precipitation data not reliable, not used
	1994	28-Mar	60,484	Selected for validation run
	1990	14-Mar	56,998	6-hr precipitation data not reliable, not used
	1996	27-Jan	55,133	Selected for validation run
Basin 3	1994	28-Mar	51,151	Not available for validation (used for development of new UH)
	2004	17-Sep	48,021	Not available for validation (used for development of new UH)
	1990	17-Mar	43,422	6-hr precipitation data not reliable, not used
	2003	6-May	42,240	Selected for validation run
	1996	27-Jan	38,448	Selected for validation run
Basin 4	1995	15-Jan	63,642	Gridded precipitation data not available
	2004	17-Sep	61,333	Selected for validation run
	1998	8-Jan	50,298	Gridded precipitation data set not complete for this year
	1994	17-Aug	40,211	Gridded precipitation data not available
	1996	19-Jan	34,100	Gridded precipitation data not available
	2003	19-Nov	32,427	Selected for validation run
Basin 5	1995	15-Jan	60,500	Gridded precipitation data not available
	2004	18-Sep	48,802	Not selected because of problems with routing - see Section 7.2.5
	2001	4-Aug	42,506	Not selected because of highly localized rainfall - see Section 7.2.5
	1994	28-Mar	42,025	Gridded precipitation data not available
	1987	5-Jul	41,602	Gridded precipitation data not available
	1998	8-Jan	37,064	Gridded precipitation data set not complete for this year
	2003	20-Nov	33,949	Selected for validation run
	1991	30-Mar	30,915	Gridded precipitation data not available
	1990	14-Mar	29,684	Gridded precipitation data not available
	1996	27-Jan	29,172	Gridded precipitation data not available
	1989	23-Sep	20,841	Gridded precipitation data not available
	1992	21-Apr	19,253	Gridded precipitation data not available
	2002	18-Mar	18,806	Selected for validation run
Basin 6	2004	17-Sep	104,405	Selected for validation run
	2003	7-May	84,957	Selected for validation run
	2002	18-Mar	72,603	

7.2 Development of Flow Series for Unit Hydrograph Validation

An observed flow series is required for the validation of each unit hydrograph, as discussed in Section 5. For subbasins that are gaged headwater catchments, the observed stream flow series can be used directly. Otherwise, hydrograph separation techniques are required, which entails routing observed hydrographs downstream. Routing is carried out in accordance with TVA methodology, as summarized in Figure 10.

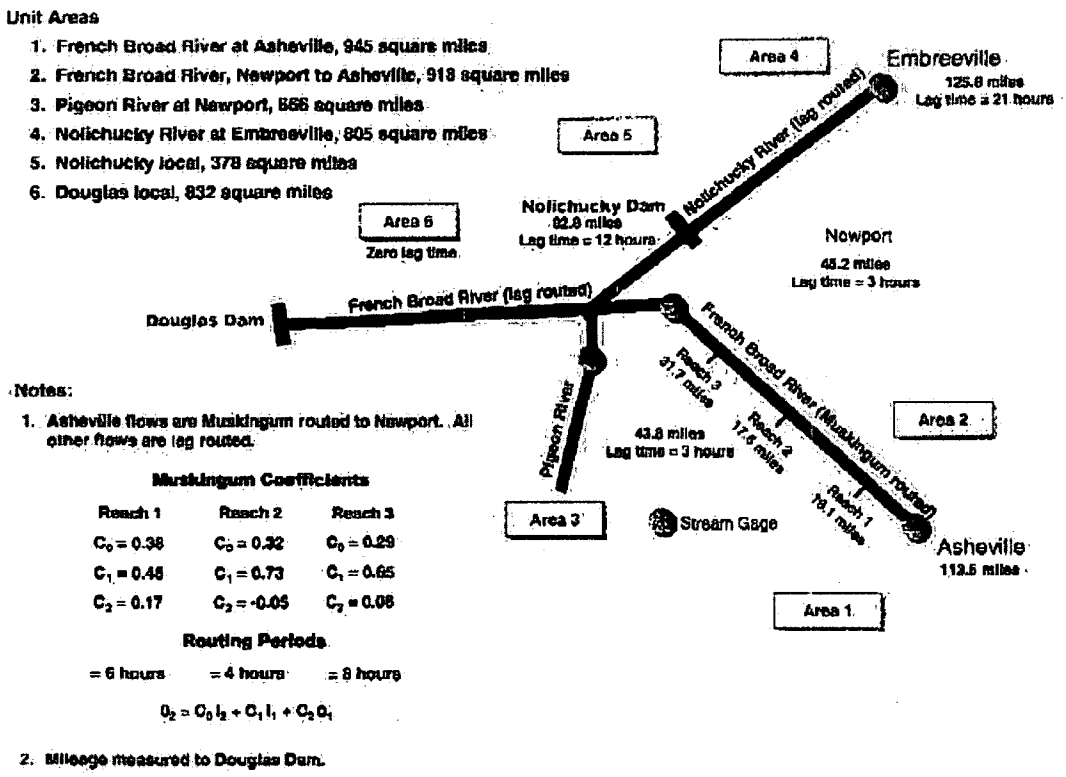


Figure 10: Routing Parameters for Douglas Dam Runoff Model Validation (References 8, 12)

The development of the flow series for the validation of the unit hydrograph for each of the subbasins within the Douglas Dam watershed is discussed in the following sections.

7.2.1 Subbasin 1 Outflow Hydrograph Development

Subbasin 1 is a headwater catchment, so the observed hydrograph for the French Broad River at Asheville can be used for validation of the unit hydrograph with no additional processing. Bihourly flow data for the validation events were provided by the TVA. This data is presented in the spreadsheet "FrenchBroadAtAshville.xls" (Reference 16), included as Attachment 1-13 to this calculation.

7.2.2 Subbasin 2 Outflow Hydrograph Development

The observed flow on the French Broad River at Newport includes local inflow from Subbasin 2 and stream flow coming down from Asheville. To obtain the flow series for the validation of the local inflow unit hydrograph for Subbasin 2, the observed flow at Asheville is routed downstream and subtracted from the observed flow at Newport.

The TVA developed a Muskingum routing model for the French Broad River between Asheville and Newport, dividing it into three reaches, with the time step and routing parameters shown in Table 11.

Table 11: Muskingum Routing Parameters for French Broad River from Asheville to Newport (Reference 8)

Reach	River Mile		C_0	C_1	C_2	Δt, hours
	from	to				
Asheville to Marshall	145.8	126.7	0.38	0.45	0.17	6.00
Marshall to Hot Springs	126.7	109.2	0.32	0.73	-0.05	4.00
Hot Springs to Newport	109.2	77.5	0.29	0.65	0.06	8.00

HEC-HMS uses the alternate parameters K and X instead of C_0, C_1, and C_2 for Muskingum routing, but they can be related per the following equations (Reference 2) as shown in Table 12:

$$C_0 = \frac{\Delta t - 2KX}{2K(1-X)+\Delta t} \qquad C_1 = \frac{\Delta t + 2KX}{2K(1-X)+\Delta t} \qquad C_0 = \frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t} \qquad C_0 + C_1 + C_2 = 1$$

Table 12: Conversion from C_0, C_1, C_2 to K, X Muskingum Routing Coefficients

Reach	K, days	K, hours	X	Δt, days	C0	C1	C2	Σ	#reaches = K/Δt *	
1	0.1844	4.43	0.05	0.25	0.39	0.45	0.17	1	2.21	use 2
2	0.1077	2.59	0.30	0.17	0.32	0.73	-0.05	1	1.29	use 1
3	0.2500	6.00	0.25	0.33	0.29	0.65	0.06	1	3.00	use 3

* Δt is the model time step

The Muskingum routing along the three reaches of the French Broad River between Asheville and Newport was implemented in the HEC-HMS project Basin_02.hms (Attachment 3-2), as shown in Figure 11.

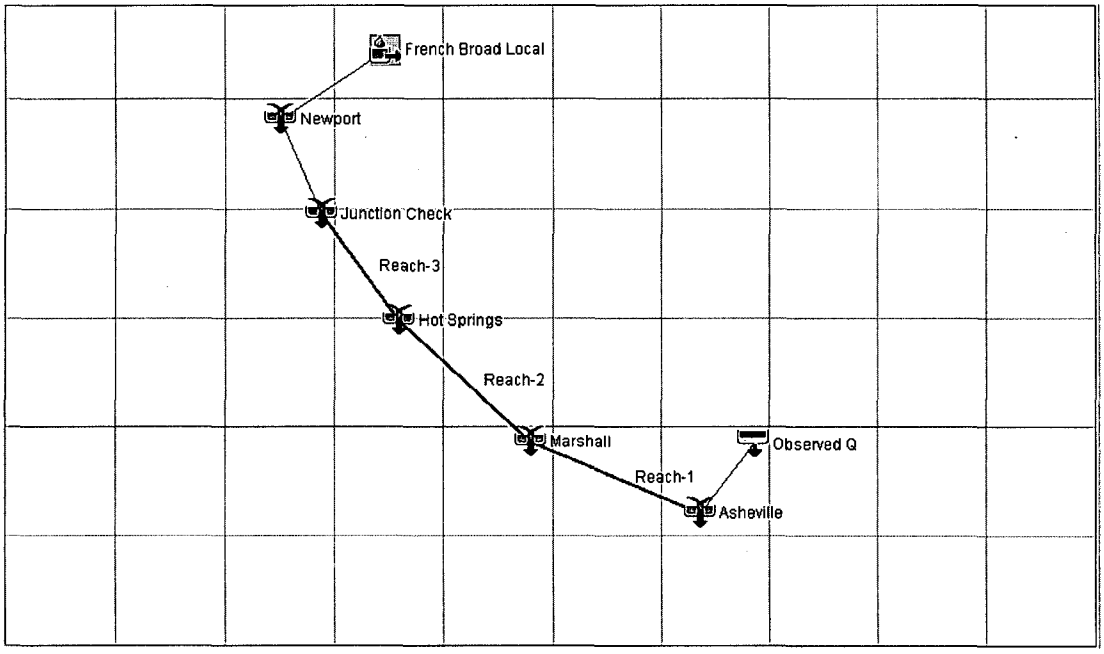


Figure 11: HEC-HMS Schematic of French Broad River Routing from Asheville to Newport

To obtain the local inflow series for validation of the unit hydrograph, preliminary runs of the HEC-HMS models for the March 1994 and January 1996 floods were made utilizing the observed stream flow on the French Broad River at Asheville as an upstream boundary condition. Bihourly flow data were provided by the TVA and are included as the spreadsheet "FrenchBroadNrNewport.xls" (Reference 17) as Attachment 1-14 to this calculation.

Three routing reaches were modeled in HEC-HMS, utilizing the modeling parameters shown in Table 12. An extra node (Junction Check) is provided just upstream of the Newport node so that the routed hydrograph can be extracted before the local flow is added in. The routed hydrograph is subtracted from the observed flow on the French Broad River at Newport to obtain the Subbasin 2 local inflow hydrographs, as shown for the 1994 and 1996 floods in Figures 12 and 13, respectively.

These calculations are presented on the tabs labeled "1994" and "1996" in the spreadsheet named "Routing&HydrographSeparationSB21994&6.xls," which is provided as Attachment 1-25.

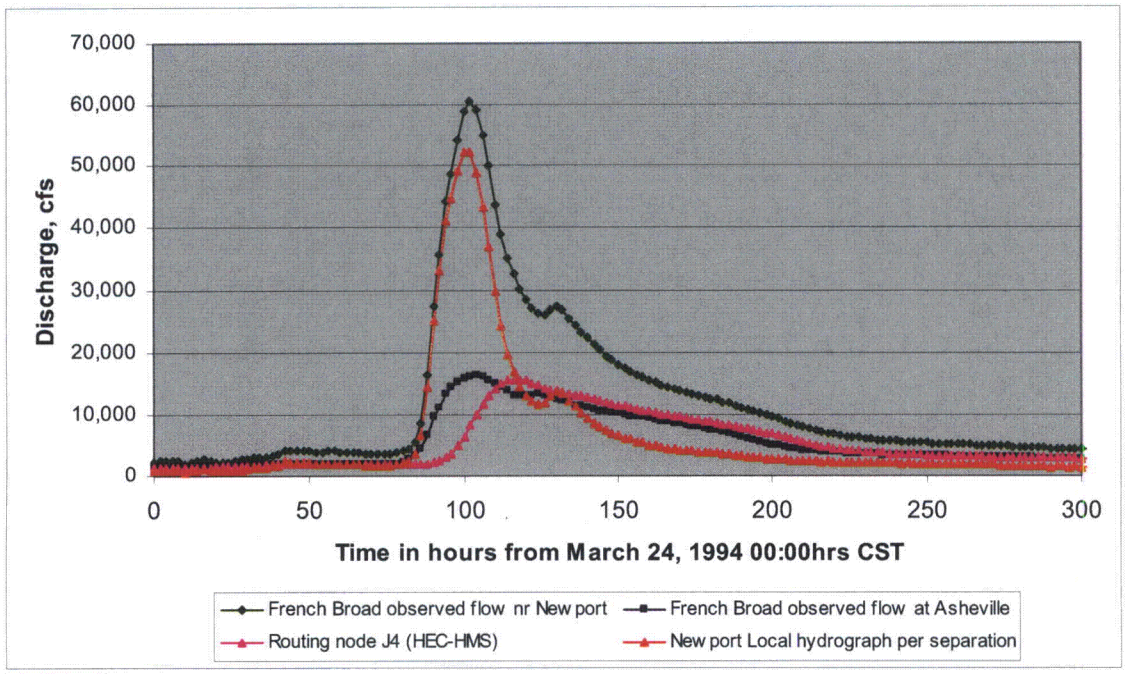


Figure 12: Hydrograph Separation for Local Flow from Subbasin 2 for the March 1994 Flood

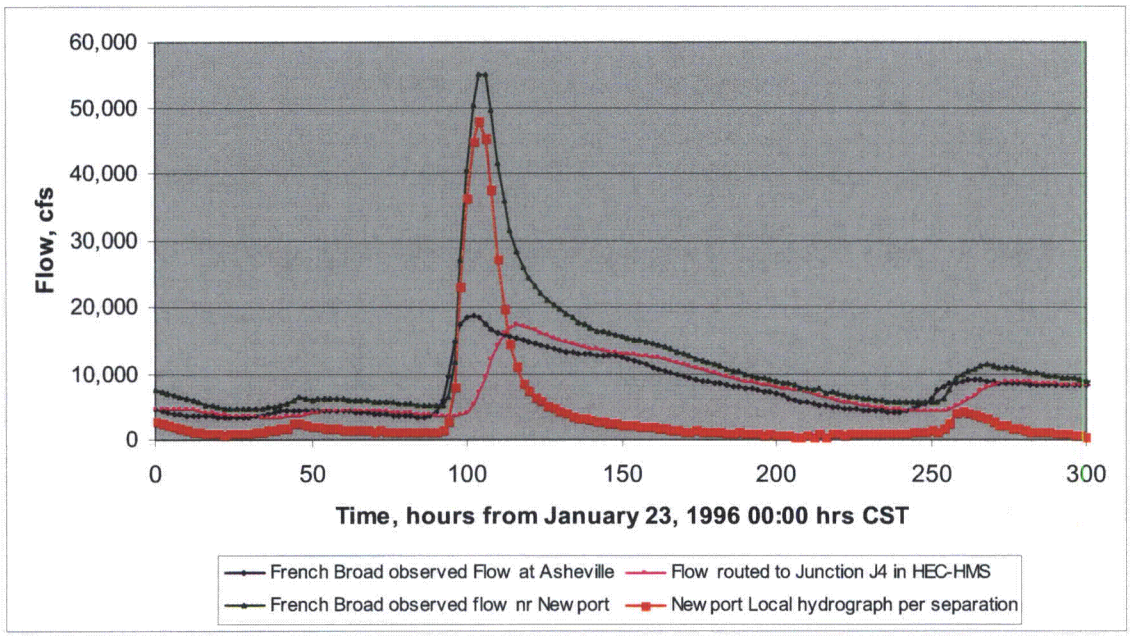


Figure 13: Hydrograph Separation for Local Flow from Subbasin 2 for the January 1996 Flood

7.2.3 Subbasin 3 Outflow Hydrograph Development

Subbasin 3 is a headwater catchment, so the observed hydrograph for the Pigeon River at Newport is also the basin outflow hydrograph, and can be used for unit hydrograph validation with no additional processing. Bihourly flow data was provided by the TVA in the spreadsheet "PigeonAtNewport.xls" (Reference 18), provided as Attachment 1-21 to this calculation.

7.2.4 Subbasin 4 Outflow Hydrograph Development

Subbasin 4 is a headwater catchment, so the observed hydrograph for the Nolichucky River at Embreeville is also the basin outflow hydrograph, and can be used for unit hydrograph validation with no additional processing. Bihourly flow data was obtained from the TVA and is provided in the spreadsheet "NolichuckyAtEmbreeville.xls" (Reference 19) as Attachment 1-19 to this calculation.

7.2.5 Subbasin 5 Outflow Hydrograph Development

The observed flow on the Nolichucky River at Nolichucky Dam includes local inflow from Subbasin 5 and stream flow coming down from Embreeville. Conceptually, it is possible to obtain the local inflow hydrograph for Subbasin 5 by hydrograph separation, i.e. routing the observed flow at Embreeville downstream to the outlet of Subbasin 5 and subtracting it from the observed flow at Nolichucky Dam.

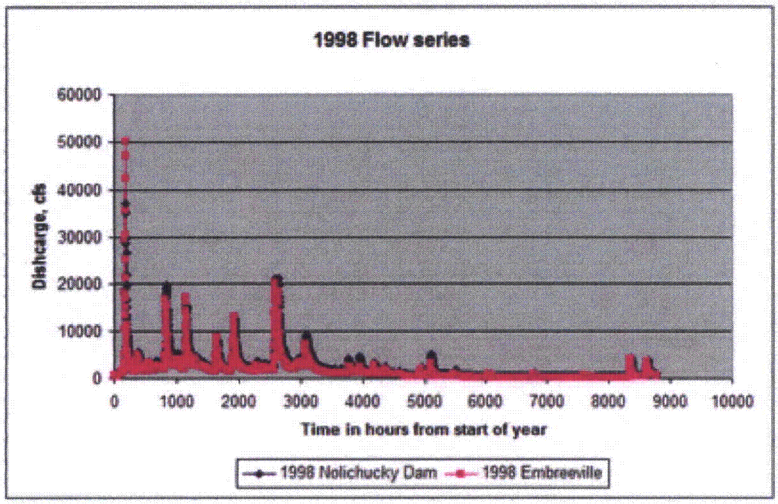
In practice, however, this has not been possible because of limitations in the flood routing procedure. The use of simple lag routing for the reach of the Nolichucky River between Embreeville and Nolichucky Dam, shown in Figure 10, does not account for attenuation of the flood wave, most likely due to extensive floodplain storage along the reach, resulting in observed peak flows at the upstream Embreeville gage being higher than at the downstream Nolichucky Dam gage for most of the peak flood events that might be used for validation studies (see Figures 14, 15, and 16 and the spreadsheet "Nolichucky vs Embreeville hydrographs.xls", provided as Attachment 1-18).

For example, the hydrographs for September 2004 flows at Embreeville and Nolichucky, shown in the lower graph in Figure 16, clearly show flood wave attenuation along the reach which cannot be accounted for with the straight lag routing coefficients available for this study.

The fact that these hydrographs do not result from errors in gage measurements is supported by calculations of the area under the hydrographs which indicate that the seasonal volumes of flow at Nolichucky Dam exceed the values at Embreeville, as would be expected.

The possibility that this attenuation is due to storage behind Nolichucky Dam was also checked and discounted. Based on reverse reservoir routing, the Nolichucky Dam was confirmed to be essentially "run of river" with little to no attenuation of peak discharges.

Since the lag-routed flow series does not accurately model the attenuation and spreading of the inflow from upstream, subtracting it from the observed flow series at the Nolichucky gage results in a local hydrograph with negative ordinates, and unrealistic shapes and timing for most floods.



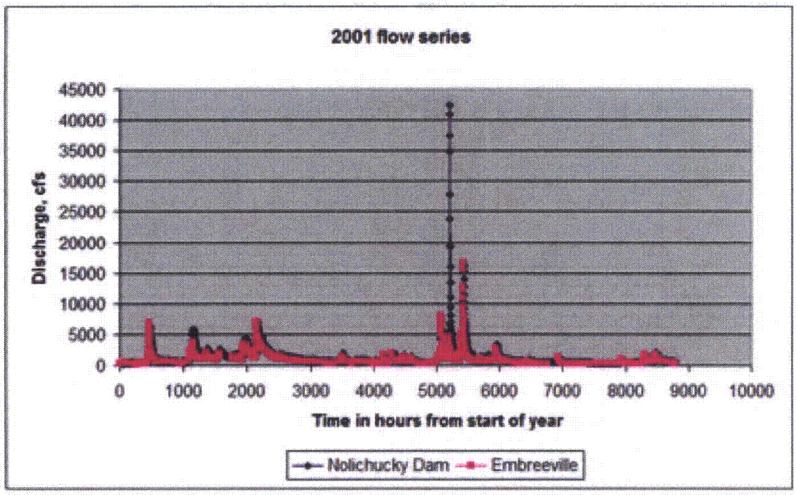
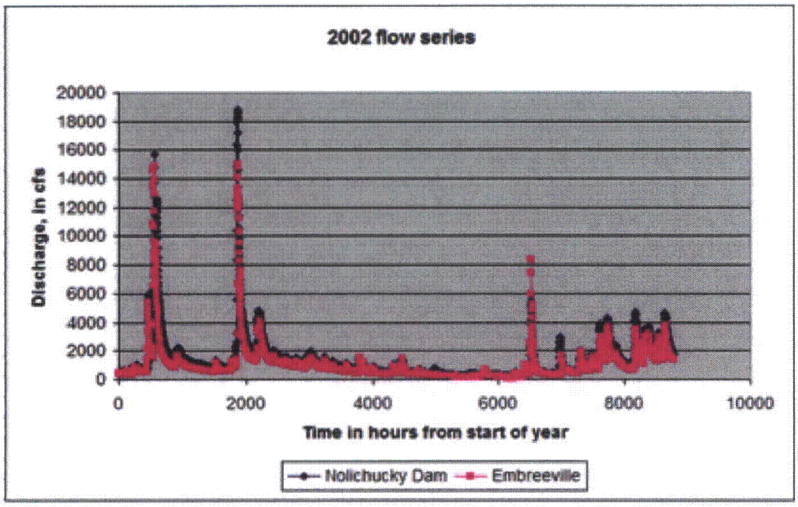


Figure 14: Observed Flow Series on the Nolichucky River at Embreeville and Nolichucky Dam for 1998 and 2001 (Attachment 1-18)

The largest flood event localized within Subbasin 5 occurred in August 2001, shown in Figure 14. Because this flood was caused by intense rainfall localized in the lower reaches of the subbasin, with little inflow from upstream, hydrograph separation provided very good results, i.e. there were no negative ordinates and the timing of the peak discharge was reasonable. The unique nature of this storm

makes it unusable for validation, however, because the non-uniform distribution of rainfall violates basic conditions of unit hydrograph theory, as discussed in Section 4.



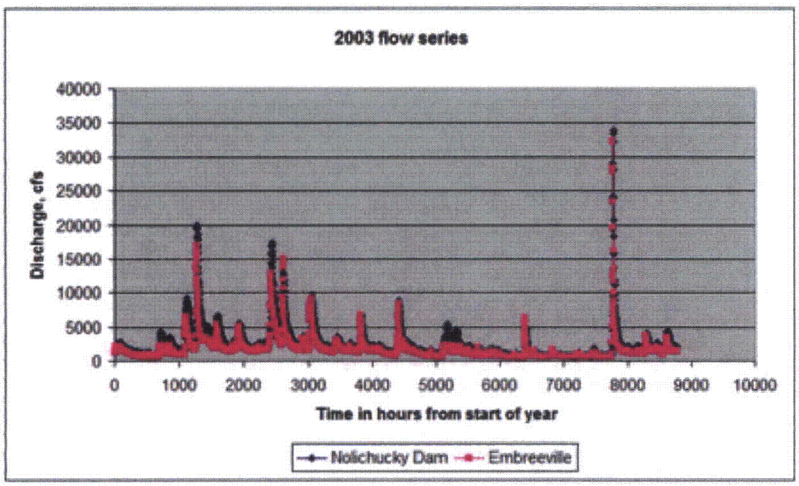
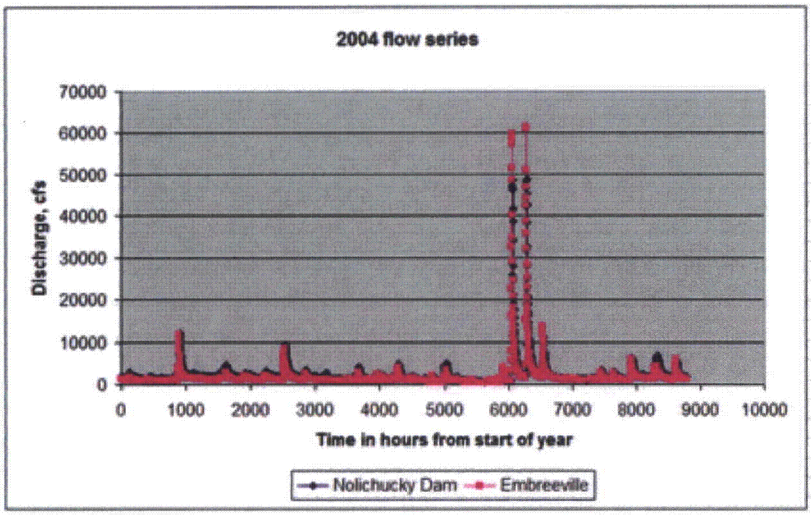


Figure 15: Observed Flow Series on the Nolichucky River at Embreeville and Nolichucky Dam for 2002 and 2003 (Attachment 1-18)



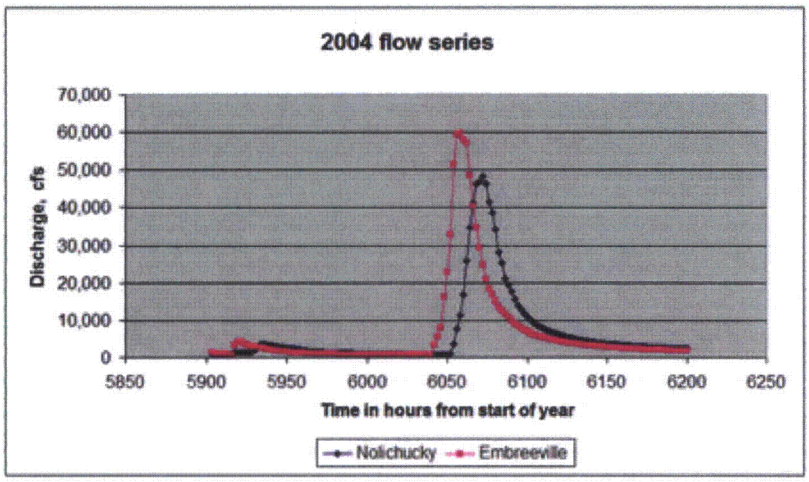


Figure 16: Observed Flow Series on the Nolichucky River at Embreeville and Nolichucky Dam for 2004 and zoomed in on September 2004 (Attachment 1-18)

For the reasons discussed above, the Subbasin 5 outflow hydrograph was not developed using hydrograph separation techniques. Instead, the total volume of direct runoff at Embreeville was subtracted from the total volume of direct runoff estimated at Nolichucky Dam to obtain an estimate of the total volume of direct runoff for the local hydrograph (i.e. the contribution to flow along the

Nolichucky River from Embreeville to Nolichucky Dam), which is used for the calculation of effective rainfall, as described in Section 7.5.5.

