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

ASSOCIATED ATTACHMENTS/ENCLOSURES:

Attachment 02.04.03-8AL: Unit Hydrograph Validation for Subbasin 44A, the Lower Hiwassee River from Charleston (River Mile 18.9) to Apalachia and Ocoee No. 1 Dams

(32 Pages including Cover Sheet)

NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV 0 EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58 090216 006	calculations(nuclear)	L58 091230 047

Calc Title: Unit Hydrograph Validation for Subbasin 44A, the Lower Hiwassee River from Charleston (River Mile 18.9) to Apalachia and Ocoee No. 1 Dams

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080071	1	2	Entire calc ☒ Selected pages ☐

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 7	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Carrie L. Stokes	12/11/09	Karl Stickley	12/11/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Karl Stickley	12/11/09	K.R. Stokes	12/23/09

STATEMENT OF PROBLEM/ABSTRACT

Validate the existing unit hydrograph for the Lower Hiwassee River from the Charleston gage at River Mile 18.9 to Apalachia and Ocoee No. 1 Dams for two 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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REV 0 EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58 090216 006	calculations(nuclear)	L58 090707 002

Calc Title: Unit Hydrograph Validation for Subbasin 44A, the Lower Hiwassee River from Charleston (River Mile 18.9) to Apalachia and Ocoee No. 1 Dams

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080071	0	1	Entire calc ☒ Selected pages ☐
NEW	CN	NUC						

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
PDMADDUX	(423) 751-8015	CEB	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Perry D. Maddux	07/01/2009	Dennis L. Lundy	7-1-09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Dennis L. Lundy	7-1-09	for K.R. Spates	7-2-09

SCB

STATEMENT OF PROBLEM/ABSTRACT

Validate the existing unit hydrograph for the Lower Hiwassee River from the Charleston gage at River Mile 18.9 to Apalachia and Ocoee No. 1 Dams for two recent floods.

Revision 1 Issued to address PER 171268, and lift UVA.

*EDCN Numbers:
WBN: 54018
SQN: 22404
BFN: (Later)

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

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CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	REV
	CN	NUC	GEN	CEB	CDQ000020080071	2

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	CO	GEN	CEB	FLDHYDRO Version 1.0	
A	P	CO	GEN	CEB	UNITGRPH 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 CDQ000020080071

Title: Unit Hydrograph Validation for Subbasin 44A, the Lower Hiwassee River from Charleston (River Mile 18.9) to Apalachia and Ocoee No. 1 Dams.

Revision No.	DESCRIPTION OF REVISION
0	Initial issue
1	Revision 1 lifts the UVA under Section 3.2, and addresses PER 171268, which identified an incorrect version of FLDHYDRO that was used in development of Revision 0 of this calculation. The UVA was lifted by issuance of the SPP 2.6 software documentation (Users Manual - Ref. 3) for FLDHYDRO, and Reference 2.3 was revised to reflect the EDMS number of the issued document. Two electronically attached FLDHYDRO output files were replaced with equivalent files generated using current QA Version 1.0 of FLDHYDRO, dated 11/04/2008. Results of FLDHYDRO and this calculation were unaffected by the version change. Revised page 12 to add the word "data" following the word "precipitation" in the ANSI/ANI-2.8-1992 quotation. Significant changes in Revision 1 are noted with a right margin revision bar. Pages replaced: 1, 2, 3, 6, 9, 12 Pages Added / Deleted: None Attachments 3-2 and 3-4 (electronically attached FLDHYDRO output files) were replaced. See page 6 for the listing of file names and their associated attachment numbers. Total pages of calculation hardcopy for Revision 1 = 29 pages
2	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 204081- The verification of Rev 1 of the calculation was completed by a TVA Project Engineer with expired qualifications. • PER 203872 – Replace NEDP 2 forms on pages 2 through 6 with the forms from the NEDP-2 Revision in effect at the time of calculations issuance Significant changes in Revision 2 are noted with a right margin revision bar. Administrative changes and typos are excluded. Pages Added: 1a & 7a Pages Replaced: 1-7 & 9 Total pages of calculation hard copy for Revision 2= 31

NPG CALCULATION TABLE OF CONTENTS

Calculation Identifier: CDQ000020080071 | Revision: 2

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

NPG COMPUTER INPUT FILE STORAGE INFORMATION SHEET

Document CDQ000020080071	Rev. 2	Plant: GEN	

Subject: Unit Hydrograph Validation for Subbasin 44A, the Lower Hiwassee River from Charleston (River Mile 18.9) to Apalachia and Ocoee No. 1 Dams

☐ 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.)

Electronic Attachment	Name of File or Folder	File Location
Supporting Spreadsheets		
Attachment 1-1	Unit Hydrograph for Subbasin 44A.xls	Attached to PDF
Attachment 1-2	Hiwassee peak_discharge.txt	Attached to PDF
Attachment 1-3	apalachia.xls (TVA hourly Apalachia Reservoir database)	Attached to PDF
Attachment 1-4	ocoeeno1.xls(TVA hourly Ocoee No. 1 Reservoir database)	Attached to PDF
Attachment 1-5	Subbasin 44A precipitation data.xls	Attached to PDF
Attachment 1-6	Hiwassee River - Hydrograph Separation.xls	Attached to PDF
Attachment 1-7	Hiwassee River - Baseflow Separation.xls	Attached to PDF
Attachment 1-8	Subbasin 44A FLDHYDRO & HEC-HMS Results.xls	Attached to PDF
UNITGRPH Files		
Attachment 2-1	Basin44A_Composite.dat	Attached to PDF
Attachment 2-2	Basin44A_Composite.out	Attached to PDF
Attachment 2-3	Basin44A_Composite.plt	Attached to PDF
FLDHYDRO Files		
Attachment 3-1	44A_May2003_CHKVOL.dat	Attached to PDF
Attachment 3-2	44A_May2003_CHKVOL.out (Revised by Revision 1)	Attached to PDF
Attachment 3-3	44A_Sept2004_CHKVOL.dat	Attached to PDF
Attachment 3-4	44A_Sept2004_CHKVOL.out (Revised by Revision 1)	Attached to PDF
HEC-HMS File Folders		
Attachment 4-1	Basin 44A_ CDQ000020080071.zip (HEC-HMS files)	Filekeeper No. 311365

☐ Microfiche/eFiche

NPG CALCULATION VERIFICATION FORM

Calculation Identifier CDQ000020080071 Revision 2

Method of verification used:

1. Design Review ☒
2. Alternate Calculation ☐
3. Qualification Test ☐

Verifier Karl E. Stickley Date 12/11/09

Comments:

This calculation entitled, "Unit Hydrograph Validation for Subbasin 44A, the Lower Hiwassee River from Charleston (River Mile 18.9) to Apalachia and Ocoee No. 1 Dams" was verified by 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. The inputs were reviewed and determined to be appropriate inputs for this calculation. The results of the calculation were reviewed and were found to be reasonable and consistent with the inputs provided. Backup files and documents were consulted as necessary to verify data and analysis details found in the calculation.

Detailed comments and editorial suggestions for the changes made in this revision were transmitted to the author and reviewer by email along with a marked up copy of the calculation.

FLDHYDRO input files for this calculation were developed with a check volume used to calibrate the modeled. This is an acceptable practice, but the FLDHYDRO output calibrated with a check volume should have been compared to FLDHYDRO output for the same storm that was not calibrated with a check volume. This comparison allows better selection of storms that have runoff and environmental characteristics most compatible with the FLDHYDRO program. This verification process included a comparison of FLDHYDRO runs calibrated with check volumes and FLDHYDRO runs that were not calibrated with check volumes, no notable discrepancies were found.

The calculations tried to use a straight-line interpolation between data points for the S-Graph Method. This resulted in a "stair-step" hydrograph with a steep rise in one hour followed by a horizontal line for the subsequent time periods (Figure 4). A curvilinear approximation of the S-Graph should have been used to determine the hourly data points, which would have resulted in a smooth hydrograph. As the "stair-step" hydrograph was not adopted for use, the methodology does not materially affect the results of the calculations.

(Note: The design verification of this calculation revision is for the total calculation, not just the changes made in the revision. This complete re-verification is performed to disposition PER 203951 as described in the Calculation Revision Log on Page 3)

NPG CALCULATION VERIFICATION FORM

Calculation Identifier CDQ000020080071 Revision 0

Method of verification used:

1. Design Review ☒
2. Alternate Calculation ☐
3. Qualification Test ☐

Verifier Bob Swain Date 2/4/2009

Comments:

The calculation entitled, "Unit Hydrograph Validation for Subbasin 44A, the Lower Hiwassee River from Charleston (River Mile 18.9) to Apalachia and Ocoee No 1 Dams" 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. All of the comments were minor in nature. Most of the editorial suggestions were adopted in the final document.

The primary issue raised during the verification process was with the method of calculating the one-hour unit hydrograph. Originally, the one-hour unit hydrograph was derived from the six-hour unit hydrograph provided by the TVA using the S-graph method in a spreadsheet application. The approach produced a one-hour unit hydrograph that was correct but had the shape of a step function. In keeping with the process used in previous calculations, the one-hour unit hydrograph was recomputed using the S-graph approach found in the computer program HEC-HMS. This did not result in a significantly different unit hydrograph; however, the unit hydrograph had a smoother shape. When the unit hydrograph was applied to the precipitation excess for the 2004 storm, the comparison between the simulated and observed floods was fair. For the simulation of the 2003 flood, which is more than twice as large as the 2004 flood, the comparison between the simulated and observed floods was excellent.

