ASSOCIATED ATTACHMENTS/ENCLOSURES:

Attachment 02.04.03-8Z: Subbasin 46 (South Chickamauga Creek) Unit Hydrograph Validation

(31 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 081105 002	calculations(nuclear)	L58 100113 002

Calc Title: Subbasin 46 (South Chickamauga Creek) Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080058	1	2	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 7a	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Carrie L. Stokes *Carrie L Stokes*	12/11/09	Mark Crisp *Mark Crisp*	12/11/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Mark Crisp *Mark Crisp*	12/11/09	*G Malek*	1/12/10

12/11/09

STATEMENT OF PROBLEM/ABSTRACT

Validate existing unit hydrograph for South Chickamauga Creek (Subbasin 46) using three recent flood events.

*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)

☐ LOAD INTO EDMS AND DESTROY
☒ LOAD INTO EDMS AND RETURN CALCULATION TO CALCULATION LIBRARY. ADDRESS: LP4D-C
☐ LOAD INTO EDMS AND RETURN CALCULATION TO:

NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV 0 EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58081105002	calculations(nuclear)	L58 090625 003

Calc Title: Subbasin 46 (South Chickamauga Creek) Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080058	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
PDMADDUX	423-751-8015	NGD (CEB)	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Perry D. Maddux [signature]	06/24/2009	Dennis L. Lundy [signature]	6/24/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Dennis L. Lundy [signature]	6/24/09	K.R. Spates [signature]	6/25/09

SB

STATEMENT OF PROBLEM/ABSTRACT

Validate existing unit hydrograph for South Chickamauga Creek (Subbasin 46) using three recent flood events.

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

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

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NPG CALCULATION COVERSHEET/CCRIS UPDATE

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	REV
	CN	NUC	GEN	CEB	CDQ000020080058	2

ALTERNATE CALCULATION IDENTIFICATION

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

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	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	CDQ000020080058
Title	Subbasin 46 (South Chickamauga Creek) Unit Hydrograph Validation

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. 5) for FLDHYDRO, and Reference 2.5 was revised to reflect the EDMS number of the issued document. Three 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. Updated "TVAN" to "NPG" on forms. Significant changes in Revision 1 are noted with a right margin revision bar. Pages replaced: 1, 2, 3, 7, 9 Pages Added / Deleted: None Attachments 2-4, 2-5, and 2-6 (electronically attached FLDHYDRO output Files Basin46ppt2002.out, Basin46ppt2003.out, and Basin46ppt2004.out, which appear in the Adobe file Attachment Tab as Att 2-4 Basin46ppt2002.out, Att 2-5 Basin46ppt2003.out, and Att 2-6 Basin46ppt2004.out) were replaced. Total pages of calculation hardcopy for Revision 1 = 28 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 212592 - this calculation was revised but not issued prior to issuance of successor calculations. There are no impacts to successor calculations due to issuance of 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 1 through 7 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: 1-6 & 9 Total pages of calculation hard copy for Revision 2= 30

NPG CALCULATION TABLE OF CONTENTS

Calculation Identifier: CDQ000020080058	Revision: 2	

TABLE OF CONTENTS

List of Tables:

NPG CALCULATION TABLE OF CONTENTS

Calculation Identifier: CDQ000020080058	Revision: 2	

TABLE OF CONTENTS

SECTION	TITLE	PAGE

List of Figures:

List of Attachments:

See list of electronic attachments on page 6.

NPG COMPUTER INPUT FILE
STORAGE INFORMATION SHEET

Document CDQ000020080058	Rev. 2	Plant: GEN	

Subject: Subbasin 46 (South Chickamauga Creek) 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 Input & Output files on the following page

☐ Microfiche/eFiche

ELECTRONIC FILE ATTACHMENTS			
Document: CDQ000020080058	Rev. 1	Plant: Gen	
Subject: Subbasin 46 (South Chickamauga Creek) Unit Hydrograph Validation			

Electronic Attachment	Name of File or Folder	File Location
	Supporting Spreadsheets	
Attachment 1-1	SChickNrChickamauga.xls	Attached to PDF
Attachment 1-2	StreamOutflowRecords.xls	Attached to PDF
Attachment 1-3	Basin46-BaseFlowSeparation2002.xls	Attached to PDF
Attachment 1-4	Basin46-BaseFlowSeparation2003.xls	Attached to PDF
Attachment 1-5	Basin46-BaseFlowSeparation2004.xls	Attached to PDF
Attachment 1-6	Basin46PrecipitationDataProcessing2002.xls	Attached to PDF
Attachment 1-7	Basin46PrecipitationDataProcessing2003.xls	Attached to PDF
Attachment 1-8	Basin46PrecipitationDataProcessing2004.xls	Attached to PDF
	FLDHYDRO Files	
Attachment 2-1	Basin46ppt2002.dat	Attached to PDF
Attachment 2-2	Basin46ppt2003.dat	Attached to PDF
Attachment 2-3	Basin46ppt2004.dat	Attached to PDF
Attachment 2-4	Basin46ppt2002.out (Revised by Rev 1)	Attached to PDF
Attachment 2-5	Basin46ppt2003.out (Revised by Rev 1)	Attached to PDF
Attachment 2-6	Basin46ppt2004.out (Revised by Rev 1)	Attached to PDF
	HEC-HMS File Folders	
Attachment 3	Basin46-20080058.zip (HEC-HMS project files)	Filekeeper No. 310968

NPG CALCULATION VERIFICATION FORM

Calculation Identifier CDQ000020080058 Revision 2

Method of verification used:		
1. Design Review	☒	Verifier Mark Crisp Date 12/11/09
2. Alternate Calculation	☐	Mark W Crisp
3. Qualification Test	☐	

Comments:

This calculation was revised to address 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. The verification is inclusive of work completed prior to this revision.

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. For sub basin 46 there was a notable difference in the comparison of FLDHYDRO output for the September of 2004 storm. However, the May of 2002 storm and May of 2003 storm FLDHYDRO comparisons did not demonstrate these discrepancies. The unit hydrograph for sub basin 46 reproduced all three of these storms well. Due to the fact that 3 storms were reproduced well, the FLDHYDRO comparison issue for the September 2004 storm is not a concern.

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 of the Tennessee River upstream of the Guntersville Dam for use in the Probable Maximum Flood (PMF) and dam break analysis at the proposed Bellefonte Nuclear Power Plant site, presented in Calculation CDQ000020080054.

Inputs to the dynamic model include hydrographs for 46 subbasins developed from design rainfall inputs convoluted with unit hydrographs developed specifically for each subbasin. These unit hydrographs were developed by the TVA in previous studies, mostly in the 1970s, utilizing observed rainfall and streamflow and reservoir headwater and discharge data, and are being validated by checking their performance in reproducing recent flood events.

This calculation presents the validation of the unit hydrograph developed by the TVA in 1977 for the South Chickamauga creek, Subbasin 46, located within the Tennessee River watershed as shown in Figure 1.