The calculations of these lumped volumes are presented in Section 7.3 for the Nolichucky River at Embreeville and Nolichucky Dam for 2002 and 2003 storms. The storms with greatest annual peak discharges within the selected period of record (the 2004, 2001, and 1998, as indicated in Table 10) could not be used for validation because of problems with the rainfall data or, for the 2004 record, because flood volumes calculated from measured flow at Embreeville were greater than at Nolichucky Dam, as discussed above.

7.2.6 Subbasin 6 Outflow Hydrograph Development

Theoretically, it is possible to obtain a local inflow hydrograph for Subbasin 6 by routing the observed flow series for the Nolichucky River at Nolichucky Dam, the French Broad River near Newport, and the Pigeon River at Newport downstream to the Douglas Dam reservoir, and subtracting the resulting hydrograph from the reservoir inflow hydrograph at Douglas Dam, as shown schematically in Figure 17.

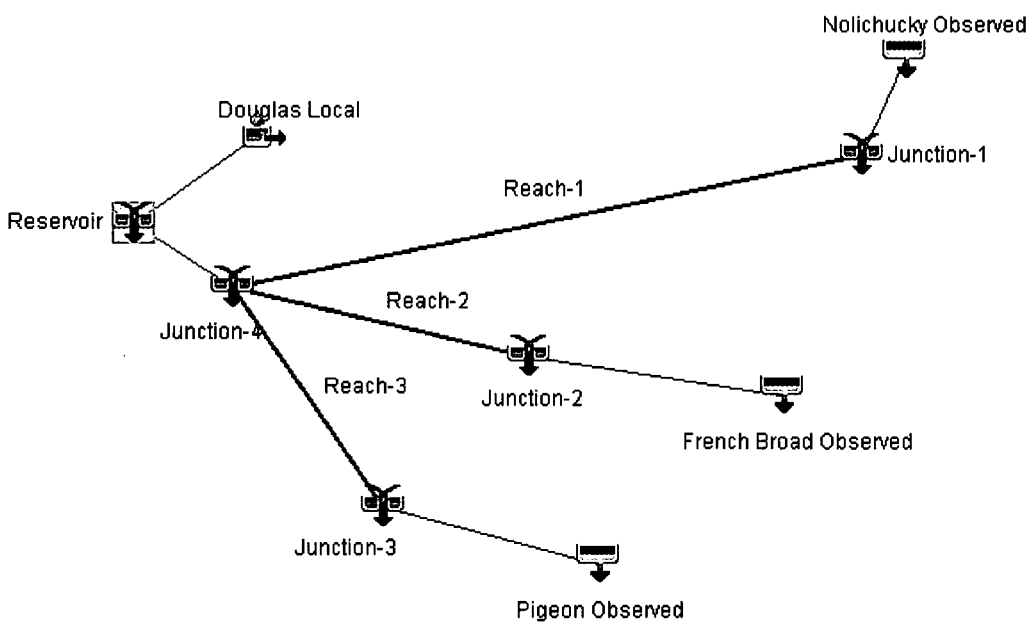


Figure 17: HEC-HMS Schematic of Douglas Dam Watershed Routing to Obtain Basin 6 Inflow

The reservoir inflow hydrograph is obtained from the observed outflows from Douglas Dam by reverse reservoir routing, which consists of solving the continuity equation for the reservoir, which can be stated as (Reference 28):

$$\frac{dS}{dt} = I(t) - Q(S(t)) \tag{2}$$

where $I(t)$ is the inflow rate, Q is the outflow rate, and S is storage at time t. Total outflow from the dam for each hour is provided by the TVA from the sum of measured turbine and spillway discharges; the observed headwater stage can be used to determine the associated storage, $S(t)$, given the stage-volume curve for the reservoir.

This equation can be written using a centered finite-difference scheme as follows, where the terms $t+\Delta t$ and $t-\Delta t$ refer to the following and preceding time steps, respectively (Reference 28):

$$I(t) = \frac{S(t+\Delta t) - S(t-\Delta t)}{2\Delta t} + Q(S(t)) \tag{3}$$

Using the records of outflow and headwater for Douglas Dam and the stage-volume relationship for the reservoir (enumerated in Section 6.4), reverse reservoir routing was performed for the May 2003 and the September 2004 flood events. These calculations are presented in the following spreadsheets, provided as electronic attachments to this calculation:

- Douglas Dam RRR 2003.xls (Electronic Attachment 1-6)
- Douglas Dam RRR 2004.xls (Electronic Attachment 1-7)

Fluctuations in the estimated inflow can occur when the water surface elevation of the reservoir is changing slowly, and surface elevations are measured at discrete height intervals (i.e., to the nearest hundredth foot). This is demonstrated in Figures 18 and 19 for the May 2003 and September 2004 floods, respectively, developed in HEC-HMS.

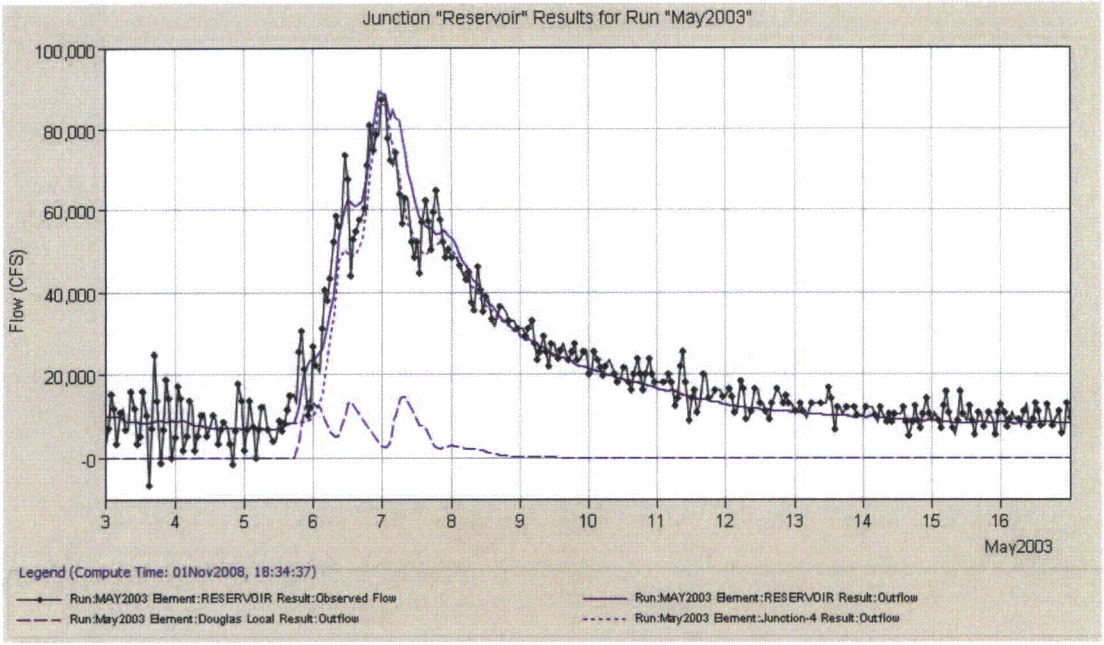


Figure 18: Calculated Douglas Dam Reservoir Inflow Hydrograph for May 2003

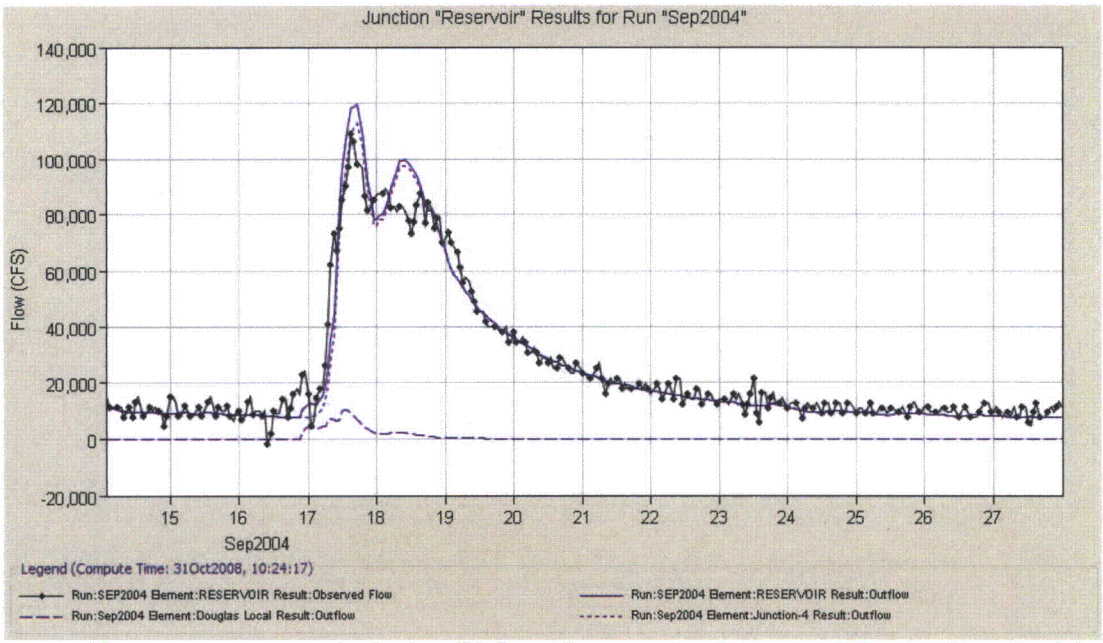


Figure 19: Calculated Douglas Dam Reservoir Inflow Hydrograph for September 2004

In Figures 18 and 19, the heavy dotted black line shows the reservoir inflow series determined by reverse reservoir routing, input as an observed flow series in HEC-HMS, and the flow series at Junction 4, calculated in HEC-HMS by combining the inflow hydrograph routed downstream along Reaches 1, 2, and 3, using straight lag times provided by the TVA, as shown schematically in Figure 17.

As discussed above, it is theoretically possible to obtain the local runoff hydrograph for Subbasin 6 by subtracting the hydrograph at Junction 4 from the hydrograph obtained at the reservoir as a check on the local runoff hydrograph generated for Subbasin 6 in HEC-HMS using the TVA unit hydrograph.

In practice, the local hydrograph generated in this manner is not reliable. Even when the fluctuations in the reverse reservoir routing-derived hydrograph are smoothed out and negative flows are removed, the fact that the straight lag routing does not account for any flood wave attenuation on the reach can result in a hydrograph separation yielding an unrealistic local flow series with negative flows. Obviously the local runoff volume calculated from such a hydrograph would be unreliable.

As an alternative, the lumped volume of local runoff is determined by subtracting the lumped volume of direct runoff at Junction 4 from the lumped volume of direct runoff determined from the reservoir inflow hydrograph after carrying out hydrograph smoothing (the calculation of direct runoff by the subtraction of base flow is presented in Section 7.3 for all subbasins).

Hydrograph smoothing for the reverse reservoir routing-derived hydrographs was carried out in the spreadsheet "RRRhydrograph smoothing.xls," provided as Attachment 1-26. The steps required for hydrograph smoothing include:

- Use J4 ordinates on the rising and falling limbs of the hydrograph outside of the period of local inflow (previous to the arrival and subsequent to the end of the local inflow, the difference between discharge at the reservoir and the upstream junction is negligible).
- Remove any significant remaining fluctuations by averaging.
- Adjust all hydrograph ordinates not on the rising and falling limbs by a constant factor to maintain the hydrograph volume calculated from the beginning and ending time steps of the reverse reservoir routing calculations, based on the fact that the total inflow volume = the (measured) total outflow volume + the total change in storage, as summarized in Table 13.

Table 13: Calculation of Total Inflow Volume to Douglas Dam Reservoir

Year	Note	2003	2004
Start/stop date and time		5/3 0:00 to 5/17 0:00	9/14 0:00 to 9/28 0:00
Starting Volume, ft^3	(1)	52,077,145,399	54,954,896,027
Finishing Volume, ft^3	(1)	54,967,482,619	53,047,332,445
total Volume Δ, ft^3	(2)	2,890,337,220	-1,907,563,582
Total volume outflow, ft^3	(3)	23,351,853,600	32,213,845,800
Total inflow volume, ft^3	(4)	26,242,190,820	30,306,282,218

(1) Volumes determined from observed stage per TVA stage hydrographs
(2) Total Δvolume = Ending Volume - Starting Volume
(3) Total outflow volume = Σ Average hourly discharges in cfs x 3600 sec/hr
(4) Total inflow = O + ΔV

The reverse reservoir routing-derived hydrographs for the inflow to the Douglas Dam reservoir for May 2003 and September 2004 are presented in Figures 20 and 21, respectively.

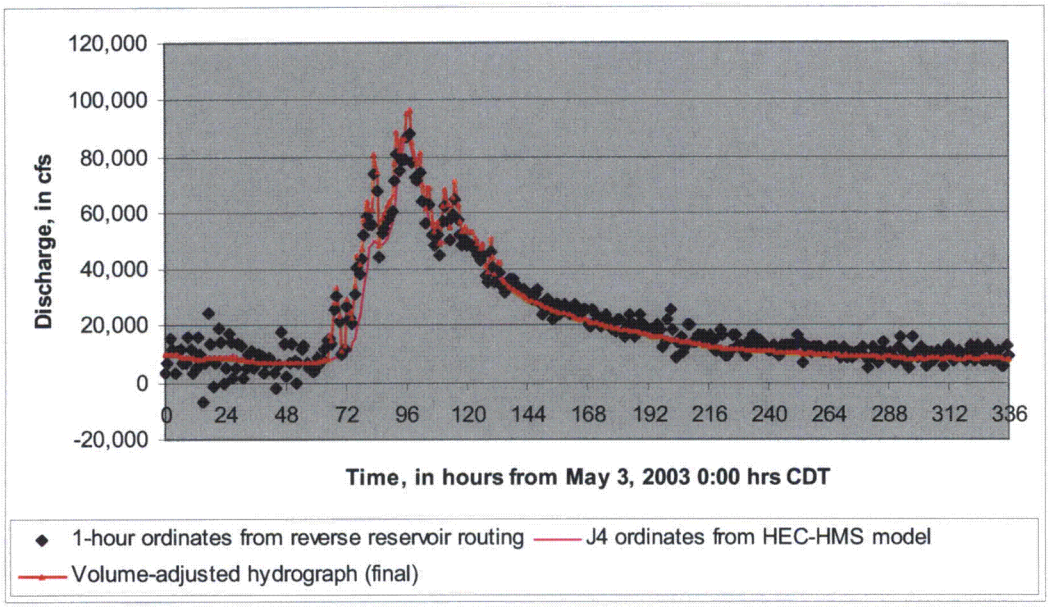


Figure 20: Smoothing of reverse reservoir routing-derived hydrograph at Douglas Dam Reservoir for May 2003

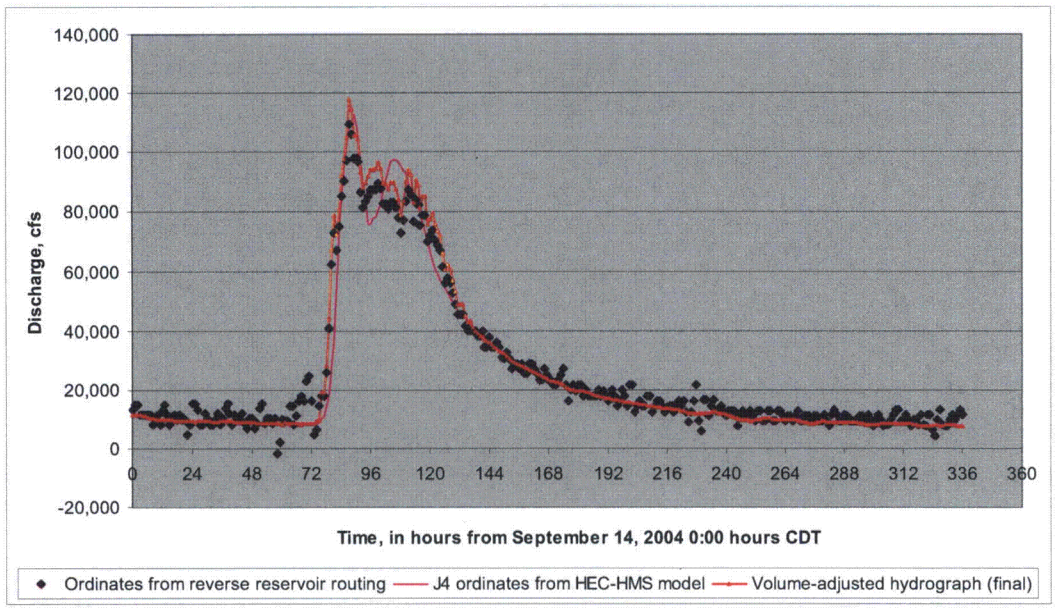


Figure 21: Smoothing of reverse reservoir routing-derived hydrograph at Douglas Dam Reservoir for September 2004

7.3 Base Flow Separation and Calculation of Direct Runoff

Base flow separation is required to determine an estimate of direct runoff associated with the rainfall event. The direct runoff volume is used as the effective rainfall volume in FLDHYDRO, as described in Section 7.4. For this calculation, the base flow is drawn from the starting point of runoff to a point on the receding limb of the hydrograph *N* days after the time of peak discharge, where *N* is the drainage area of the basin in square miles, raised to the one-fifth power per the criterion proposed by Linsley et al. (Reference 4). The drainage area used for separating base flow for in-stream hydrographs is the total upstream drainage area; the drainage area used for local runoff base flow separation is the area of the single basin, independent of upstream contributions.

The calculation of the time in days (converted to hours) from the peak discharge to the point of the intersection of the base flow line with the receding limb of the hydrograph is presented in Table 14. The separation of base flow from direct runoff for each of the simulations is presented graphically in Figures 22 to 35.

Table 14: Point of Intersection of Base Flow with Receding Limb of Hydrograph

Basin #	Basin Identification	Drainage area, mi^2	N, in days (1)	N, hrs
1	French Broad River at Asheville	944.4	3.94	94
2	French Broad River at Newport	913.1	3.91	94
3	Pigeon River at Newport	667.1	3.67	88
4	Nolichucky River at Embreesville	804.8	3.81	91
5	Nolichucky Dam Local Inflow	378.7	3.28	79
-	Nolichucky Dam watershed	1183.5	4.12	99
6	Douglas Dam Local Inflow	835.0	3.84	92
-	Douglas Dam watershed	4543.1	5.39	129
-	J4 drainage area (2)	4125.6	5.29	127

1) N = $Area^{02}$ (see Reference 4)

2) J4 drainage area = Douglas Dam watershed area - 0.5*Basin 6 area

For Subbasins 1 through 4, for which reliable local runoff hydrographs can be developed, it is possible to determine direct runoff volume by the numerical integration of the hydrographs. Direct runoff volume, *V*, is calculated from period average flow rate, *Q*, and the length of the period, *Δt*, as:

$$V(ac-ft) = \sum Q(cfs)\ x \left(\Delta t(hr) * \frac{3{,}600(s/hr)}{43{,}560(ft^2/ac)} \right)$$

For two complex storms, it was necessary to separate direct runoff into two parts corresponding to separated periods of rainfall to provide a better estimate of excess rainfall than would be obtained for a single calculation of cumulative runoff (see Section 7.4). The floods treated in this way were:

- The May 2003 flood in Subbasin 3 (Pigeon River at Newport), in which 2.68 inches of runoff is separated into a first period volume of 2.16 inches and a second period volume of 0.52 inches.

The separation is effected by applying a recession constant of 0.88 to all ordinates following hour 104 as $Q_{t+1} = 0.88Q_t$.

- The March 1994 flood in Subbasin 2 (French Broad River near Newport), in which 2.33 inches of direct runoff is separated into a first period volume of 1.99 inches and a second period volume of 0.34 inches. The separation is effected by applying a recession constant of 0.83 to all ordinates following hour 112 as $Q_{t+1} = 0.83Q_t$

Routing procedures were not available to determine reliable local runoff hydrographs for Subbasins 5 and 6; for these subbasins the total, lumped local runoff volume is determined by subtracting the direct runoff from the upstream basins, as follows:

- The total direct runoff volume for Subbasin 5 is determined by subtracting the total volume of observed flow at Embreeville, with base flow removed, from the total direct volume measured on the Nolichucky River at Nolichucky Dam
- The total direct runoff volume for Subbasin 6 is determined by subtracting the total volume of observed flow from Nolichucky Dam, French Broad River near Newport, and the Pigeon River at Newport routed down to Junction 4 (see Figure 17) from the total volume of direct runoff entering the Douglas Dam reservoir, as determined by reverse reservoir routing.

