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

ASSOCIATED ATTACHMENTS/ENCLOSURES:

Attachment 02.04.03-8AA: Nickajack Dam Local Watershed Subbasins 47A and 47B Unit Hydrograph Validation

(57 Pages including Cover Sheet)

NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV 0 EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58090424005	Calculations (nuclear)	L58 091230 036

Calc Title: Nickajack Dam Local Watershed (Subbasins 47A and 47B) Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080060	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
HSSawyer	(615) 252-4362	CEB	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
[signature] Heather Smith Sawyer	12/16/09	*[signature]* Bill Hamilton	12/16/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
[signature] Bill Hamilton	12/16/09	*[signature]* K.R. Coates	12/23/09

STATEMENT OF PROBLEM/ABSTRACT

Validate existing unit hydrographs for the subbasins of the Nickajack Dam watershed (Subbasins 47A and 47B) using the 1973 and 2003 floods of record.

**EDCN- 22404A (SQN), EDCN- 54018A (WBN), EDCN- 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
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NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV 0 EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58 090424 005	Calculations (nuclear)	N/A

Calc Title: Calculation of Initial Flood Flows from Subbasins 47A and 47B for use in the SOCH Model Calibration and Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC						Entire calc ☐ Selected pages ☐
NEW	CN	NUC	GEN	CEB	CDQ000020080060	N/A	0	

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

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

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

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

PREPARER ID	PREPARER PHONE NO	PREPARING ORG (BRANCH)	VERIFICATION METHOD	NEW METHOD OF ANALYSIS
NDMARTIN	(415) 768-3941	Bechtel (CEB)	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Nicholas D. Martin *Nicholas D. Martin*	4/17/2009	Thomas H. Jackson *Thomas H. Jackson*	4-17-09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Robert E. Swain *Robert E. Swain*	4/17/2009	*K.R. Spates* K.R. Spates	4/24/2009

STATEMENT OF PROBLEM/ABSTRACT

Prepare initial flood flow hydrographs for Subbasin 47A, Nickajack local, and Subbasin 47B, North Chickamauga Creek, for two floods that occurred in March 1973 and in May 2003 to be used in the SOCH model calibration and unit hydrograph validation.

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)
L58090424005	Calculations (nuclear)	L58 090710 002

Calc Title: Nickajack Dam Local Watershed (Subbasins 47A and 47B) Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080060	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
HSSawyer	(615) 252-4362	BWSC (CEB)	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Heather Smith Sawyer (signed)	7/6/09	Bill Hamilton (signed)	7/6/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
Bill Hamilton (signed)	7/6/09	K. R. Scates (signed)	7/10/09

STATEMENT OF PROBLEM/ABSTRACT

Validate existing unit hydrographs for the subbasins of the Nickajack Dam watershed (subbasins 47A and 47B) using the 1973 and 2003 floods of record.

**EDCN- 22404 (SQN), EDCN- 54018 (WBN), EDCN- 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
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NPG CALCULATION COVERSHEET/CCRIS UPDATE

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	REV
	CN	NUC	GEN	CEB	CDQ000020080060	2

ALTERNATE CALCULATION IDENTIFICATION

BLDG	ROOM	ELEV	COORD/AZIM	FIRM	Print Report
				BWSC	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	

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:

Heather Smith Sawyer PREPARER SIGNATURE	DATE	Bill Hamilton CHECKER SIGNATURE	DATE
PREPARER PHONE NO.	EDMS ACCESSION NO.		

NPG CALCULATION RECORD OF REVISION

CALCULATION IDENTIFIER	CDQ000020080060
Title	Nickajack Dam Local Watershed (Subbasins 47A and 47B) Unit Hydrograph Validation

Revision No.	DESCRIPTION OF REVISION
0	Initial issue 43 pages
1	This calculation was revised to validate existing unit hydrographs for the subbasins of the Nickajack Dam Local Watershed (Subbasins 47A and 47B) using the 1973 and 2003 floods of record. As a result of this revision, the calculation title has been changed to reflect final validation of the local unit hydrographs. Significant changes to text marked with a right-hand margin revision bar. Changes and Additions: Content on pages 1 – 13 of R0 was modified as indicated on pages 1 – 14 of R1 (additional page added due to page content roll-over to following page). Content on pages 14 – 42 of R0 was modified due only to content carry-over and now equivalent to pages 15 – 44 of R1 (additional pages added due to page content roll-over to following page) Content on page 43 of R0 (the final page of R0) was replaced and new pages 45 – 52 were added Calculation header was revised (Nickajack Dam Local Watershed (Subbasins 47A and 47B) Unit Hydrograph Validation, Revision 1) on all pages. Added new electronic Attachments 4-1, 4-2 and 4-3 Total hardcopy pages Revision 1: 55
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 included only changes made in this revision as the checking of the calculation was not impacted by PER 203951. The verification is inclusive of work completed prior to this revision. • PER 203872- replace NEDP-2 forms on Pages 1 through 7 & 9 with the forms from the NEDP-2 Revision in effect at the time of calculations issuance. The unverified assumption associated with the approval of the Nickajack SOCH Calibration calculation, CDQ000020080040, has been removed. Final calibration has been completed and the calculation has been approved. Significant changes in Revision 2 are noted with a right margin revision bar. Administrative changes and typos are excluded Changes and additions: Content on pages 1-9, 11, and 46 – 49 R1 has been modified as indicated on pages 1-9, 11, and 46-49, R2. Pages 1b and 9b were added. Total hardcopy pages Revision 2: 56

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	Attachment 1- 4: SouthChickamaugaCreek.txt	N/A
	Attachment 1- 5: NickajackDam_Hourly_Precip_01012003_12312003_R000A.xls	N/A
	Attachment 1- 6: NWS_Precip_Basins-47AandB_CT.xls	N/A
	Attachment 1- 7: MassBalance&Baseflow_Separation.xls	N/A
	Attachment 1- 8: Rainfall_Nickajack_ Reservoir_Calculations.xls	N/A

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Calculation Identifier: CDQ000020080060	Revision: 2	

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Attachment 1- 9: Rainfall_1973.xls	N/A
Attachment 1- 10: Antecedent_1973.xls	N/A
Attachment 1- 11: FLDHYDRO_Output.xls	N/A
Attachment 1- 12: Nickajack Reservoir_Results.xls	N/A
Attachment 1- 13: Initial_Flood_Hydrographs.xls	N/A
Attachment 2- 1: B47_1973.dat	N/A
Attachment 2- 2: B47_2003.dat	N/A
Attachment 2- 3: NRes_1973.dat	N/A
Attachment 2- 4: B47_1973.out	N/A
Attachment 2- 5: B47_2003.out	N/A
Attachment 2- 6: NRes_1973.out	N/A
Attachment 4-1: Attachment_4-1_Observed vs. SOCH Unsteady State Mar 1973 Hydrographs.xls	N/A
Attachment 4-2: Attachment_4-2_Observed vs. SOCH Mar 2003 Hydrographs.xls	N/A
Attachment 4-3: Attachment_4-3_Validated_6HR_UH.xls	N/A
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Note: N/A indicates an electronically attached file(s).

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NPG COMPUTER INPUT FILE STORAGE INFORMATION SHEET			
Document CDQ000020080060	Rev. 2	Plant: GEN	
Subject: Nickajack Dam Local Watershed (Subbasins 47A and 47B) 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: CDQ000020080060	Rev. 1	Plant: GEN	
Subject: Nickajack Dam Local Watershed (Subbasins 47A and 47B) Unit Hydrograph Validation			

Electronic Attachment: Name of File or Folder	File Location
Supporting Spreadsheets	
Attachment 1-1: nickajack_rev0.xls	Attached to PDF
Attachment 1-2: chickamauga_rev0.xls	Attached to PDF
Attachment 1-3: SChickNrChickamauga_rev0.xls	Attached to PDF
Attachment 1-4: SouthChickamaugaCreek.txt	Attached to PDF
Attachment 1-5: NickajackDam_Hourly_Precip_01012003_12312003_R000A.xls	Attached to PDF
Attachment 1-6: NWS_Precip_Basins-47AandB_CT.xls	Attached to PDF
Attachment 1-7: MassBalance&Baseflow_Separation.xls	Attached to PDF
Attachment 1-8: Rainfall_Nickajack_ Reservoir_Calculations.xls	Attached to PDF
Attachment 1-9: Rainfall_1973.xls	Attached to PDF
Attachment 1-10: Antecedent_1973.xls	Attached to PDF
Attachment 1-11: FLDHYDRO_Output.xls	Attached to PDF
Attachment 1-12: Nickajack Reservoir_Results.xls	Attached to PDF
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FLDHYDRO Files	
Attachment 2-1: B47_1973.dat	Attached to PDF
Attachment 2- 2: B47_2003.dat	Attached to PDF
Attachment 2- 3: NRes_1973.dat	Attached to PDF
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Attachment 2- 6: NRes_1973.out	Attached to PDF
UH Validation Files	
Attachment 4-1: Attachment_4-1_Observed vs. SOCH Unsteady State Mar 1973 Hydrographs.xls	Attached to PDF
Attachment 4-2: Attachment_4-2_Observed vs. SOCH Mar 2003 Hydrographs.xls	Attached to PDF
Attachment 4-3: Attachment_4-3_Validated_6HR_UH.xls	Attached to PDF

NPG CALCULATION VERIFICATION FORM

Calculation Identifier	CDQ000020080060	Revision 2

Method of verification used:		Verifier Bill Hamilton (signature) Date 12/16/09
1. Design Review	☒	
2. Alternate Calculation	☐	
3. Qualification Test	☐	

Comments:

The calculation entitled, "Nickajack Dam Local Watershed (Subbasins 47A and 47B) Unit Hydrograph Validation" was verified by an independent design review. The process involved a critical review of the calculation to ensure that it is correct and complete, uses appropriate methodologies, and achieves its intended purpose. Backup files and documents were consulted as necessary to verify data and analysis details found in the calculation. Detailed comments and editorial suggestions were transmitted to the author and reviewer by email along with a marked up copy of the calculation.