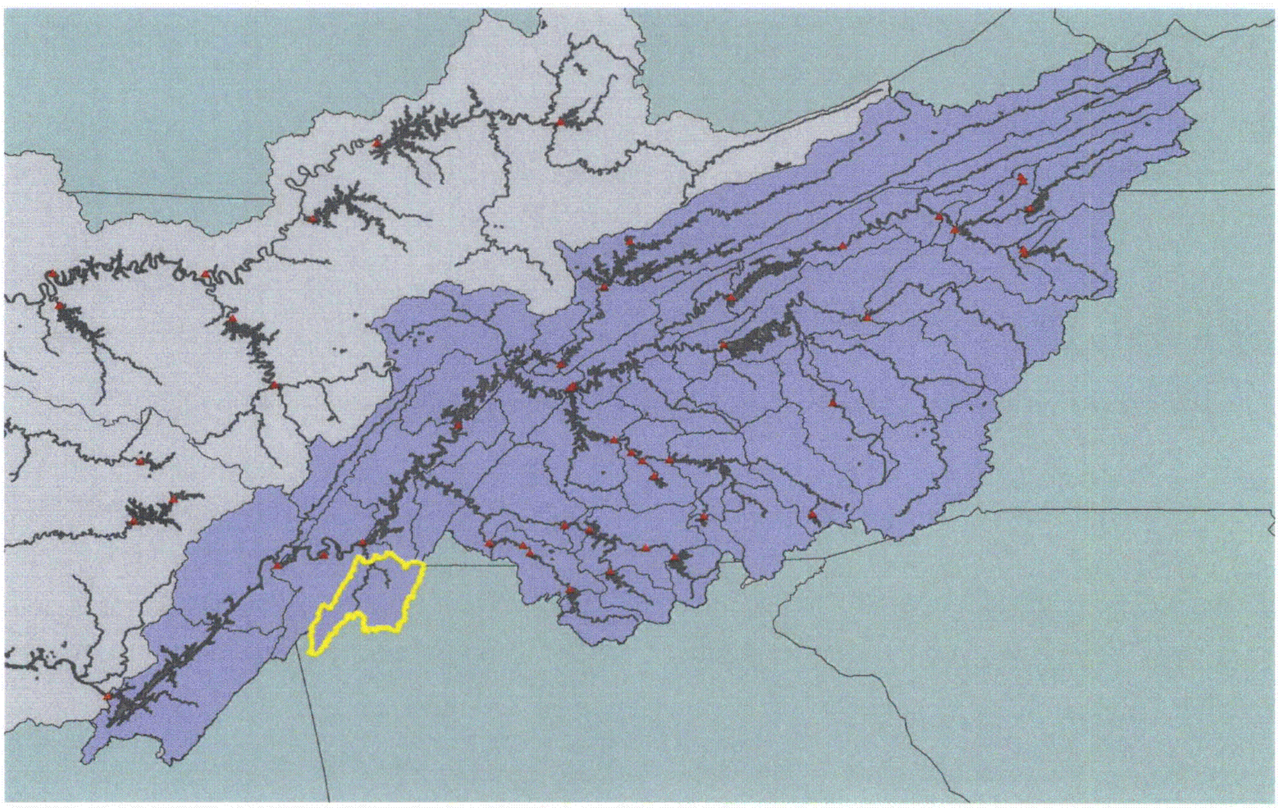


Figure 1: Location of South Chickamauga Creek Subbasin (No. 46) within the Tennessee River watershed

2 References

1. Viessman, W., J.W. Knapp, G.L. Lewis,, and T.E. Harbaugh, *Introduction to Hydrology, Second Edition,* Harper & Row, Publishers, 1977.
2. Chow, V.T., D.R. Maidment, and L.W. Mays, *Applied Hydrology*, McGraw-Hill Book Company, 1988.
3. American Nuclear Society, American National Standard for Determining Design Basis Flooding at Power Reactor Sites, ANSI/ANS-2.8-1992, 1992.
4. U.S. Nuclear Regulatory Commission, Standard Review Plan 2.4.3, Probable Maximum Flood (PMF) on Streams and Rivers, NUREG-0800, Revision 4, March 2007.
5. Tennessee Valley Authority, UNITGRPH-FLDHYDRO-TRBROUTE-CHANROUT User's Manual, Version 1.0, November 2008 (L58090325001).
6. U.S. Army Corps of Engineers, Hydrologic Modeling System HEC-HMS User's Manual, Version 3.2, April 2008.
7. U.S. Army Corps of Engineers, Hydrologic Modeling System HEC-HMS Technical Reference Manual, March 2000.
8. Tennessee Valley Authority, Unit Area 46, South Chickamauga Creek, File Book Reference. (EDMS No. L58 081017 001)
9. Newton, D.R., and J.W. Vinyard, Computer-Determined Unit Hydrograph from Floods, Journal of the Hydraulics Division, ASCE, Vol. 93, No. HY5, September, 1967.
10. Tennessee Valley Authority, Calculation No. CDQ000020080055, Processing and Validation of National Weather Service's NEXRAD Stage III Hourly Precipitation Data for Hydrologic Analysis of Watersheds, Revision 3
11. Linsley, R.K., Kohler, M.A., and J.L. Paulhus, *Hydrology for Engineers*, McGraw-Hill Book Company 1982.
12. Tennessee Valley Authority, Bellefonte Nuclear Plant - White Paper, Hydrologic Analysis, Revision 1, July 25, 2008. (EDMS No. L58 080725 006) FOR INFORMATION ONLY
13. 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

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 1 and 2).

5 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 1 and 2).

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 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} 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 is used to derive the ordinates of the unit hydrograph by reconstituting floods from precipitation and streamflow data.

Unit hydrograph theory is applicable under the following conditions (Reference 2):

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."

It should be noted that any given unit hydrograph is associated with an excess rainfall duration.

6 Methodology

The methodology used for unit hydrograph validation follows that described in ANSI/ANS-2.8-1992 (Reference 3). 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 4). 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 are available."

For the purpose of validating the unit hydrograph for Subbasin 46, the period of record from which the highest two or more 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 46 was developed from floods that occurred between 1963 and 1973 (see 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 35 to 45 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 streamflow data from the 1997-2007 period to identify the two highest flood events. These flood events are used for unit hydrograph validation.
2. Obtain the observed hydrograph data for the two flood events and transfer the flow series to the subbasin outlet using established hydrologic procedures, as necessary, to develop the local basin hydrograph.
3. Separate baseflow 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 flood events 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 5). 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 6 and 7) 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.

Note that in selecting the flood events for unit hydrograph validation (Step 1), preference is given to storms that produce continuous excess rainfall over a relatively short period, as opposed to storms for which the excess rainfall is not continuous, because the former storms produce a well-defined flood hydrograph that is better suited for unit hydrograph validation. This preference may result in the selection of a flood event for unit hydrograph validation with a peak discharge that does not rank as one of the two highest peak discharges within the period considered.

7 Design Input Data

The input data necessary for validating the unit hydrograph for South Chickamauga Creek, Subbasin 46 are summarized below.

- Unit hydrograph ordinates and duration
- Observed outflows from South Chickamauga Creek at the gage
- Observed rainfall data associated with the selected flood events

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

7.1 Unit Hydrograph Ordinates

The drainage area of the South Chickamauga Creek subbasin is given in the TVA File Book Reference as 428 mi^2 (Reference 8) and was calculated in GIS as 428.1mi^2. The unit hydrograph for this subbasin is described in the TVA File Book Reference (Reference 8) and was developed using the methodology proposed by Newton and Vinyard (Reference 9). This methodology evaluates possible errors in the initial estimate of the time distribution of precipitation excess, and makes corrections to the precipitation excess in the development of the unit hydrograph. The data used to develop the unit hydrograph includes streamflow records from the following historical floods:

- March 13, 1963
- March 17, 1973

The flood hydrographs used to develop the unit hydrograph were estimated from published daily averages and peak discharges, as the gage readings were affected by Tennessee River backwater. Single unit hydrographs were computed for each of the two floods and a composite unit hydrograph was computed using both floods. The resulting unit hydrograph is plotted in Figure 2. The time base and ordinates for the derived unit hydrograph are provided in Table 1 along with a volume check demonstrating that volume of runoff is equivalent to one inch of excess rainfall over the entire basin.