Direct runoff volume calculations are summarized in Table 15 and are presented in detail in the following spreadsheets, provided as the indicated attachments:

- "DirectROCalcs2002.xls" (Attachment 1-2)
- "DirectROCalcs2003.xls" (Attachment 1-3)
- "DirectROCalcs2004.xls" (Attachment 1-4)
- "DirectROCalcsSB2-1994&6.xls (Attachment 1-5)

Table 15: Summary of Direct Runoff Calculation for Each Flood

Basin Number & Identification		Fig. #	Storm Date	N, hrs	Peak hour	End hour		Stream flow volume, acft	inches stream flow	Direct RO volume , acft	Direct R.O. inches
						per Eq.	used				
1	French Broad River at Asheville	22	May-03	94	112	206	206	158,489	3.14	72,352	1.44
1	French Broad River at Asheville	23	Sep-04	94	84	176	178	247,828	4.92	111,382	2.21
2	French Broad Local Inflow at Newport	24	Mar-94	94	100	194	194	169,761	3.49	113,238	2.33
2	French Broad Local Inflow at Newport	25	Feb-96	94	104	198	198	95,931	1.97	61,013	1.25
3	Pigeon River at Newport	26	Jan-96	88	78	166	166	116,293	3.27	60,143	1.69
3	Pigeon River at Newport	27	May-03	88	92	180	180	152,192	4.28	95,361	2.68
4	Nolichucky River at Embreesville	28	Nov-03	91	62	153	154	74,043	1.78	53,864	1.25
4	Nolichucky River at Embreesville	29	Sep-04	91	82	173	174	177,903	4.14	110,670	2.58
	Nolichucky Dam watershed	30	Mar-02	99	66	165	166	116,926	1.85	60,037	0.95
5	Nolichucky Dam Local Inflow	n/a	Mar-02	Calculated by subtracting Embreeville from Nolichucky Dam volume						18,637	0.92
	Nolichucky Dam watershed	31	Nov-03	99	74	173	172	99,991	1.54	70,289	1.11
5	Nolichucky Dam Local Inflow	n/a	Nov-03	Calculated by subtracting Embreeville from Nolichucky Dam volume						16,424	0.81
	Junction J4	32	May-03	127	97	224	224	548,693	2.49	289,534	1.32
	Douglas Dam watershed	33	May-03	129	97	226	226	602,438	2.49	339,726	1.40
6	French Broad Local Inflow at Douglas Dam	n/a	May-03	Calculated by subtracting J4 from Douglas Dam volume						50,191	1.13
	Junction J4	34	Sep-04	127	89	216	216	663,086	3.01	387,144	1.76
	Douglas Dam watershed	35	Sep-04	129	87	216	216	695,737	2.87	415,528	1.71
6	French Broad Local Inflow at Douglas Dam	n/a	Sep-04	Calculated by subtracting J4 from Douglas Dam volume						28,384	0.64

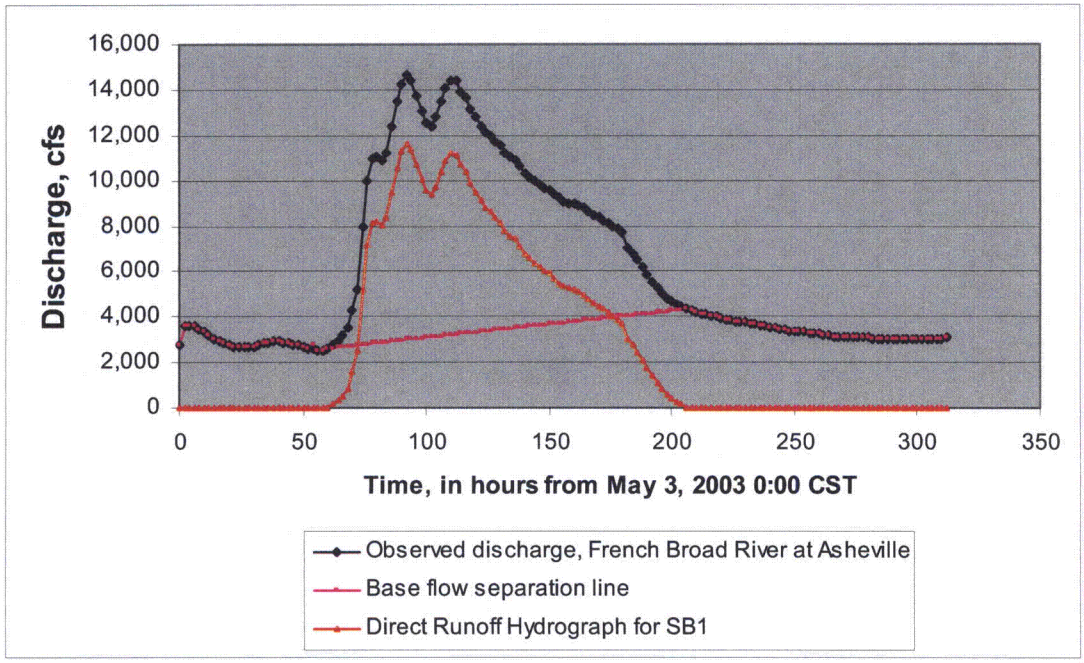


Figure 22: Base Flow Separation for the French Broad River at Asheville, May 2003

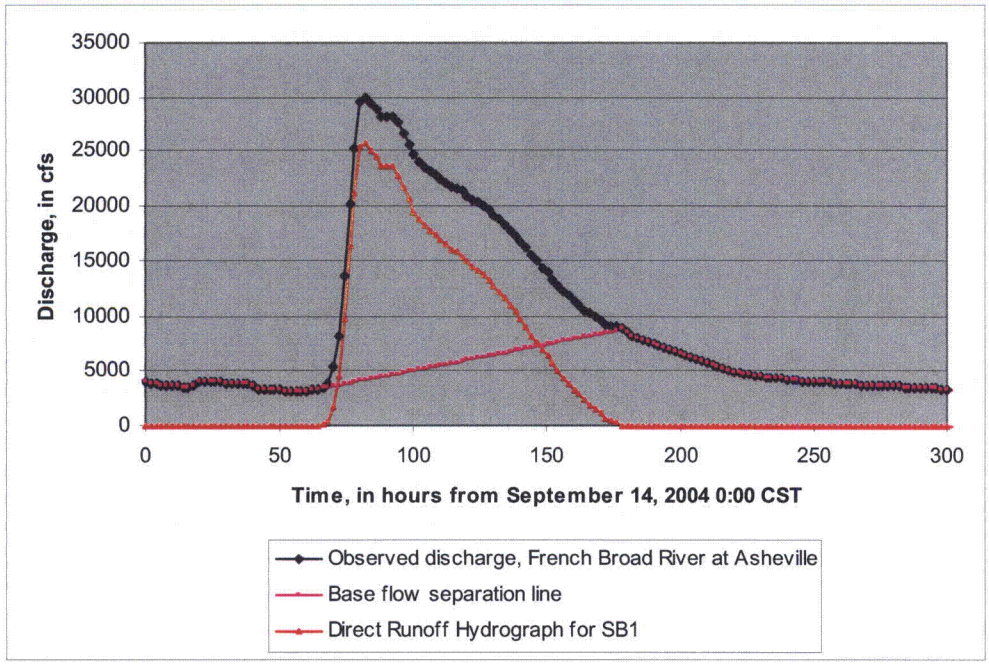


Figure 23: Base Flow Separation for the French Broad River at Asheville, September 2004

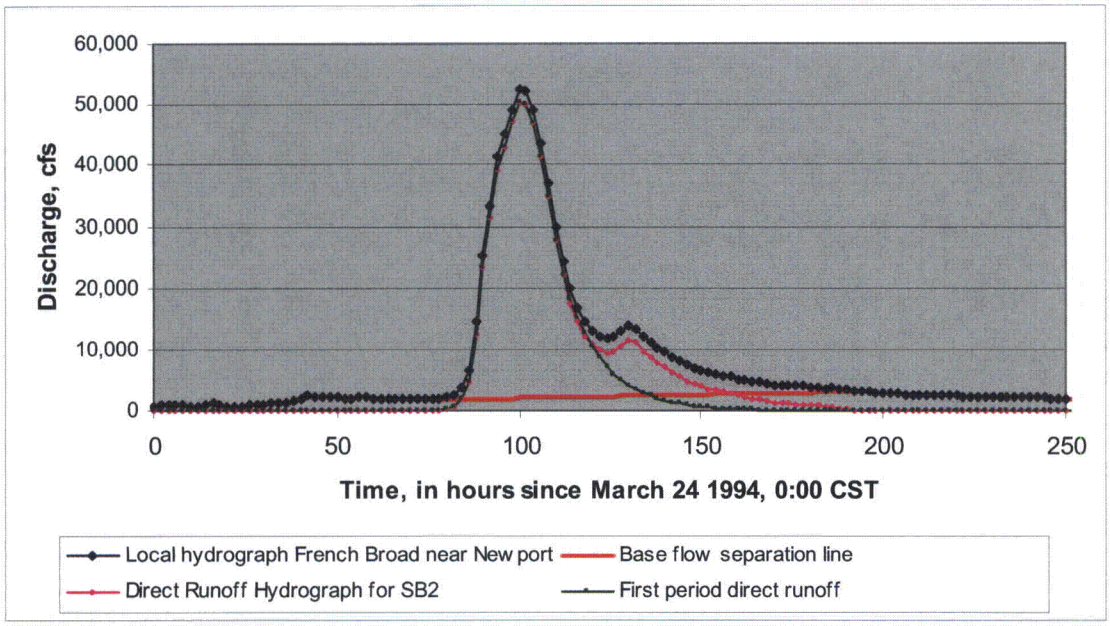


Figure 24: Base Flow Separation for the French Broad River Local Inflow nr Newport, March 1994 (direct runoff is divided into two periods)

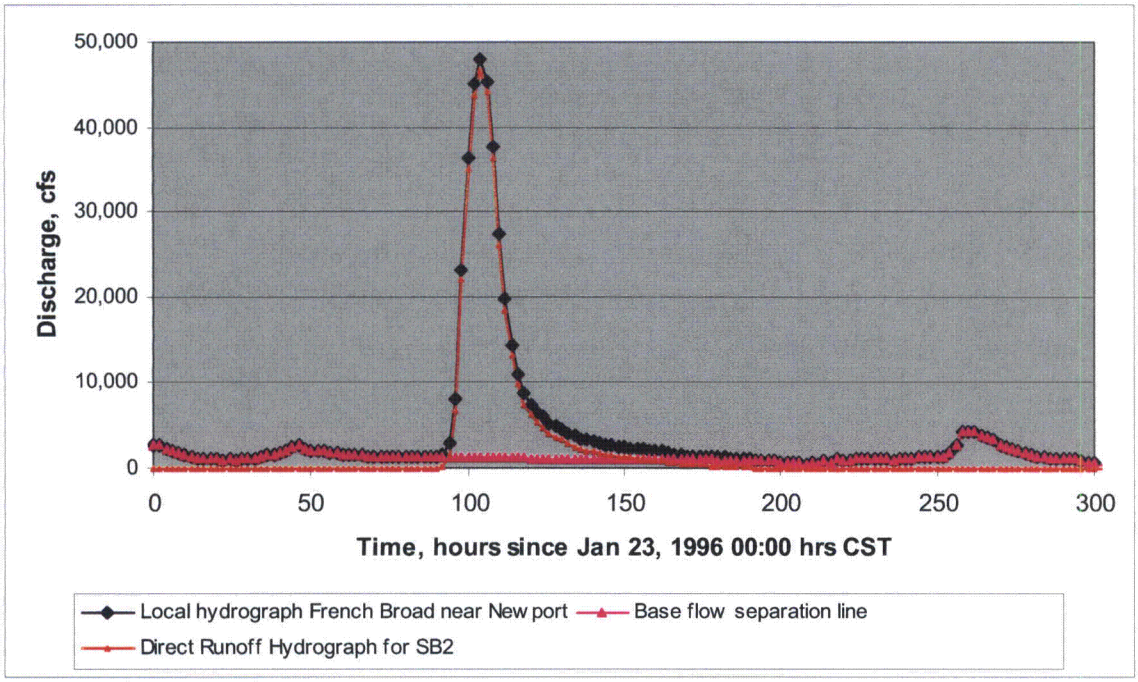


Figure 25: Base Flow Separation for the French Broad River Local Inflow nr Newport, Jan. 1996

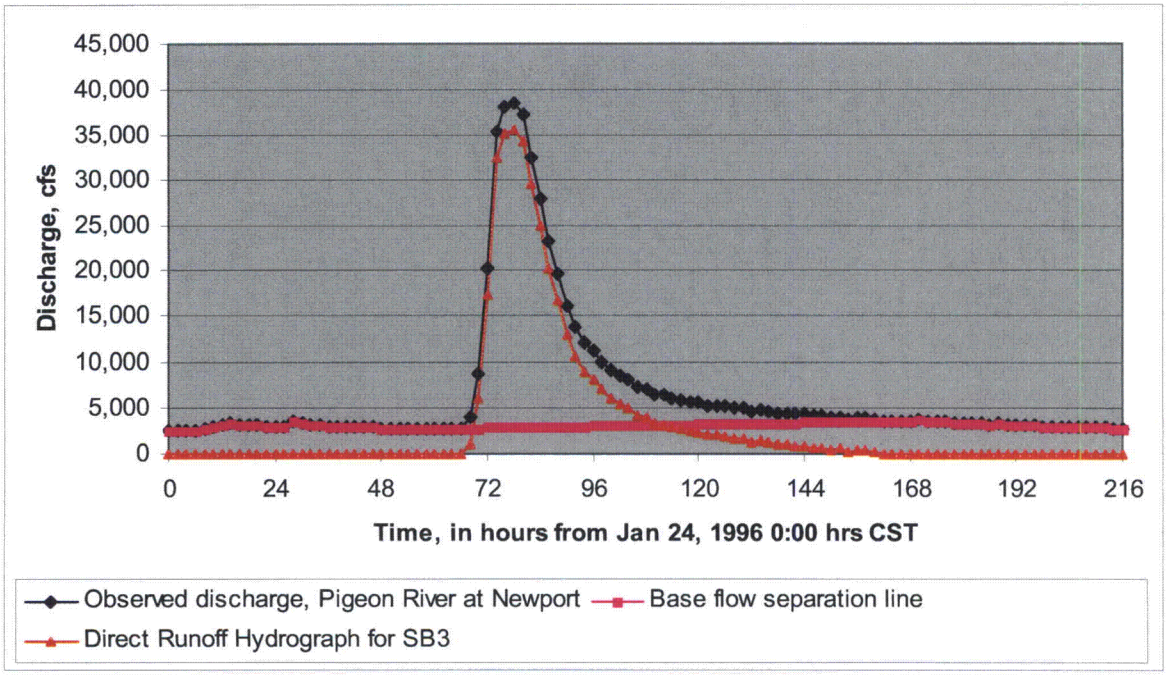


Figure 26: Base Flow Separation for the Pigeon River at Newport, January 1996

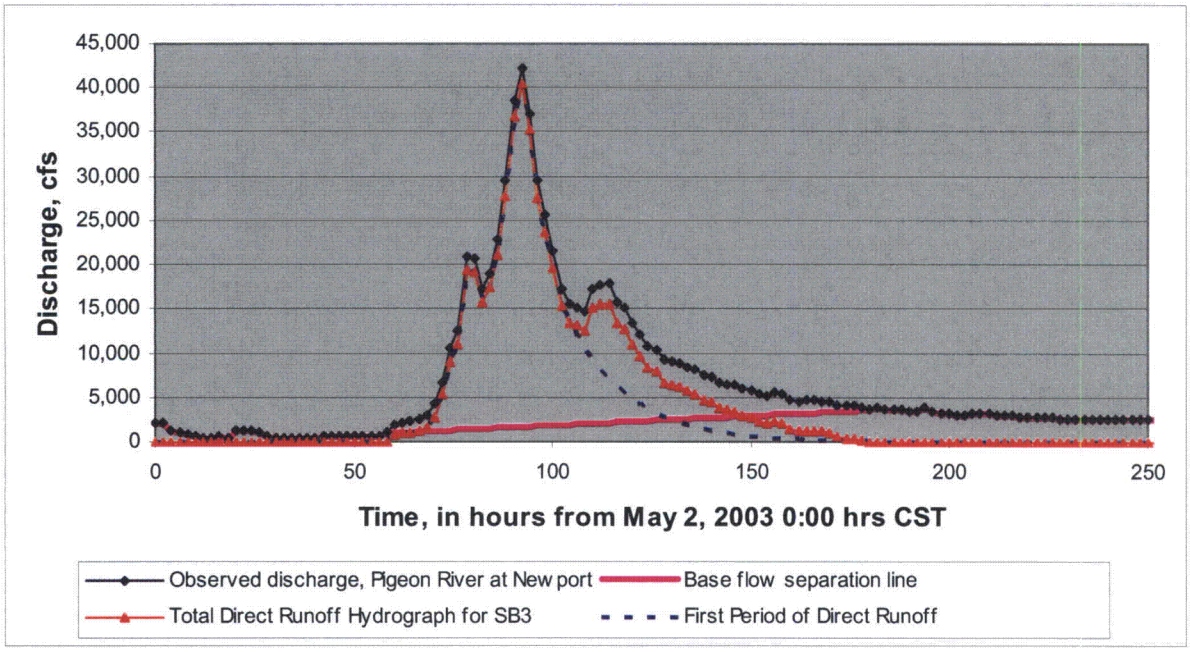


Figure 27: Base Flow Separation for the Pigeon River at Newport, May 2003 (direct runoff is divided into two periods)

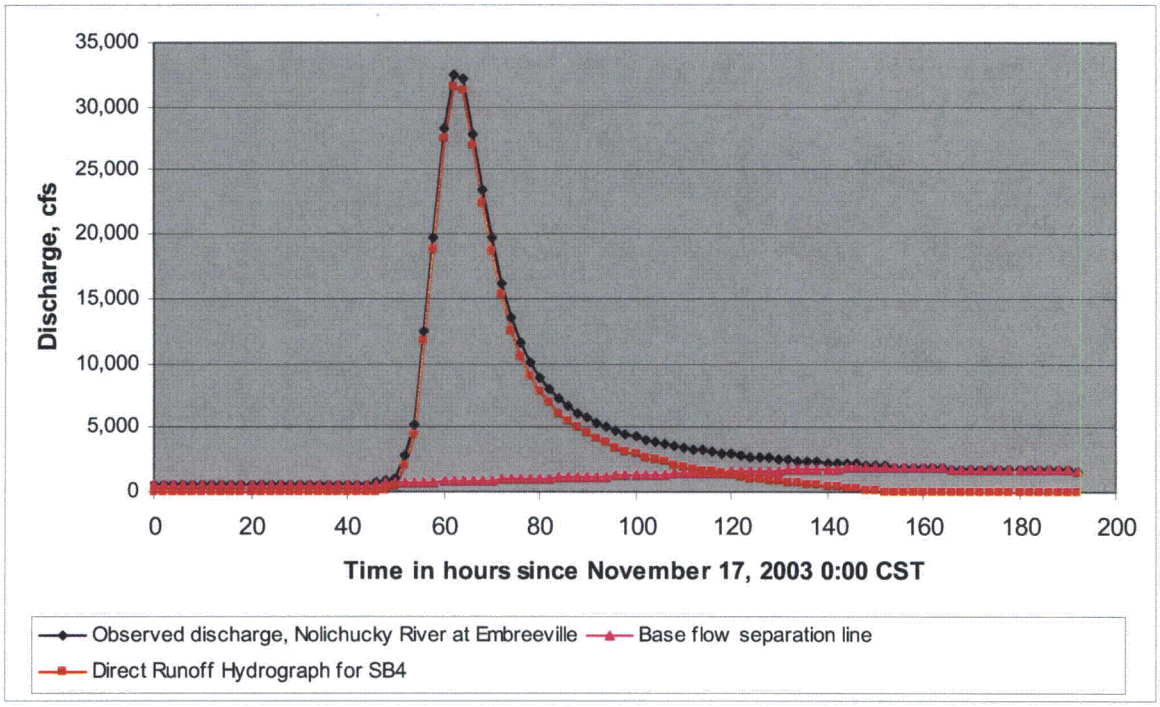


Figure 28: Base Flow Separation for the Nolichucky River at Embreeville, November 2003

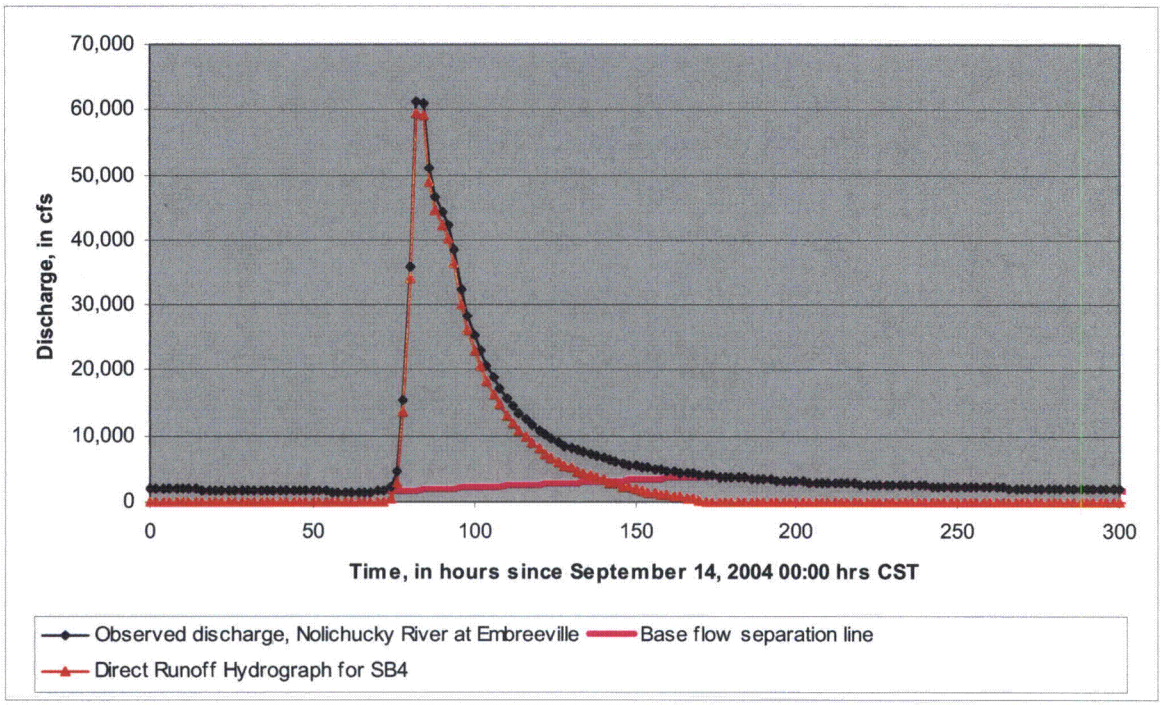


Figure 29: Base Flow Separation for the Nolichucky River at Embreeville, September 2004

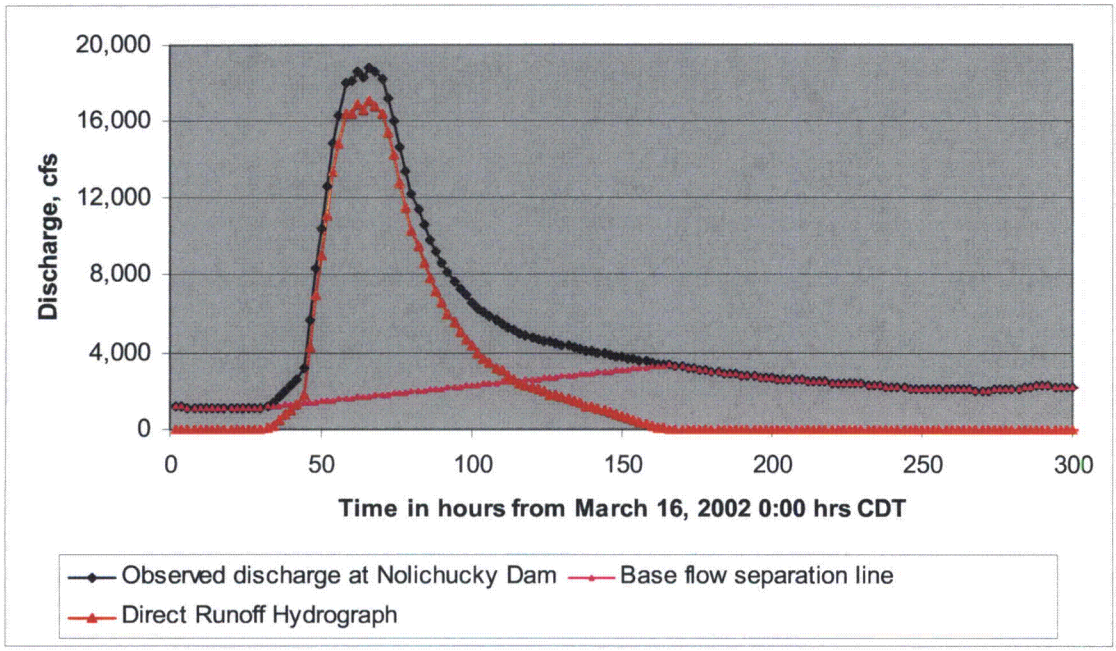


Figure 30: Base Flow Separation for Nolichucky Dam Watershed, March 2002

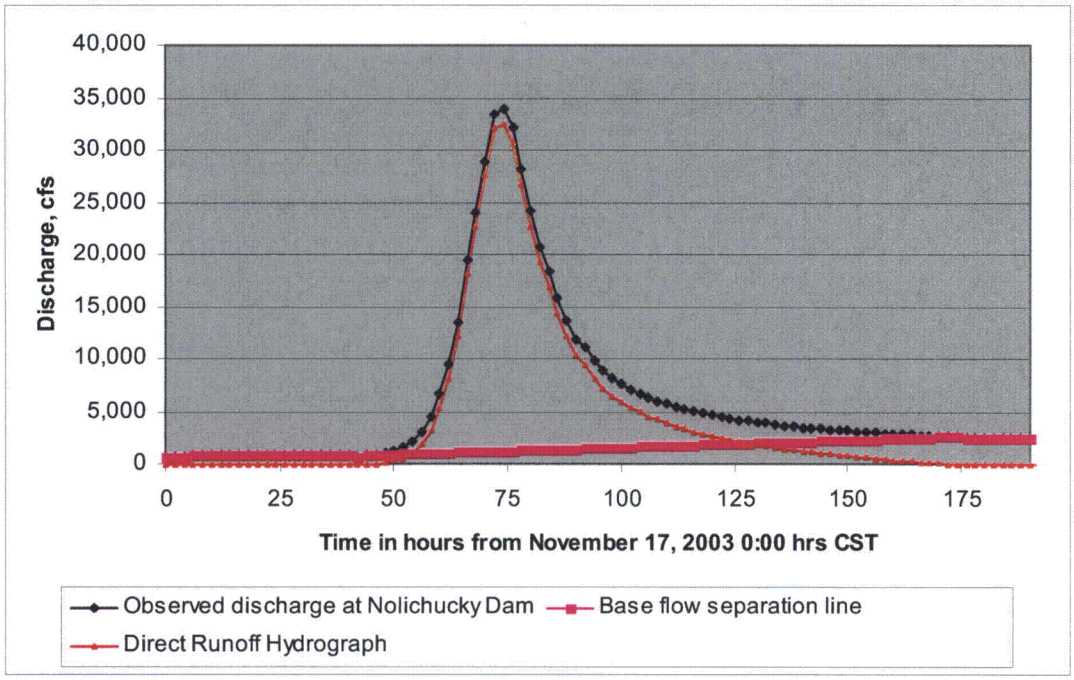


Figure 31: Base Flow Separation for Nolichucky Dam Watershed, November 2003

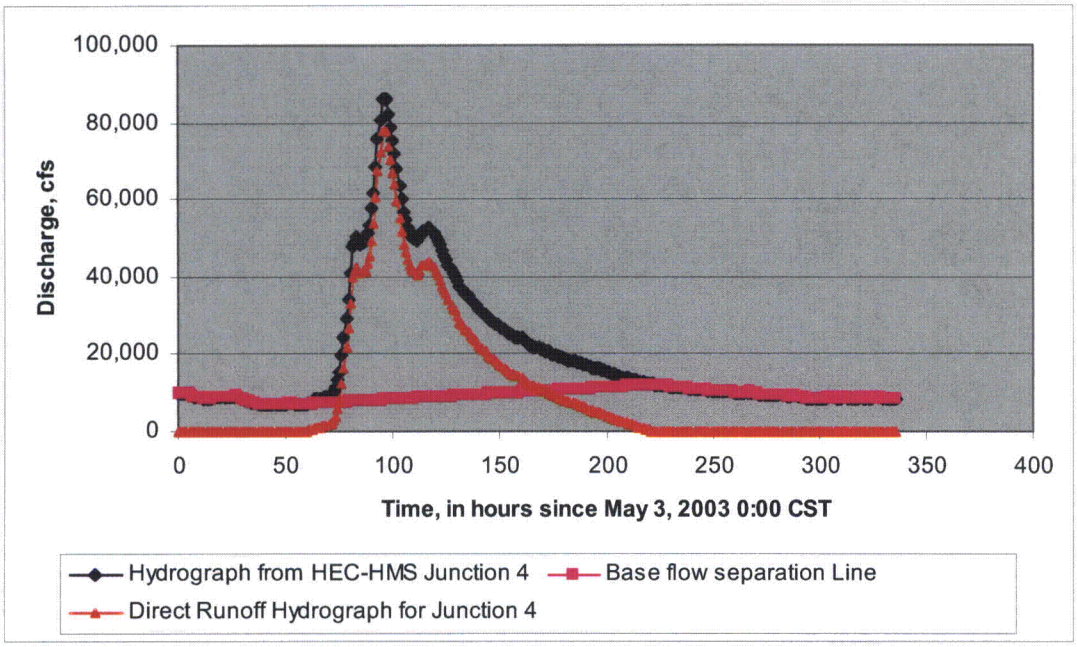


Figure 32: Base Flow Separation for Junction 4 on the French Broad River, May 2003