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.

(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	CDQ000020080060	Revision 0

Method of verification used:

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

Verifier Bob Swain Date 4/10/2009

Comments:

The calculation entitled, "Calculation of Initial Flood Flows from Subbasins 47A and 47B for use in the SOCH Model Calibration and Unit Hydrograph Validation" was verified by an independent design review. The process involved a critical review of the calculation to ensure that it is correct and complete, uses appropriate methodologies, and achieves its intended purpose. Backup files and documents were consulted as necessary to verify data and analysis details found in the calculation. Detailed comments and editorial suggestions were transmitted to the author and reviewer by email along with a marked up copy of the calculation.

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

1. Rainfall hyetographs were added to the report to show the precipitation magnitude and distribution for each storm.

2. The baseflow separation calculation for the 2003 flood was changed. Direct runoff ended about two days after the storm rather than six days after the storm, which was used in the initial calculation. The change resulted in direct runoff ending the same number of days after the rain as the 1973 baseflow separation.

3. Baseflow was disaggregated to each subbasin for use in developing the initial subbasin inflow hydrographs.

4. Nickajack Reservoir area-elevation data were added to the report to support use of the 16.3 mi^2 reservoir surface area to determine the quantity of "additional" reservoir runoff for both floods.

The calculation presents the development of initial simulated flows from Subbasins 47A and 47B for floods that occurred in March 1973 and May 2003. The initial simulated flows are for use in the calibration of the SOCH model and to validate the unit hydrographs for Subbasins 47A and 47B.

NPG CALCULATION VERIFICATION FORM

Calculation Identifier CDQ000020080060 Revision 1

Method of verification used:		
1. Design Review	☒	
2. Alternate Calculation	☐	Verifier Bill Hamilton Date 7/1/09
3. Qualification Test	☐	

Comments:

The calculation entitled, "Nickajack Dam Local Watershed (Subbasins 47A and 47B) Unit Hydrograph Validation" was verified by an independent design review. The process involved a critical review of the calculation to ensure that it is correct and complete, uses appropriate methodologies, and achieves its intended purpose. Backup files and documents were consulted as necessary to verify data and analysis details found in the calculation. Detailed comments and editorial suggestions were transmitted to the author and reviewer by email along with a marked up copy of the calculation.

The calculation presents the development of initial simulated flows from Subbasins 47A and 47B for floods that occurred in March 1973 and May 2003, which are for use in the calibration of the SOCH model. The initial simulated flows are for use in the calibration of the SOCH model and to validate the unit hydrographs for Subbasins 47A and 47B. The comparison between the observed and simulated flows and water surface elevations at several locations supports the conclusion that the unit hydrographs developed for Subbasins 47A and 47B have been indirectly validated against floods that occurred in March 1973 and May 2003.

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**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 Sequoyah, Watts Bar and planned Bellefonte Nuclear Plant sites (Note that this calculation will also be used in similar future PMF and dam break analyses for the Browns Ferry Nuclear Plant).

Inputs to the dynamic model include hydrographs for 47 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 and early 1980s, utilizing the observed rainfall and stream flow and reservoir headwater and discharge data, and are being validated by checking their performance in reproducing recent floods.

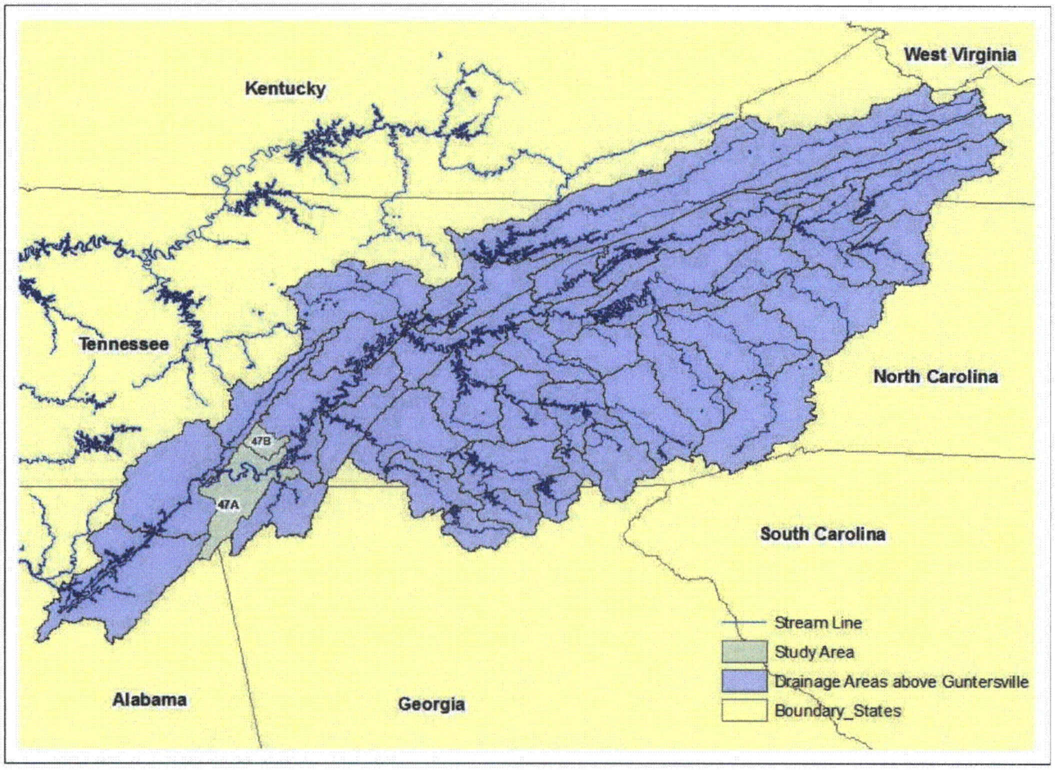

Figure 1: Location of Study Area (Subbasins 47A and 47B) within the Tennessee River Watershed

As part of the dynamic hydrologic model of the Tennessee River system, the subbasin flood hydrographs are used as inputs to the Simulated Open Channel Hydraulic (SOCH) code. The

SOCH model provides elevation and discharge hydrographs at selected locations within the modeled reach. This calculation presents the generation of initial simulated flows from Subbasin 47A, Subbasin 47B, and from the Nickajack Reservoir surface as well as the unit hydrograph validation for floods that occurred in March 1973 and May 2003. The March 1973 and May 2003 floods were selected by the TVA to be analyzed using the SOCH model. The simulated flows will be used by the TVA in the calibration of the SOCH model and to validate the unit hydrographs for Subbasins 47A and 47B. Subbasins 47A and 47B are located in the Tennessee River watershed as shown in Figure 1.

2 References

Reference 1: Tennessee Valley Authority, Bellefonte Nuclear Plant - White Paper, Hydrologic Analysis, Revision 1, July 25, 2008. (EDMS No. L58 081219 800). FOR INFORMATION ONLY

Reference 2: Viessman, W., J.W. Knapp, G.L. Lewis,, and T.E. Harbaugh, *Introduction to Hydrology*, Second Edition, Harper & Row, Publishers, 1977.

Reference 3: Chow, V.T., D.R. Maidment, and L.W. Mays, *Applied Hydrology*, McGraw-Hill Book Company, 1988.

Reference 4: Tennessee Valley Authority, *UNITGRPH-FLDHYDRO-TRBROUTE-CHANROUT User's Manual*, Version 1.0, March 2009 (EDMS No. L58 090325 001).

Reference 5: Tennessee Valley Authority, [Map] Drainage Areas above Guntersville Dam, June 18, 2008 (6 GIE 301 E 200801 R0 D).

Reference 6: Tennessee Valley Authority, Unit Area 47, Nickajack Local, File Book Reference. (EDMS No. L58 081223 833)

Reference 7: Bechtel, Request for Information RFI 25447-000-GRI-GEX-00052, November 7, 2008. (EDMS No. L58 081119 804)

Reference 8: Tennessee Valley Authority, Observed Outflow and Headwater Elevation Data for Nickajack Dam (EDMS L58 090311 802, nickajack_rev0.xls see Attachment 1-1).

Reference 9: Tennessee Valley Authority, Observed Outflow and Headwater Elevation Data for Chickamauga Dam (EDMS L58 090311 802, chickamauga_rev0.xls see Attachment 1-2).