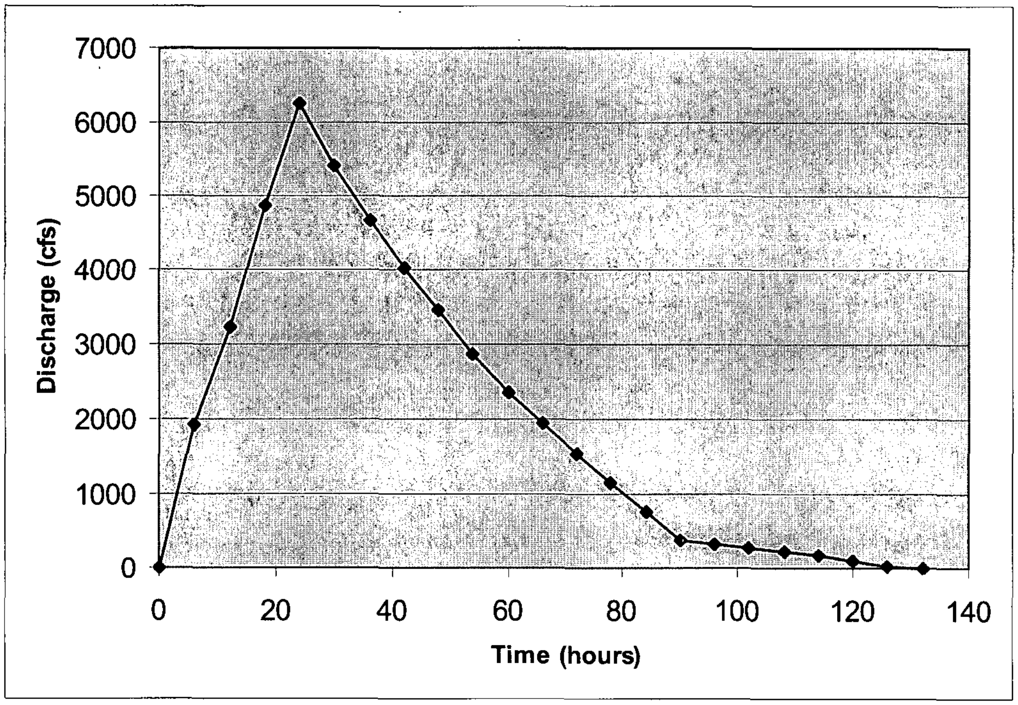


Figure 2: Six-hour unit hydrograph for Subbasin 46 (South Chickamauga Creek)

Table 1: Six-hour unit hydrograph ordinates for the South Chickamauga Creek subbasin (Reference 8)

Time (hour)	Discharge (ft^3/s)
0	0
6	1917
12	3219
18	4860
24	6267
30	5413
36	4670
42	4036
48	3451
54	2884
60	2359
66	1954
72	1526
78	1148
84	770
90	393
96	341
102	289
108	238
114	169
120	99
126	30
132	0

$$\text{Volume} = \Delta t \sum Q = 6\text{ h} \times 3600\text{ s/h} \times \sum Q \times 1\text{ ac-ft} / 43{,}560\text{ ft}^3 = 22{,}846\text{ ac-ft}$$

$$\text{Depth} = \text{Volume/Area} = 22{,}846\text{ ac} - \text{ft} / 428\text{ mi}^2 / 640\text{ ac/mi}^2 \times 12\text{ in/ft} = 1.00\text{ in}$$

7.2 Observed Streamflows

Bi-hourly streamflow data recorded at the South Chickamauga Creek gage were obtained from TVA in the spreadsheet "SChickNrChickamauga.xls" (Attachment 1-1) and are contained on the tabs "Flow2002," "Flow2003," and "Flow2004" of the spreadsheet "StreamOuflowRecords.xls" provided as electronic Attachment 1-2 to this calculation.

7.3 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/ back to 2005. 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 10). 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 10 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.

8 Computations and Analyses

8.1 Flood Events for Unit Hydrograph Validation

Three 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 2008 are available from the U.S. National Weather Service (NWS) Lower Mississippi River Forecast Center (LMRFC). Streamflow data for the same period are available for the South Chickamauga River near Chickamauga. Table 2 summarizes and ranks the annual peak discharges for this period.

Table 2: Annual Peak Discharges in Subbasin 46 from 1997 through 2007

Year	Peak Discharge (ft^3/s)	Date	Rank	Comment
1997	9,424	4-Mar	7	
1998	11,427	20-Apr	4	
1999	10,797	7-May	5	
2000	15,957	4-Apr	3	
2001	8,684	21-Mar	8	
2002	8,432	25-Jan	9	
2003	28,455	8-May	1	Use for unit hydrograph validation
2004	20,317	18-Sep	2	Use for unit hydrograph validation
2005	9,528	22-Feb	6	
2006	4,357	16-Nov	11	
2007	5,079	20-Nov	10	

From amongst these years, 2003 and 2004 were selected as they have largest flows for the period where the rainfall data are available. The observed magnitude of the peaks for 2003 and 2004 flood events were 27,355 ft^3/s and 19,775 ft^3/s, respectively, after baseflow separation. Apart from these an isolated smaller flood event that occurred in 2002 with a peak magnitude of 6,563 ft^3/s, after baseflow separation, was selected to check the behavior of the hydrograph against a smaller flood. The dates and times of the three storm/flood events selected for unit hydrograph validation are as follows:

- May 2, 2002, 01:00 hrs to May 09, 2002, 24:00 hrs, the "May 2002" storm
- May 4, 2003, 01:00 hrs to May 14, 2003, 24:00 hrs, the "May 2003" storm
- September 15, 2004, 00:00 hrs to September 22, 2004, 24:00 hrs, the "September 2004" storm

8.2 Baseflow Separation

Baseflow separation is required to determine an estimate of direct runoff associated with the rainfall event. 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 baseflow resumes (References 2 and 11). The total streamflow and resulting baseflow hydrographs for the May 2002, May 2003 and September 2004 events are plotted on Figures 3, 4 and 5, respectively.