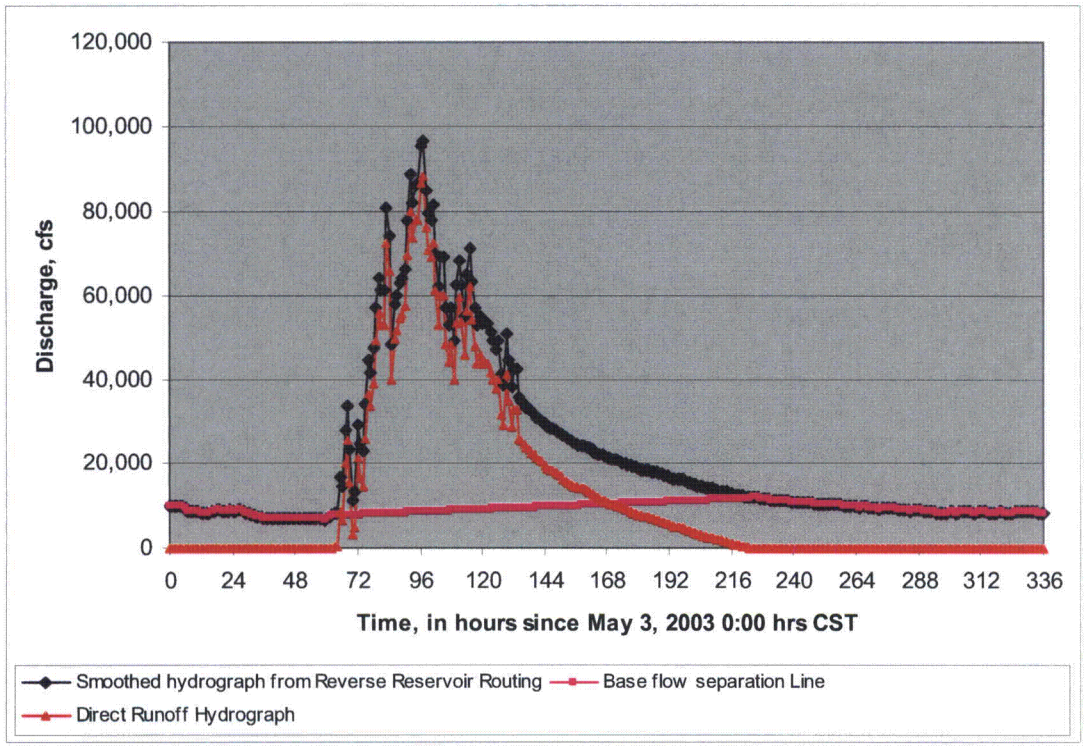


Figure 33: Base Flow Separation at Douglas Dam Reservoir on the French Broad River, May 2003

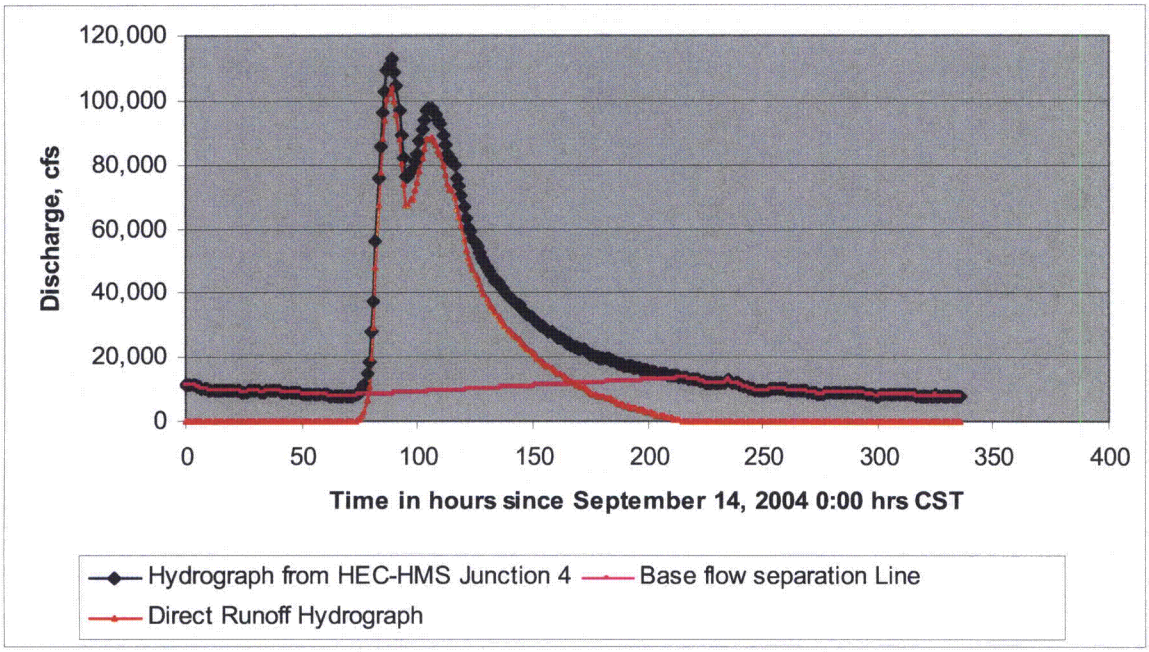


Figure 34: Base Flow Separation for Junction 4 on the French Broad River, September 2004

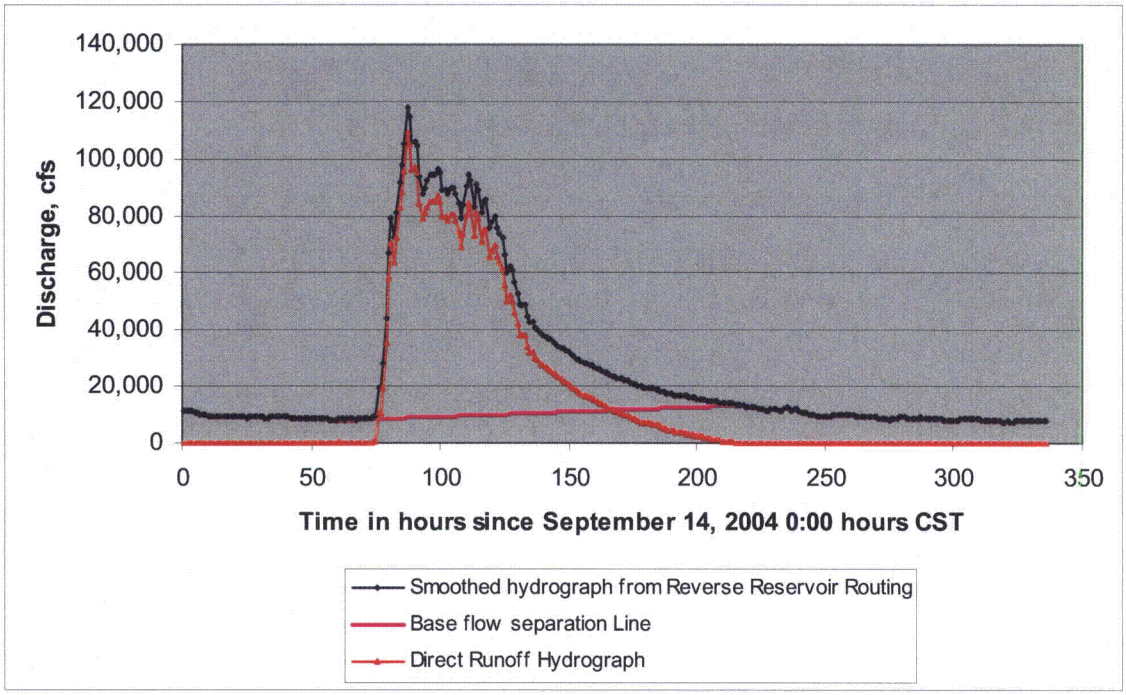


Figure 35: Base Flow Separation for Douglas Dam Reservoir on the French Broad River, September 2004

7.4 Effective Basin Average Rainfall

The effective (or excess) rainfall hyetograph is the input to the basin model that is converted into direct runoff at the basin outlet. This is developed from the observed rainfall hyetograph by the application of a loss rate function which accounts for the hydrologic abstractions of evaporation and transpiration, interception, depression storage, and infiltration (Reference 27).

Effective rainfall is obtained from observed rainfall data with the FLDHYDRO program (Reference 6). The FLDHYDRO program was developed by the TVA to implement the API/RI methodology developed by the United States Weather Bureau (USWB), as described in References 3 and 4. In brief, the method uses the Antecedent Precipitation Index (API) for a given day, which is calculated on the basis of a recession constant normally reported to range from 0.85 to 0.98 (Reference 27, page 101). A recession constant of 0.9 is assumed for this calculation. The API is used to obtain a Runoff Index (RI) that has been determined for the Tennessee River Valley region as a function of precipitation, location, and season. The RI is then used to obtain precipitation losses for each increment of rainfall.

The use of the loss function is discussed in the TVA White Paper (Reference 22), and the methodology is described in detail in the Kohler and Linsley publication (Reference 3). Input to FLDHYDRO is via a column delimited batch file. Input includes:

- Hourly precipitation gage readings for a maximum of 30 recording gages and daily precipitation readings for a maximum of 100 non-recording gages (For the gridded precipitation data sets, daily precipitation depths were calculated by summing up hourly rainfall depths.)
- Indices to relate each non-recording gage record to a recording gage record for interpolation
- Thiessen coefficients to weight gage records for the calculation of basin average precipitation depths (not used for gridded precipitation data)
- Depth of runoff for the period of rainfall

Using the gridded precipitation data simplifies the setup of input to the FLDHYDRO model because only one "gage reading" is needed for each hour. When using gridded precipitation data, input for each run includes the following data and "flags":

- NARFE = 1 to obtain a printout of flood hydrographs only
- NRI = 1 for the number of Rainfall Indices to be used per basin
- NCPTS = 1 for the number of sites for surface runoff volume check (set to zero if a runoff check volume is not supplied)
- NSUBW = 1 for the number of sub-watersheds (each subbasin is run separately)
- NREC = 1 for the number of recorders (run using only gridded precipitation data as one "recorder")
- NSTNS = 1 for total number of stations (i.e. no non-recording stations used)
- STAB = 1 when all stations are in the same API area
- ITDGR = 0 for the hour at which each gage is read
- BEGDR = The starting date (entered in MMDDYY format)
- BEGTR = Time at which the first hour of rainfall has been recorded (between 01 to 24)

- NHR = The number of hourly readings for the storm
- SHRAIN = The time series of hourly rainfall readings (in 10F8.0 format) obtained from processing of NWS gridded rainfall
- NDRAPI = The number of days of antecedent rainfall listed before the storm
- API = The initial API at the beginning of the antecedent daily rainfall series (setting this value to 1.0 is sufficient when a month of data is used because the initial condition has negligible impact on the final API for a sufficiently long series)
- APRAIN = The time series of daily rainfall readings (in 10F8.0 format) obtained from the sum of hourly rainfall data for approximately one month prior to the start of the hourly rainfall
- BAREA = The subbasin area in square miles
- APITYPE = The API zone with SE = 1, E = 2, NE = 3, N = 4, W = 5, and S = 6. The Douglas Dam watershed subbasins are within the NE, E, and SE zones (see Figure 36).
- NSPW = 1 for number of rainfall stations for each sub-watershed (for gridded data there are no Thiessen weighting factors)
- NUMVOL = Number of watersheds above surface runoff volume check point
- CHKVOL = The volume of surface runoff in inches (calculated from outflow hydrographs after base flow separation); when CHKVOL is greater than zero, the final runoff index is adjusted, if necessary, to provide a volume equal to CHKVOL

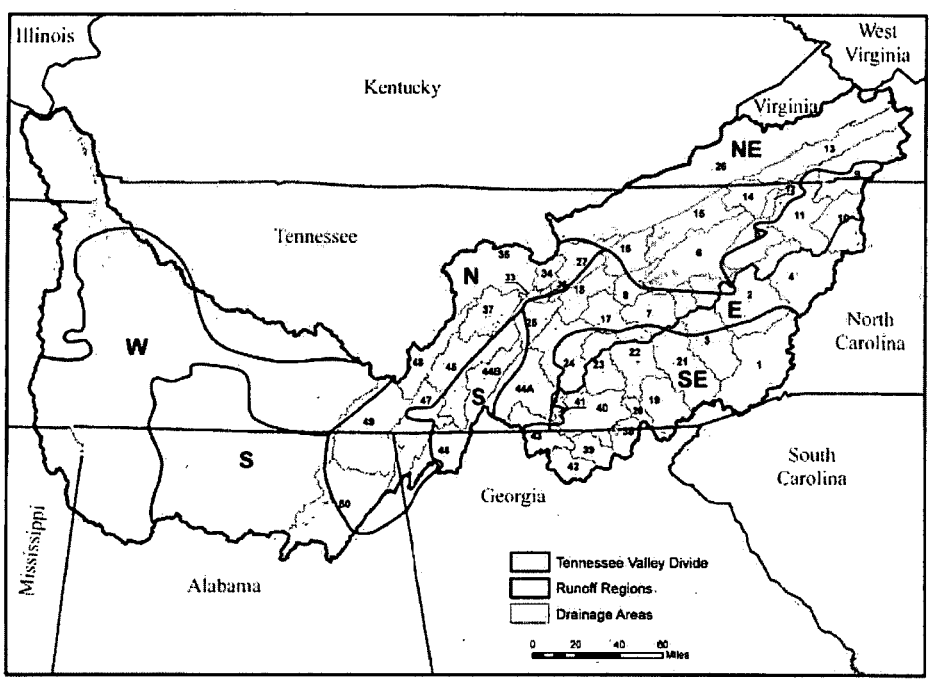


Figure 36: Runoff Regions for Application of TVA FLDHYDRO Program

Input data and parameters for running FLDHYDRO to get effective basin average rainfall for the six subbasins of the Douglas Dam watershed for the simulation periods were written to the following batch input files, included as attachments to this calculation:

- Attachment 2-1 Basin01ppt2003.dat
- Attachment 2-2 Basin01ppt2004.dat
- Attachment 2-3 Basin03pptPartA2003.dat
- Attachment 2-4 Basin03pptPartB2003.dat
- Attachment 2-5 Basin04pptNov2003.dat
- Attachment 2-6 Basin04ppt2004.dat
- Attachment 2-7 Basin05ppt2002.dat
- Attachment 2-8 Basin05pptNov2003.dat
- Attachment 2-9 Basin06ppt2003.dat
- Attachment 2-10 Basin06ppt2004.dat

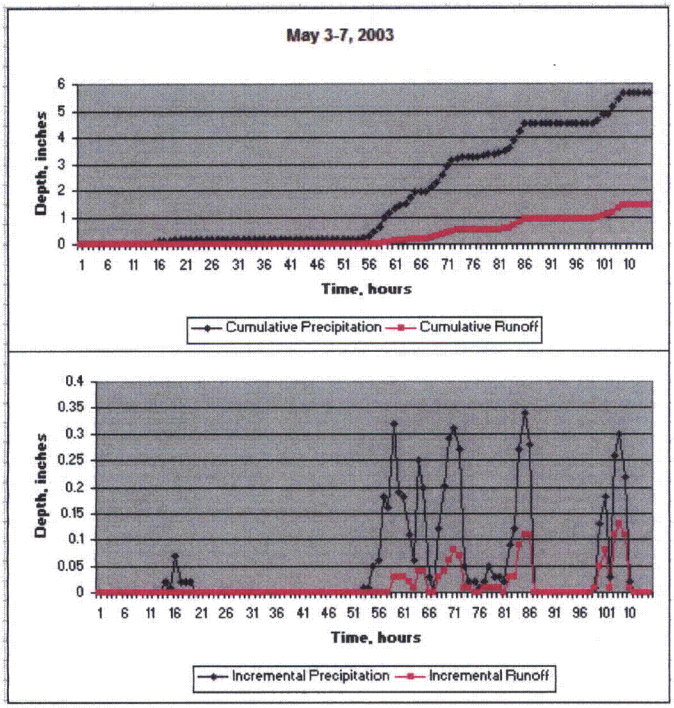
The corresponding FLDHYDRO output files are also provided as attachments:

- Attachment 2-11 Basin01ppt2003.out
- Attachment 2-12 Basin01ppt2004.out
- Attachment 2-13 Basin03pptPartA2003.out
- Attachment 2-14 Basin03pptPartB2003.out
- Attachment 2-15 Basin04pptNov2003.out
- Attachment 2-16 Basin04ppt2004.out
- Attachment 2-17 Basin05ppt2002.out
- Attachment 2-18 Basin05pptNov2003.out
- Attachment 2-19 Basin06ppt2003.out
- Attachment 2-20 Basin06ppt2004.out

The output for each basin provides an echo of data input and tabulated cumulative rainfall and effective rainfall (runoff) depths. The cumulative effective rainfall depth series were converted to incremental time series for input to HEC-HMS in the spreadsheet "FLDHYDRO processing.xls," provided as Attachment 1-11 to this calculation.

As noted in Section 7.1, it was necessary to use TVA 6-hour precipitation data for the validation runs for Subbasin 2 and for one of the validation runs for Subbasin 3 because no suitable one-hour point rainfall or gridded precipitation data were available. For these runs, FLDHYDRO, which uses one-hour rainfall depths for input, was not used. Instead, a relation between cumulative rainfall and runoff (effective runoff) was calculated from the tables incorporated in the TVA's FLDHYDRO program (Reference 6) and fit to a third-order polynomial to facilitate interpolation. The spreadsheets developed for these calculations, "EffectivePPTcalcSB2-1994&6.xls" and "EffectivePPTcalcSB3-1996.xls" are provided as Attachment Nos. 1-9 and 1-10, respectively.

The incremental and cumulative precipitation and excess rainfall depths for the two validation runs for each of the subbasins are plotted in Figures 37 to 42. The use of the excess rainfall, or runoff, time series as input to the HEC-HMS models is described in the next section.



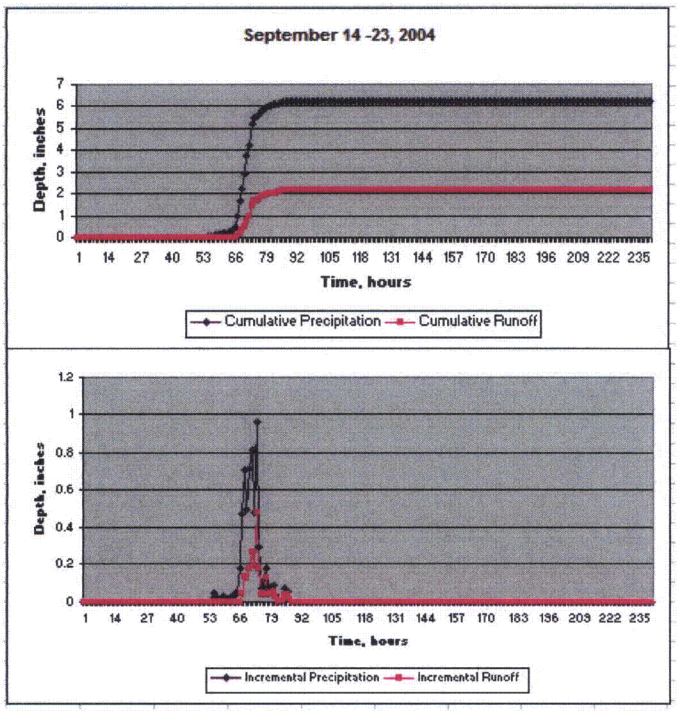


Figure 37: FLDHYDRO-derived Precipitation and Runoff Inputs for Subbasin 1 Simulations

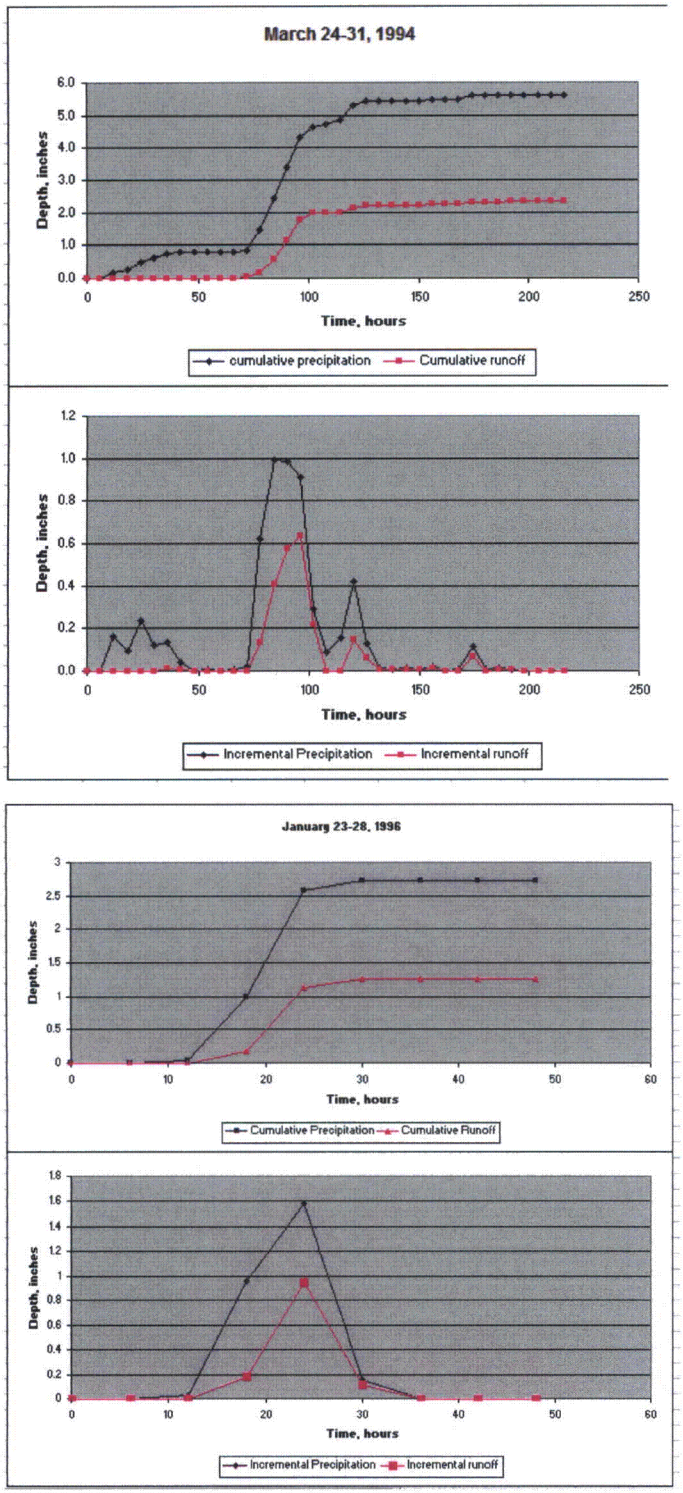
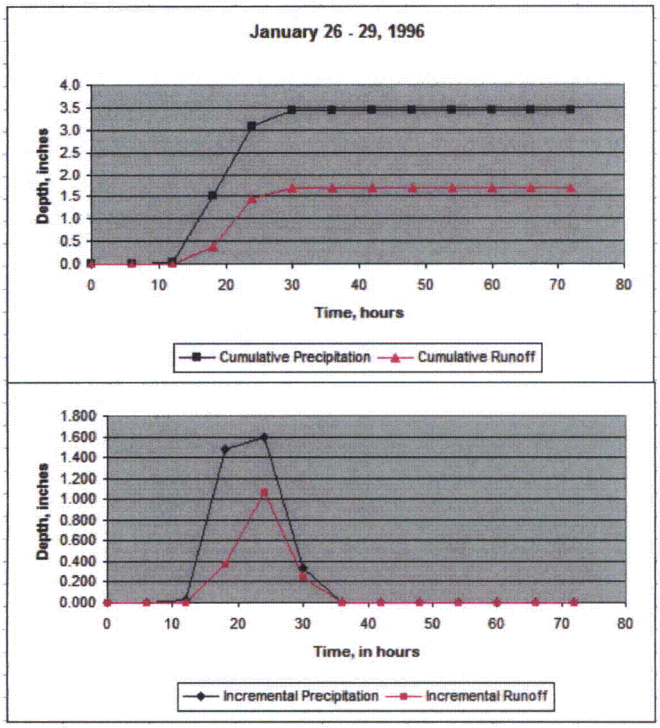