Reference 10: Tennessee Valley Authority, Observed Stage and Streamflow Data for South Chickamauga Creek (EDMS L58 090311 802, SChickNrChickamauga_rev0.xls see Attachment 1-3).

Reference 11: United States Geological Survey (USGS), Daily discharge data for years 1929 to 1996 at gage 03567500 South Chickamauga Creek near Chickamauga, TN, obtained from the National Water Information System (NWIS), online at: http://waterdata.usgs.gov/nwis, accessed 10/30/2008 (see Attachment 1-4)

Reference 12: Bechtel, Request for Information RFI 25447-000-GRI-GEX-00040, September 25, 2008. (EDMS No. L58 081030 002)

Reference 13: 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 1, February 2009. (EDMS No. L58 081030 008)

Reference 14: Linsley, R.K., Kohler, M.A., and J.L. Paulhus, *Hydrology for Engineers*, McGraw-Hill Book Company 1982.

Reference 15: Tennessee Valley Authority, TVA Water Control Projects and Other Major Hydro Developments in the Tennessee and Cumberland Valleys, *Technical Monograph No. 55*, Volume 1, March 1980.

Reference 16: 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)

Reference 17. Tennessee Valley Authority, Calculation No. CDQ00020080040, Revision 0, SOCH Model Calibration, Nickajack.

Reference 18. American Nuclear Society, *American National Standard for Determining Design Basis Flooding at Power Reactor Sites*, ANSI/ANS-2.8-1992, 1992.

Reference 19. US Nuclear Regulatory Commission, Standard Review Plan 2.4.3, *Probable Maximum Flood (PMF) on Streams and Rivers*, NUREG-0800, Revision 4, March 2007.

3 Assumptions

3.1 General Assumptions

None.

3.2 Unverified Assumptions

None.

4 Background

The unit hydrograph (UH) is used to predict the runoff response at the outlet of a watershed, or subbasin, to the input of one unit of excess rainfall applied uniformly over a given duration of time. Runoff from other depths of excess rainfall can be obtained by scaling (Reference 2 and Reference 3).

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 direct runoff, Q, is obtained by summing the products of the excess rainfall depths (direct runoff depths), P, and the unit hydrograph ordinates, U (Reference 2 and Reference 3). 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 3):

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.

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Unit hydrograph theory is applicable under the following conditions (Reference 3):

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

5 Methodology

Direct runoff originating within several subbasins of the Tennessee Valley watershed, which empty directly into the Tennessee River, cannot be accurately calculated because the observed flood hydrograph at the subbasin outlet is not available. For these subbasins, the TVA will employ SOCH model results to validate the unit hydrograph. The SOCH model requires estimated flood hydrographs for these subbasins as inputs during the model calibration process.

Input flood hydrographs for individual subbasins requiring SOCH model validation are estimated by using a water budget to calculate total flow volume during a flood. The water budget area is chosen so that the observed flood hydrograph at the outlet of the water budget area can be reliably estimated. Total inflow to the water budget area is then partitioned among the component subbasins, as enumerated below, to obtain input flood hydrographs for each subbasin.

The methodology used for unit hydrograph validation follows that described in ANSI/ANS-2.8-1992 (Reference 18). This document is included as a reference in the NRC's Standard Review Plan 2.4.3, *Probable Maximum Flood on Streams and Rivers* (Reference 19). ANSI/ANS-2.8-1992 states that "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."

The methodology used for this calculation includes the following steps:

1. Delineate the area for water budgeting, which in this calculation is the combined area of Subbasins 47A and 47B. Perform water budget calculations for the March 1973

and May 2003 floods to estimate the volume of each flood that originates within this area.

2. Separate base flow from the total local flow to obtain the direct runoff for the budget area.
3. Obtain observed rainfall data for the March 1973 and May 2003 floods and calculate the basin-average rainfall for each subbasin and also for the reservoir area.
4. Convert the observed rainfall series to excess precipitation series using the TVA's Antecedent Precipitation Index (API)/Runoff Index (RI) method as implemented in FLDHYDRO (Reference 4). Observed direct runoff volumes are used by FLDHYDRO to ensure that the calculated excess precipitation volumes agree with the observed. FLDHYDRO allocates excess precipitation among the subbasins according to their calculated API values.

5. Compute the additional direct runoff generated by rainfall on the surface of the reservoir. All rain falling on the reservoir surface becomes runoff. Therefore, the additional direct runoff is equal to the observed rainfall over the reservoir area (Step 3) less the direct runoff calculated in Step 4 for the reservoir area. Check that the volume of direct runoff from Step 2 equals the sum of the direct runoff from Steps 4 and 5. If necessary, adjust the CHKVOL value in FLDHYDRO and redo Steps 4 and 5.
6. Convolute the TVA unit hydrograph and the excess rainfall series to generate the initial, simulated local direct runoff hydrograph for each subbasin. Partition total base flow volume, from Step 2, according to relative subbasin areas and add to direct runoff to obtain the initial flood hydrograph for each subbasin.

7. Compare the SOCH model simulated and observed discharge and stage hydrographs for appropriate stations along the Tennessee River to indirectly validate the performance of the TVA unit hydrographs in simulating local runoff along the study reach of the Tennessee River.

6 Design Input Data

The input data necessary for developing initial SOCH inflow hydrographs for Subbasins 47A and 47B are summarized below.

- Subbasin drainage areas and the surface area of Nickajack Reservoir
- Unit hydrograph ordinates and duration

- South Chickamauga Creek stream flow observed at the gage located at the Subbasin 47A boundary
- Observed daily storage and discharges at Nickajack Dam
- Observed daily discharges at Chickamauga Dam
- Rainfall data associated with the March 1973 and May 2003 floods

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

6.1 Subbasin Characteristics

The joint area of Subbasins 47A and 47B was measured as 644.0 mi^2 in GIS (Reference 5). The Nickajack Reservoir area is included within Subbasin 47A. Subbasins 47A and 47B are shown in Figure 2. Watershed areas for these subbasins and for Nickajack Reservoir are provided in Table 1.

Table 1: Subbasin Drainage Areas

Basin ID	Subbasin Name	Area mi^2 (measured in GIS)
47B	North Chickamauga Creek	98.3
47A	Nickajack local	545.71
Nickajack Reservoir	Reservoir Area in Subbasin 47A	16.31
Total Area		644.0

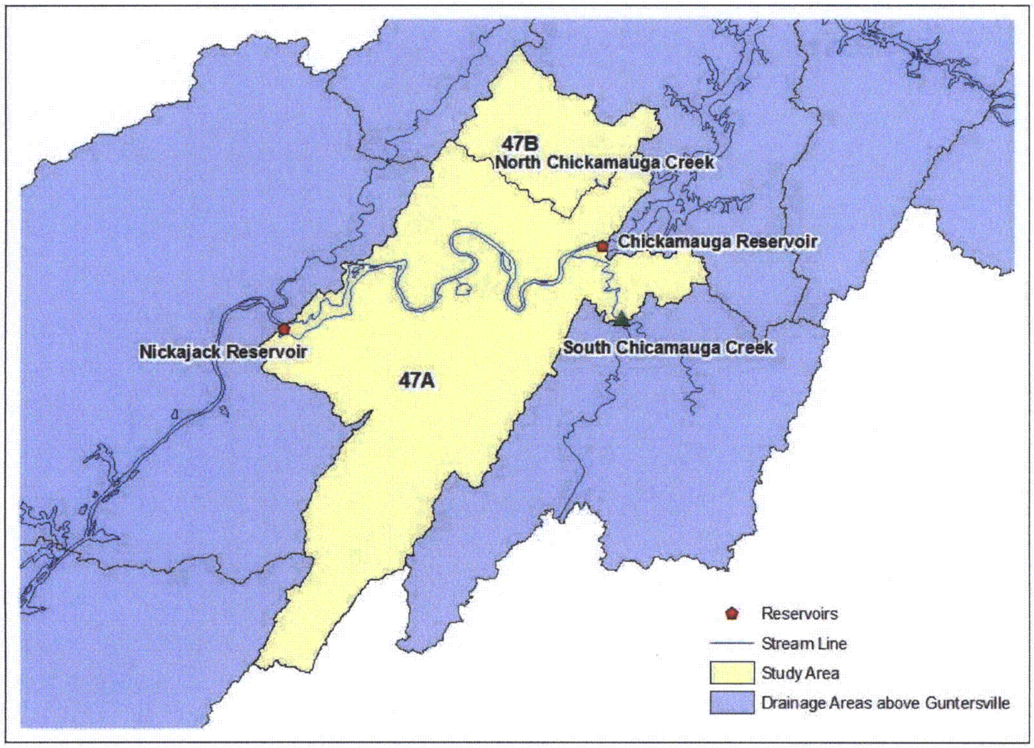

Figure 2: Location of Subbasins 47A and 47B

6.2 Unit Hydrograph Ordinates

The unit hydrograph provides the response of a watershed to one inch of excess precipitation, as described in Section 4. A unit hydrograph was originally developed for the total basin (47A and 47B combined) (Reference 6).