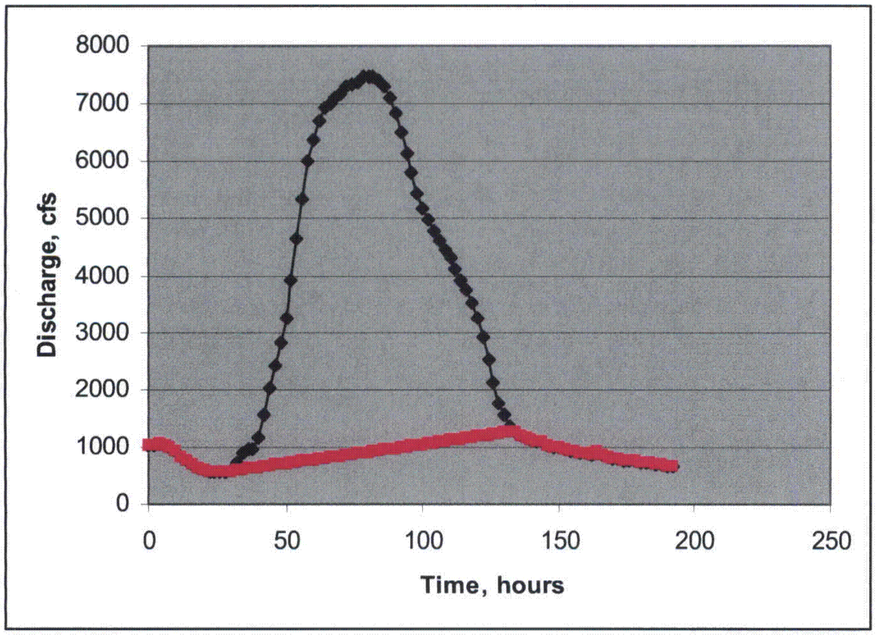


Figure 3: South Chickamauga Creek baseflow separation for the May 2002 event

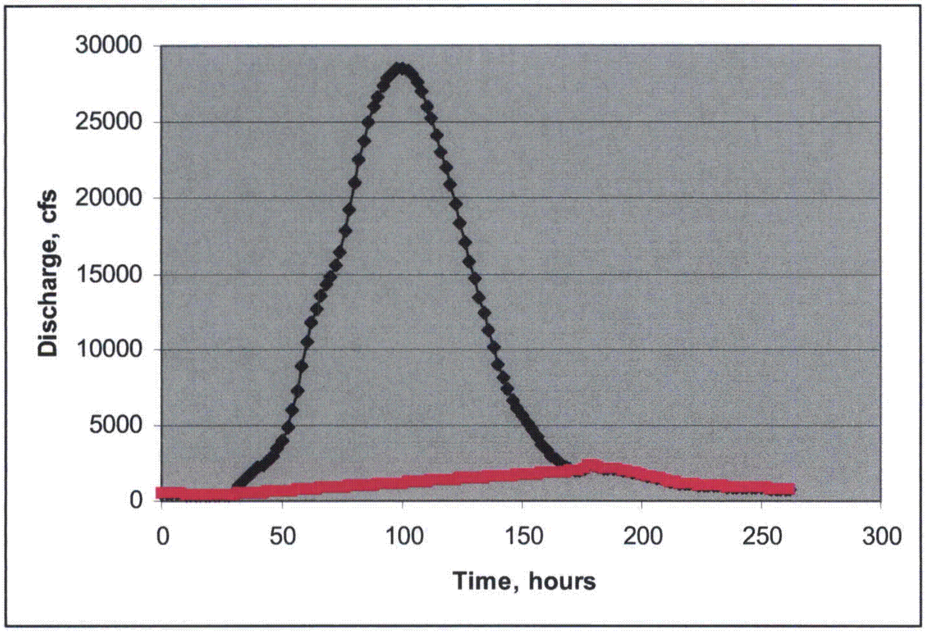


Figure 4: South Chickamauga Creek baseflow separation for the May 2003 event

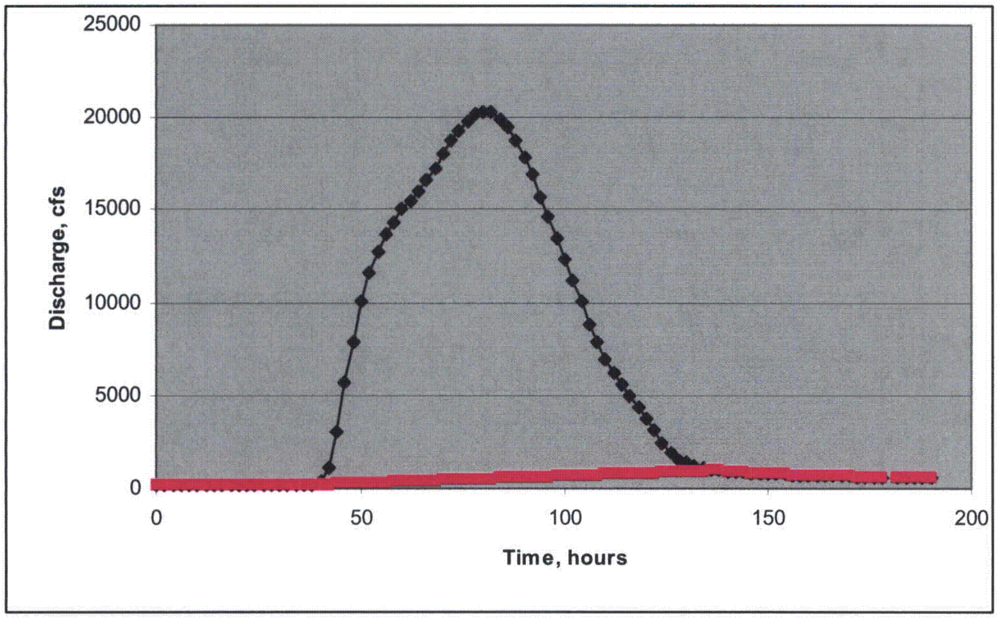


Figure 5: South Chickamauga Creek baseflow separation for the September 2004 event

Baseflow was removed from the inflow hydrographs to calculate the direct runoff volume. This volume is used in adjusting the effective rainfall volume, as noted in Section 5. The direct runoff volume calculation is summarized in Table 3. The runoff volume, in units of acre-feet, is calculated from the observed bi-hourly streamflows after subtracting baseflow as:

$$\text{Runoff Volume} = \Delta t \sum Q = 2\ \text{h} \times 3600\ \text{s/h} \times \sum Q \times 1\ \text{ac-ft} / 43{,}560\ \text{ft}^3$$

The runoff depth, in units of inches, is then determined by dividing by the drainage area, i.e.,

$$\text{Runoff Depth (in)} = \text{Volume/Area} = \mathit{Volume}\ (ac - ft) / 428\ \text{mi}^2 / 640\ \text{ac/mi}^2 \times 12\ \text{in/ft}$$

Baseflow separation and runoff volume calculations for the May 2002, May 2003 and September 2004 events are included in spreadsheets electronically attached to this calculation as follows:

- Basin46-BaseflowSeparation2002.xls (Attachment 1-3)
- Basin46-BaseflowSeparation2003.xls (Attachment 1-4)
- Basin46-BaseflowSeparation2004xls (Attachment 1-5)

Table 3: Direct runoff volumes for the May 2002, May 2003 and September 2004 events

Storm/Flood Event	Total Runoff Volume (ac-ft)	Drainage Area (mi^2)	Runoff Depth (in)
May 2002	30,899	428.1	1.35
May 2003	142,223	428.1	6.23
Sep 2004	82,797	428.1	3.63

8.3 Observed Basin Average Rainfall

Observed basin average rainfall depths for the May 2002, May 2003, and September 2004 events were obtained from Reference 10. The hourly precipitation series developed from NWS gridded data for 2002, 2003 and 2004 are provided in the spreadsheets "Basin46PrecipitationDataProcessing2002.xls," "Basin46PrecipitationDataProcessing2003.xls," and "Basin46PrecipitationDataProcessing2004.xls" along with adjustments for local time and unit conversion. These spreadsheets are included as electronic Attachments 1-6, 1-7, and 1-8 to this calculation.

8.4 Effective Basin Average 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 1). 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 5). The FLDHYDRO program was developed by the TVA to implement the API/RI methodology developed by the NWS, as described in Reference 5. 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 (see Reference 1, page 101). A recession constant of 0.9 is used 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 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 12), and the methodology is described in detail in a NWS publication (Reference 13).