Figure 38: RI Table-derived Precipitation and Runoff Inputs for Subbasin 2 Simulations



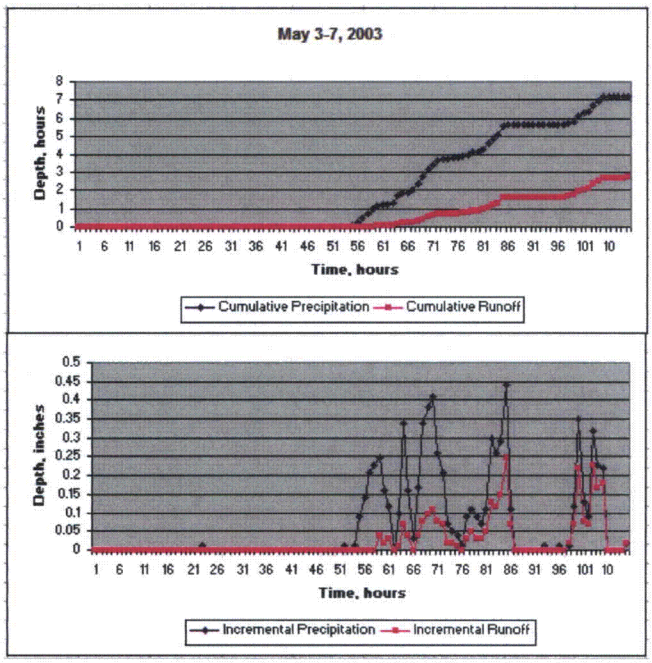
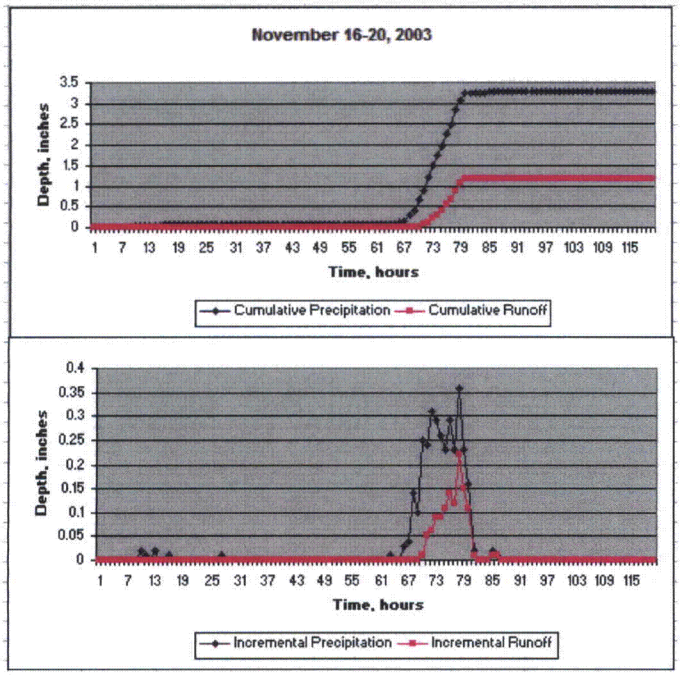


Figure 39: FLDHYDRO-derived Precipitation and Runoff Inputs for Subbasin 3 Simulations



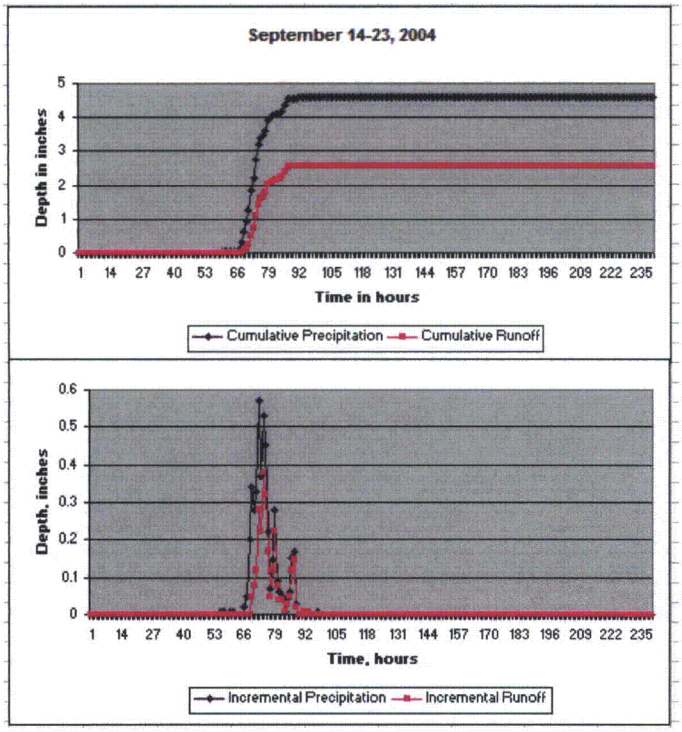
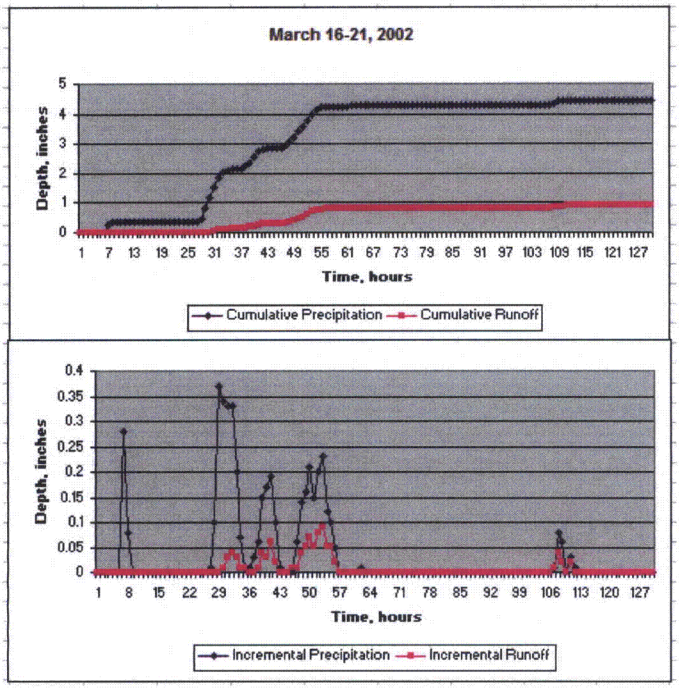


Figure 40: FLDHYDRO-derived Precipitation and Runoff Inputs for Subbasin 4 Simulations



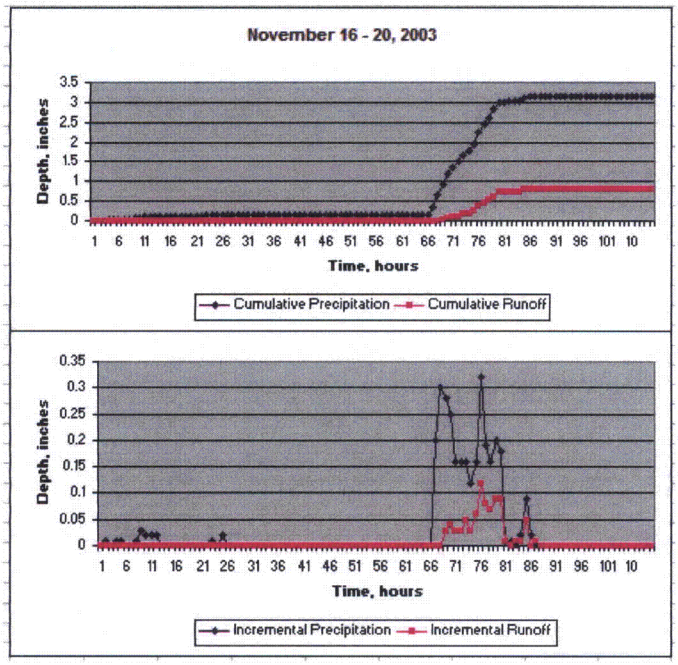
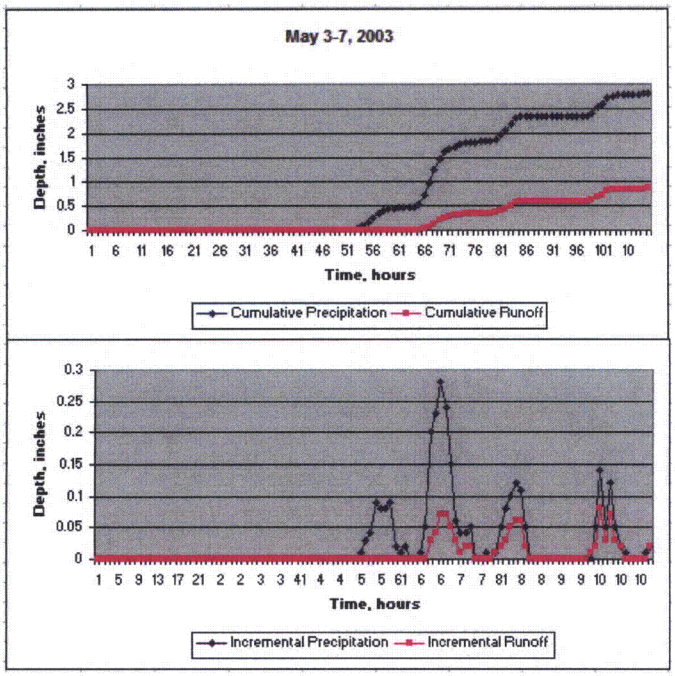


Figure 41: FLDHYDRO-derived Precipitation and Runoff Inputs for Subbasin 5 Simulations



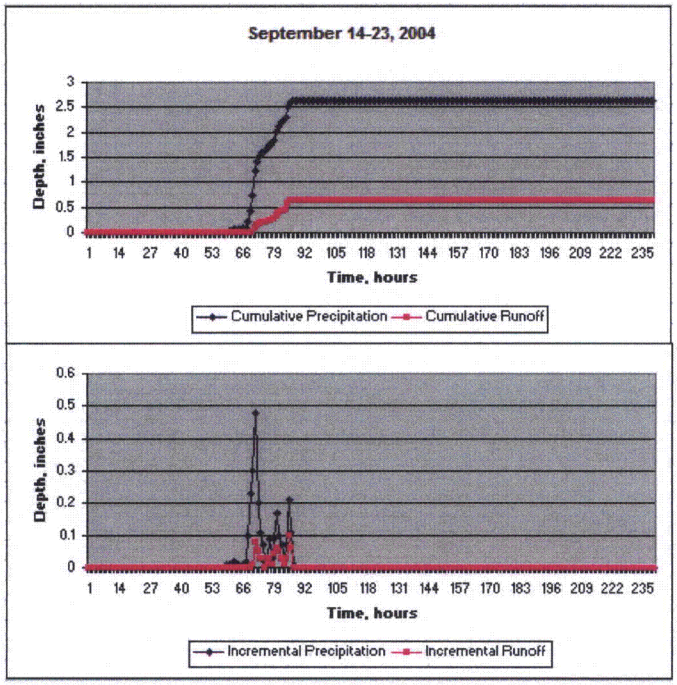


Figure 42: FLDHYDRO-derived Precipitation and Runoff Inputs for Subbasin 6 Simulations

7.5 HEC-HMS Simulations

HEC-HMS models were developed for testing the unit hydrographs developed by the TVA for the Douglas Dam watershed using the simulation periods indicated in Table 16. All HEC-HMS project files are provided as electronic attachments as indicated.

Table 16: HEC-HMS Simulations for Validation of Subbasin Unit Hydrographs

Model	Attachment	Simulation Period
Basin_1.hms	3-1	May 3 - 16, 2003
		September 14 - 28, 2004
Basin_02.hms	3-2	March 24 - April 7, 1994
		January 23 - February 5, 1996
Basin_03.hms	3-3	January 24 - February 1, 1996
		May 3 - 15, 2003
Basin_04.hms	3-4	November 16 - 27, 2003
		September 14 - 28, 2004
Basin_5.hms	3-5	March 16 - 24, 2002
		November 17- 24, 2003
Basin_6.hms	3-6	May 3 - 17, 2003
		September 14 - 28, 2004

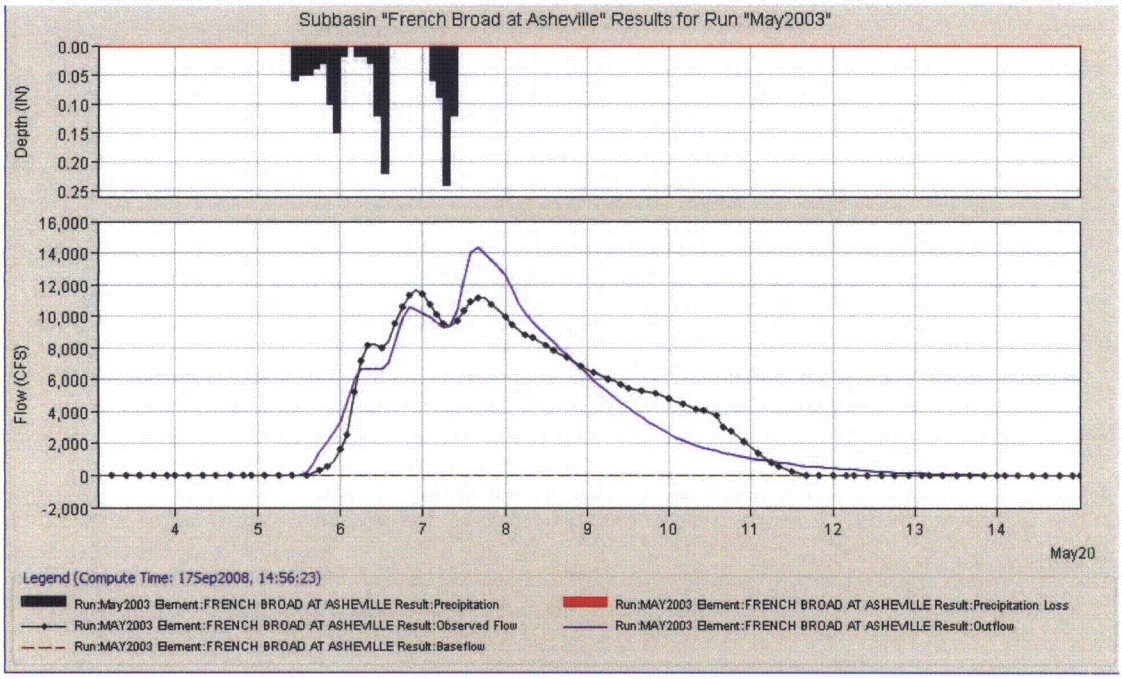
The following general observations apply to the development of each of the HEC-HMS models (References 23 and 24):

- Effective rainfall (runoff) time series developed from FLDHYDRO output files were input as precipitation data using the Time Series Data Manager in HEC-HMS. Because rainfall losses are accounted for in FLDHYDRO, no HEC-HMS loss function was used.
- The flow series developed for use in validation of the unit hydrograph for each subbasin, as described in Section 6.2, were input as discharge gage data in HEC-HMS using the Time Series Data Manager and were set as Observed Flow series using the Option tab for the appropriate subbasin or junction node.
- The TVA unit hydrograph to be evaluated for each subbasin was input as a user-specified hydrograph using the Paired Data Manager in HEC-HMS. The time interval was set equal to the duration of the unit hydrograph as provided by the TVA.
- A time step appropriate for the simulation was set with the Control Specifications Manager dialog box. HEC-HMS automatically adjusts the duration of the user-specified hydrograph using the S-curve technique to match the simulation time interval.

A description of each of the models is provided in the following subsections. Modeling considerations specific to each basin are discussed, graphical output from the HEC-HMS simulations and an analysis of the results for each subbasin are discussed. All results are summarized in Section 7.6.

7.5.1 Subbasin 1 HEC-HMS Model

The unit hydrograph developed by the TVA for the French Broad River at Asheville was validated in the HEC-HMS model Basin_1.hms. All Basin_1 project files are provided in electronic format as part of Attachment 3-1. HEC-HMS graphical output is presented for the May 2003 and September 2004 floods in Figures 43 and 44, respectively.



Project: Basin 1
Simulation Run: May2003 Subbasin: French Broad at Asheville

Start of Run:	03May2003, 02:00	Basin Model:	French Broad2003
End of Run:	15May2003, 00:00	Meteorologic Model:	May2003
Compute Time:	17Sep2008, 14:56:23	Control Specifications:	May2003

Volume Units: (•) IN ( ) AC-FT

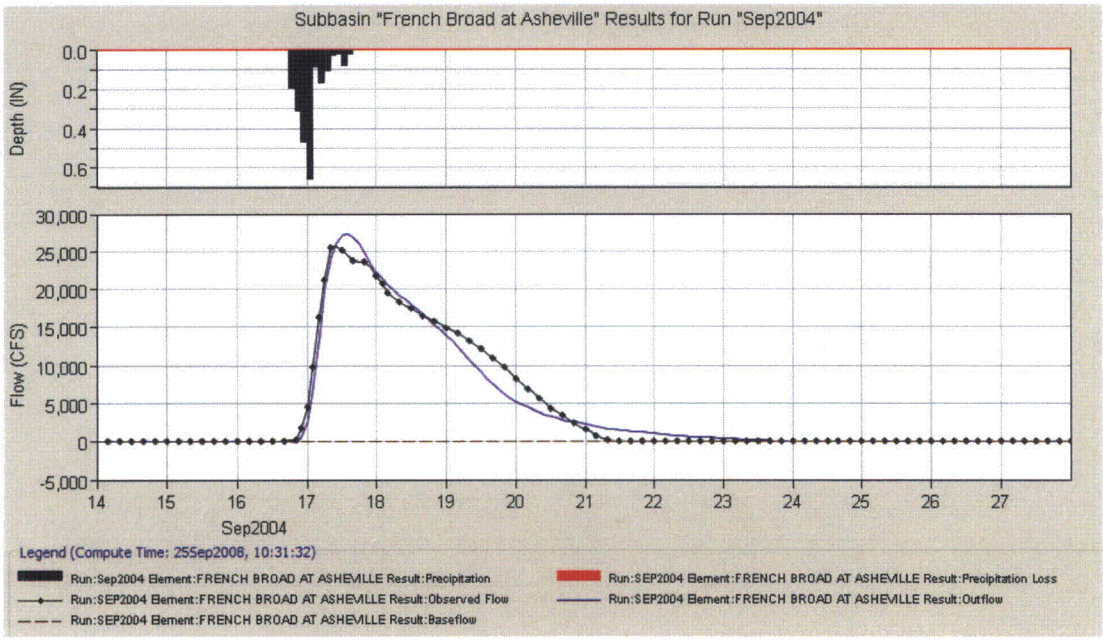
Computed Results

Peak Discharge :	14304.1 (CFS)	Date/Time of Peak Discharge :	07May2003, 16:00
Total Precipitation :	1.42 (IN)	Total Direct Runoff :	1.42 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	1.42 (IN)	Discharge :	1.42 (IN)

Observed Hydrograph at Gage 2003AshvilleLocal

Peak Discharge :	11673.00 (CFS)	Date/Time of Peak Discharge :	06May2003, 22:00
Avg Abs Residual :	685.70 (CFS)		
Total Residual :	-0.02 (IN)	Total Obs Q :	1.44 (IN)

Figure 43: HEC-HMS Graphical Output for the Subbasin 1 Outflow for May 2003



Project: Basin 1
Simulation Run: Sep2004 Subbasin: French Broad at Asheville

Start of Run:	14Sep2004, 00:00	Basin Model:	French Broad 2004
End of Run:	28Sep2004, 00:00	Meteorologic Model:	Sep2004
Compute Time:	25Sep2008, 10:31:32	Control Specifications:	Sep2004

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	27305.0 (CFS)	Date/Time of Peak Discharge :	17Sep2004, 14:00
Total Precipitation :	2.15 (IN)	Total Direct Runoff :	2.15 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	2.15 (IN)	Discharge :	2.15 (IN)

Observed Hydrograph at Gage 2004AshvilleLocal

Peak Discharge :	25704.00 (CFS)	Date/Time of Peak Discharge :	17Sep2004, 10:00
Avg Abs Residual :	631.21 (CFS)		
Total Residual :	-0.06 (IN)	Total Obs Q :	2.21 (IN)

Figure 44: HEC-HMS Graphical Output for the Subbasin 1 Outflow for September 2004

Simulation of the May 2003 flood

The May 2003 observed flow series for subbasin 1, shown with the heavy-dotted black line in the HEC-HMS screen capture provided as Figure 43 is taken from gage records and, therefore, can be considered reliable. The simulated hydrograph, shown in blue, produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown above the hydrograph), is a reasonably good fit to the observed hydrograph.

The three discrete periods of excess rainfall lead the three observed peaks by a reasonable amount of time, providing confidence in the gridded precipitation data. The peaks of the simulated flood hydrograph coincide with the observed peaks, indicating that the timing of the peak of the TVA unit hydrograph developed for the subbasin is valid – even for this relatively complex rain storm. Simulated and observed volumes match quite closely for the May 2003 flood.

The magnitude of the simulated peak discharge is about 23% higher than the observed value and comes after the third burst of rainfall, rather than after the second burst, as observed. Separation of runoff caused by individual bursts of rainfall in complex floods such as this one is usually necessary to obtain a good match. In this case, separation would be difficult at best and because the simulation is conservative, separation was not attempted

Simulation of the September 2004 flood

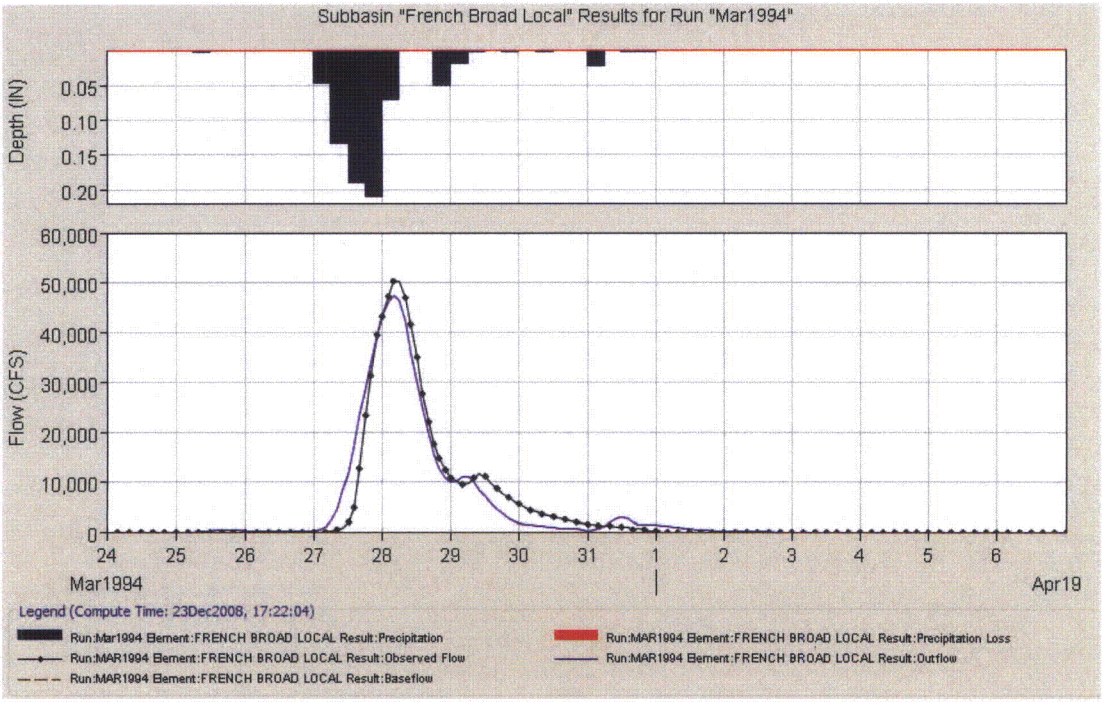
The September 2004 observed flow series, shown with the heavy-dotted black line in the HEC-HMS screen capture provided as Figure 44 is taken from gage records and, therefore, can be considered reliable. The simulated hydrograph, shown in blue, produced from the convolution of the TVA unit hydrograph with excess rainfall hyetograph shown above the hydrograph, is an excellent fit to the observed hydrograph, with the peak discharge overestimated by about 6% and occurring only 4 hours later than the observed peak.

The greater success of the 2004 simulation compared with the 2003 simulation can be attributed to the fact that the rainfall occurred continuously, without interruption.

Based upon the generally good simulation it is concluded that the unit hydrograph developed by the TVA for Subbasin 1 provides a reliable simulation of runoff response to excess rainfall inputs.

7.5.2 Subbasin 2 HEC-HMS Model

The new unit hydrograph developed in this study for the local inflow to the French Broad River near Newport was validated in the HEC-HMS model Basin_02.hms. All Basin_2 project files are provided in electronic format as Attachment 3-2. HEC-HMS graphical output is presented for the March 1994 and January 1996 floods in Figures 45 and 46, respectively.