Because Subbasin 47 was split into Subbasins 47A and 47B, unit hydrographs were developed by the TVA for each of these sub-areas with adjustments made to the ordinates to reflect the 644 mi^2 total area for these two subbasins. Reference 7 provides documentation of the unit hydrographs for Subbasins 47A and 47B. The UH for Subbasin 47A is shown in Figure 3; the time base and ordinates are listed in Table 2. Figure 4 displays the UH for Subbasin 47B, and Table 3 provides the unit hydrograph ordinates. A summary of the key parameters associated with each of the unit hydrographs is presented in Table 4. As shown in the final column of the table, the volume of runoff is approximately one inch for each unit hydrograph as calculated from Equation (1).

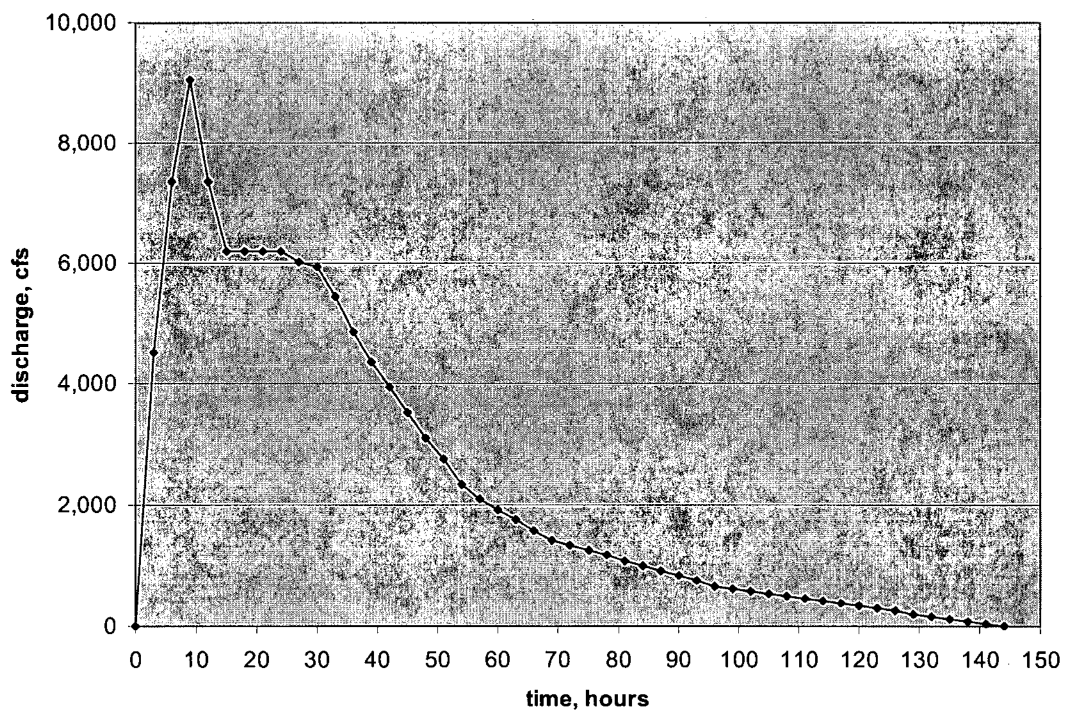

Figure 3: Six-Hour Unit Hydrograph for Subbasin 47A (Chickamauga Local)

Table 2: Time Base and Ordinates for Subbasin 47A Six-Hour Unit Hydrograph

Time (hours)	Discharge (cfs)
0	0
3	4,520
6	7,366
9	9,059
12	7,366
15	6,194
18	6,194
21	6,194
24	6,194
27	6,026
30	5,943
33	5,441
36	4,855
39	4,352
42	3,934
45	3,515

Time (hours)	Discharge (cfs)
48	3,097
51	2,762
54	2,344
57	2,093
60	1,925
63	1,758
66	1,590
69	1,423
72	1,339
75	1,256
78	1,172
81	1,088
84	1,004
87	921
90	837
93	753

Time (hours)	Discharge (cfs)
96	670
99	628
102	586
105	544
108	502
111	460
114	419
117	377
120	335
123	293

Time (hours)	Discharge (cfs)
126	251
129	209
132	167
135	126
138	84
141	42
144	0
Volume:	1.01 in

$$Volume\ (in) = \left(\sum Q \frac{ft^3}{\sec} \times 3600 \frac{\sec}{hr} \times Period\ in\ hrs \times \left(\frac{1}{area\ mi^2} \times \frac{1\ mi^2}{5280^2\ ft^2} \right) \right) \times \frac{12\ in}{1\ ft} \qquad (1)$$

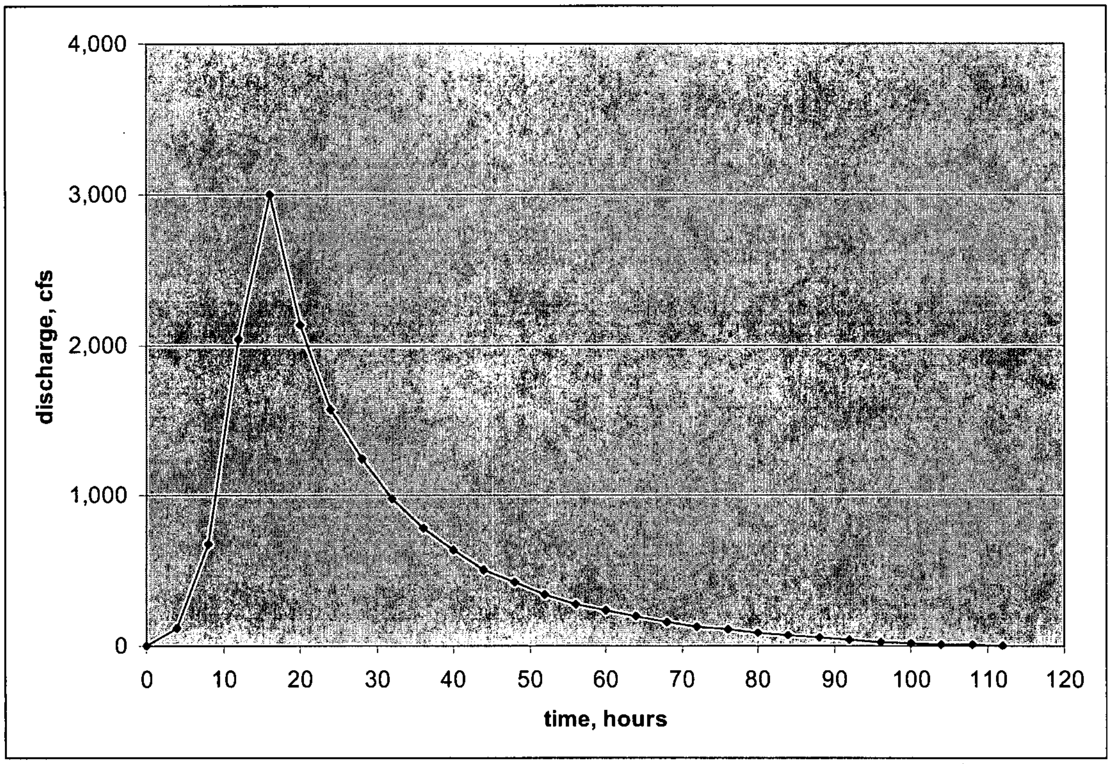

Figure 4: Four-Hour Unit Hydrograph for Subbasin 47B (North Chickamauga Creek)

Table 3: Time Base and Ordinates for Subbasin 47B Four-Hour Unit Hydrograph

Time (hours)	Discharge (cfs)
0	0
4	124
8	671
12	2,038
16	3,000
20	2,137
24	1,566
28	1,243
32	974
36	780
40	636
44	507
48	422
52	348
56	283
60	239

Time (hours)	Discharge (cfs)
64	199
68	164
72	129
76	109
80	89
84	70
88	55
92	40
96	25
100	15
104	10
108	5
112	0
Volume:	1.001 in

Table 4: TVA Unit Hydrograph Parameters for Subbasins 47A and 47B

Subbasin	Effective Duration (hours)	Ordinate Interval (hours)	Number of Ordinates	Peak Discharge (cfs)	Time to Peak (hours)	Area (mi^2)	Volume (inches)
47A	6	3	49	9059	9	545.71	1.01
47B	4	4	29	3000	16	98.3	1.001

6.3 Observed Discharge and Storage

Observed daily reservoir storage and discharge at Nickajack Dam and the observed daily discharge from Chickamauga Dam were obtained from TVA and are enclosed as Attachment 1-1 (Reference 8) and Attachment 1- 2 (Reference 9). Bi-hourly streamflow values recorded at the South Chickamauga Creek gage, also obtained from the TVA, are included as Attachment 1- 3 (Reference 10). The daily discharge record at USGS gage 03567500 South Chickamauga Creek near Chickamauga, TN was obtained from the USGS for the March 1973 flood (Reference 11; Attachment 1- 4).

6.4 Observed Rainfall

Two sources of observed rainfall data were used in this calculation. TVA rain gage data with Thiessen weights were employed to simulate the March 1973 flood. Gridded precipitation data from the U.S. National Weather Service (NWS) were used to simulate the May 2003 flood. The TVA rainfall data are presented in Reference 12. The NWS gridded precipitation data (Reference 13) are discussed in this section.