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

- Hourly and daily precipitation gage readings
- Flags and indices to relate each daily gage record to an hourly 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
- STAB = 1 for all stations are in the same API area
- ITDGR = 0 for the hour at which each gage is read
- BEGDR = the starting date (May 2, 2002, May 3, 2003 or September 15, 2004, depending on the run, given as MMDDYY)
- 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 (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 South Chickamauga Creek subbasin is within the S zone (see Figure 6).
- 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 baseflow separation)

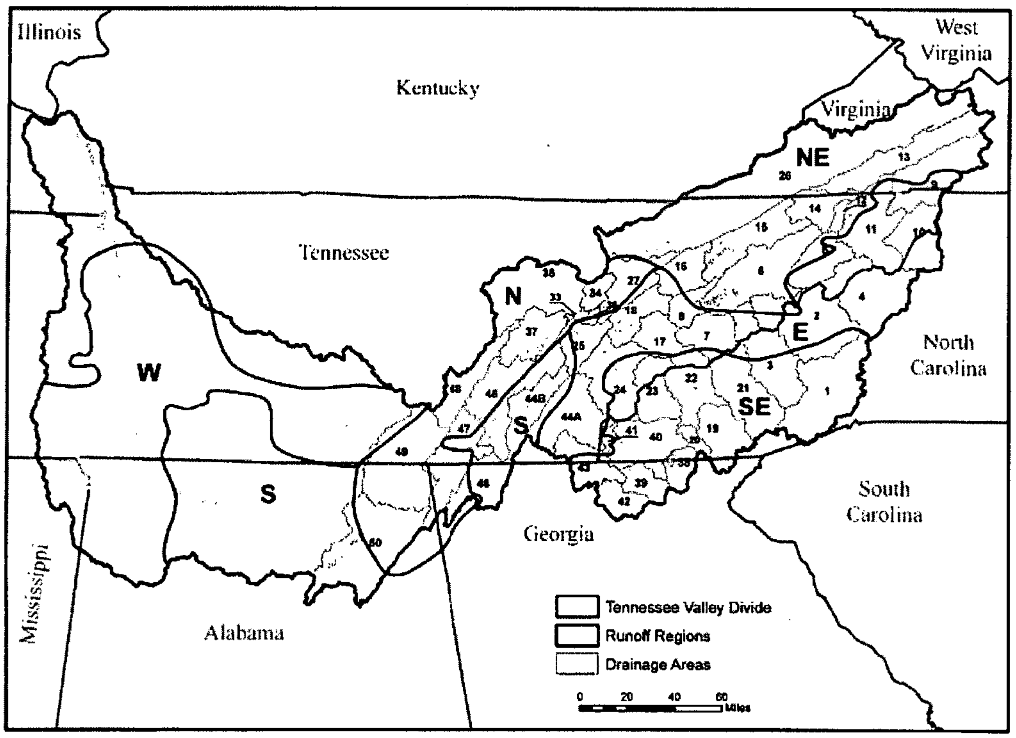


Figure 6: Runoff regions for application of TVA FLDHYDRO program

The antecedent rainfall days used for the May 2002, May 2003 and September 2004 simulations are presented in Table 4. The tabs "2002 Hourly ppt," "2003 Hourly ppt," and "2004 Hourly ppt" of the spreadsheets "Basin46PrecipitationDataProcessing2002.xls," "Basin46PrecipitationDataProcessing2003.xls," and "Basin46PrecipitationDataProcessing2004.xls" are used to obtain hourly storm depths and format them for entry into FLDHYDRO. The tabs "API ppt" in the respective spreadsheets are used to obtain daily antecedent rainfall depths. These spreadsheets are provided as electronic Attachments 1-6, 1-7, and 1-8 to this calculation.

Table 4: Daily basin average rainfall depths used in API calculations

May 2002 Event		May 2003 Event		September 2004 Event	
Date	Rainfall (in)	Date	Rainfall (in)	Date	Rainfall (in)
4/4/2002	0.000	4/6/2003	0.348	8/18/2004	0.000
4/5/2002	0.000	4/7/2003	0.382	8/19/2004	0.025
4/6/2002	0.000	4/8/2003	0.593	8/20/2004	0.740
4/7/2002	0.000	4/9/2003	0.198	8/21/2004	0.480
4/8/2002	0.091	4/10/2003	0.251	8/22/2004	0.009
4/9/2002	0.25	4/11/2003	0.000	8/23/2004	0.037
4/10/2002	0.002	4/12/2003	0.000	8/24/2004	0.288
4/11/2002	0.015	4/13/2003	0.000	8/25/2004	0.007
4/12/2002	0.097	4/14/2003	0.000	8/26/2004	0.000
4/13/2002	0.000	4/15/2003	0.017	8/27/2004	0.005
4/14/2002	0.000	4/16/2003	0.002	8/28/2004	0.021
4/15/2002	0.000	4/17/2003	0.280	8/29/2004	0.121
4/16/2002	0.002	4/18/2003	0.000	8/30/2004	0.027
4/17/2002	0.023	4/19/2003	0.000	8/31/2004	0.000
4/18/2002	0.000	4/20/2003	0.001	9/1/2004	0.007
4/19/2002	0.000	4/21/2003	1.331	9/2/2004	0.029
4/20/2002	0.001	4/22/2003	0.000	9/3/2004	0.139
4/21/2002	0.000	4/23/2003	0.000	9/4/2004	0.017
4/22/2002	0.018	4/24/2003	0.454	9/5/2004	0.000
4/23/2002	0.000	4/25/2003	0.357	9/6/2004	0.000
4/24/2002	0.123	4/26/2003	0.000	9/7/2004	2.076
4/25/2002	0.355	4/27/2003	0.000	9/8/2004	0.019
4/26/2002	0.106	4/28/2003	0.000	9/9/2004	0.000
4/27/2002	0.000	4/29/2003	0.000	9/10/2004	0.000
4/28/2002	0.039	4/30/2003	0.204	9/11/2004	0.000
4/29/2002	0.000	5/1/2003	0.068	9/12/2004	0.000
4/30/2002	0.142	5/2/2003	0.353	9/13/2004	0.000
5/1/2002	1.309	5/3/2003	0.003	9/14/2004	0.000

Input data and parameters for running FLDHYDRO to get effective basin average rainfall for the South Chickamauga Creek were written to the following files, which are included as electronic attachments this calculation:

- Basin46ppt2002.dat (Attachment 2-1)
- Basin46ppt2003.dat (Attachment 2-2)
- Basin46ppt2004.dat (Attachment 2-3)

Output files (echoing input) are provided for each run of the May 2002, May 2003, and September 2004 storm series in electronic attachments to this calculation as follows:

- Basin46ppt2002.out (Attachment 2-4)
- Basin46ppt2003.out (Attachment 2-5)
- Basin46ppt2004.out (Attachment 2-6)

Figures 7, 8, and 9 provide a plot of the output for the 2002, 2003 and 2004 events. The tabs labeled "FLDHYDRO Output" of the spreadsheets "Basin46PrecipitationDataProcessing2002.xls," "Basin46PrecipitationDataProcessing2003.xls," and "Basin46PrecipitationDataProcessing2004.xls" represent the output from FLDHYDRO runs. The same spreadsheets were used to convert cumulative effective rainfall depth to incremental effective rainfall depth for input to HEC-HMS.