Based on the successful simulations of the May 2003 and September 2004 floods, the calculation supports the conclusion that the unit hydrograph developed for Subbasin 44A has been validated against recent floods.

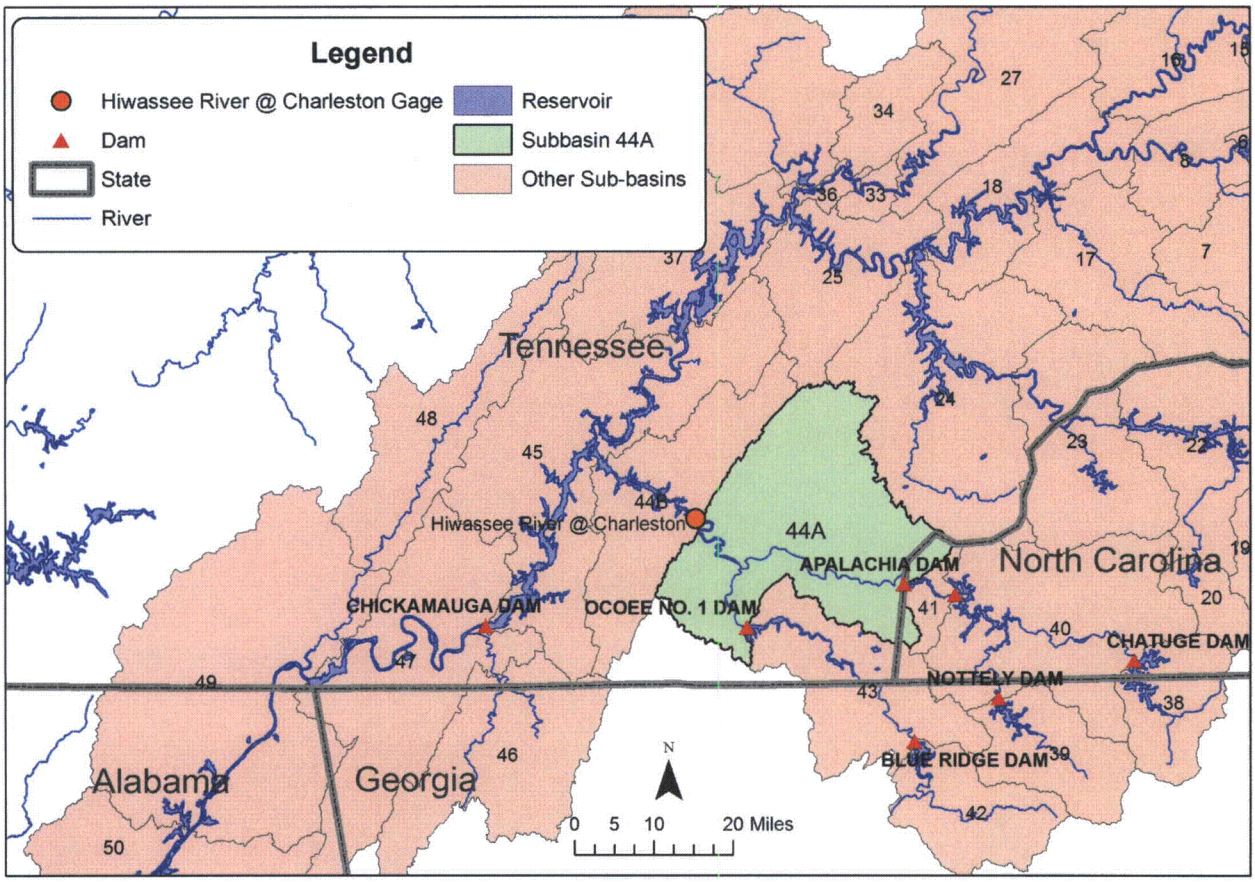
1 Purpose

The TVA's 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 1) of the Tennessee River upstream of the Guntersville Dam for use in the Probable Maximum Flood (PMF) and dam break analysis for the proposed Bellefonte Nuclear Power Plant site.

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 1970s and early 1980s, using observed rainfall and streamflow 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 hydrograph developed by the TVA in 1988 for subbasin 44A, the Lower Hiwassee River from Charleston, at River Mile (RM) 18.9, to Apalachia and Ocoee No. 1 Dams (Reference 2). This subbasin is located in the Tennessee River watershed as shown in Figure 1.

Figure 1: Hydrologic Map of Subbasin 44A.



2 References

1. Tennessee Valley Authority, Bellefonte Nuclear Plant - White Paper, Hydrologic Analysis, Revision 1, July 25, 2008, (EDMS No. L58 081219 800). FOR INFORMATION ONLY
2. Tennessee Valley Authority, Untitled File Book Reference for Subbasin 44A called "Untitled.pdf" (EDMS No. L58 081223 830).
3. Tennessee Valley Authority, *UNITGRPH-FLDHYDRO-TRBROUTE-CHANROUT User's Manual*, Version 1.0, November 2008 (EDMS No. L58 090325 001).
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6. USGS Water-Data Report 2007 for gage 03566000 Hiwassee River at Charleston, TN, available online at: http://wdr.water.usgs.gov/, accessed on Nov. 11, 2008.
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9. U.S. Army Corps of Engineers, *Hydrologic Modeling System HEC-HMS User's Manual*, Version 3.2, April 2008.
10. U.S. Army Corps of Engineers, *Hydrologic Modeling System HEC-HMS Technical Reference Manual*, March 2000.
11. USGS, Hourly discharge data for years 1998 to 2007 at gage 03566000 Hiwasseee River at Charleston, TN, provided via email from George S. Law, USGS Tennessee Water Science Center, Nashville, TN on Oct. 30, 2008.
12. Tennessee Valley Authority, Calculation No. CDQ000020080055, Processing and Validation of National Weather Service's NEXRAD Stage III Hourly Precipitation Data for Hydrologic and Hydraulic Analysis of Watersheds, Revision 3
13. Linsley, R.K., Kohler, M.A., and J.L.H.Paulhus, *Hydrology for Engineers*, McGraw-Hill Book Company, 1982.
14. Kohler, M.A., and R.K. Linsley, Predicting the Runoff from Storm Rainfall, *Research Paper No. 34*, U.S. Department of Commerce, September 1951. (EDMS No. L58 080910 001)

3 Assumptions

3.1 General Assumptions

None.

3.2 Unverified Assumptions

None.

4 Background

4.1 Unit Hydrograph Theory

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 4 and 5).

The unit hydrograph is used to obtain the streamflow hydrograph resulting from a series of excess rainfall inputs of any depth using the process of "convolution." The discrete convolution equation, states that the streamflow, Q, is obtained by summing the products of the excess rainfall depths (direct runoff depths), P, and the unit hydrograph ordinates, U (References 4 and 5). The reverse process, called deconvolution, is used to derive the ordinates of the unit hydrograph by reconstituting floods from precipitation and streamflow data. The unit hydrograph is derived from the unit duration of uniform excess precipitation applied evenly across the watershed.

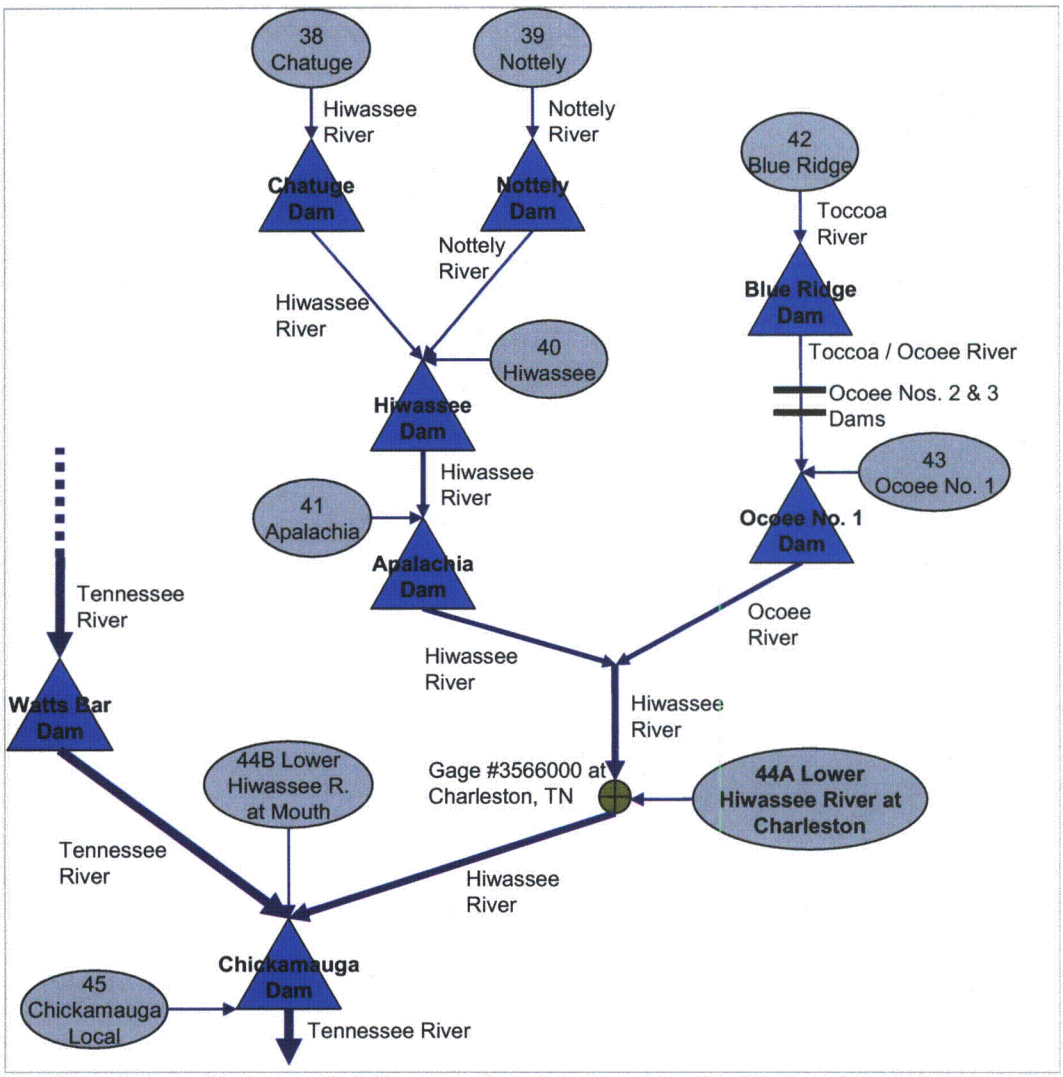
Unit hydrograph theory is applicable under the following conditions (Reference 5):