Project: Basin 02
Simulation Run: Mar1994 Subbasin: French Broad Local

Start of Run:	24Mar1994, 00:00	Basin Model:	French Broad 1994
End of Run:	07Apr1994, 00:00	Meteorologic Model:	Mar1994
Compute Time:	24Dec2008, 10:44:37	Control Specifications:	Mar1994

Volume Units: (•) IN ( ) AC-FT

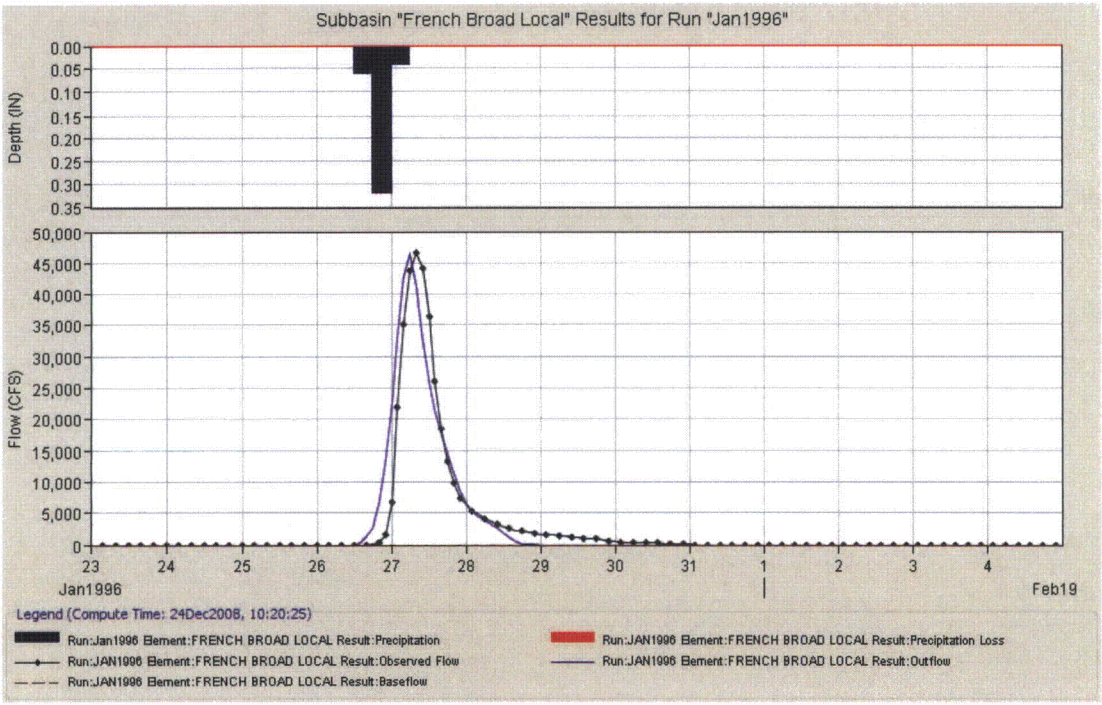
Computed Results

Peak Discharge :	47412.6 (CFS)	Date/Time of Peak Discharge :	28Mar1994, 04:00
Total Precipitation :	2.29 (IN)	Total Direct Runoff :	2.29 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	2.29 (IN)	Discharge :	2.29 (IN)

Observed Hydrograph at Gage 1994NewportLocal

Peak Discharge :	50354.00 (CFS)	Date/Time of Peak Discharge :	28Mar1994, 04:00
Avg Abs Residual :	1045.61 (CFS)		
Total Residual :	-0.04 (IN)	Total Obs Q :	2.33 (IN)

Figure 45: HEC-HMS Graphical Output for the Subbasin 2 Local Inflow for March 1994



Project: Basin 02
Simulation Run: Jan1996 Subbasin: French Broad Local

Start of Run:	23Jan1996, 00:00	Basin Model:	French Broad 1996
End of Run:	05Feb1996, 00:00	Meteorologic Model:	Jan1996
Compute Time:	24Dec2008, 10:20:25	Control Specifications:	Jan1996

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	46416.2 (CFS)	Date/Time of Peak Discharge :	27Jan1996, 06:00
Total Precipitation :	1.26 (IN)	Total Direct Runoff :	1.26 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	1.26 (IN)	Discharge :	1.26 (IN)

Observed Hydrograph at Gage 1996NewportLocal

Peak Discharge :	46688.00 (CFS)	Date/Time of Peak Discharge :	27Jan1996, 08:00
Avg Abs Residual :	803.95 (CFS)		
Total Residual :	0.00 (IN)	Total Obs Q :	1.25 (IN)

Figure 46: HEC-HMS Graphical Output for Subbasin 2 Local Inflow for January 1996

In addition to the local inflow hydrograph for the French Broad River near Newport, the in-stream flow series was simulated in the Basin_02 model by adding the local flow hydrograph to the discharge observed at Asheville, routed downstream (see Figure 11). Comparisons of observed and simulated stream flow for the French Broad River near Newport for the March 1994 and January 1996 floods are provided in Figures 47 and 48.

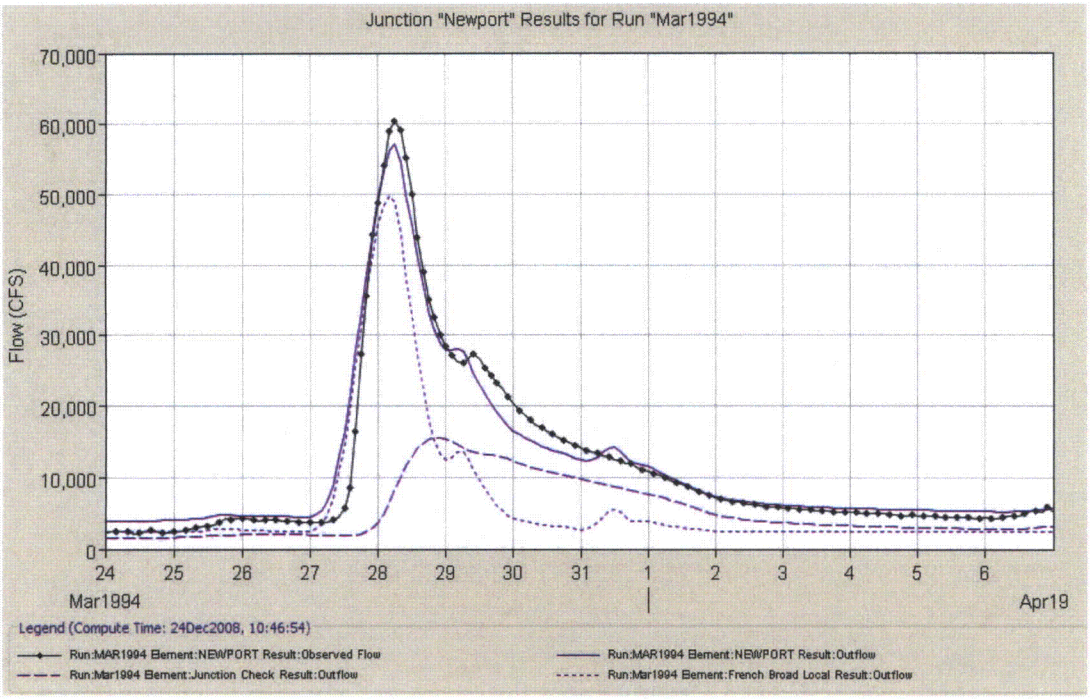


Figure 47: Simulated and Observed March 1994 Flows on the French Broad River near Newport

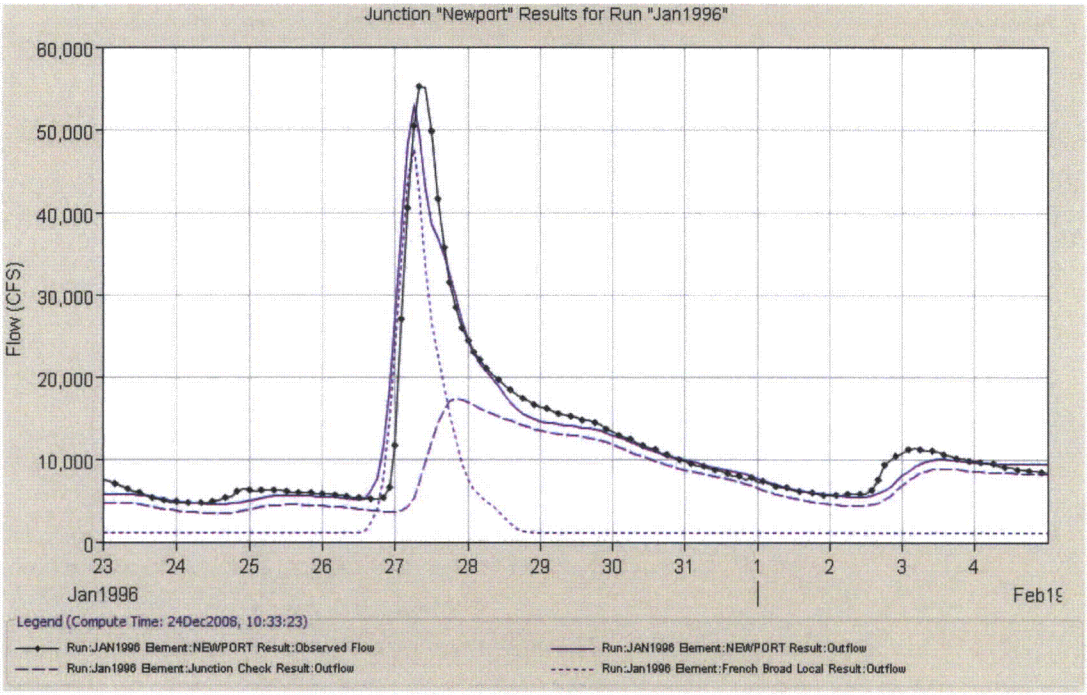


Figure 48: Simulated and Observed Jan. 1996 Flows for the French Broad River near Newport

Simulation of the March 1994 flood

The March 1994 local flow series, shown with the heavy-dotted black line in the HEC-HMS screen capture provided as Figure 45, was developed by routing the observed flow series at Asheville 68 miles downstream to Newport using Muskingum routing parameters provided by the TVA, followed by subtraction from the observed flow series on the French Broad River near Newport. The reliability of this local hydrograph depends on how well the flood routing procedure simulates the actual translation of the flood wave downstream. The simulated hydrograph, shown in blue, represents the local runoff resulting from runoff over Subbasin 2.

Referring to the tabulated values in the bottom half of Figure 45, the computed discharge of 2.29 inches is compared to an observed discharge of 2.33 inches, as determined in HEC-HMS by numerical integration. The difference between observed and simulated volumes is about 2%.

The shape of the simulated hydrograph is a very close match to the observed hydrograph with the peak discharge of 47,413 cfs about 6% below the observed value of 50,354 cfs, and both peaks occurring at the same time.

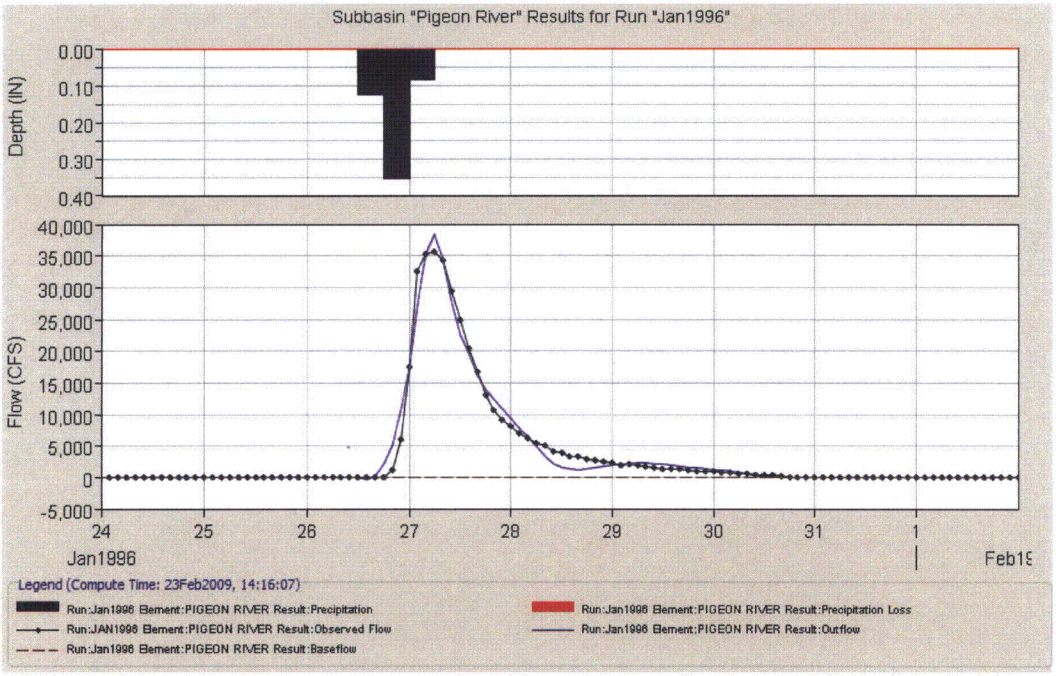
Simulation of the January 1996 flood

The January 1996 "observed" local flow series, shown with the heavy-dotted black line in the HEC-HMS screen capture provided as Figure 46, was developed in the same way as described for the 1994 event. The simulated local hydrograph, shown in blue, reproduces the shape of the observed flow series very closely, except that the rising limb of the simulated hydrograph starts 6 hours before that of the observed hydrograph, and the simulated peak is two hours ahead of the observed. This is an acceptable simulation considering that 6-hour rainfall depths are used. The magnitude of the simulated peak, 46,416 cfs, is approximately equal to the 46,688 cfs observed peak discharge.

Figures 47 and 48 show a comparison of observed and modeled in-stream flows for the French Broad River near Newport in 1994 and 1996, respectively. The observed flow is shown in black; the simulated discharge, shown in blue, is obtained by routing the observed flow series for the French Broad at Asheville down to Newport and adding in the simulated local flow for Subbasin 2 and the estimated base flow. For both runs the timing of the rising and falling limbs and the timing and magnitude of the peak of the two hydrographs agree quite closely with the observed values, validating the routing procedure developed by the TVA. Based on these results it is concluded that the new unit hydrograph for Subbasin 2 provides a reliable simulation of runoff response to excess runoff.

7.5.3 Subbasin 3 HEC-HMS Model

The new unit hydrograph developed in this study for the Pigeon River at Newport was validated in the HEC-HMS model Basin_03.hms. All Basin_03 project files are provided in electronic format as Attachment 3-3. HEC-HMS graphical output is presented for the January 1996 and May 2003 floods in Figures 49 and 50, respectively.



Project: Basin 03
Simulation Run: Jan1996 Subbasin: Pigeon River

Start of Run:	24Jan1996, 00:00	Basin Model:	Pigeon River 1996
End of Run:	02Feb1996, 00:00	Meteorologic Model:	EffJan1996
Compute Time:	23Feb2009, 14:16:07	Control Specifications:	Jan1996

Volume Units: (•) IN ( ) AC-FT

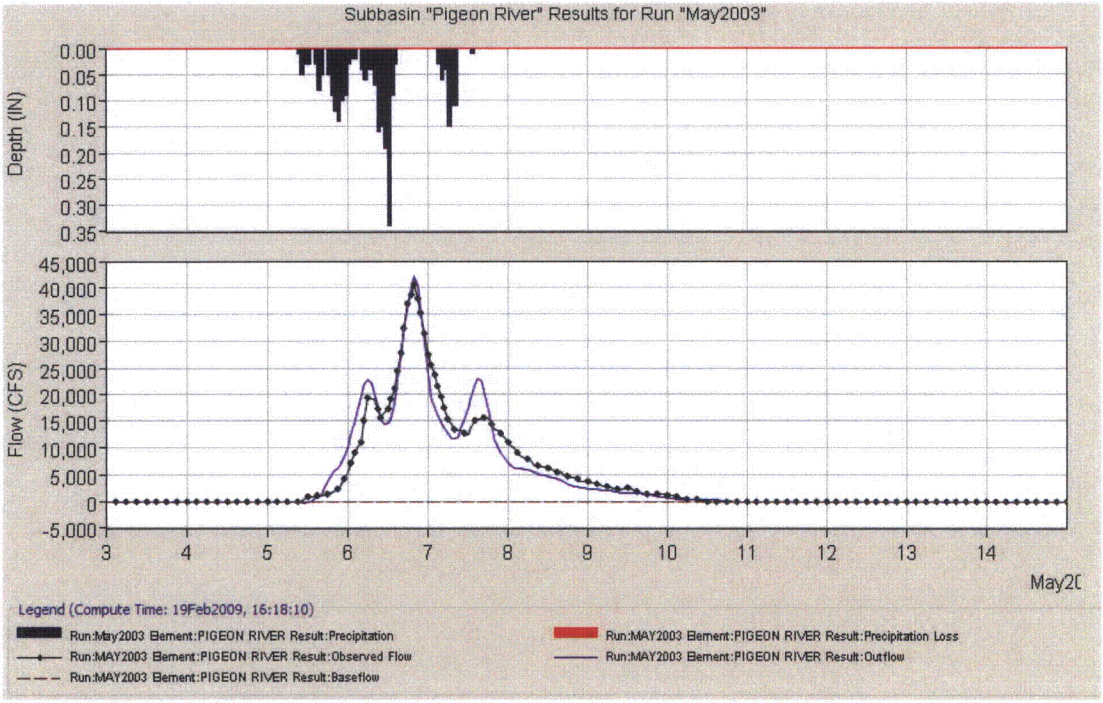
Computed Results

Peak Discharge :	38331.8 (CFS)	Date/Time of Peak Discharge :	27Jan1996, 06:00
Total Precipitation :	1.688 (IN)	Total Direct Runoff :	1.688 (IN)
Total Loss :	0.000 (IN)	Total Baseflow :	0.000 (IN)
Total Excess :	1.688 (IN)	Discharge :	1.688 (IN)

Observed Hydrograph at Gage PigeonJan1996

Peak Discharge :	35555.00 (CFS)	Date/Time of Peak Discharge :	27Jan1996, 06:00
Avg Abs Residual :	496.32 (CFS)		
Total Residual :	-0.003 (IN)	Total Obs Q :	1.69 (IN)

Figure 49: HEC-HMS Graphical Output for the Subbasin 3 Outlet for January 1996



Project: Basin 03
Simulation Run: May2003 Subbasin: Pigeon River

Start of Run:	03May2003, 00:00	Basin Model:	Pigeon River2003
End of Run:	15May2003, 00:00	Meteorologic Model:	EffMay2003
Compute Time:	19Feb2009, 16:18:10	Control Specifications:	May2003

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	42052.2 (CFS)	Date/Time of Peak Discharge :	06May2003, 20:00
Total Precipitation :	2.660 (IN)	Total Direct Runoff :	2.660 (IN)
Total Loss :	0.000 (IN)	Total Baseflow :	0.000 (IN)
Total Excess :	2.660 (IN)	Discharge :	2.660 (IN)

Observed Hydrograph at Gage PigeonMay2003

Peak Discharge :	40475.00 (CFS)	Date/Time of Peak Discharge :	06May2003, 20:00
Avg Abs Residual :	867.03 (CFS)		
Total Residual :	-0.021 (IN)	Total Obs Q :	2.68 (IN)

Figure 50: HEC-HMS Graphical Output for the Subbasin 3 Outlet for May 2003

Simulation of the January 1996 flood

Figure 49 shows the simulated and observed flows on the Pigeon River at Newport for the January 1996 flood.

The heavy-dotted black line is the observed flow series with base flow removed using standard methodology (Figure 26). This permits a direct comparison with the local runoff hydrograph determined by convolution of the unit hydrograph with excess rainfall. The timing of the peak discharge is excellent, and the timing and duration of the rising and falling limbs of the simulated and observed hydrographs are also good.

The six-hour effective rainfall blocks are plotted in the inverted hyetograph at the top of the figure. As noted above, hourly precipitation data were not available for the 1996 year of record. Note the "dip" in the falling limb of the simulated hydrograph below that of the observed flow series. It is possible that that discrepancy could be eliminated by the iterative adjustment of the ordinates on the tail of the unit hydrograph (Figure 8). Since the peak discharge and the rising and falling limbs of the hydrographs are modeled so well, however, this final refinement was not carried out.

Simulation of the May 2003 flood

Figure 50 shows the simulated and observed flows on the Pigeon River at Newport for the May 2003 flood.

As noted above, the heavy-dotted black line is the observed flow series with base flow removed using standard methodology, permitting a direct comparison between the observed flow series and the simulated runoff hydrograph determined by convolution of the unit hydrograph with excess rainfall. The timing of the peaks and the timing and duration of the rising and falling limbs of the simulated and observed hydrographs are very good.

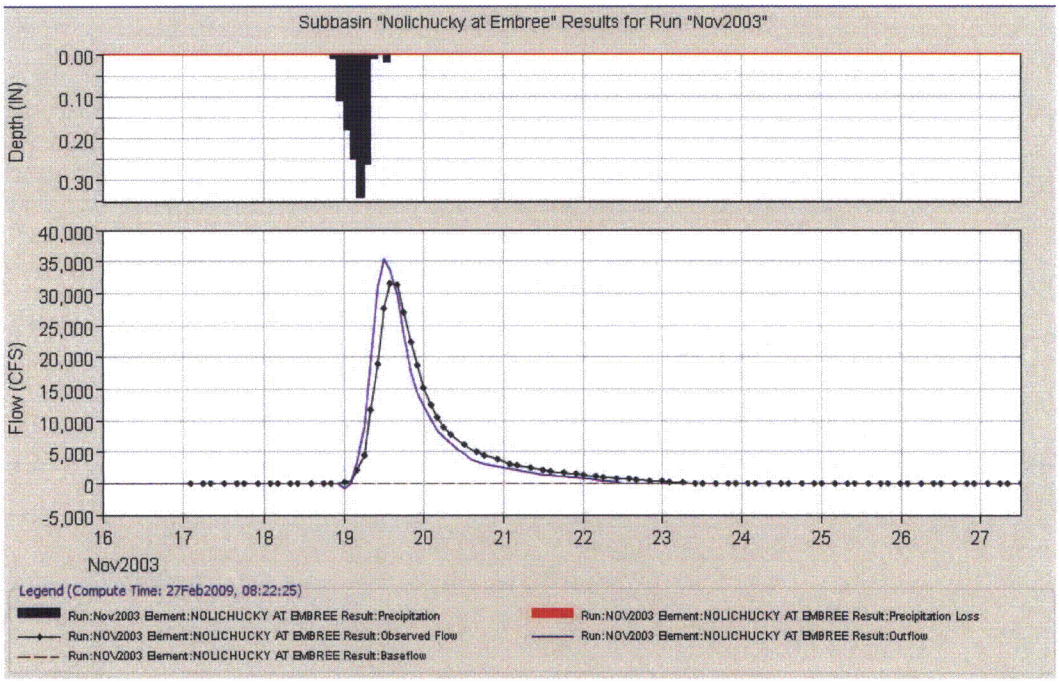
Following TVA methodology, the direct runoff hydrograph was separated into two parts, corresponding to the two isolated periods of continuous rainfall (the first, with two peaks, and the second with a single peak) discernable from the one-hour rainfall data set available for the 2003 storm. The volume of each part was calculated separately to provide the CHKVOL values for two runs of FLDHYDRO, yielding an excess precipitation series that provides a more accurate representation of the runoff from the individual rainfall bursts.

The simulation provides a good match of simulated and observed direct runoff at the site. The timing of the three peaks is duplicated very well, and the magnitudes are in reasonable agreement – with the maximum peak overestimated by only 4%.

Based on the evaluation of the validation runs discussed above, the new unit hydrograph for Subbasin 3 is considered representative of current conditions within the watershed and provides a reliable simulation of runoff response to excess rainfall inputs.

7.5.4 Subbasin 4 HEC-HMS Model

The unit hydrograph developed by the TVA for the Nolichucky River at Embreeville was validated in the HEC-HMS model Basin_04.hms. All Basin_04 project files are provided in electronic format as part of Attachment No. 3-4. HEC-HMS graphical output is presented for the November 2003 and September 2004 floods in Figures 51 and 52, respectively.