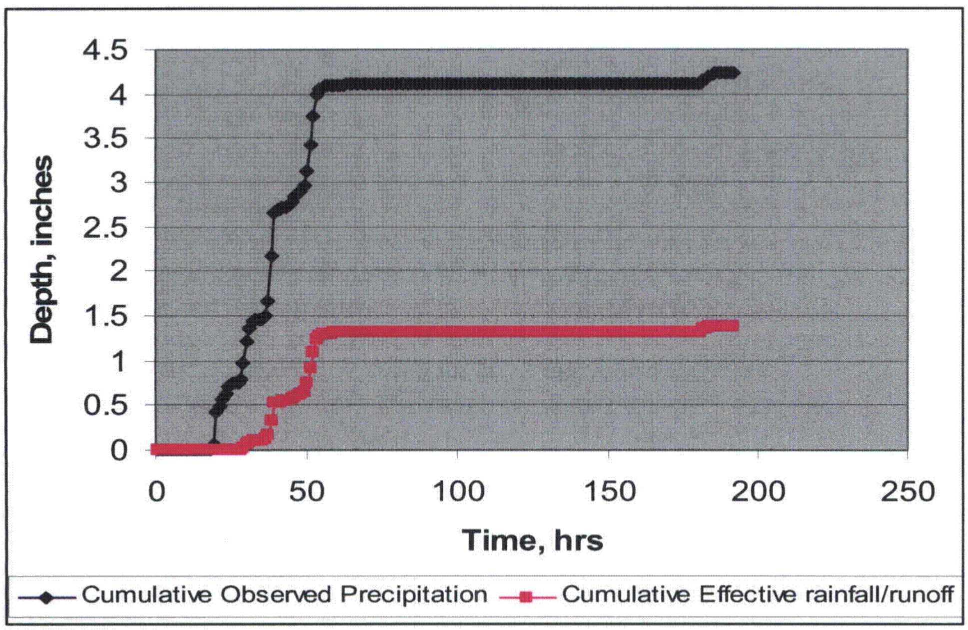


Figure 7: Cumulative observed and effective basin average precipitation for the May 2002 event

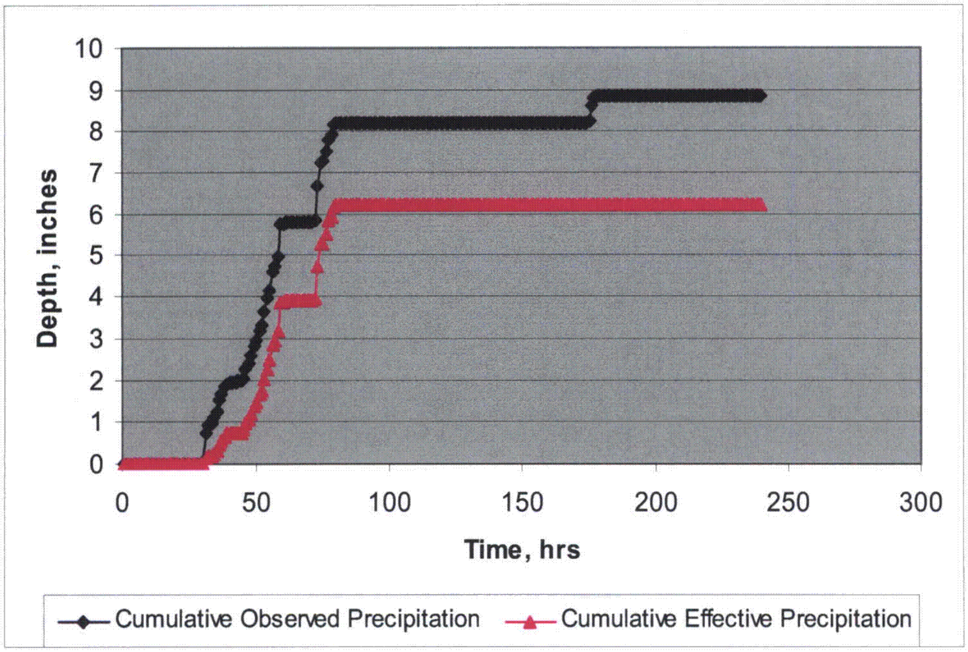


Figure 8: Cumulative observed and effective basin average precipitation for the May 2003 event

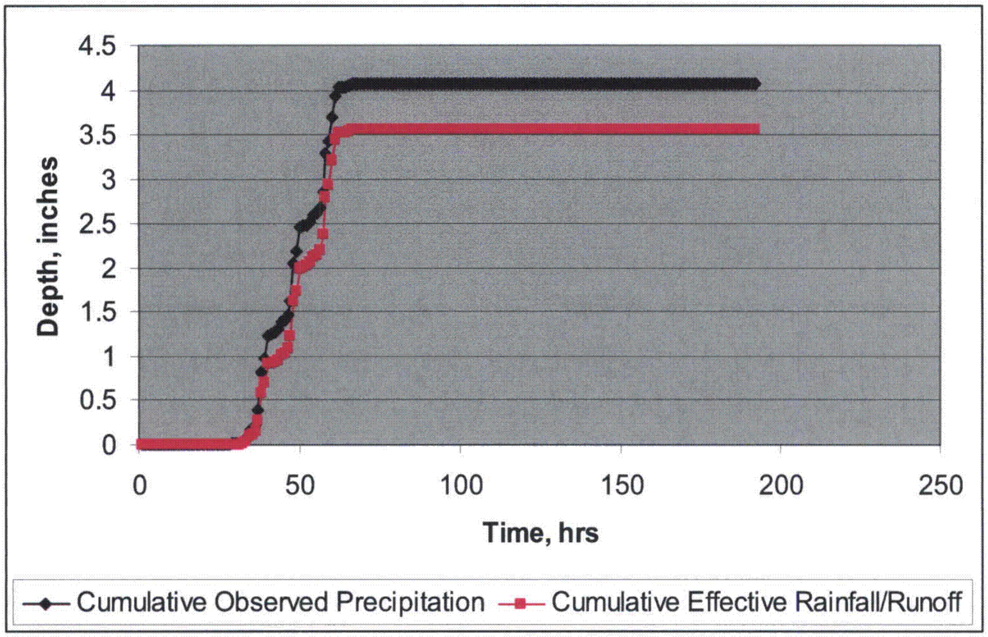


Figure 9: Cumulative observed and effective basin average precipitation for the September 2004 event

8.5 HEC-HMS Simulations of Flood Events

A HEC-HMS project file was developed for validating the unit hydrograph developed by the TVA for the South Chickamauga Creek subbasin using the March 2002, May 2003, and September 2004 storm events. This project file has been compressed into a zip file to preserve the folder structure and has been stored in FILEKEEPER (Attachment 3). The output associated with the HEC-HMS program, while stored within the zip file for convenience and preservation, is provided in the calculation as Figures 10 through 12.

The following input files were developed for the project and input to HEC-HMS (Reference 6) via the Time Series Data Manager (all time series are adjusted to Central Time for this calculation):

- Precipitation Gage "May2002" with hourly data incremental depths
- Precipitation Gage "May2003" with hourly data incremental depths
- Precipitation Gage "Sep2004" with hourly data incremental depths
- Discharge Gage "ObservedMay2002" with bi-hourly direct runoff discharge in cfs
- Discharge Gage "ObservedMay2003" with bi-hourly direct runoff discharge in cfs
- Discharge Gage "ObservedMay2004" with bi-hourly direct runoff discharge in cfs

The following general observations apply to the development of each of the HEC-HMS models:

- Effective rainfall (runoff) time series developed from FLDHDYRO 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 basin outlet hydrographs developed for each model, as described in Section 7.2, were input as discharge gage data using the Time Series Data Manager in HEC-HMS.
- 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 (Reference 7).