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."

4.2 Subbasin 44A

A hydrologic map of subbasin 44A, the Lower Hiwassee River from Charleston, at River Mile (RM) 18.9, to Apalachia and Ocoee No. 1 Dams is shown in Figure 1 above. A schematic diagram of the Hiwassee River system, including subbasin 44A, is shown in Figure 2.

Figure 2: Schematic of the Hiwassee River Portion of the Tennessee River System.



Note: Circles indicate subbasins, triangles indicate reservoirs, and blue arrows show flow directions of rivers.

As may be seen from Figure 2, the flows of the Hiwassee River at Charleston are affected by multiple upstream dams. In addition, due to backwater effects, reverse flows at Charleston have occurred for short periods in each year since closure of Chickamauga Dam downstream on the Tennessee River in 1939 (Reference 6).

5 Methodology

The methodology used for unit hydrograph validation follows that described in ANSI/ANS-2.8-1992 (Reference 7). 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 8). 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 hydrograph for Subbasin 44A, the period of record from which the highest two floods are selected extends 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 6.3. Furthermore, since the original unit hydrograph for Subbasin 44A was developed from floods that occurred between 1963 and 1973 (Section 6.1), it was necessary to use recent rainfall and streamflow 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 this unit hydrograph validation includes the following steps:

1. Screen historical streamflow data from the 1997-2007 period to identify the two highest floods. These floods are used for unit hydrograph validation.
2. Obtain the observed hydrograph data for the two floods and transfer the flow series to the subbasin outlet using established hydrologic procedures, as necessary, 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 the direct runoff based on the 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 3). 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 9 and 10) using 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.

6 Design Input Data

The input data necessary for validating the unit hydrograph for Subbasin 44A, the Lower Hiwassee River from Charleston (RM 18.9) to Apalachia and Ocoee No. 1 Dams, are summarized below.

- Unit hydrograph ordinates and duration
- Observed flows of the Hiwassee River at Charleston

-
- Observed outflows from Apalachia and Ocoee No. 1 Dams
- Routing parameters for the reaches between Apalachia and Ocoee No. 1 Dams and Charleston
- Observed rainfall data associated with the selected recent floods

Each of these inputs is described in more detail in the following sub-sections.

6.1 Unit Hydrograph Ordinates

The TVA File Book (Reference 2) indicates a drainage area of 685 square miles for subbasin 44A. The GIS calculated drainage area for the basin yielded 686.6 square miles, which agrees within 0.23% of the original TVA estimate. The GIS drainage area was used in the present calculation.

The six-hour unit hydrograph for subbasin 44A is presented in column "K" on page 45 in the TVA File Book (Reference 2). The unit hydrograph was developed in 1988 using the TVA's UNITGRPH computer program to compute a composite from three floods that occurred in March 1963, March 1965, and March 1973. The calculated unit hydrograph was then manually smoothed by the TVA. It should be noted that the daily average discharge values were disaggregated to obtain the six-hour discharge data utilized in the unit hydrograph derivation. Considering this, the unit hydrograph may perform better when applied to longer duration storms than to brief storms, because the timing of the six-hour discharges may not be as well resolved as if six-hour data had been available.

The TVA inputs for the UNITGRPH program for subbasin 44A were obtained from Reference 2 and reran using the revised 2008 version UNITGRPH program to verify the existing TVA unit hydrograph, which was developed in 1988. Attachments 2-1 to 2-3 provide the input and output files for this verification. The TVA's original unit hydrograph for subbasin 44A is used in the analyses presented in this calculation.

The subbasin 44A unit hydrograph is plotted in Figure 3. The time base and ordinates for the derived unit hydrograph are provided in Table 1, along with a volume check demonstrating that the total volume of runoff is equivalent to one inch of excess rainfall over the subbasin. The unit hydrograph discharges are specified in units of cubic feet per second (cfs).

Figure 3: Six-Hour Unit Hydrograph for Subbasin 44A, the Hiwassee River from Charleston (RM 18.9) to Apalachia and Ocoee No. 1 Dams.

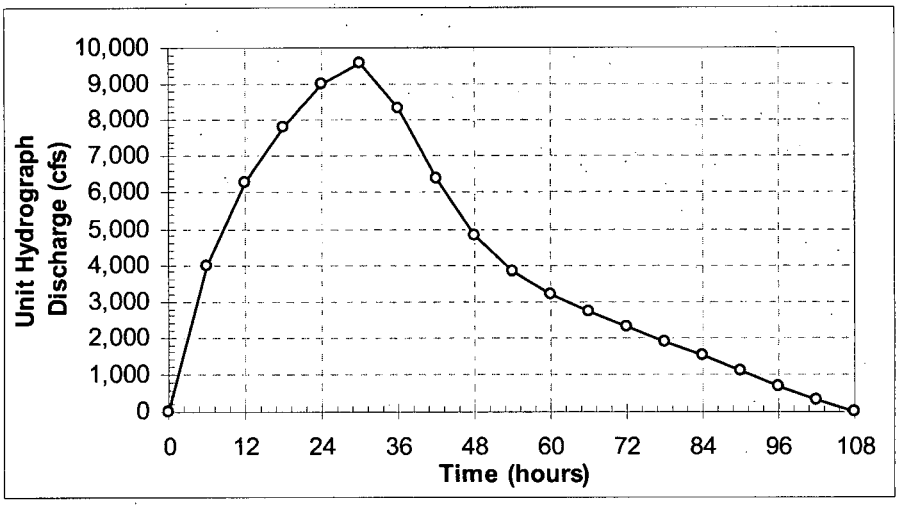


Table 1: Six-Hour Unit Hydrograph for Subbasin 44A, the Hiwassee River from Charleston (RM 18.9) to Apalachia and Ocoee No. 1 Dams (Reference 2).

Ordinate no.	t, hours	Q, cfs
1	0	0
2	6	4,000
3	12	6,300
4	18	7,800
5	24	9,000
6	30	9,600
7	36	8,300
8	42	6,400
9	48	4,800
10	54	3,800
11	60	3,200
12	66	2,700
13	72	2,300
14	78	1,900
15	84	1,500
16	90	1,100
17	96	700
18	102	300
19	108	0
Volume, acre-feet (1)		36,545
Drainage Area (square miles)		686.6
Runoff depth, inches (2)		0.99799

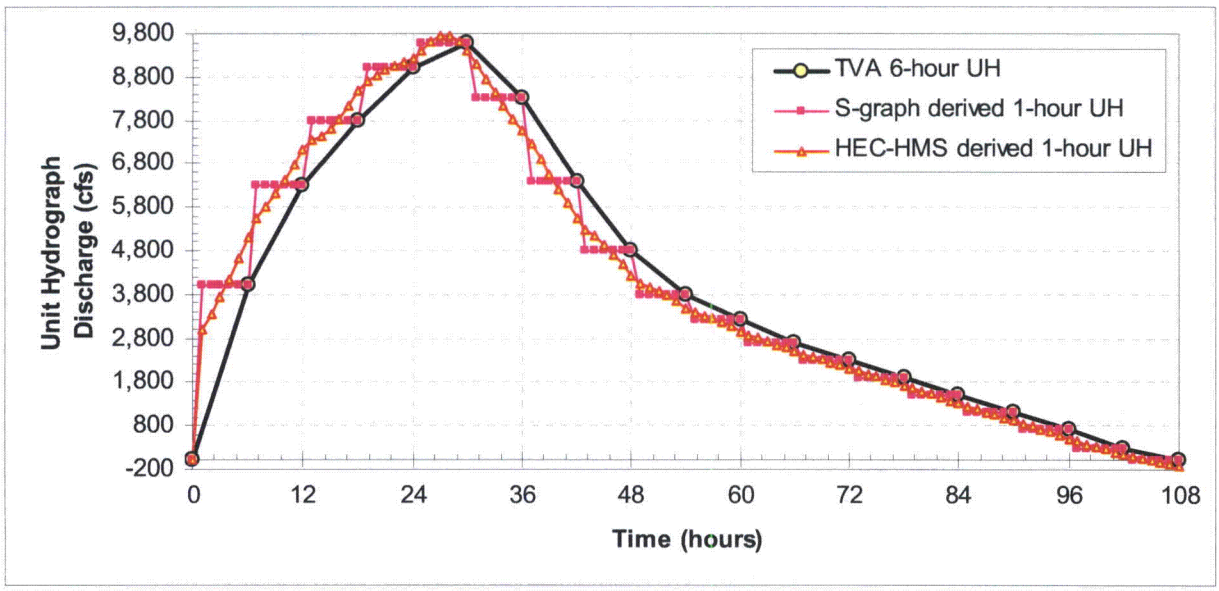
Notes:

1) $$Volume = \sum_{i=1}^{19} Q_i \frac{ft^3}{\sec} \times 3600 \frac{\sec}{hr} \times 6hrs \times \frac{1acft}{43560\, ft^3}$$

2) $$Depth = \frac{Volume.acft}{Area.mi^2} \frac{mi^2}{640.acre} \frac{12.inch}{ft}$$

Due to the availability of hourly precipitation and discharge data (Sections 7.4 and 7.3), HEC-HMS model simulations were performed using a one-hour time step. Therefore, a one-hour unit hydrograph was derived from the TVA's six-hour unit hydrograph via the S-hydrograph method (Reference 5; Attachment 1-1) and also via the HEC-HMS software. The HEC-HMS software uses the S-hydrograph method, but also applies some internal smoothing / shaping. The resulting one-hour unit hydrographs are shown in Figure 4, along with the original six-hour unit hydrograph for comparison.

Figure 4: Derived One-Hour Unit Hydrographs, Along with the TVA's Six-Hour Unit Hydrograph, for Subbasin 44A Hiwassee River at Charleston.



It may be seen from Figure 4 that the 1-hour unit hydrographs are very similar, except that the HEC-HMS derived unit hydrograph has a smoother shape. The total UH flow volumes are equal. The HEC-HMS derived 1-hour UH has three small negative discharge ordinates in its tail which may produce some instances of minor negative flows when convoluted with excess precipitation. Otherwise, both 1-hour unit hydrographs will yield very similar results. Because the S-hydrograph method is reversible, the one-hour unit hydrographs are both equivalent to the TVA's original six-hour unit hydrograph.

6.2 Observed Flows

Annual peak discharge records for the U.S. Geological Survey (USGS) gage 03566000 Hiwassee River at Charleston, Tennessee were obtained from the National Water Information System (NWIS) for the available period of record (Attachment 1-2). The hourly discharges at this gage were obtained for years 1998 to 2007 from the USGS (Reference 11; Attachment 1-6). Although, hourly flows were not obtained for the year 1997, the USGS peak flow records indicate that the peak discharge for 1997 was smaller than at least six other annual peak discharges in the past 11 years. Therefore, the 1998 to 2007 period of hourly flow data is considered adequate for this calculation. The implied assumption, that for

large floods the peak gage flows provide an indication of the peak local runoff, was confirmed by the hydrograph separation analysis (Section 7.2).

In addition to the observed flows at Charleston, the observed hourly outflows from Apalachia Dam and from Ocoee No. 1 Dam were obtained from the TVA databases (Attachments 1-3 and 1-4). These observed flows were used in the hydrograph separation analysis (Section 7.2).

6.3 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 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 12). 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 12 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.

7 Computations and Analyses

7.1 Floods for Unit Hydrograph Validation

Two recent storms/floods were selected for the validation process based on the availability of rainfall and streamflow data. Gridded hourly rainfall data for the period from 1997 to 2007 are available from the U.S. National Weather Service (NWS) Lower Mississippi River Forecast Center (LMRFC). In addition, hourly discharges for the USGS gage 03566000 Hiwassee River at Charleston were obtained for the period 1998 to 2007 (Reference 11; Attachment 1-6).

Based on the hourly flow data, the two largest floods in recent years occurred in May 2003 and September 2004. The gridded hourly rainfall data are available for the periods preceding and during these storms. Therefore, these storms were selected for use in the unit hydrograph validation process. The storms span the following times:

- May 4, 2003, 00:00 hrs to May 11, 2003, 00:00 hrs, the "May 2003" storm
- September 15, 2004, 00:00 hrs to September 21, 2004, 00:00 hrs, the "Sept. 2004" storm

7.2 Hydrograph Separation

The available streamflow data are the observed hourly flows of the Hiwassee River at the Charleston gage (Reference 11) and the hourly discharges from Apalachia and Ocoee No. 1 Dams (Attachments 1-3 and 1-4). The observed flows at Charleston reflect the combined effects of upstream reservoir storage and releases as well as local runoff. To determine the local flows for subbasin 44A, the discharges from Apalachia and Ocoee No. 1 Dams were routed to the Charleston gage and subtracted from the observed flows; this procedure is referred to as hydrograph separation. According to Reference 2, the TVA uses straight lag routing for the Hiwassee River reach from Apalachia Dam to Charleston, with a fixed lag time of 12 hours. For the Ocoee-Hiwassee River reach from Ocoee No. 1 Dam to Charleston, Muskingum routing is used with the parameters (Reference 2, pages 23-30):

$$C_1 = 0.14 \quad C_2 = 0.29 \quad C_3 = 0.57,$$

where C_1, C_2, and C_3 are coefficients in the routing equation that calculates the reach outflow, O_t, (at Charleston) at time t as:

$$O_t = C_1 I_t + C_2 I_{t-1} + C_3 O_{t-1},$$

in which I_t is the reach inflow at Ocoee No. 1 Dam at time t, and I_{t-1} and O_{t-1} are respectively the reach inflow and the reach outflow at time t-1 (Reference 4). The TVA performed its flow routing calculations using a six-hour time step or time increment; this time step was also used in the present hydrograph separation analysis. The flow routing and hydrograph separation calculations are contained in the spreadsheet "Hiwassee River – Hydrograph Separation.xls" (Attachment 1-6).

In order to identify the largest local runoff events in recent years, the hydrograph separation calculations were performed for the nine largest floods indicated by the hourly gage flow record. The results of this analysis are summarized in Table 2.

Table 2: Maximum Observed Hourly Flows for the Nine Largest Floods During 1998-2007, and Corresponding Maximum 6-Hour Local Flows for Subbasin 44A.

Rank	Observed Hourly Gage Flow		Max 6-Hour Local Flow	
	Discharge (cfs)	Date & Hour	Discharge (cfs)	Date & Hour
1	64,963	5/7/03 21:00	51,594	5/7/03 6:00
2	33,261	9/17/04 20:00	20,906	9/17/04 18:00
3	27,483	11/24/04 23:00	20,797	11/25/04 0:00
4	27,059	12/9/04 20:00	18,039	12/10/04 0:00
5	26,501	2/22/03 21:00	20,022	2/23/03 0:00
6	25,232	12/7/04 10:00	16,952	12/7/04 6:00
7	24,509	1/25/02 7:00	17,340	1/25/02 12:00
8	24,347	4/4/00 7:00	17,276	4/4/00 12:00
9	24,234	7/2/03 15:00	11,126	7/2/03 11:00

It may be seen from Table 2 that the two largest discharges among the calculated six-hour local flows occurred during the same floods as the two largest observed hourly gage flows. Therefore, the selection of the May 2003 and Sept. 2004 floods as the two largest on the local area during 1998-2007 is considered confirmed by the hydrograph separation analysis.

The resulting 2003 and 2004 local runoff hydrographs for subbasin 44A are shown in Figure 5 and Figure 6, respectively, along with the observed flows at Charleston and below Apalachia and Ocoee No. 1 Dams.

Figure 5: Hydrograph Separation for the May 2003 Flood in Subbasin 44A.