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 NWS.

NWS NEXRAD Stage III hourly precipitation data were obtained from the Lower Mississippi River Forecast Center (LMRFC) from January 1997 to April 2008. A Microsoft.Net utility was developed to generate radar-based Mean Areal Precipitation (MAPX) time series for each of the subbasins. 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 13 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. The precipitation data needed to simulate the May 2003 flood were obtained from this database.

7 Computations and Analyses

7.1 Floods for SOCH Model Calibration

The May 2003 and March 1973 floods were selected by the TVA for analysis because these two floods were significant across the Tennessee River watershed. In Subbasins 47A and 47B, the storms generating these floods spanned the following times:

- May 5, 2003, 01:00 hrs to May 7, 2003, 16:00 hrs, the "May 2003" storm
- March 15,1973, 05:00 hrs to March 17, 1973 00: 00 hrs, the "March 1973" storm

7.2 Observed Subbasin Average Rainfall

Observed basin-average rainfall for the May 2003 storm was obtained from Reference 13. The hourly precipitation series developed from NWS gridded data for Subbasins 47A and 47B are provided in Attachment 1- 5. Calculations representing adjustments to Central Time and unit conversion of the NWS gridded data are enclosed as Attachment 1- 6. Observed basin average rainfall for the March 1973 storm was obtained from Reference 12.

7.3 Water Budget Computation

A daily water budget analysis was performed to determine daily flood flows originating within Subbasin 47A and 47B for the March 1973 and May 2003 floods. Base flows were removed from the flood flows to obtain direct runoff hydrographs.

7.3.1 Flood Volumes

The water budget analysis consists of solving the continuity equation for the water budget area:

$$\bar{L} = \frac{dS}{dt} + \bar{O} - \bar{I} \qquad (2)$$

where L is the local inflow rate to the budget area, O is the outflow rate from the budget area outlet, I is inflow rate from upstream subbasins, and S is storage within the budget area. An interval of one day was selected for the analysis (i.e. dt = 1 day), and the bars above L, O, and I represent daily-average flow rates.

The water budget area in this calculation is comprised of Subbasins 47A and 47B. The change in storage within the budget area is represented by the change in Nickajack Reservoir storage under the requirement that channel storage within the budget area, outside of the reservoir boundaries, is constant during the calculation. The analysis interval of one day is sufficiently long such that the travel time within the boundaries of the budget area can be neglected when daily-averaged values are used. Given these conditions, the water budget computation simplifies to calculating the inflow to Nickajack Reservoir using reverse reservoir routing and then subtracting inflows to the water budget area from upstream subbasins.

Reverse reservoir routing involves solving the continuity equation for a reservoir (Reference 3):

$$\overline{R_i} = \frac{dS}{dt} + \overline{O} \qquad (3)$$

where R_i is the reservoir inflow rate. Again an interval of one day was selected for the analysis, and the over bars represent daily-averages; S, t, and O are defined above. Equation (3) requires a level water surface in the reservoir (i.e. level-pool routing). The change in storage over a day is calculated as the observed storage volume for one day less the observed storage volume for the preceding day. Equations (2) and (3) can be combined to provide the simplified water budget computation in Equation (4).

$$\overline{L} = \overline{R_i} - \overline{I} \qquad (4)$$

The local inflow to the budget area, L, is composed of direct runoff and base flow originating within Subbasins 47A and 47B and of direct runoff produced by rain falling on the surface of the Nickajack Reservoir. Upstream inflows (I) to the budget area come from Chickamauga Reservoir releases and flow in South Chickamauga Creek. Data required to calculate inflow (L) to the budget area are listed below.

- Nickajack Reservoir storage (S) and outflow (O) measured at Nickajack Dam are used in reverse reservoir routing calculations, Equation (3). These data are enclosed in Attachment 1- 1 (Reference 8).
- Daily averaged outflows from Chickamauga Reservoir provide an inflow (I) to the budget area. Observed releases at Chickamauga Dam are attached as Attachment 1- 2 (Reference 9).
- Observed stream flow in South Chickamauga Creek provide another inflow (I) to the budget area. These data are enclosed as Attachment 1- 3 (Reference 10) and Attachment 1- 4 (Reference 11).

The calculated inflow to Nickajack Reservoir for each day during the March 1973 and May 2003 floods provides the flood hydrographs for the budget area. These hydrographs represent the aggregated flood discharge from Subbasins 47A and 47B and from rainfall on the surface of Nickajack Reservoir. Table 5 and Table 6 present the calculated total local inflows to the budget area for the March 1973 and May 2003 floods. The calculated inflows and the measured outflows for Nickajack Reservoir for the March 1973 and May 2003 floods are shown in Figure 5 and Figure 6. The spreadsheet used for these calculations is provided as Attachment 1- 7.

Table 5: Water Budget Calculation for March 1973 Flood

Date	Nickajack Headwater Elevation	$\bar{O}$	S	$\overline{R_i} = \frac{dS}{dt} + \overline{O}$	$\bar{I}$			$\overline{L} = \overline{R_i} - \overline{I}$
		Nickajack Average Daily Discharges	Nickajack Midnight Storage Volume	Nickajack Inflows	Chickamauga Daily Outflows	South Chickamauga Daily Flows	Total Inflows from Upstream	Total Local Flows [1]
	ft	cfs	1000 dsf[2]	cfs	cfs	cfs	cfs	cfs
	Attachment 1- 1				Attachment 1-2	Attachment 1-4		
3/10/1973	633.27	35,200	123	34,710	25,500	4,300	29,800	4,910
3/11/1973	633.57	32,100	123	32,400	21,400	3,920	25,320	7,080
3/12/1973	633.61	38,400	123	38,290	25,900	4,830	30,730	7,560
3/13/1973	633.70	35,600	122	35,170	25,400	3,740	29,140	6,030
3/14/1973	633.74	34,100	123	34,860	28,500	2,550	31,050	3,810
3/15/1973	633.55	47,800	126	50,180	41,000	1,960	42,960	7,220
3/16/1973	632.35	144,900	164	183,650	116,700	12,500	129,200	54,450
3/17/1973	632.10	233,700	199	268,510	215,900	26,500	242,400	26,110
3/18/1973	632.20	248,500	188	237,410	219,000	16,500	235,500	1,910
3/19/1973	632.08	218,500	159	189,410	182,900	7,600	190,500	-1,090
3/20/1973	632.06	162,700	137	140,420	138,300	3,200	141,500	-1,080
3/21/1973	632.25	118,600	129	111,350	109,100	1,860	110,960	390
3/22/1973	632.13	101,800	128	100,760	101,200	1,320	102,520	-1,760
3/23/1973	632.31	97,500	129	97,770	99,700	1,070	100,770	-3,000
3/24/1973	632.29	98,400	128.21	97,960	97,900	952	98,852	-892

[1] Several of the calculated Total Local Flows (L) are negative. These negative values are artifacts of the calculation method that occur because the water budget computation does not account for routing of flows across the water budget area and reservoir to Nickajack Dam. These negative values are outside the range of the March 1973 flood which extends from 3/14/1973 to 3/18/1973.

[2] A dsf is the volume of water resulting from a flow of one cfs for one day (86,400 seconds). This is equal to 86,400 cubic feet of water or about 1.9835 acre-feet.

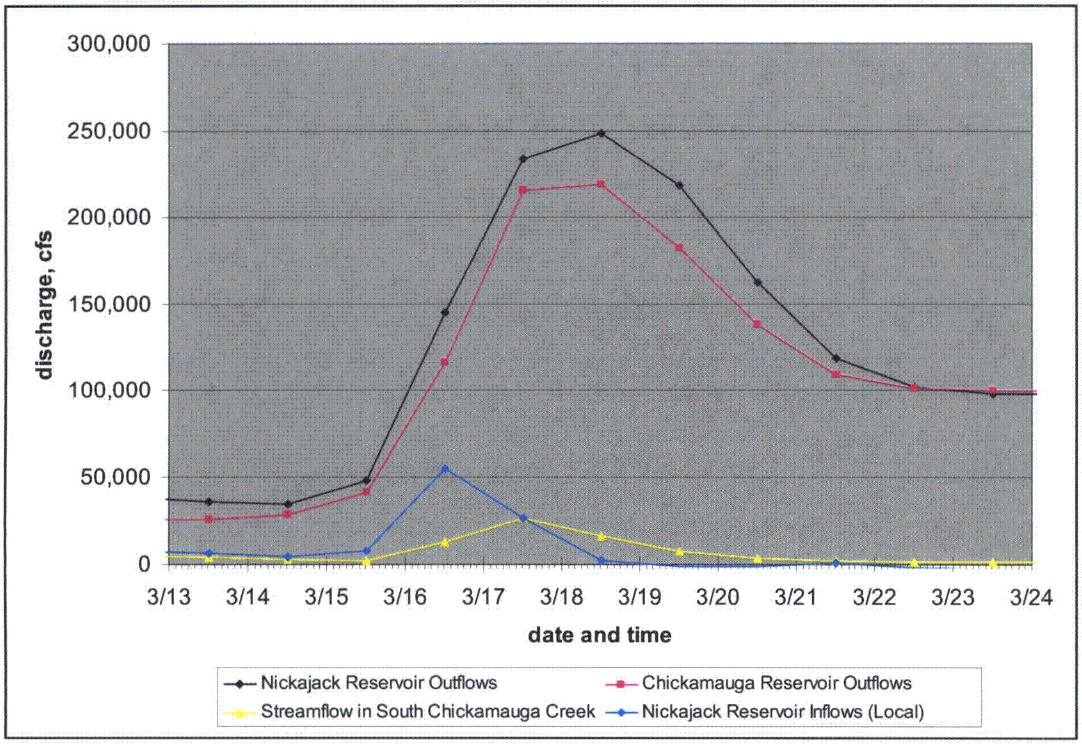

Figure 5: Calculated Nickajack Reservoir Local Inflow (*L*), Measured Upstream Inflows (*I*), and Measured Nickajack Reservoir Outflows (*O*) for March 1973 Flood