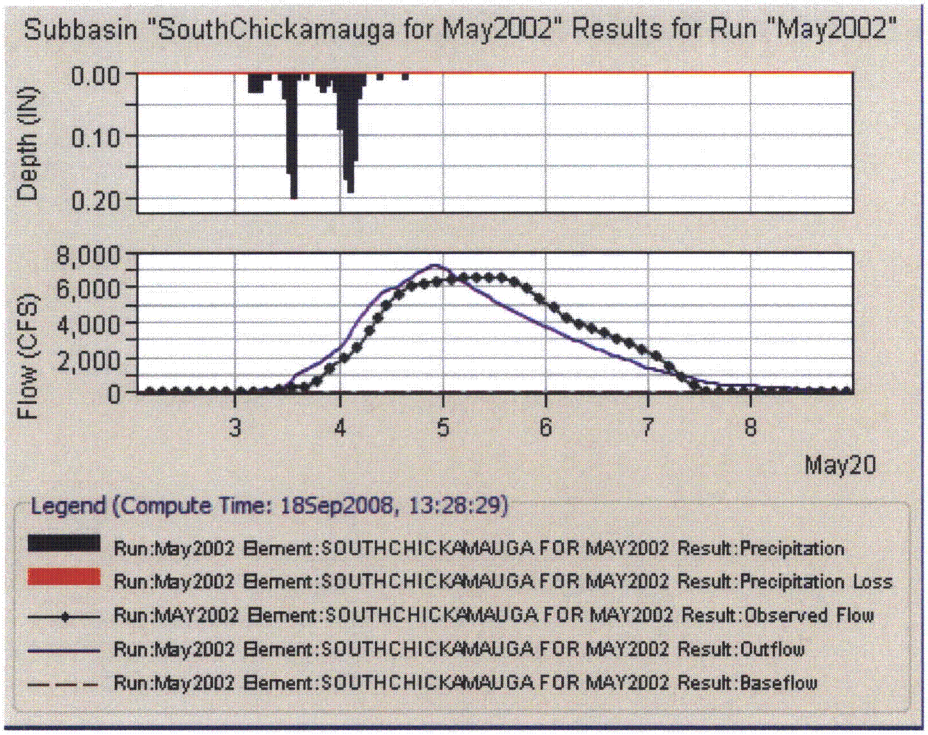
The TVA unit hydrograph (input as Unit Hydrograph Curve TVAUH) was used to simulate the May 2002, May 2003 and September 2004 storm events in HEC-HMS using effective basin average rainfall determined with FLDHYDRO. The simulated hydrograph is compared to the observed hydrograph for each run in Figures 10, 11, and 12 obtained from the HEC-HMS Graphic User Interface. An assessment of the results of the simulations is presented in Table 5.

Table 5: Assessment of the observed versus simulated flood hydrographs

Storm Event	Peak Discharge (ft3/s)			Time to Peak Discharge[1] (h)		
	Simulated	Observed	Error (%)	Simulated	Observed	Error (%)
May-02	7,211	6,563	9.9%	71	81	-12%
May-03	28,037	27,355	2.5%	94	102	-8%
Sep-04	18,378	19,775	-7.1%	78	82	-5%

[1] Time to peak discharge defined as time elapsed from onset of excess rainfall to time of peak discharge.

The results presented in Table 5 indicate that the TVA unit hydrograph, when convoluted with excess rainfall from three more recent storm events, predicts the observed peak discharges quite well, especially for the two largest events. The time to peak discharge for the simulated hydrographs is predicted somewhat early in all three events. In the case of the May 2002 event, it should be noted that the peak of the observed hydrograph is relatively broad, which increases the uncertainty in defining the time to peak discharge for the observed hydrograph. The time to peak is much better defined for the May 2003 and September 2004 events for which the simulated times to peak discharge are within 10 percent of the observed values.



Project: Basin46

Simulation Run: May2002 Subbasin: SouthChickamauga for May2002

Start of Run:	02May2002, 01:00	Basin Model:	SouthChickamauga May2002
End of Run:	09May2002, 00:00	Meteorologic Model:	May2002
Compute Time:	18Sep2008, 13:28:29	Control Specifications:	May02-09,2002

Volume Units: (•) IN ( ) AC-FT

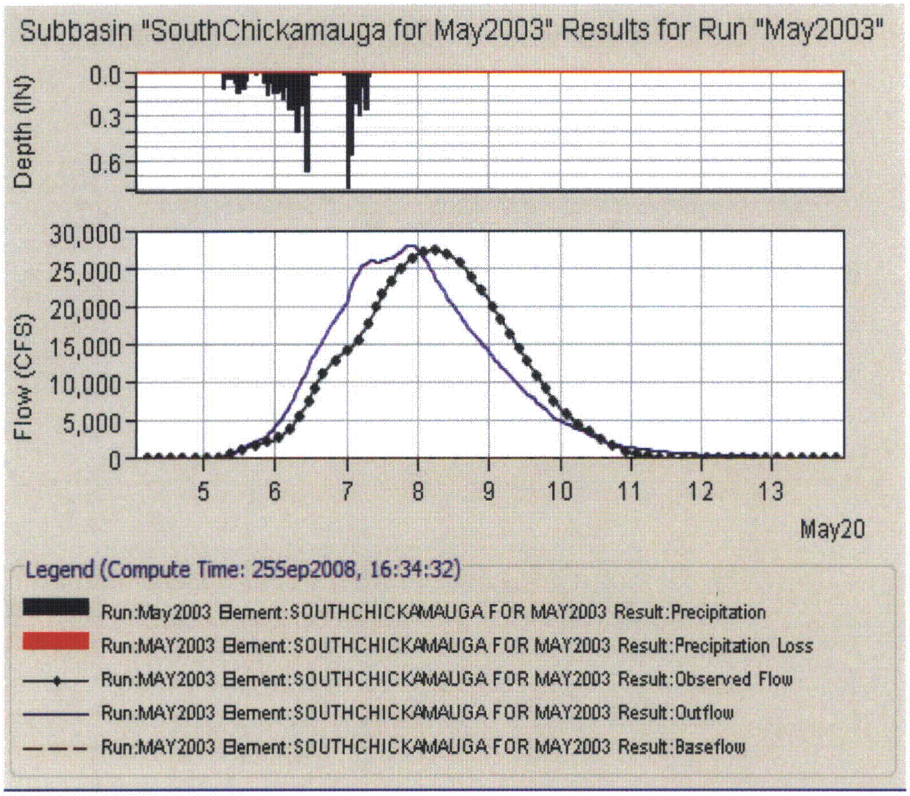
Computed Results

Peak Discharge :	7210.9 (CFS)	Date/Time of Peak Discharge :	04May2002, 23:00
Total Precipitation :	1.32 (IN)	Total Direct Runoff :	1.32 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	1.32 (IN)	Discharge :	1.32 (IN)

Observed Hydrograph at Gage Observed May 2002

Peak Discharge :	6563.20 (CFS)	Date/Time of Peak Discharge :	05May2002, 08:00
Avg Abs Residual :	590.23 (CFS)		
Total Residual :	-0.03 (IN)	Total Obs Q :	1.35 (IN)

Figure 10: HEC-HMS results for Subbasin 46 for the May 2002 event



Project: Basin46
Simulation Run: May2003 Subbasin: SouthChickamauga for May2003

Start of Run:	04May2003, 01:00	Basin Model:	SouthChickamauga-May 2003
End of Run:	14May2003, 00:00	Meteorologic Model:	May 2003
Compute Time:	25Sep2008, 16:34:32	Control Specifications:	May 04-142003