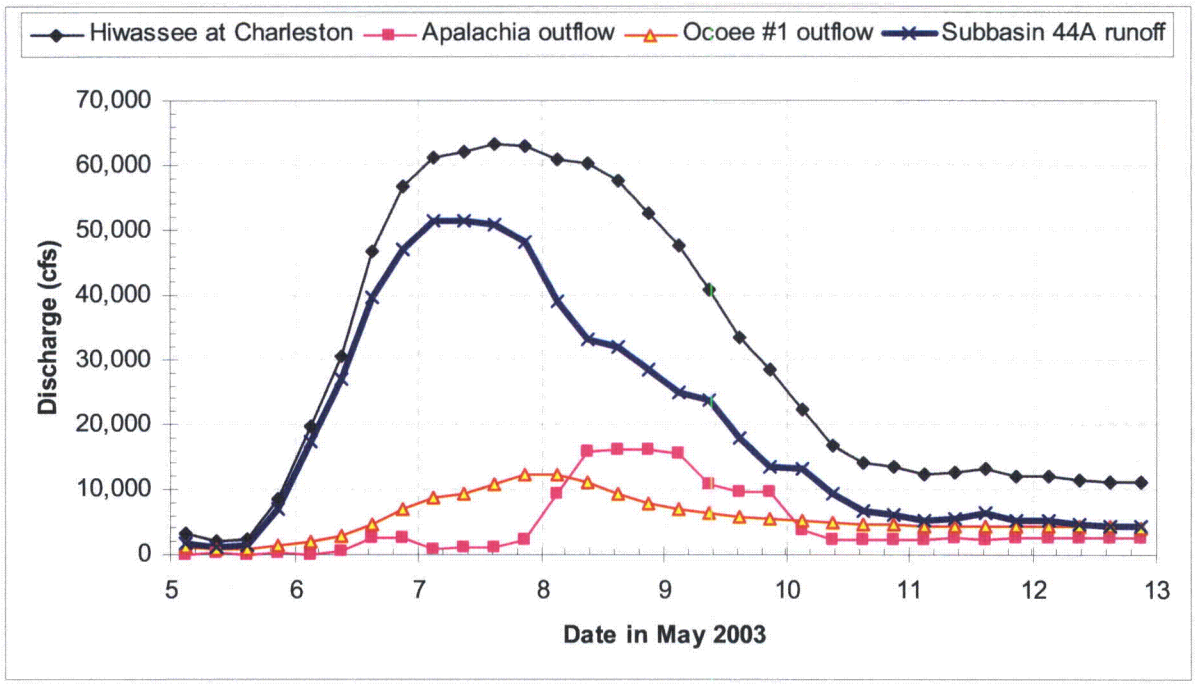
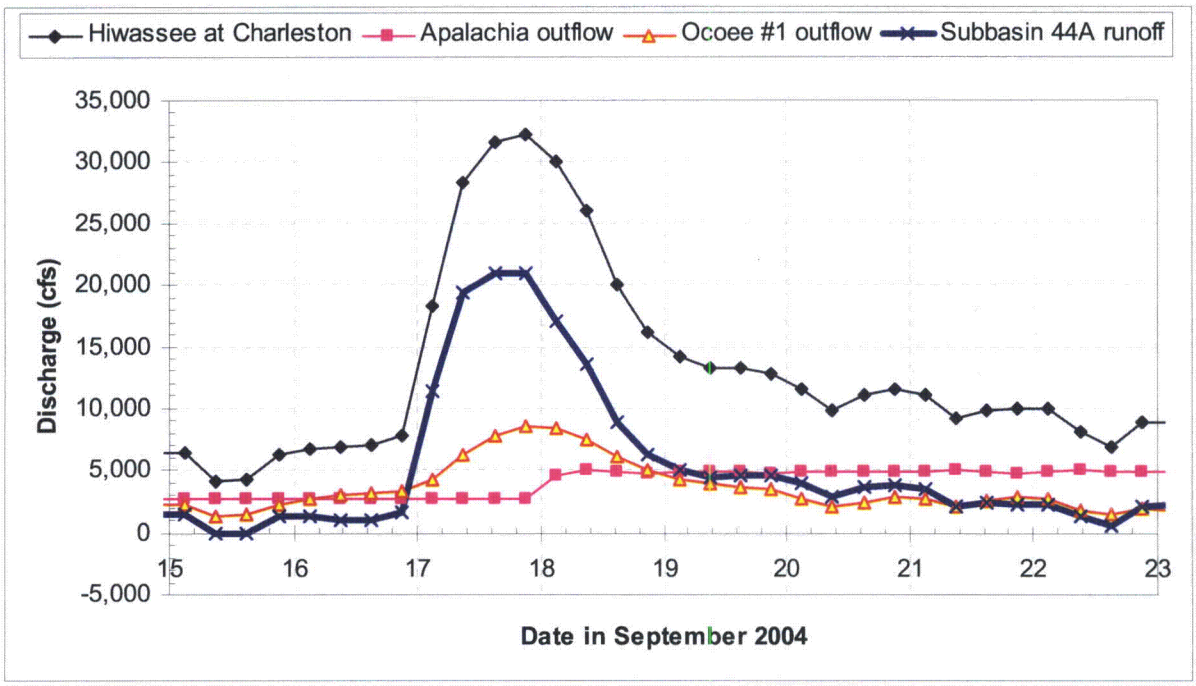


Figure 6: Hydrograph Separation for the September 2004 Flood in Subbasin 44A.



7.3 Baseflow Separation

Baseflow separation is required to determine an estimate of direct runoff associated with each flood. For this calculation, the inclined straight line method is employed, with the base line drawn from the starting point of runoff to a point on the receding limb of the hydrograph where base flow resumes (Reference 5). Results for the May 2003 and Sept. 2004 floods are plotted in Figure 7 and Figure 8.

Baseflow was removed from the inflow hydrographs to calculate the direct runoff volume. This volume is used to adjust the effective rainfall volume, as noted in Section 5. Direct runoff depth, in inches, is calculated from the n six-hour direct runoff values, Q_i, in cubic feet per second (cfs), as:

$$Runoff.Depth = \frac{\sum_{i=1}^{n} Q_i \frac{ft^3}{\sec} \times 3600 \frac{\sec}{hour} \times 6hours \times \frac{12inches}{foot}}{DrainageArea(mi^2) \times \left(5280 \frac{feet}{mile}\right)^2}.$$

The calculations of base flow and direct runoff volumes for the May 2003 and Sept. 2004 floods are provided in the spreadsheet "Hiwassee River - Baseflow Separation.xls" (Attachment 1-7).

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 hours after the time of peak discharge, where A is the area of the watershed in square miles, raised to the one-fifth power per the criterion proposed in Reference 13.

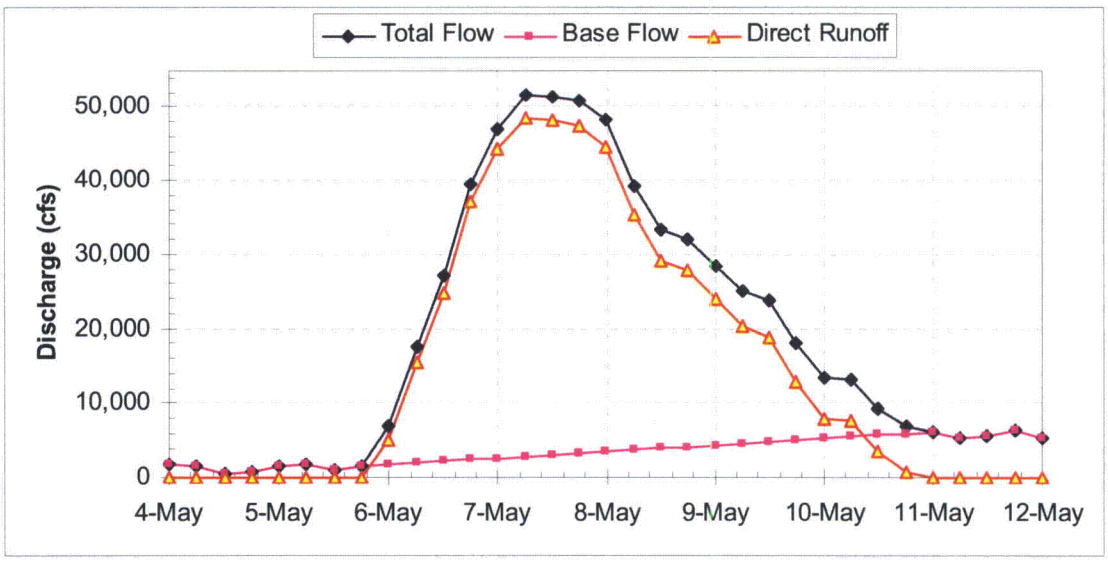
$$N = A^{0.2}$$

For the Hiwassee River at Charleston drainage area of 686.6 square miles, this method yields an estimated *N* of 3.69 days or 88.6 hours; this value was rounded to the nearest six-hour time step. The resulting baseflow start and end times and corresponding direct runoff volumes are presented in Table 3.

Table 3: Summary of Base Flow Calculations for the May 2003 and Sept. 2004 Floods in Subbasin 44A.

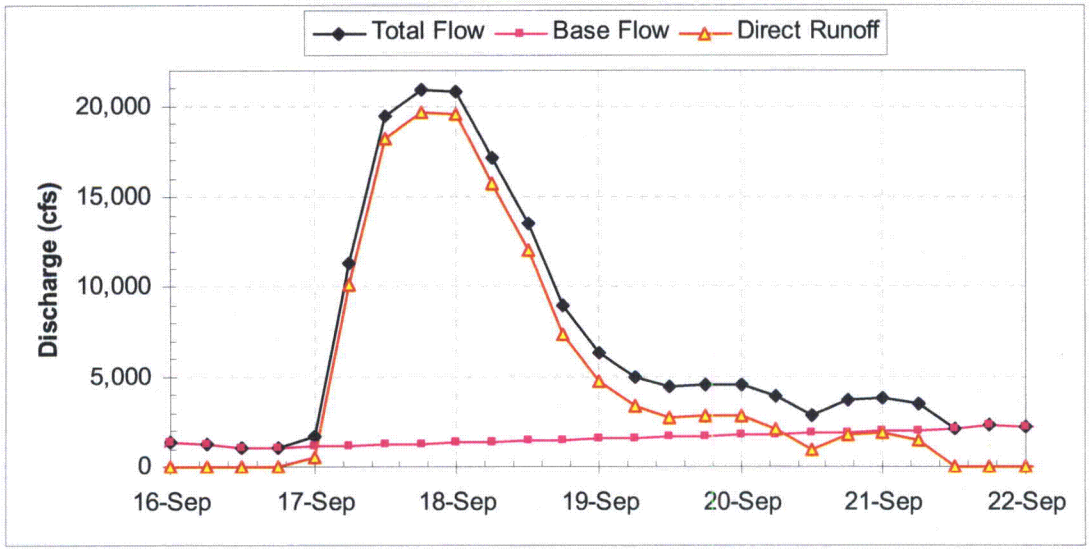
Storm Event	May 2003	Sept. 2004
Start hour of direct runoff	5/5/03 6:00 PM	9/16/04 6:00 PM
Peak hour of direct runoff	5/7/03 6:00 AM	9/17/04 6:00 PM
End hour of direct runoff	5/11/03 12:00 AM	9/21/04 12:00 PM
Total Flow volume, ac-ft	295,757	79,209
Total Flow volume, inches[1]	8.08	2.16
Base Flow volume, ac-ft	45,490	15,608
Base Flow volume, inches	1.24	0.43
Direct Runoff volume, ac-ft	250,266	63,600
Direct Runoff volume, inches	6.83	1.74

Figure 7: Base Flow Separation for the May 2003 Flood in Subbasin 44A.