Table 6: Water Budget Calculation for May 2003 Flood

Date	Nickajack Headwater Elevation	$\bar{O}$	S	$\overline{R_i} = \frac{dS}{dt} + \overline{O}$	$\bar{I}$			$\overline{L} = \overline{R_i} - \overline{I}$
		Nickajack Average Daily Discharges	Nickajack Midnight Storage Volume	Nickajack Inflows	Chickamauga Daily Outflows	South Chickamauga Daily Flows	Total Inflows from Upstream	Total Local Flows [3]
	ft	cfs	1000 dsf	cfs	cfs	cfs	cfs	cfs
	Attachment 1- 1				Attachment 1-2	Attachment 1- 3		
5/1/2003	633.82	30,056	120	30,689	27,870	413	28,283	2,406
5/2/2003	634.04	34,380	122	35,897	33,766	460	34,226	1,671
5/3/2003	634.31	22,935	124	24,649	28,983	424	29,407	-4,758
5/4/2003	634.15	17,586	122	16,316	22,521	433	22,954	-6,638
5/5/2003	633.54	33,191	123	33,611	42,149	1,519	43,668	-10,057
5/6/2003	631.98	145,107	169	191,712	142,194	9,352	151,546	40,167
5/7/2003	632.34	243,498	198	272,176	213,404	22,405	235,809	36,367
5/8/2003	632.41	258,901	191	251,751	214,906	26,382	241,288	10,463
5/9/2003	632.77	234,297	174	217,709	200,276	14,222	214,498	3,211
5/10/2003	633.21	200,850	157	183,399	173,781	4,595	178,376	5,023
5/11/2003	632.63	165,058	140	148,411	141,200	2,192	143,392	5,019
5/12/2003	632.52	134,740	136	130,791	122,287	1,636	123,923	6,868
5/13/2003	632.52	126,692	130	120,678	110,610	1,024	111,634	9,044
5/14/2003	633.00	99,540	128	97,198	92,433	833	93,266	3,932
5/15/2003	632.73	87689	124.003	83,731	77629	756	78,385	5,346
5/16/2003	632.84	77706	124.17	77,873	71242	714	71,956	5,917

[3] Several of the calculated Total Local Flows (*L*) are negative. These negative values are artifacts of the calculation method that occur because the water budget computation does not account for routing of flows across the water budget area and reservoir to Nickajack Dam. These negative values are outside the range of the May 2003 flood which extends from 5/6/2003 to 5/9/2003.

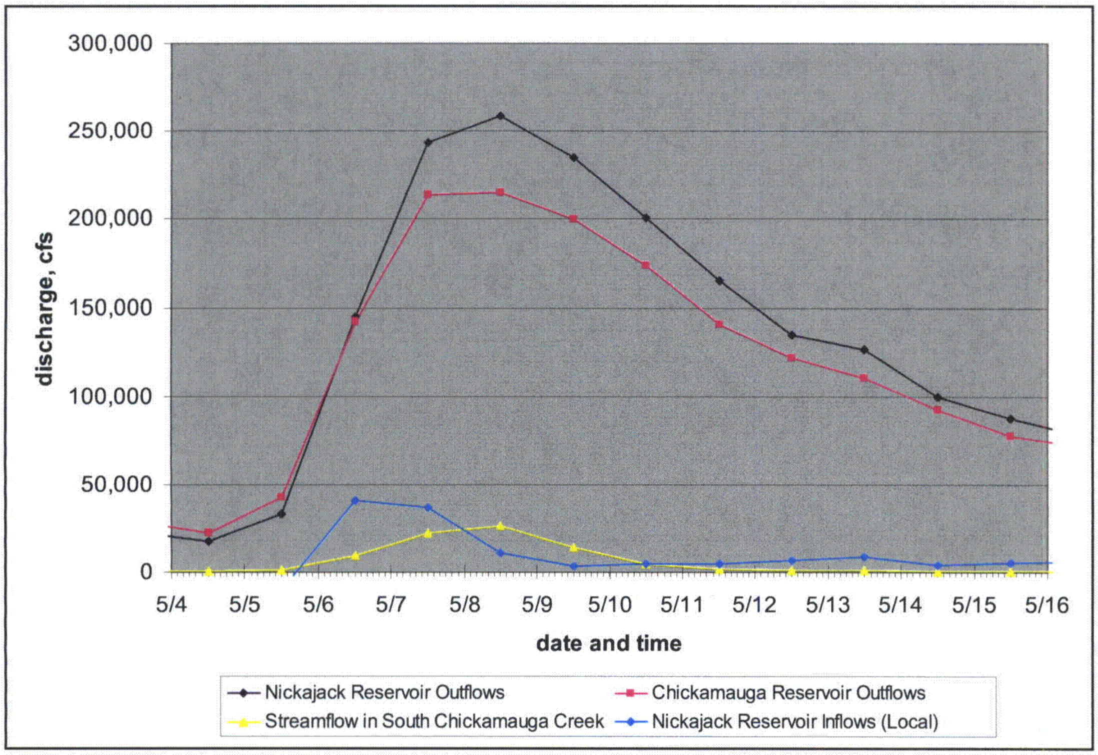

Figure 6: Calculated Nickajack Reservoir Inflow (*L*), Measured Upstream Inflows (*I*), and Measured Nickajack Reservoir Outflows (*O*) for May 2003 Flood

7.3.2 Base Flow Separation

The Nickajack inflow hydrographs ($\overline{L}$) shown in Figure 5 and Figure 6 represent the total inflows to the reservoir. A portion of the total flow comes from groundwater contributions to the river system. Base flow separation involves the estimation of the groundwater contribution to total flow and the removal of the groundwater-contributed portion of the flow from the flood hydrograph. Base flow separation is required to determine an estimate of direct runoff associated with the flood.

For this calculation, the straight line method was used for base flow separation with the separation line drawn from the starting point of runoff to a point on the receding limb of the hydrograph where base flow resumes (Reference 3 and Reference 14). Visual inspection of the flood hydrographs was employed to select starting and ending points for the separation line. Daily average reservoir inflow values provide an approximation of the total runoff volume from Subbasins 47A and 47B and from direct rainfall on Nickajack Reservoir. Given the inaccuracies inherent in this approximation method, a simple visual determination of estimated base flow is appropriate for the May 2003 and March 1973 floods. The total streamflow and resulting base flow hydrographs for the May 2003 and March 1973 floods are plotted on Figure 7 and Figure 8, respectively.