Project: Basin 04
Simulation Run: Nov2003 Subbasin: Nolichucky at Embree

Start of Run:	16Nov2003, 00:00	Basin Model:	Nolichucky at Embre NOV 03
End of Run:	27Nov2003, 12:00	Meteorologic Model:	Nov2003
Compute Time:	27Feb2009, 08:22:25	Control Specifications:	Nov2003

Volume Units: (•) IN ( ) AC-FT

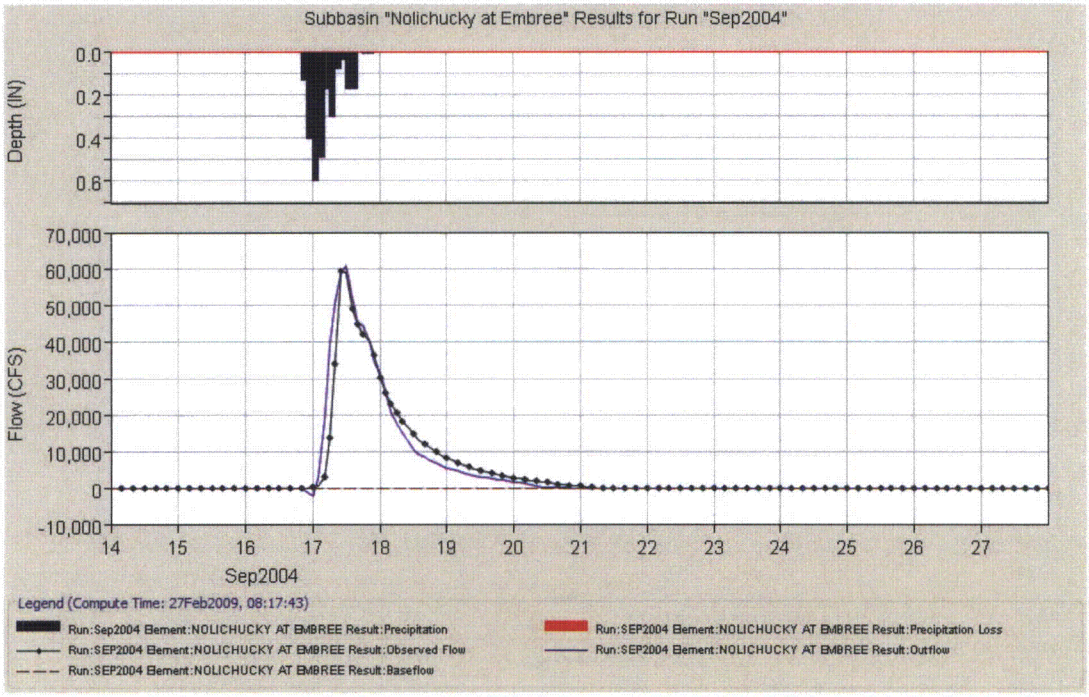
Computed Results

Peak Discharge :	35379.9 (CFS)	Date/Time of Peak Discharge :	19Nov2003, 12:00
Total Precipitation :	1.180 (IN)	Total Direct Runoff :	1.180 (IN)
Total Loss :	0.000 (IN)	Total Baseflow :	0.000 (IN)
Total Excess :	1.180 (IN)	Discharge :	1.180 (IN)

Observed Hydrograph at Gage NolichuckyNov2003

Peak Discharge :	31568.00 (CFS)	Date/Time of Peak Discharge :	19Nov2003, 14:00
Avg Abs Residual :	701.82 (CFS)		
Total Residual :	-0.075 (IN)	Total Obs Q :	1.25 (IN)

Figure 51: HEC-HMS Graphical Output for the Subbasin 4 Outlet for November 2003



Project: Basin 04
Simulation Run: Sep2004 Subbasin: Nolichucky at Embree

Start of Run:	14Sep2004, 00:00	Basin Model:	Nolichucky at Embree2004
End of Run:	28Sep2004, 00:00	Meteorologic Model:	Sep2004
Compute Time:	27Feb2009, 08:17:43	Control Specifications:	Sep2004

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	60989.4 (CFS)	Date/Time of Peak Discharge :	17Sep2004, 12:00
Total Precipitation :	2.570 (IN)	Total Direct Runoff :	2.571 (IN)
Total Loss :	0.000 (IN)	Total Baseflow :	0.000 (IN)
Total Excess :	2.570 (IN)	Discharge :	2.571 (IN)

Observed Hydrograph at Gage Nolichucky2004

Peak Discharge :	59452.00 (CFS)	Date/Time of Peak Discharge :	17Sep2004, 10:00
Avg Abs Residual :	837.68 (CFS)		
Total Residual :	-0.008 (IN)	Total Obs Q :	2.58 (IN)

Figure 52: HEC-HMS Graphical Output for the Subbasin 4 Outlet for September 2004

Simulation of the November 2003 flood

Figure 51 shows the simulated and observed flow series for the Nolichucky River at Embreeville for the November 2003 flood (there was very low flow observed at this location for the May 2003 flood used in the validation for the other subbasins in the watershed). The observed flow series, shown with the heavy

dotted black line was adjusted to remove base flow to permit a direct comparison with the local runoff simulated with the unit hydrograph.

The simulated flow series, shown in blue, preserves the general form of the observed series, although it peaks two hours ahead of the observed hydrograph, and overestimates the peak flow by about 12%.

Simulation of the September 2004 flood

Figure 52 shows the simulated and observed flow series for the Nolichucky River at Embreeville for the September 2004 flood. The observed flow series, shown with the heavy dotted black line was adjusted to remove base flow to permit a direct comparison with the local runoff simulated with the unit hydrograph.

The simulated flow series, shown in blue, matches the timing of the peak discharge, and overestimates the peak flow by about 3%.

Based on these results it is concluded that the unit hydrograph developed by the TVA for Subbasin 4 provides a reliable simulation of runoff response to excess rainfall inputs.

7.5.5 Subbasin 5 HEC-HMS Model

The unit hydrograph developed by the TVA for local inflow from Embreeville to Nolichucky Dam (Subbasin 5) was validated in the "Basin 5 March 2002" and "Basin 5 November 2003" basin models developed within the "Basin_5" HEC-HMS project, shown schematically in Figure 53. All Basin_5 project files are provided in Attachment No. 3-5.

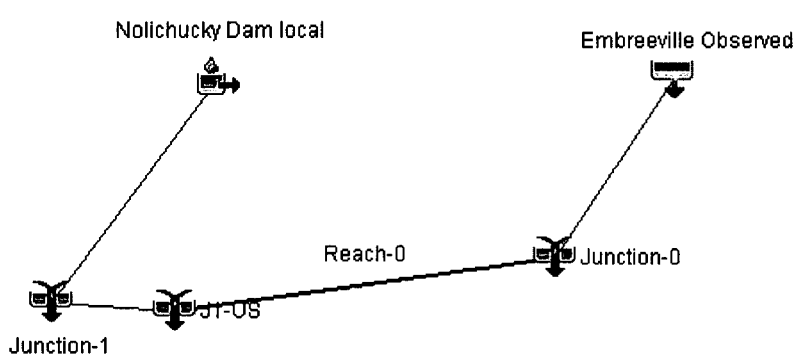
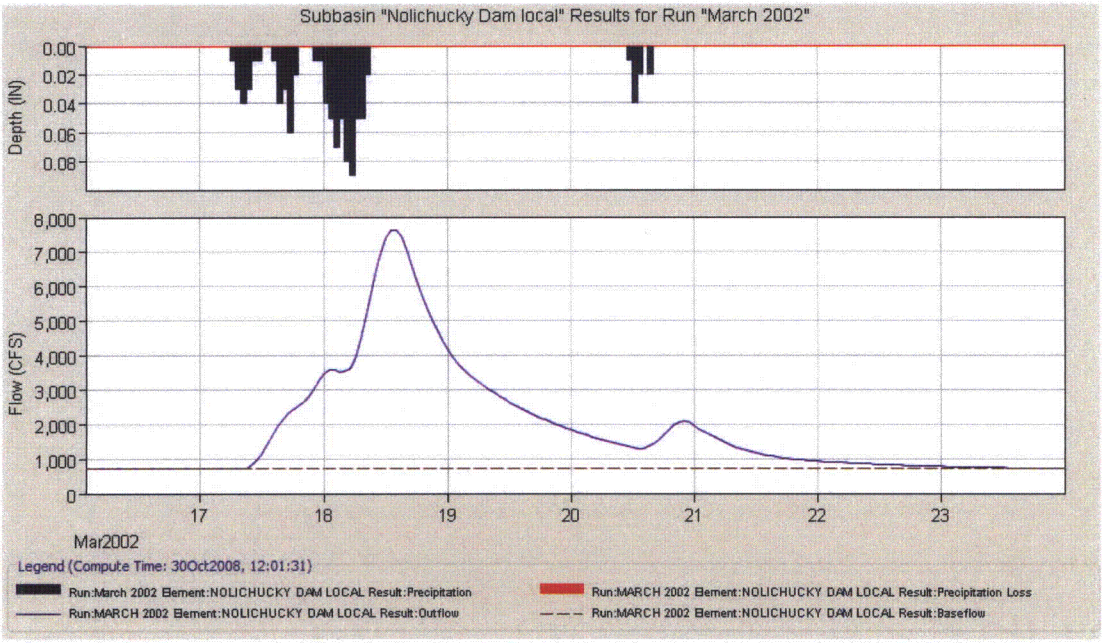


Figure 53: HEC-HMS Schematic of the Nolichucky River from Embreeville to Nolichucky Dam

In theory, a local inflow hydrograph for Basin 5 can be obtained by hydrograph separation, i.e. routing the observed flow series of the Nolichucky River at Embreeville downstream to Nolichucky Dam and subtracting it from the observed flow series at that point. As noted in Section 7.2.5, this operation resulted in unrealistic hydrographs with periods of negative flow, so no reliable local runoff hydrograph could be developed to compare directly with the hydrograph developed from the TVA unit hydrograph.

Because it was not possible to develop realistic local runoff hydrographs, the unit hydrograph was validated indirectly by comparing the observed and simulated flows on the Nolichucky River at Nolichucky Dam, located at the downstream end of Basin 5 (Junction 1 in Figure 53). This hydrograph includes the contribution of the local runoff as well as the inflow from Embreeville routed to Nolichucky Dam.

HEC-HMS graphical output of the local runoff hydrograph and a comparison of the simulated and observed flow series at Junction-1 are presented for the March 2002 flood in Figures 54 and 55, respectively. Similar output is presented for the November 2003 flood in Figures 56 and 57.



Project: Basin_5

Simulation Run: March 2002 Subbasin: Nolichucky Dam local

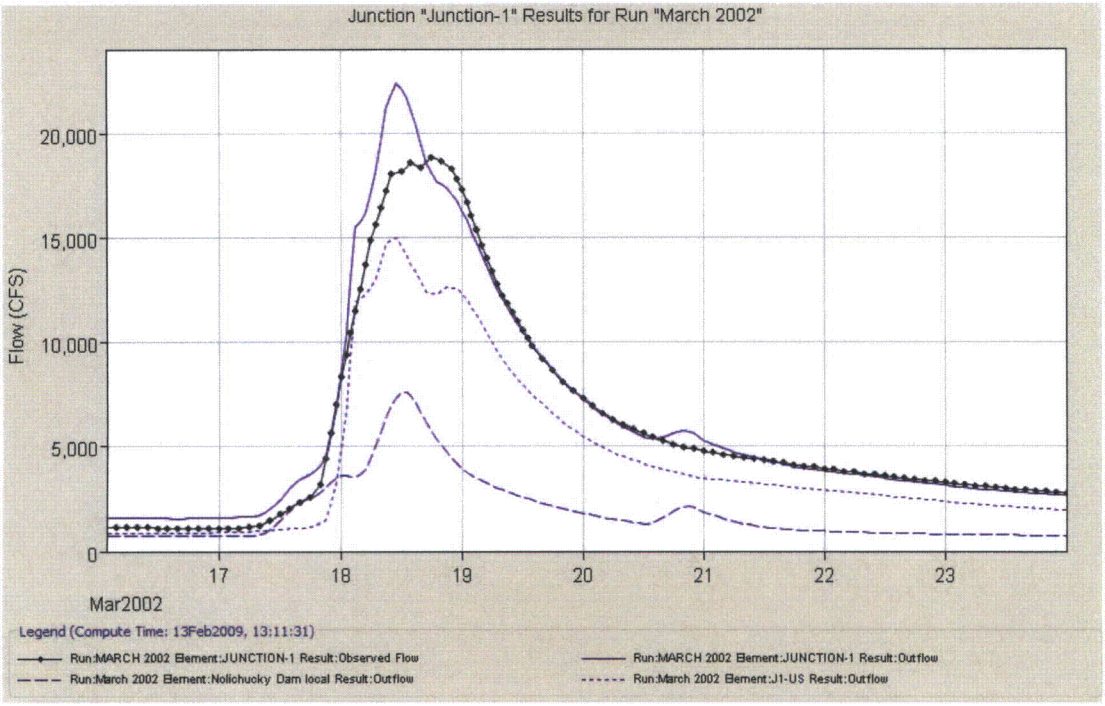
Start of Run:	16Mar2002, 02:00	Basin Model:	Basin 5 March 2002
End of Run:	24Mar2002, 00:00	Meteorologic Model:	Mar2002
Compute Time:	30Oct2008, 12:01:31	Control Specifications:	Mar2002

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	7600.0 (CFS)	Date/Time of Peak Discharge :	18Mar2002, 14:00
Total Precipitation :	0.90 (IN)	Total Direct Runoff :	0.90 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.55 (IN)
Total Excess :	0.90 (IN)	Discharge :	1.46 (IN)

Figure 54: HEC-HMS Graphical Output for the Subbasin 5 Local Inflow for March 2002 (No reliable local flow series could be developed for comparison with the simulated local flow)



Project: Basin_5
Simulation Run: March 2002 Junction: Junction-1

Start of Run:	16Mar2002, 02:00	Basin Model:	Basin 5 March 2002
End of Run:	24Mar2002, 00:00	Meteorologic Model:	Mar2002
Compute Time:	30Oct2008, 12:01:31	Control Specifications:	Mar2002

Volume Units: (•) IN ( ) AC-FT

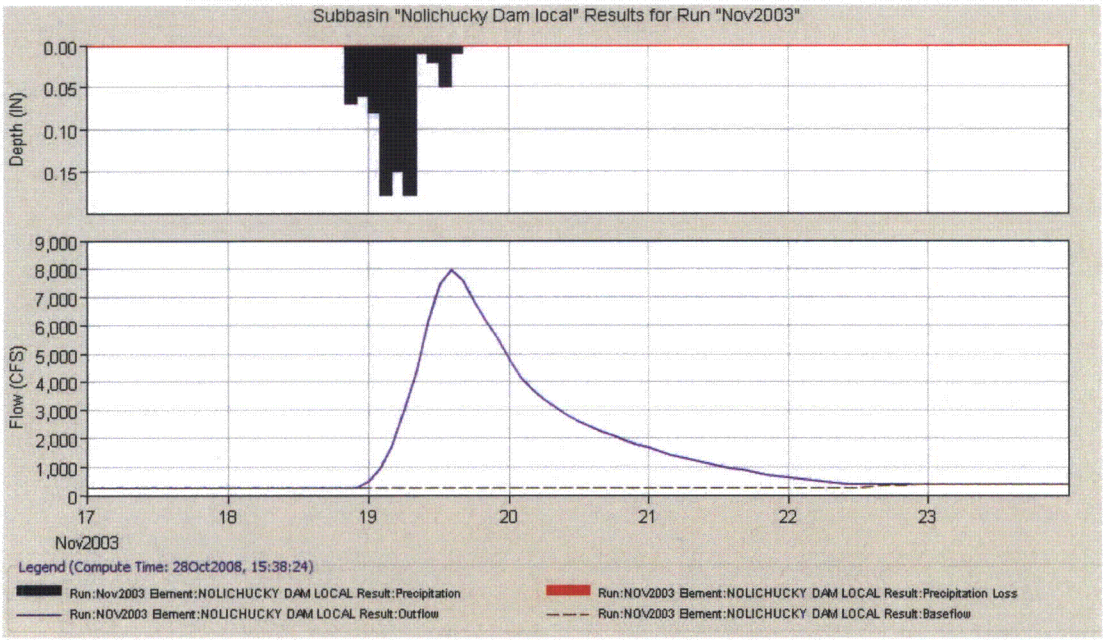
Computed Results

Peak Outflow : 21953.2 (CFS) Date/Time of Peak Outflow : 18Mar2002, 11:00
Total Outflow : (IN)

Observed Hydrograph at Gage Nolichucky 2002

Peak Discharge : 18806.00 (CFS) Date/Time of Peak Discharge : 18Mar2002, 18:00
Avg Abs Residual : 477.29 (CFS)
Total Residual : (IN) Total Obs Q : (IN)

Figure 55: Comparison of Simulated and Observed Flow Series for the Nolichucky River at Nolichucky Dam (Junction-1) for March 2002



Project: Basin_5

Simulation Run: Nov2003 Subbasin: Nolichucky Dam local

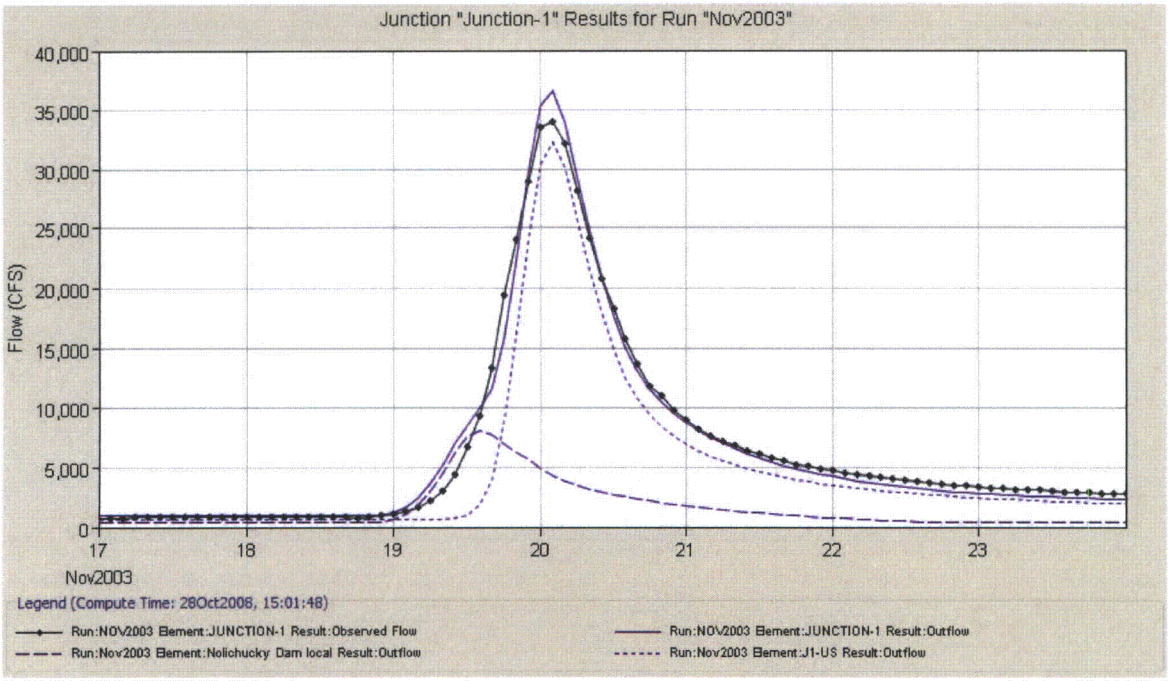
Start of Run:	17Nov2003, 00:00	Basin Model:	Basin5 November2003
End of Run:	24Nov2003, 00:00	Meteorologic Model:	Nov2003
Compute Time:	28Oct2008, 15:38:24	Control Specifications:	Nov2003

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	7950.2 (CFS)	Date/Time of Peak Discharge :	19Nov2003, 14:00
Total Precipitation :	0.81 (IN)	Total Direct Runoff :	0.81 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.19 (IN)
Total Excess :	0.81 (IN)	Discharge :	1.00 (IN)

Figure 56: HEC-HMS Graphical Output for the Subbasin 5 Outlet for November 2003 (No reliable local flow series could be developed for comparison with the simulated local flow)



Project: Basin_5
Simulation Run: Nov2003 Junction: Junction-1

Start of Run:	17Nov2003, 00:00	Basin Model:	Basin5 November2003
End of Run:	24Nov2003, 00:00	Meteorologic Model:	Nov2003
Compute Time:	28Oct2008, 15:01:48	Control Specifications:	Nov2003

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Outflow : 36602.4 (CFS) Date/Time of Peak Outflow : 20Nov2003, 02:00
Total Outflow : (IN)

Observed Hydrograph at Gage NolichuckNov2003

Peak Discharge : 33949.00 (CFS) Date/Time of Peak Discharge : 20Nov2003, 02:00
Avg Abs Residual : 570.30 (CFS)
Total Residual : (IN) Total Obs Q : (IN)

Figure 57: Comparison of Simulated and Observed Flow Series for the Nolichucky River at Nolichucky Dam (Junction-1) for November 2003

Simulation of the March 2002 flood

Figure 54 shows the simulated local runoff hydrograph for Subbasin 5 for the March 2002 flood. As noted above, it was not possible to develop a reliable flow series by hydrograph separation to compare with it. A constant base flow of 709 cfs is added to the local runoff for comparison with observed flows at Nolichucky Dam. The value is obtained by multiplying the observed base flow of 2215 cfs by the ratio of the local flow area and the total drainage area upstream of Nolichucky Dam, i.e. 2215 cfs x 378.7 mi^2/(378.7 mi^2 + 804.8 mi^2) = 709 cfs.

The lag time for routing the Embreeville hydrograph was changed from 540 minutes (as shown in Figure 10) to 660 minutes so that the falling limb of the observed and composite hydrograph would coincide.

The observed flow series for the Nolichucky River at the Nolichucky Dam is shown in Figure 55 with the heavy-dotted black line; the simulated hydrograph is shown with the solid blue line. The two components of this hydrograph are the observed flow series at Embreeville routed downstream to the Nolichucky Dam (the dotted blue line) and the local runoff from Subbasin 5 (the dashed blue line).

The simulated hydrograph compares fairly well with the observed flow series in terms of the timing of the rising and falling limbs of the hydrographs, although the peak discharge is about 19% higher than observed. This may be due to the simplified flood routing used in the model, which does not adequately replicate the complex flood wave attenuation that actually occurs along the reach of the Nolichucky River between Embreeville and Nolichucky Dam, as discussed in Section 7.2.5.

Simulation of the November 2003 flood

Figure 56 shows the simulated local runoff hydrograph for Subbasin 5 for the November 2003 flood (which is larger than the flood occurring in March 2002) For this run, a constant base flow of 256 cfs is added to the local runoff for comparison with observed flows at Nolichucky Dam. The value is obtained by multiplying the observed average base flow of 800 cfs by the ratio of the local flow area and the total drainage area upstream of Nolichucky Dam, i.e. 800 cfs * 378.7 mi^2/(378.7 mi^2 + 804.8 mi^2) = 256 cfs.

The observed flow series at the Nolichucky Dam is shown in Figure 57 with the heavy-dotted black line; the simulated hydrograph is shown with the solid blue line. The two components of this hydrograph are the observed flow series at Embreeville routed downstream to the Nolichucky Dam (the dotted blue line) and the local runoff from Subbasin 5 (the dashed blue line).

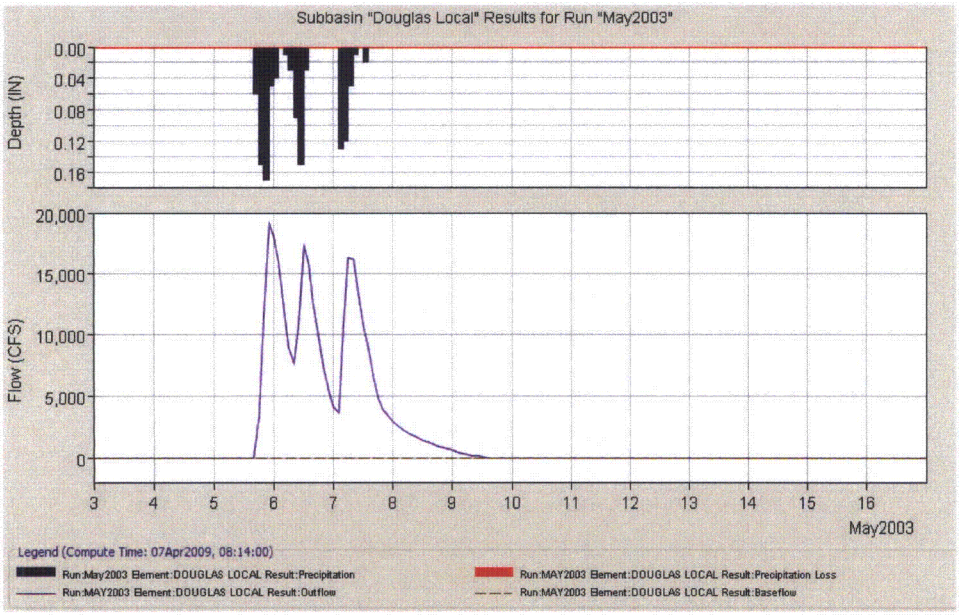
The simulated hydrograph compares quite well with the observed flow series, with the magnitude of the peak discharge being overestimated by about 8%. Also the rising limbs of the observed and simulated hydrographs coincide quite closely, therefore it is concluded that the timing of the local inflow hydrograph simulated with the TVA unit hydrograph is correct.

Based on successful simulations of large and small floods, it is concluded that the unit hydrograph developed for Subbasin 5 is validated indirectly, or "operationally," for the current modeling effort.

7.5.6 Subbasin 6 HEC-HMS Model

The unit hydrograph developed by the TVA for local inflow from the Douglas Dam (Subbasin 6) was validated in the "Douglas Local May 2003" and "Douglas Local 2004" models within the Basin_6.hms project file, shown schematically in Figure 17. All Basin_6 project files are provided in Attachment 3-6.

HEC-HMS graphical output of the local runoff hydrograph and a comparison of the simulated and observed flow series at the reservoir are presented for the May 2003 flood in Figures 58 and 59, respectively. Similar output is presented for the September 2004 flood in Figures 60 and 61.