[1] Runoff Depth [in] = 12 in/ft × Runoff Volume [ac-ft] / (640 acres/mi^2 × Drainage Area [mi^2]).

Figure 8: Base Flow Separation for the Sept. 2004 Flood in Subbasin 44A.



7.4 Observed Basin Average Rainfall

Observed average basin rainfall for the May 2003 and Sept. 2004 storms were obtained from Reference 12. The hourly precipitation series developed from NWS gridded data for these storms are provided in the spreadsheet "Subbasin 44A precipitation data.xls" along with adjustments for Central time and unit conversion (Attachment 1-5).

7.5 Basin Average Effective Rainfall

The effective 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 4). Excess precipitation is often referred to as "runoff" in TVA documents because the two terms are identical.

Effective rainfall is obtained from observed rainfall data with the FLDHYDRO program (Reference 3). The FLDHYDRO program was developed by the TVA to implement the API/RI methodology developed by the United States Weather Bureau, as described in Reference 3. 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 4, page 101). A recession constant of 0.9 is assumed for this calculation. The API is used to obtain a Rainfall 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 1) and the methodology is described in detail in Kohler and Linsley's publication (Reference 14).

Input to FLDHYDRO is via a column delimited batch file. Input includes:

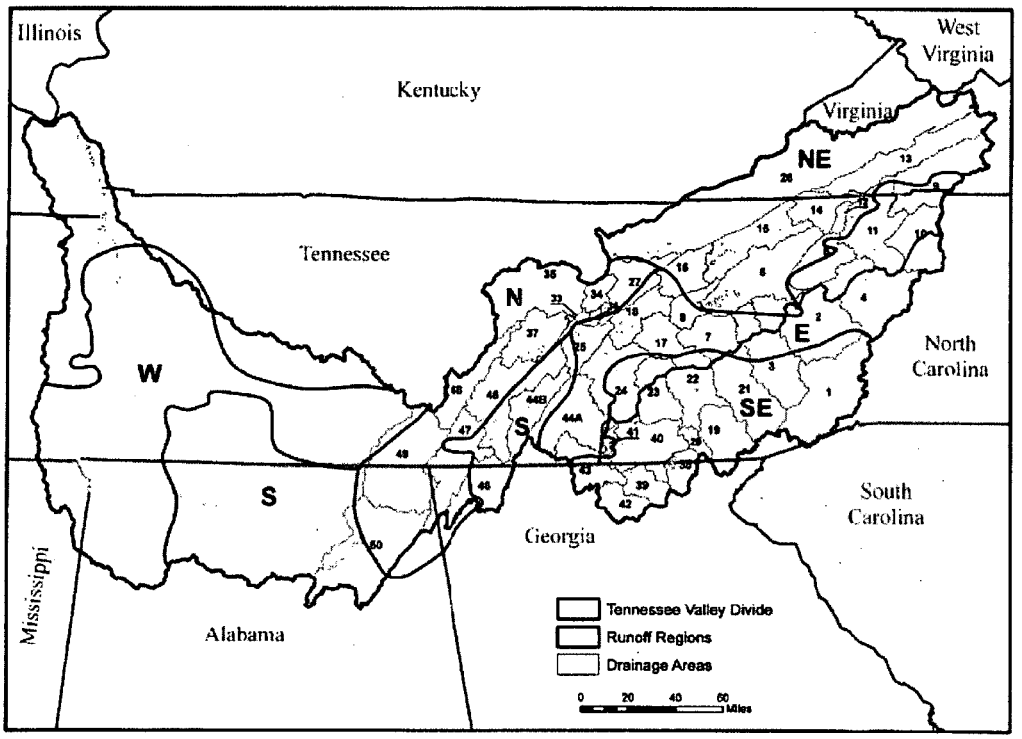
- Hourly and daily precipitation gage readings for a maximum of 30 recording gages and daily precipitation readings for a maximum of 100 non-recording gages
- Flags and indices to relate each non-recording gage record to a recording gage record for interpolation
- Thiessen coefficients to weight gage 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 for the NORO runs).
- NSUBW = 1 for 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 (given as MMDDYY for the given run).
- BEGTR = Time at which the first hour of rainfall has been recorded (a two digit number ranging from 01 to 24).
- NHR = The number of hourly readings for the storm.
- SHRAIN = The time series of hourly rainfall readings 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 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). Subbasin 44A is mainly located within the E zone (Figure 9).
- 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, which is calculated from outflow hydrographs after base flow separation, as shown in Table 3; when CHKVOL is greater than zero, the final runoff index is adjusted, if necessary, to provide a volume equal to CHKVOL.

Figure 9: Runoff Regions for Application of TVA FLDHYDRO program.



The antecedent rainfall days and the hourly basin average rainfall used as inputs to FLDHYDRO for the May 2003 and Sept. 2004 simulations are presented in the spreadsheet "Subbasin 44A precipitation data.xls" (Attachment 1-5).

Input data and parameters for running FLDHYDRO to get basin average effective rainfall for the Hiwassee River at Charleston model were written to the files (Attachments 3-1 and 3-3):

- 44A_May2003_CHKVOL.dat (May 2003 storm)
- 44A_Sept2004_CHKVOL.dat (Sept. 2004 storm)

Output files (echoing input) are provided for each run of the May 2003 and Sept. 2004 storm series in Attachments 3-2 and 3-4. Figure 10 and Figure 11 provide plots of the outputs for the two storms. The FLDHYDRO calculated effective precipitation totals are very close to, but not exactly equal to, the values in Table 3, which were entered as CHKVOL inputs. A comparison of these values is shown in Table 4.

Table 4: Comparison of Direct Runoff Volumes and FLDHYDRO Effective Precipitation Depths.

Storm/ Flood Event	Direct Runoff Volume (inches)	FLDHYDRO Results (inches)	Difference (%)
May 2003	6.83	6.87	0.6%
Sept. 2004	1.74	1.72	-1.1%

The FLDHYDRO results are shown on the spreadsheet "Subbasin 44A FLDHYDRO & HEC-HMS Results.xls" (Attachment 1-8).

Figure 10: FLDHYDRO Calculated Hourly Precipitation Losses and Runoff for the May 2003 Storm.