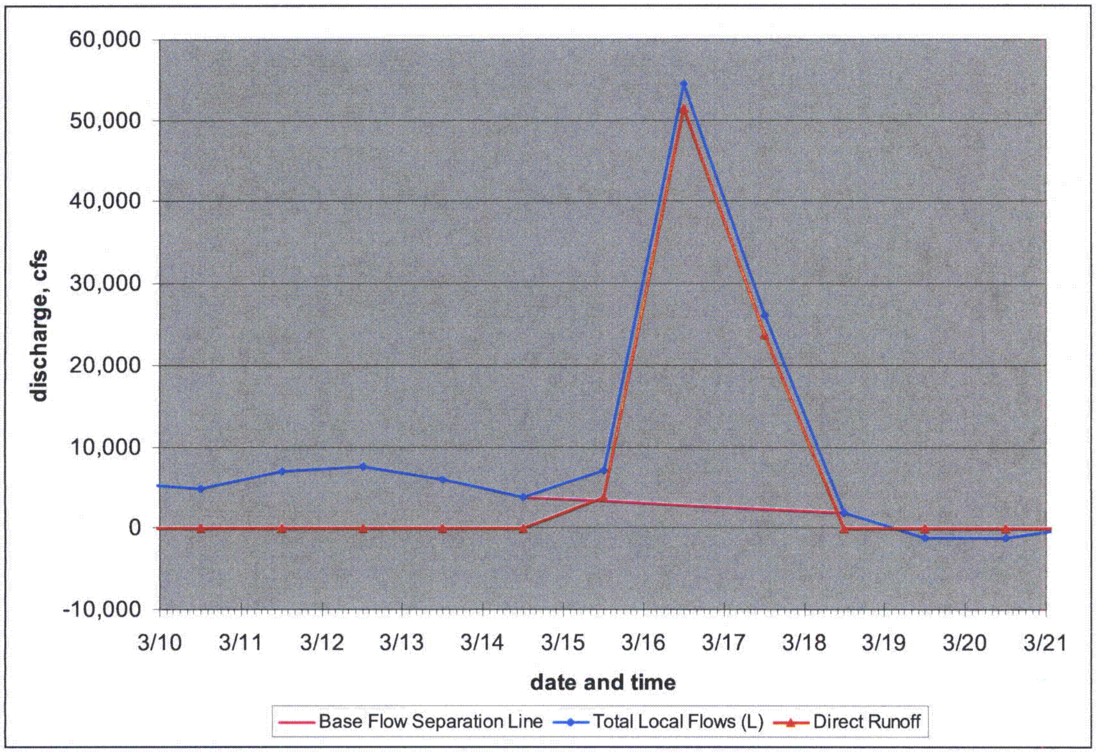

Figure 7: Base Flow Separation for the March 1973 Flood

Reference 12 provides an estimate of base flow that was used for the 1973 flood in a previous study. The separation line shown in Figure 7 is slightly different from that provided in Reference 12. However, the separation line in Figure 7 provides a better visual fit to the calculated total inflow. The separation line Figure 7 also slopes downward from March 14 to March 18; typically, an upward sloping, or a flat, separation line is expected. The downward slope is attributed to the water budget computation which does not account for routing of flows through the subbasins to Nickajack Dam. Additionally, flows in the Tennessee River in the water budget area are controlled by releases from Chickamauga Dam at the upstream boundary and Nickajack Dam at the downstream boundary of the budget area. The controlled nature of Tennessee River flows across the budget area may also contribute to the downward slope.

Direct runoff hydrographs for the May 2003 flood and March 1973 flood were calculated by removing the estimated base flow from the total flow hydrographs for the water budget area. Direct runoff and base flow volumes are summarized in Table 7. Runoff values in Table 7 represent the aggregated runoff volume from Subbasins 47A and 47B and from direct rainfall on Nickajack Reservoir. Base flow volumes in Table 7 are the total volume for the budget area.

Base flow separation and runoff volume calculations for the March 1973 and May 2003 floods are enclosed in Attachment 1- 7.

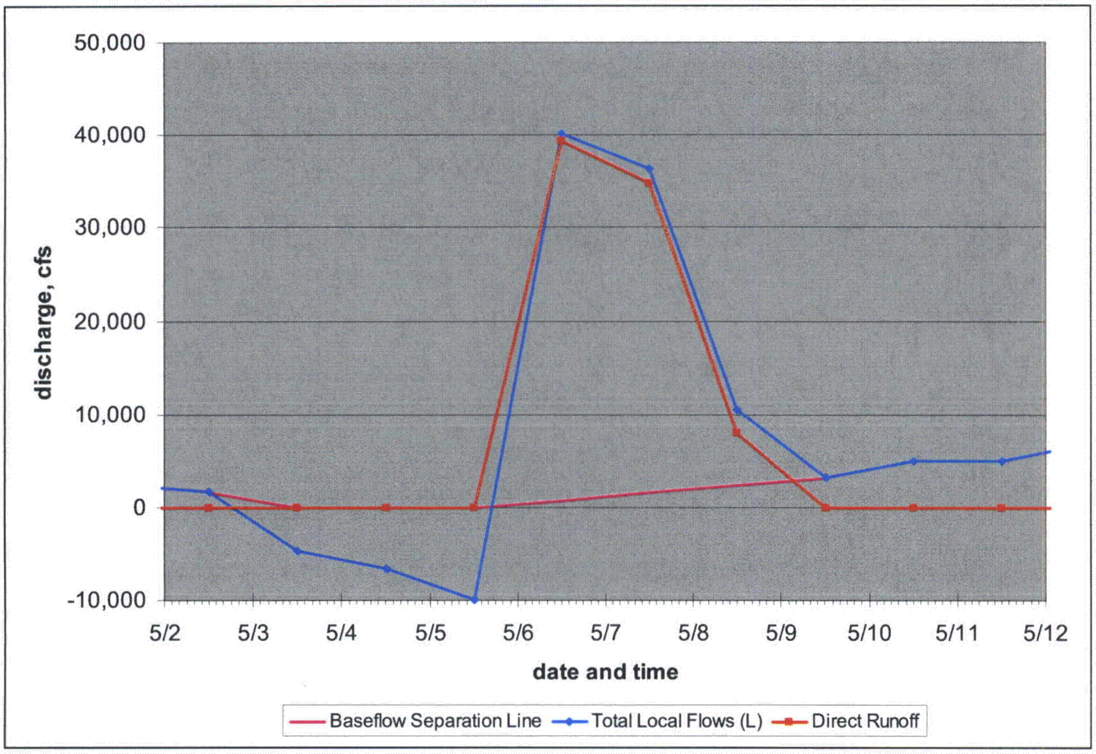

Figure 8: Base Flow Separation for the May 2003 Flood

Table 7: Total Base Flow and Direct Runoff Volumes for the March 1973 and May 2003 Floods

Flood	Drainage Area (mi^2)	Base Flow		Direct Runoff	
		Total Volume (cf)	Total Volume (acre-ft)	Total Runoff Volume (acre-ft)	Runoff Depth (in)
March 1973	644.0	1,235,520,000	28,364	157,091	4.57
May 2003	644.0	693,522,000	15,921	163,002	4.75

7.4 Direct Runoff from Rainfall on Nickajack Reservoir

Nickajack Reservoir has a surface area of approximately 16.3 mi^2 (Reference 12). As shown in Figure 2, the reservoir lies within the boundaries of Subbasin 47A, and the surface area of the reservoir is included in the area of Subbasin 47A provided in Table 1. Rain that falls on the reservoir surface contributes directly to the inflow to the reservoir (I) calculated with Equation (3) and to the estimated direct runoff volumes for the March 1973 and May 2003 floods listed in Table 7. The contribution of rainfall on the reservoir surface to the direct runoff volume for each flood can be calculated as the depth of rainfall falling on the reservoir during the storm multiplied by the reservoir surface area. The equivalent direct runoff time series, for rainfall on the reservoir surface, can be estimated as depth of rainfall each hour during the storm multiplied by the surface area of the reservoir with appropriate unit conversions incorporated into the calculation.

The observed rain falling on the reservoir surface during the March 1973 storm was provided by the TVA in Reference 12. For the May 2003 storm, the NWS basin average rainfall for Subbasin 47A was used to represent rainfall on the reservoir surface. The watershed area for the unit hydrograph for Subbasin 47A includes Nickajack Reservoir. As a result, a portion of the direct runoff generated by rain falling on the reservoir surface is accounted for with the excess precipitation, or direct runoff, estimated for Subbasin 47A. Because the rain falling on the reservoir surface is all converted to direct runoff, an additional direct runoff contribution was calculated for the reservoir.

This additional direct runoff contribution is the difference between measured rainfall depth and estimated excess precipitation depth for each measurement interval (excess precipitation is equivalent to runoff and is calculated using FLDHYDRO as discussed in Section 7.5). Figure 9 and Figure 10 display the additional direct runoff calculated for the March 1973 and May 2003 floods. These additional contributions were converted to an equivalent volume of additional direct runoff as outlined above. The additional direct runoff volume is presented in Table 8 for the March 1973 and May 2003 floods. The time series of additional direct runoff on Nickajack Reservoir during the March 1973 and May 2003 floods is displayed in Figure 11 and Figure 12, respectively. Additional direct runoff time series calculations are enclosed in Attachment 1- 8.

The volume of additional direct runoff (i.e. the difference between rainfall and excess precipitation over the reservoir surface) was subtracted from the water budget area volume to estimate the volume of direct runoff from land surface in the water budget area. Although the Nickajack Reservoir lies within Subbasin 47A, the combined runoff volume from Subbasins 47A and 47B was adjusted because the combined runoff volume is given to FLDHYDRO as the CHKVOL parameter and FLDHYDRO partitions the runoff volume between the subbasins. The adjustment to the combined runoff volume for the March 1973 and May 2003 floods is roughly 0.1 inch as shown in Table 8. This approximation is reasonable given the small magnitude of the adjustment and the intended purpose of the calculation, which is to calculate initial inflow hydrographs for SOCH model calibration.

Table 8: Additional Direct Runoff Volume Corresponding to the Difference between Rainfall on Nickajack Reservoir and Excess Precipitation Calculated for Subbasin 47A

Flood	Nickajack Reservoir (inches per 16.3 mi^2)			Water Budget Area (inches per 644.0 mi^2)*		
	Observed Rainfall	Excess Precipitation (Runoff from FLDHYDRO)	Additional Direct Runoff Volume from Nickajack Reservoir	Water Budget Area Runoff Volume from Table 7	Additional Direct Runoff Volume from Nickajack Reservoir	Direct Runoff Volume from Subbasins 47A and 47B
March 1973	8.57	4.42	4.15	4.57	0.10	4.47
May 2003	7.96	4.63	3.33	4.75	0.09	4.66

* The entire water budget area, rather than only the Subbasin 47A area, is used as an approximation to adjust the direct runoff volume to account for rain falling on the Nickajack Reservoir as discussed in Section 7.4.