Project: Basin_6
Simulation Run: May2003 Subbasin: Douglas Local

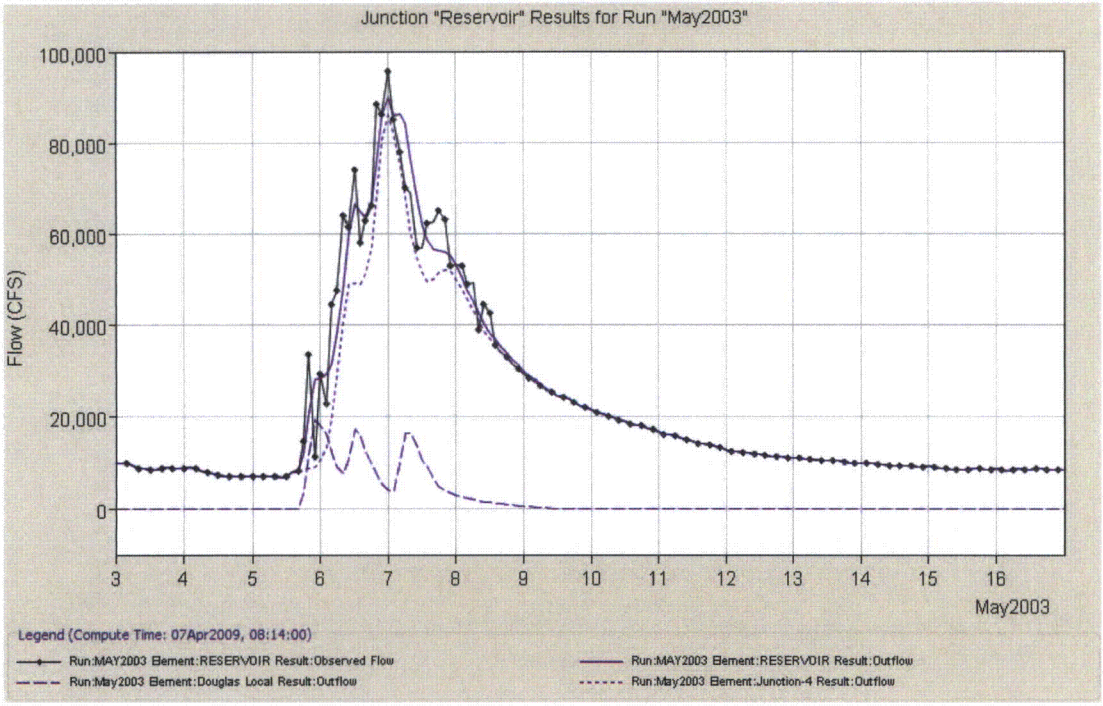
Start of Run:	03May2003, 00:00	Basin Model:	Douglas Local May 2003
End of Run:	17May2003, 00:00	Meteorologic Model:	May2003
Compute Time:	07Apr2009, 08:14:00	Control Specifications:	May2003

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	19157.4 (CFS)	Date/Time of Peak Discharge :	05May2003, 22:00
Total Precipitation :	1.110 (IN)	Total Direct Runoff :	1.110 (IN)
Total Loss :	0.000 (IN)	Total Baseflow :	0.000 (IN)
Total Excess :	1.110 (IN)	Discharge :	1.110 (IN)

Figure 58: HEC-HMS Graphical Output for the Subbasin 6 Local Inflow for May 2003 (No reliable local flow series could be developed for comparison with the simulated local flow)



Project: Basin_6
Simulation Run: May2003 Junction: Reservoir

Start of Run:	03May2003, 00:00	Basin Model:	Douglas Local May 2003
End of Run:	17May2003, 00:00	Meteorologic Model:	May2003
Compute Time:	07Apr2009, 08:14:00	Control Specifications:	May2003

Volume Units: (•) IN ( ) AC-FT

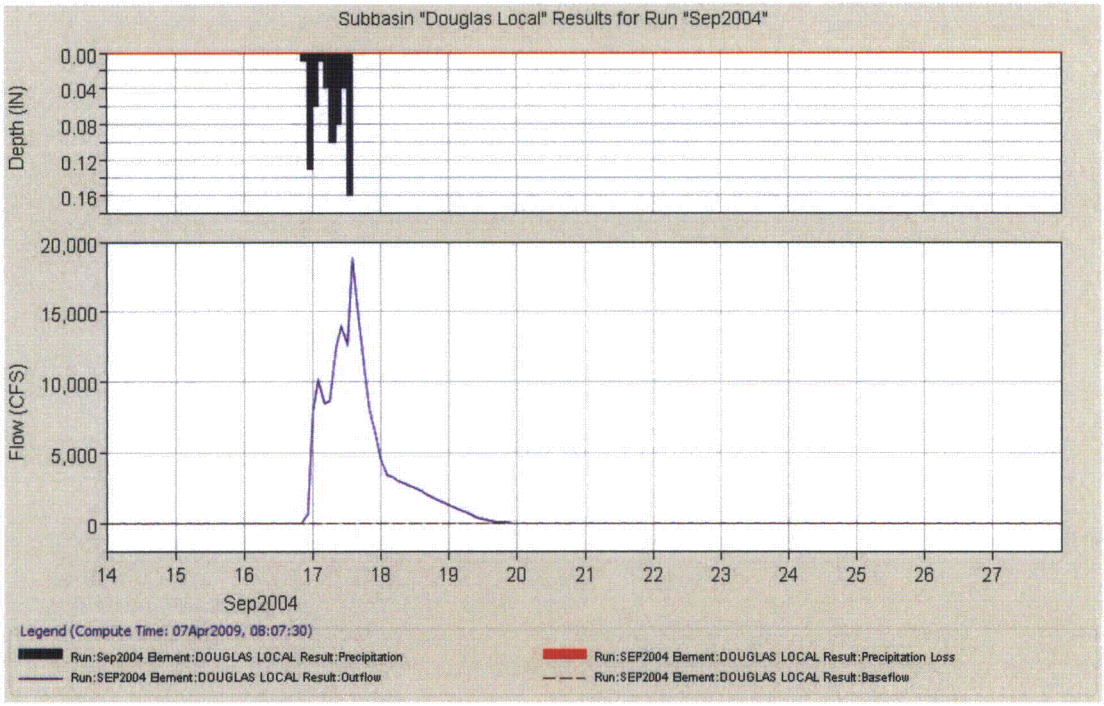
Computed Results

Peak Outflow : 90023.8 (CFS) Date/Time of Peak Outflow : 07May2003, 00:00
Total Outflow : (IN)

Observed Hydrograph at Gage DougDamInflowMay03

Peak Discharge : 95535.00 (CFS) Date/Time of Peak Discharge : 07May2003, 00:00
Avg Abs Residual : 1278.84 (CFS)
Total Residual : (IN) Total Obs Q : (IN)

Figure 59: Comparison of simulated and reverse reservoir routing-derived flow series at Douglas Dam Reservoir for May 2003 (Subbasin 6 Simulation)



Project: Basin_6
Simulation Run: Sep2004 Subbasin: Douglas Local

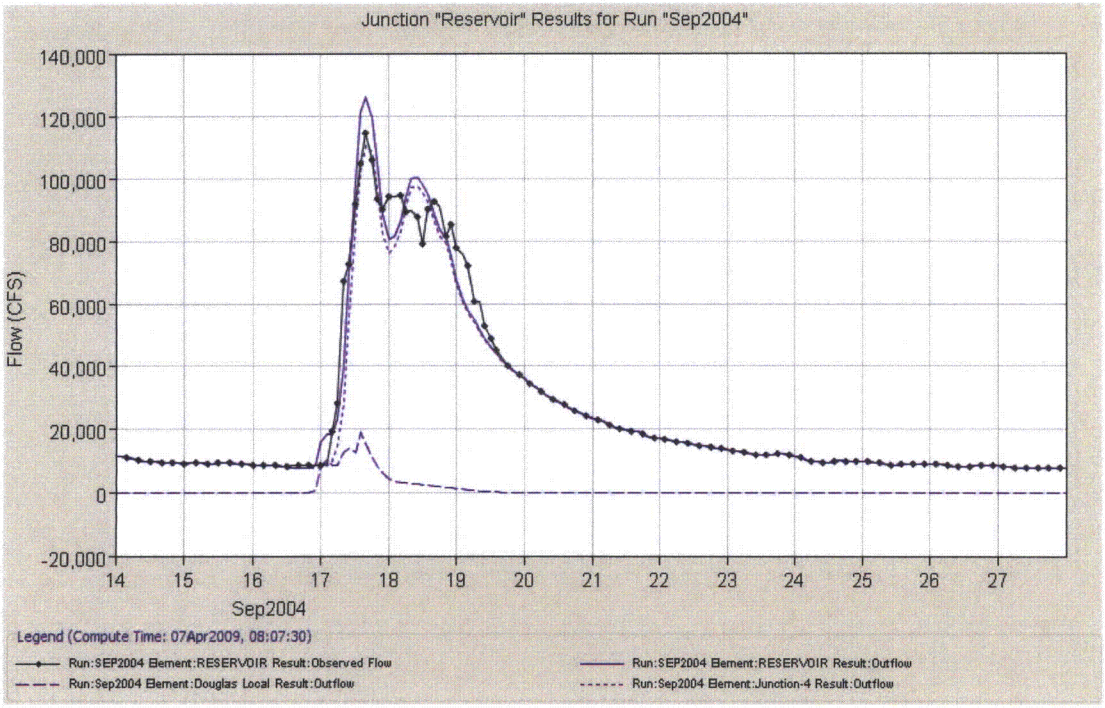
Start of Run:	14Sep2004, 00:00	Basin Model:	Douglas Local 2004
End of Run:	28Sep2004, 00:00	Meteorologic Model:	Sep2004
Compute Time:	07Apr2009, 08:07:30	Control Specifications:	Sep2004

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Discharge :	18846.7 (CFS)	Date/Time of Peak Discharge :	17Sep2004, 14:00
Total Precipitation :	0.630 (IN)	Total Direct Runoff :	0.630 (IN)
Total Loss :	0.000 (IN)	Total Baseflow :	0.000 (IN)
Total Excess :	0.630 (IN)	Discharge :	0.630 (IN)

Figure 60: HEC-HMS Graphical Output for the Subbasin 6 Local Inflow for September 2004 (No reliable local flow series could be developed for comparison with the simulated local flow)



Project: Basin_6
Simulation Run: Sep2004 Junction: Reservoir

Start of Run:	14Sep2004, 00:00	Basin Model:	Douglas Local 2004
End of Run:	28Sep2004, 00:00	Meteorologic Model:	Sep2004
Compute Time:	07Apr2009, 08:07:30	Control Specifications:	Sep2004

Volume Units: (•) IN ( ) AC-FT

Computed Results

Peak Outflow : 125895.1 (CFS) Date/Time of Peak Outflow : 17Sep2004, 16:00
Total Outflow : (IN)

Observed Hydrograph at Gage DougDamInflow2004

Peak Discharge : 114582.00 (CFS) Date/Time of Peak Discharge : 17Sep2004, 16:00
Avg Abs Residual : 1693.66 (CFS)
Total Residual : (IN) Total Obs Q : (IN)

Figure 61: Comparison of simulated and reverse reservoir routing-derived flow series at Douglas Dam Reservoir for September 2004 (Subbasin 6 simulation)

Simulation of the May 2003 flood

Figure 58 shows the simulated local runoff hydrograph for Subbasin 6 for the May 2003 flood. As noted above, a flow series was not computed by hydrograph separation to compare with it. No base flow is added to the local hydrograph for this simulation because it is included in the flow series obtained by reverse reservoir routing.

The observed flow series for the French Broad River at Douglas Dam is shown in Figure 59 with the heavy-dotted black line; the simulated hydrograph is shown with the solid blue line. The components of this hydrograph include the flow series at Junction 4 (the dotted blue line), which is the sum of the observed flows routed down from the Nolichucky Dam, the French Broad River near Newport, and Pigeon River at Newport, and the triple-peaked local runoff from Subbasin 6 (the dashed blue line).

The simulated hydrograph compares very well with the observed flow series in terms of the timing of the rising and falling limbs of the hydrographs and the timing of the peak discharge. The simulated local inflow peak occurs within the early part of the storm and its rising limb is coincident with the rising limb of the observed hydrograph, as would be expected for the local inflow at the outlet of a large watershed. The magnitude of the peak discharge is underestimated by about 6%, which is well within the acceptable error in modeling.

Simulation of the September 2004 flood

Figure 60 shows the simulated local runoff hydrograph for Subbasin 6 for the September 2004 flood. Again, a flow series was not computed by hydrograph separation to compare with it. No base flow is added to the local hydrograph for this simulation because it is included in the flow series obtained by reverse reservoir routing.

The observed and simulated flow series for the French Broad River at Douglas Dam are shown for the September 2004 storm in Figure 61 with similar results. The timing of peak discharge and of the rising and falling limbs of the flood hydrograph are simulated accurately, as is the impact of local flow on the total discharge. The magnitude of the peak discharge is overestimated by about 10%.

Based on the results for simulating these two floods, it is concluded that the unit hydrograph developed by the TVA for Subbasin 6 is validated indirectly, or "operationally," for the current modeling effort.

7.6 Summary of HEC-HMS Modeling Results

A qualitative assessment of the results of the simulations is presented in Table 17. A comparison of the magnitude of peak discharges for each run is provided in Table 18.

Table 17: Qualitative Assessment of Comparison of Observed and Simulated Flood Hydrographs

Point of Comparison & HEC-HMS Model	First Simulation	Second Simulation
Basin 1 outlet French Broad at Asheville (simulation in Basin_1.hms)	May 2003	September 2004
	Figure 43: fair reproduction of observed hydrograph shape; good timing of peak discharge and form of rising limb of hydrograph; fair match to falling limb.	Figure 44: good reproduction of observed hydrograph shape; good timing of peak discharge; excellent timing and length of rising and falling limbs of hydrograph
	Number of peaks coincide; magnitude of peak discharge overestimated 23%	Magnitude of peak discharge overestimated by 6%
Basin 2 Local Inflow French Broad near Newport (Simulation in Basin_2.hms)	March 1994	January 1996
	Figure 45: good reproduction of observed hydrograph shape; good timing of peak discharge and of rising limb; excellent timing and length of falling limb of hydrograph.	Figure 46: good reproduction of observed hydrograph shape; good timing of peak discharge; fair timing of rising limb; good timing falling limb of hydrograph
	Magnitude of peak discharge underestimated by 6%	Magnitude of peak discharge underestimated by less than 1%
In-stream flow French Broad at Newport (Simulation in Basin_2.hms)	March 1994	January 1996
	Figure 47: excellent reproduction of observed hydrograph shape; good timing of peak discharge; excellent timing and length of rising and falling limbs of hydrograph.	Figure 48: excellent reproduction of observed hydrograph shape; fair to good timing of peak discharge; excellent timing and length of rising and falling limbs of hydrograph
	Magnitude of peak discharge underestimated by 5%	Magnitude of peak discharge underestimated by 4%
Basin 3 Outlet Pigeon River at Newport Simulation in Basin_3.hms	January 1996	May 2003
	Figure 49: very good reproduction of observed hydrograph shape; excellent timing of peak discharge; excellent timing and length of rising and falling limbs of hydrograph.	Figure 50: very good reproduction of observed hydrograph shape; excellent timing of peak discharge; excellent timing and length of rising and falling limbs of hydrograph.
	Excellent estimate of peak discharge; magnitude of peak discharge overestimated by about 8%	Fair to good estimate of secondary peaks; magnitude of peak discharge overestimated by 4%
Basin 4 Outlet Nolichucky at Embreeville (Simulation in Basin_4.hms)	November 2003	September 2004
	Figure 51: very good reproduction of observed hydrograph shape; good timing and magnitude of peak discharge; good timing and length of rising and falling limbs of hydrograph	Figure 52: excellent reproduction of observed hydrograph shape; excellent timing and magnitude of peak discharge; good timing and length of rising and falling limbs of hydrograph
	Overestimate of peak discharge by 12%.	Overestimate of peak discharge by 3%.

Table 17 continued

Point of Comparison & HEC-HMS Model	First Simulation	Second Simulation
Subbasin 5 Local Inflow * Nolichucky River Dam (Simulation in Basin_5.hms)	March 2002	November 2003
	Figure 55: fair reproduction of observed hydrograph shape; good timing of rising limb; fair timing of peak; excellent timing and length of falling limb.	Figure 57: excellent reproduction of observed hydrograph shape; good timing of rising limb, good timing of peak; good timing and length of falling limb.
	Peak discharge overestimated by 19%	Peak discharge overestimated by 8%
Subbasin 6 Local Inflow ** Douglas Dam Reservoir Inlet (Simulation in Basin_6.hms)	May 2003	September 2004
	Figure 59: good reproduction of observed hydrograph considering derivation from reverse reservoir routing; good timing for rising limb and timing of multiple peaks; good timing and shape of falling limb of hydrograph	Figure 61: good reproduction of observed hydrograph considering derivation from reverse reservoir routing; good timing for rising limb and timing of multiple peaks; good timing and shape of falling limb of hydrograph
	Peak discharge of maximum peak is underestimated by 6%	Peak discharge of maximum peak is overestimated by 10%

* No "observed" local inflow hydrograph was generated; comparison is made between total simulated and observed instream flow at Nolichucky Dam, just below Subbasin 5

** No "observed" local inflow hydrograph was generated; comparison is made between total simulated flow and "observed flow" at Douglas Dam. "Observed" flow series determined from reverse reservoir routing.

Table 18: Quantitative Comparison of Observed and Simulated Peak Discharges

	First Simulation			Second Simulation		
Point of comparison	Simulated Qpeak	Observed Q peak	% error	Simulated Qpeak	Observed Q peak	% error
Basin 1 outlet (instream)	May 2003			September 2004		
	14,304	11,673	23%	27,305	25,704	6%
Basin 2 outlet (local inflow)	March 1994			January 1996		
	47,413	50,354	-6%	46,416	46,688	-1%
French Broad at Newport (instream)	March 1994			January 1996		
	57,158	60,484	-5%	52,918	55,133	-4%
Basin 3 outlet (instream)	January 1996			May 2003		
	38,332	35,555	8%	42,052	40,475	4%
Basin 4 outlet (instream)	November 2003			September 2004		
	35,380	31,568	12%	60,989	59,452	3%
Nollichucky Dam (instream, including Subbasin 5)	March 2002			November 2003		
	22,363	18,806	19%	36,602	33,949	8%
Douglas Dam Reservoir Inflow (Subbasin 6 simulation)	May 2003			September 2004		
	90,024	95,535	-6%	125,895	114,582	10%

8 SUMMARY & CONCLUSIONS

Following NRC requirements, the unit hydrographs developed by the TVA for four of the six subbasins plus two new unit hydrographs developed for two subbasins within the Douglas Dam watershed were directly or indirectly validated by using them in HEC-HMS to simulate runoff for the highest two floods with suitable precipitation data within the period of record from 1986 to 2007, utilizing the gridded precipitation data from the period between 1999 and 2007 wherever possible.

Observed rainfall was converted to excess rainfall using rainfall-runoff relations embedded in the TVA's FLDHYDRO program. The effective rainfall was used as input to HEC-HMS to simulate stream flow at the basin outlet which was compared to observed discharges, obtained from direct measurement or estimated with hydrograph separation as necessary.

Qualitative and quantitative assessments of the success of the simulations in duplicating observed stream flow series are provided in Table 17 and 18, respectively.

In general, very good agreement between simulated and observed flows was obtained for the headwater catchments of the French Broad at Asheville, the Pigeon River at Newport, and the Nolichucky River at Embreeville (Subbasins 1, 3, and 4). For headwater basins, it is only necessary to remove base flow from the observed flow series to compare observed and simulated local hydrographs.

Very good agreement between the simulated and observed local inflow hydrographs was also obtained for the French Broad River near Newport (Subbasin 2), which required stream flow routing and hydrograph separation to convert the observed in-stream hydrographs to local inflow hydrographs before a comparison with the simulated inflow series could be made.

In theory it is also possible to develop local inflow hydrographs for the Nolichucky River at Nolichucky Dam and the French Broad River at Douglas Dam (Subbasins 5 and 6) by hydrograph separation. However, because of the inaccuracies inherent in inflow calculated using reverse reservoir routing, which is sensitive to small changes in headwater elevations, and the fact that the lag routing used for these reaches does not account for attenuation, hydrograph separation resulted in seriously distorted local inflow hydrograph shapes and negative flows.

Validation was accomplished "operationally," or indirectly, by comparing the downstream observed and simulated in-stream hydrographs, which includes the impact of the local inflow hydrograph developed by convoluting effective rainfall with the unit hydrograph. Effective rainfall volumes were estimated from lumped runoff volumes. Very good agreement was obtained between the simulated and observed in-stream flow series, indicating that the local inflow hydrographs are reasonable.

Based on the preceding discussion, it is concluded that the unit hydrographs for the six subbasins of the Douglas Dam watershed (Subbasins 1 thorough 6) have each been validated against two recent floods. Considering that, with the exception of Subbasins 2 and 3, the unit hydrographs were developed from

floods from the 1970s and earlier, and have been demonstrated in this calculation to be valid for events that occurred in more recent years, it is concluded that watershed characteristics and runoff processes have remained relatively stationary. It is also concluded that each of the unit hydrographs accurately describes the response of its catchment and is adequate for application to design storm events.

In almost all cases of discrepancies between observed and simulated storm hydrographs (where the "observed" or synthesized hydrographs are reliable), the problems may plausibly be attributed to uncertainties in the modeling of rainfall excess values with FLDHYDRO.

Since the unit hydrographs have been demonstrated to provide a reasonable response to a unit of excess rainfall (i.e. good estimates of peak discharge, good timing of peaks, shape of hydrograph especially with respect to timing and the duration of rising and falling limbs), these unit hydrographs are valid for use in hydrologic studies to determine the Probable Maximum Flood (PMF) at the TVA Nuclear Plant sites (see Section 1).

8.1 Validated Unit Hydrographs

Four of the original TVA unit hydrographs were validated for two recent flood events in this calculation. Preliminary analysis indicated that the original Subbasin 2 and 3 unit hydrographs did not provide acceptable results. The unit hydrograph for Subbasin 2 was redeveloped using rainfall and stream flow data from the 1973 and 2004 floods; the unit hydrograph for Subbasin 3 was redeveloped using data from the 1994 and 2004 floods. Each of the new unit hydrographs were validated for two recent floods. Because the local flood hydrographs for Subbasins 5 and 6 were not directly reproduced in this calculation, the unit hydrographs were not validated in the traditional sense; an "operational" validation was achieved by reproducing the total flows at the outlet.

The key parameters associated with the final unit hydrographs validated in this calculation are summarized in Table 19 (the original parameters are summarized in Table 2). The ordinates for all six unit hydrographs are summarized in Table 20 and are provided in spreadsheet form as Attachment 1-31 to facilitate use in subsequent modeling efforts.

Table 19: Final Unit Hydrograph Parameters for the Subbasins of the Douglas Dam Watershed

Subbasin	Effective Duration, hrs	Number of ordinates	Qpeak, cfs	Peak Time, hours	Area, sq. mi.	Volume, acft	Volume inches
1	6	29	14,000	12	944.4	50,355	1.000
2	6	9	43,114	12	913.1	48,698	1.000
3	6	16	30,910	12	667.1	35,575	1.000
4	4	21	33,275	12	804.8	42,934	1.000
5	6	16	11,740	12	378.7	20,226	1.001
6	6	11	47,207	6	835.0	44,533	1.000

Table 20: Unit Hydrograph Ordinates for the Subbasins of the Douglas Dam Watershed (see Attachment 1-31 for spreadsheet data)

UH 1 (duration = 6 hrs)

Time, hrs	Q, cfs/in
0	0
6	4,000
12	14,000
18	13,500
24	10,800
30	9,400
36	8,600
42	7,800
48	6,800
54	5,800
60	4,600
66	3,500
72	2,600
78	2,000
84	1,600
90	1,300
96	1,100
102	900
108	700
114	600
120	500
126	400
132	300
138	250
144	200
150	150
156	100
162	50
168	0

UH 2 (duration = 6 hrs)

Time, hrs	Q, cfs/in
0	0
6	15,374
12	43,114
18	18,839
24	11,712
30	4,585
36	3,057
42	1,528
48	0

UH 3 (duration = 6 hrs)

Time, hrs	Q, cfs/in
0	0
6	5,543
12	30,910
18	11,024
24	8,367
30	5,710
36	3,053
42	396
48	746
54	1,097
60	1,448
66	1,213
72	979
78	744
84	510
90	0

UH 4 (duration = 4 hrs)

Time, hrs	Q, cfs/in
0	0
4	1,355
8	30,641
12	33,275
16	17,109
20	12,449
24	7,790
28	6,203
32	4,615
36	3,027
40	2,665
44	2,304
48	1,943
52	1,581
56	1,220
60	1,060
64	900
68	740
72	580
76	419
80	0

UH 5 (duration = 6 hrs)

Time, hrs	Q, cfs/in
0	0
6	3,310
12	11,740
18	7,630
24	4,720
30	3,510
36	2,710
42	2,110
48	1,610
54	1,200
60	900
66	600
72	400
78	250
84	100
90	0

UH 6 (duration = 6 hrs)

Time, hrs	Q, cfs/in
0	0
6	47,207
12	19,655
18	6,103
24	5,162
30	4,220
36	3,278
42	2,336
48	1,395
54	453
60	0

8.2 Validated Routing Parameters

The routing parameters utilized by the TVA in modeling stream flow in the Douglas Dam watershed have been indirectly validated by use in the models described in the body of this report and are suitable for appropriate, joint use with the unit hydrographs in subsequent hydrologic studies to determine the Probable Maximum Flood (PMF) at the TVA Nuclear Plant sites (see Section 1).

The routing parameters used in the hydrologic modeling, presented in Section 7.2 of this calculation are summarized in Table 21 and are provided in spreadsheet form as Attachment 1-31 to facilitate use in subsequent modeling efforts.

Table 21: Routing Parameters used in Hydrologic Modeling of the Douglas Dam Watershed

Model	River	Reach	Type of Routing	C_0	C_1	C_2	Δt, hours
Subbasin 2	French Broad	Asheville to Marshall	Muskingum	0.38	0.45	0.17	6.00
	French Broad	Marshall to Hot Springs	Muskingum	0.32	0.73	-0.05	4.00
	French Broad	Hot Springs to Newport	Muskingum	0.29	0.65	0.06	8.00
Subbasin 5	Nolichucky	Embreeville to Nolichucky Dam	Straight Lag	n/a	n/a	n/a	9.00
Subbasin 6	Nolichucky	Nolichucky Dam to Douglas Dam	Straight Lag	n/a	n/a	n/a	12.00
	French Broad	Newport to Douglas Dam	Straight Lag	n/a	n/a	n/a	3.00
	Pigeon	Newport to Douglas Dam	Straight Lag	n/a	n/a	n/a	3.00