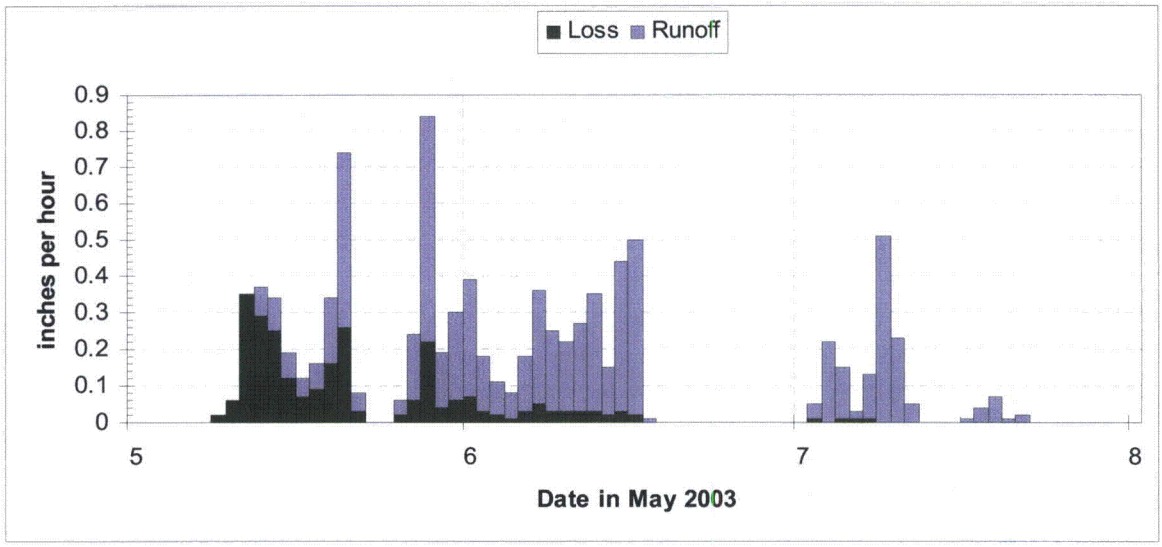
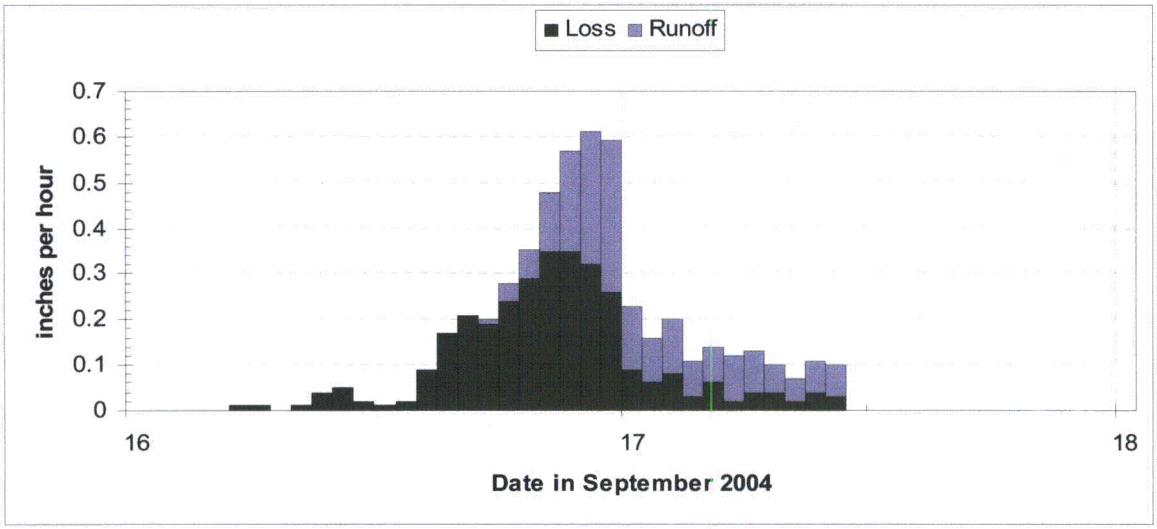


Figure 11: FLDHYDRO Calculated Hourly Precipitation Losses and Runoff for the Sept. 2004 Storm.



The sum of the hourly losses and hourly runoff values shown in Figure 10 and Figure 11 is equal to the hourly rainfall depths that were input to FLDHYDRO. It may be seen from these figures that the percentage of rainfall that becomes runoff tends to increase over the course of each storm.

7.6 HEC-HMS Simulations of Floods

A HEC-HMS project file named "Basin 44A" was developed for testing the unit hydrograph developed by the TVA for the Hiwassee River at Charleston (RM 18.9) subbasin. The HEC-HMS model files are included as Attachment 4-1. The following input files were developed for the project and input to HEC-HMS (Reference 9) via the Time Series Data Manager. The gridded precipitation time series are adjusted to Central Time for this calculation:

- Precipitation Gage "Gridded Precip" with hourly cumulative effective precipitation depths in inches for the May 2003 and Sept. 2004 storms. The gridded precipitation time series are adjusted to Central Time for this calculation.
- Discharge Gage "Observed Flows" with six-hour direct runoff discharge in cfs for the May 2003 and Sept. 2004 floods.

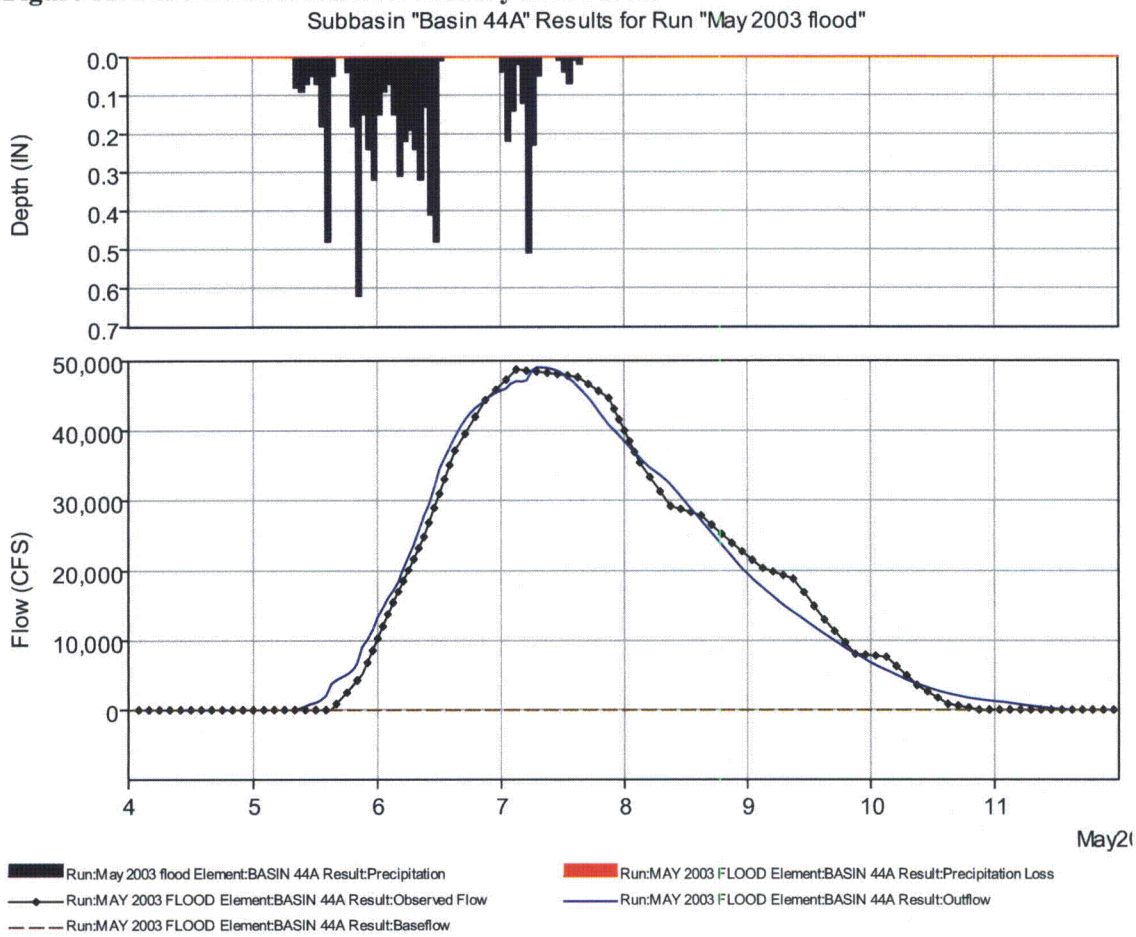
Note that instead of inputting observed basin average precipitation and using a loss function for the subbasin, the basin average effective rainfall (or runoff) output from FLDHYDRO were used as the input "precipitation data."

The TVA's six-hour unit hydrograph for Subbasin 44A was input to HEC-HMS with the Paired Data Manager as "6-hour UH." This unit hydrograph, shown in Figure 3, was used to simulate the May 2003 and Sept. 2004 floods in HEC-HMS using a 1-hour time step for the simulations. The one-hour UH was derived from the TVA's 6-hour UH using the S-hydrograph method as implemented in HEC-HMS.

The resulting simulated hydrograph is compared to the observed hydrograph for each flood in Figure 12 and Figure 13.

The HEC-HMS results were also independently obtained by calculation in an Excel spreadsheet "Subbasin 44A FLDHYDRO & HEC-HMS Results.xls" (Attachment 1-8). This calculation was performed to verify that the HEC-HMS software is performing the unit hydrograph convolution as intended.

Figure 12: HEC-HMS Results for the May 2003 Flood.



Project: Basin 44A
Simulation Run: May 2003 flood Subbasin: Basin 44A

Start of Run:	04May2003, 00:00	Basin Model:	Basin 44A
End of Run:	12May2003, 00:00	Meteorologic Model:	May 2003
Compute Time:	21Jan2009, 16:26:54	Control Specifications:	May 2003