Volume Units: (•) IN ( ) AC-FT

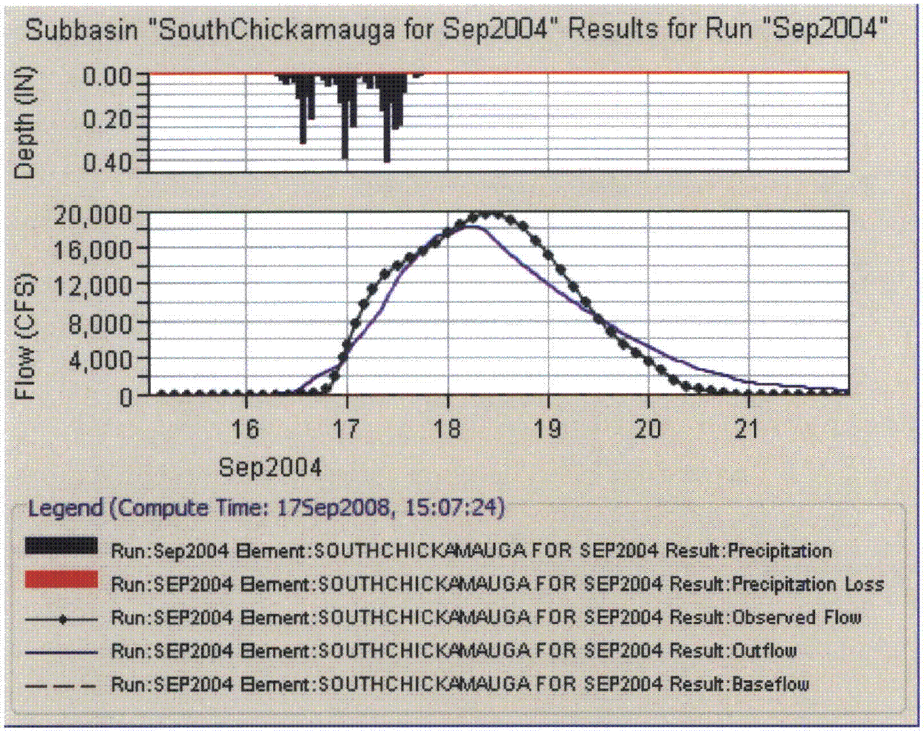
Computed Results

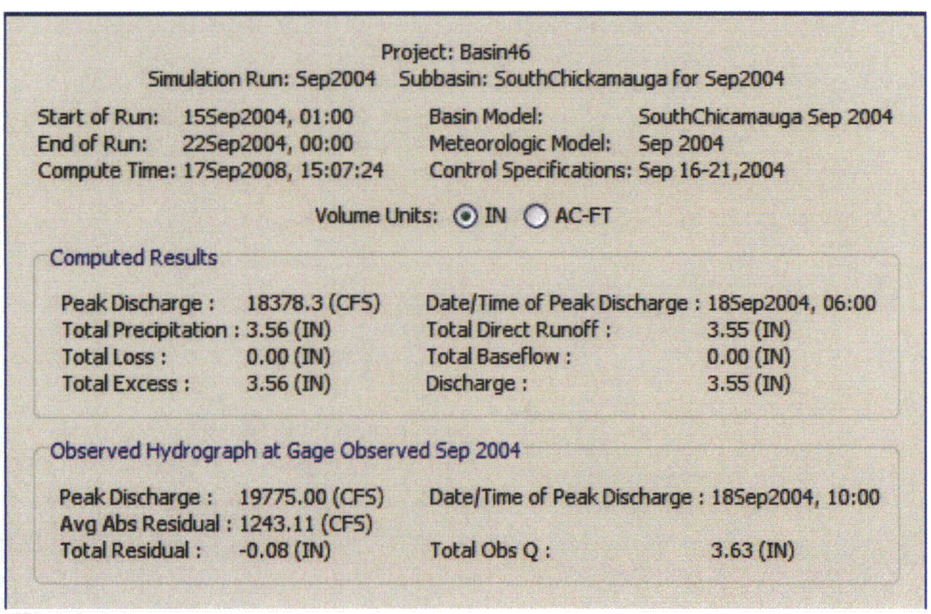
Peak Discharge :	28037.4 (CFS)	Date/Time of Peak Discharge :	07May2003, 22:00
Total Precipitation :	6.23 (IN)	Total Direct Runoff :	6.23 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	6.23 (IN)	Discharge :	6.23 (IN)

Observed Hydrograph at Gage Observed May 2003

Peak Discharge :	27355.00 (CFS)	Date/Time of Peak Discharge :	08May2003, 06:00
Avg Abs Residual :	2040.58 (CFS)		
Total Residual :	-0.00 (IN)	Total Obs Q :	6.23 (IN)

Figure 11: HEC-HMS results for Subbasin 46 for the May 2003 event





Project: Basin46

Simulation Run: Sep2004 Subbasin: SouthChickamauga for Sep2004

Start of Run:	15Sep2004, 01:00	Basin Model:	SouthChicamauga Sep 2004
End of Run:	22Sep2004, 00:00	Meteorologic Model:	Sep 2004
Compute Time:	17Sep2008, 15:07:24	Control Specifications:	Sep 16-21,2004

Volume Units: ◉ IN ○ AC-FT

Computed Results

Peak Discharge :	18378.3 (CFS)	Date/Time of Peak Discharge :	18Sep2004, 06:00
Total Precipitation :	3.56 (IN)	Total Direct Runoff :	3.55 (IN)
Total Loss :	0.00 (IN)	Total Baseflow :	0.00 (IN)
Total Excess :	3.56 (IN)	Discharge :	3.55 (IN)

Observed Hydrograph at Gage Observed Sep 2004

Peak Discharge :	19775.00 (CFS)	Date/Time of Peak Discharge :	18Sep2004, 10:00
Avg Abs Residual :	1243.11 (CFS)		
Total Residual :	-0.08 (IN)	Total Obs Q :	3.63 (IN)

Figure 12: HEC-HMS results for Subbasin 46 for the September 2004 event

9 Conclusions

FLDHYDRO was used to estimate the excess rainfall for Subbasin 46. This program uses previously established loss functions based on initial moisture conditions (API), the week of the year, and the region. The effective basin average rainfall hyetograph was adjusted to match the direct runoff volume corresponding to the prescribed basin area. The unit hydrograph for Subbasin 46 and the estimated excess rainfalls were then used in HEC-HMS to simulate the May 2002, May 2003, and September 2004 storm events within Subbasin 46. The resulting hydrographs at the subbasin outlet were compared to the observed hydrograph at the gage, with baseflow removed from each of the flow series.

The May 2002 simulation results in a basin outflow hydrograph that compares well with the observed hydrograph in terms of peak discharge and somewhat less well in terms of time to peak discharge. In addition to these metrics, overall shape of the simulated hydrograph is similar to that of the observed hydrograph.

The May 2003 simulation results in a basin outflow hydrograph that compares well with the observed hydrograph in terms of peak discharge and time to peak. Also, the simulated hydrograph captures the overall shape of the observed hydrograph.

The September 2004 simulation results in a basin outflow hydrograph that compares well with the observed hydrograph in terms of peak discharge and time to peak. The simulated hydrograph also captures the overall shape of the observed hydrograph.

Based on the preceding discussion, it is concluded that the unit hydrograph developed by the TVA for the South Chickamauga creek basin (Subbasin 46) has been validated against the May 2002, May 2003, and September 2004 storms. Considering that the unit hydrograph was developed from historical flood events that took place in 1963 and 1973 (Reference 8), and was demonstrated in this calculation to be valid for events that occurred in the 2002-2004 timeframe, it is concluded that the watershed characteristics have remained stationary. It is also concluded that the unit hydrograph, tabulated in Table 1 and plotted in Figure 2, adequately describes the response of the watershed and is adequate for application to design storm events.