Volume Units: IN

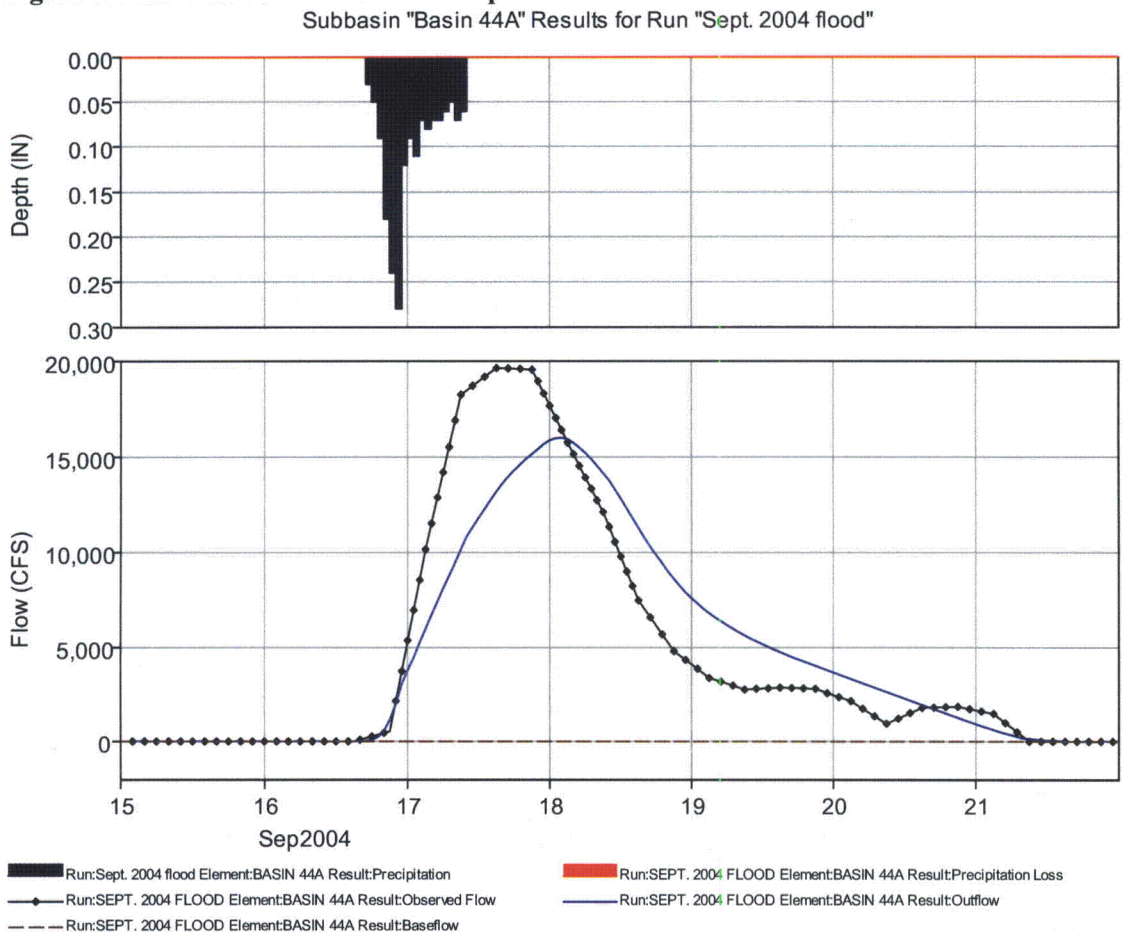
Computed Results

Peak Discharge :	49007.7997 (CFS)	Date/Time of Peak Discharge :	07May2003, 08:00
Total Precipitation :	6.87 (IN)	Total Direct Runoff :	6.87 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	6.87 (IN)	Discharge :	6.87 (IN)

Observed Hydrograph at Gage Hiwassee at Charleston

Peak Discharge :	48670.00 (CFS)	Date/Time of Peak Discharge :	07May2003, 03:00
Avg Abs Residual :	1293.51 (CFS)		
Total Residual :	0.02 (IN)	Total Obs Q :	6.85 (IN)

Figure 13: HEC-HMS Results for the Sept. 2004 Flood.



Project: Basin 44A
Simulation Run: Sept. 2004 flood Subbasin: Basin 44A

Start of Run:	15Sep2004, 00:00	Basin Model:	Basin 44A
End of Run:	22Sep2004, 00:00	Meteorologic Model:	Sept. 2004
Compute Time:	21Jan2009, 16:26:56	Control Specifications:	Sept. 2004

Volume Units: IN

Computed Results

Peak Discharge :	16007.1568 (CFS)	Date/Time of Peak Discharge :	18Sep2004, 02:0
Total Precipitation :	1.72 (IN)	Total Direct Runoff :	1.72 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	1.72 (IN)	Discharge :	1.72 (IN)

Observed Hydrograph at Gage Hiwassee at Charleston

Peak Discharge :	19631.00 (CFS)	Date/Time of Peak Discharge :	17Sep2004, 15:00
Avg Abs Residual :	1631.94 (CFS)		
Total Residual :	-0.02 (IN)	Total Obs Q :	1.74 (IN)

The May 2003 flood simulation results may be summarized from Figure 12 as follows:

1. The simulated timing agreed very well with the observed.
2. The magnitude of the simulated peak was 0.7 percent higher than the observed peak.
3. The shape of the simulated hydrograph agrees well with the observed hydrograph.

The Sept. 2004 flood simulation results may be summarized from Figure 13 as follows:

1. The simulated peak discharge occurred 11 hours after the observed peak discharge.
2. The magnitude of the simulated peak was 18.5 percent lower than the observed peak.
3. The rising limb of the simulated hydrograph is less steep than the observed hydrograph. The falling limb of the simulated hydrograph lags behind the observed hydrograph and lacks the fluctuations that appear at the tail of the observed hydrograph. However, the "observed" fluctuations might be a result of instabilities in the hydrograph separation process.

8 Discussion and Conclusions

FLDHYDRO was used to estimate the excess rainfall for subbasin 44A. The basin average effective rainfall hyetograph was adjusted to match the direct runoff volume corresponding to the prescribed basin area. A one-hour unit hydrograph was derived from the TVA's six-hour unit hydrograph via the S-hydrograph method as implemented internally in the HEC-HMS software. The one-hour unit hydrograph and the estimated excess rainfall were used by HEC-HMS to simulate the May 2003 and Sept. 2004 floods within subbasin 44A. The resulting hydrographs at the subbasin outlet were compared to the hydrographs obtained from the USGS streamflow gage, with baseflow and upstream inflows removed from each of the flow series.

A subjective, visual comparison of the HEC-HMS simulated hydrograph for each flood in subbasin 44A to the corresponding time series of "observed" subbasin direct runoff was used to determine unit hydrograph validity. This comparison involved examination of: 1) overall flood hydrograph shape; 2) timing of the flood hydrograph peak discharge; and 3) magnitude of the peak discharge. Subjectivity enters the validation process because the conditions underlying the unit hydrograph theory and the determination of excess precipitation preclude an exact match between a discharge series calculated with a unit hydrograph for a particular storm and the observed discharge series at the basin outlet.

It is considered desirable in the unit hydrograph validity assessment to demonstrate that the existing TVA unit hydrographs are adequate and in the cases of inadequacy they produce conservative estimates of peak discharges (i.e., overestimates rather than underestimates). This preference for conservatism is due to the intended use of the unit hydrographs in the probable maximum flood (PMF) calculations for the Tennessee River system upstream of the Bellefonte Nuclear Plant.

8.1 Discussion of the May 2003 Storm

The May 2003 simulation resulted in a basin outflow hydrograph that compares very well with the observed hydrograph obtained from the streamflow gage in all respects, including flow timing, magnitude, and overall hydrograph shape. The peak discharge compared extremely well with an overestimated difference of only 0.7 percent.

8.2 Discussion of the Sept. 2004 Storm

The Sept. 2004 simulation resulted in a basin outflow hydrograph that compares relatively poorly with the observed hydrograph. The rising and falling limbs of the simulated hydrograph, as well as the simulated peak discharge, lag several hours behind the observed hydrograph. The magnitude of the peak discharge was underestimated by 18.5 percent.

It should be noted that the September 2004 flood is a relatively small flood. The May 2003 storm generated more than three times as much runoff in subbasin 44A as the Sept. 2004 storm and has a peak discharge over two times as large. Therefore, the May 2003 flood is considered more important in the unit hydrograph validation than the Sept. 2004 flood. Also, the original unit hydrograph was developed from three floods that were greater than the September 2004 flood.

8.3 Conclusions

Based on the preceding discussions, it is concluded that the unit hydrograph developed by the TVA for the lower Hiwassee River from Charleston (RM 18.9) to Apalachia and Ocoee No. 1 Dams (Subbasin 44A) has been validated against the recent large flood that occurred in May 2003. Given that the May 2003 flood is the second largest on record and is even larger than the three floods used in unit hydrograph development, the close fit between the simulated and observed hydrographs for this event provides confidence in the unit hydrograph for Subbasin 44A, despite the relatively weaker performance for the smaller Sept. 2004 flood.

The routing methods used in determining the local flows (Section 7.2), which include lag routing and Muskingum routing as shown in Table 5, have also been indirectly validated by this study for joint-use with the Subbasin 44A unit hydrograph.

Table 5: Routing Parameters Used to Calculate Local Flows for Subbasin 44A.

Routing Reach	Routing Method	Lag Time
Hiwassee River Reach, Apalachia Dam to Charleston gage (RM 18.9)	Lag	12 hours
Ocoee-Hiwassee River Reach, Ocoee No 1 Dam to Charleston gage (RM 18.9)	Muskingum, with coefficients: $C_1 = 0.14 \quad C_2 = 0.29 \quad C_3 = 0.57$ (with a six-hour routing period)	N/A

Considering that the unit hydrograph was developed from historical floods that took place in March 1963, March 1965, and March 1973 (Reference 2), and was demonstrated in this calculation to be valid for the May 2003, it is concluded that the watershed runoff characteristics have remained stationary and that the TVA unit hydrograph and routing methods are suitable for appropriate, joint use in flood flow analyses, including the probable maximum flood (PMF) calculations for the Tennessee River system upstream of the Bellefonte Nuclear Plant (BNP). The sensitivity of PMF results at BNP to the routing parameters should be checked, as it is possible that PMF flow velocities could vary from the velocities of historically observed floods.

The validated unit hydrograph for subbasin 44A is presented in Figure 3 and Table 1.