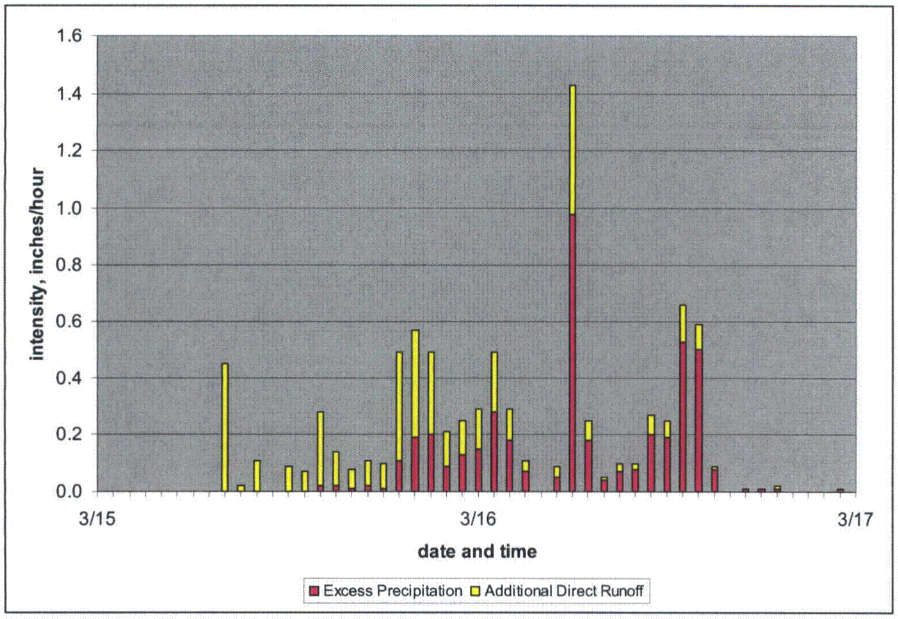

Figure 9: Excess Precipitation and Additional Direct Runoff on Nickajack Reservoir for the March 1973 Flood*

*Note: the total height of each column represents rainfall; the individual colors in each column represent the proportion of excess precipitation and additional direct runoff relative to rainfall.

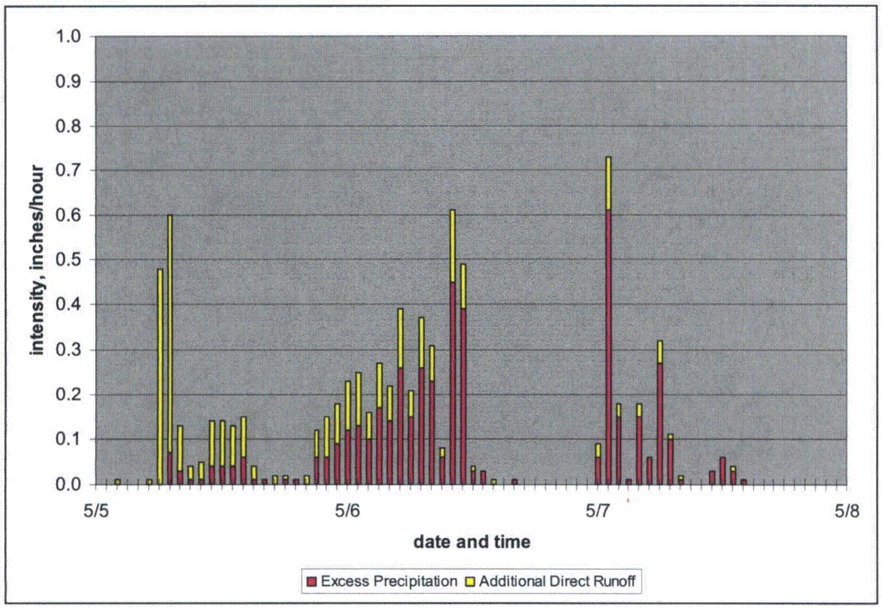

Figure 10: Excess Precipitation and Additional Direct Runoff on Nickajack Reservoir for the May 2003 Flood*

*Note: the total height of each column represents rainfall; the individual colors in each column represent the proportion of excess precipitation and additional direct runoff relative to rainfall.

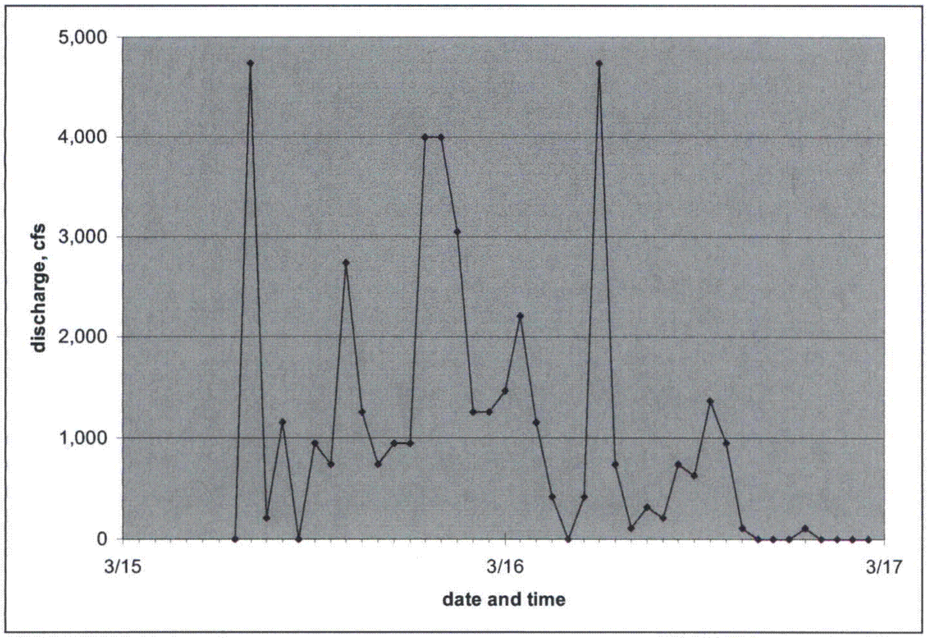

Figure 11: Additional Direct Runoff from Rainfall on Nickajack Reservoir during the March 1973 Flood

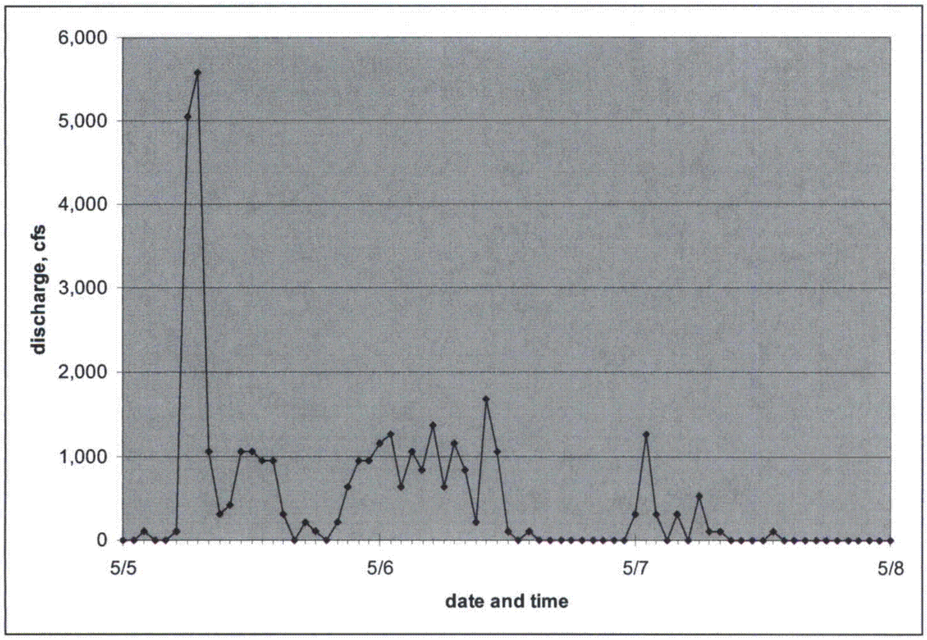

Figure 12: Additional Direct Runoff from Rainfall on Nickajack Reservoir during the May 2003 Flood

The discharge from additional direct runoff on Nickajack Reservoir for the March 1973 and May 2003 floods, which is shown in Figure 11 and Figure 12, was calculated using a constant reservoir surface area of 16.3 mi^2. The surface area of the reservoir changes over time as the depth (and volume) of water in the reservoir changes. Daily-averaged headwater elevations during March 1973 and May 2003 are provided in Table 5 and Table 6. Surface areas, corresponding to these headwater elevations, range from approximately 15.1 mi^2 to 16.4 mi^2 (Reference 15). The constant surface area of 16.3 mi^2 used for Nickajack Reservoir to generate Figure 11, and Figure 12 approximately corresponds to the maximum surface area during each flood. Surface area calculations are enclosed as Attachment 1- 8.

7.5 Allocation of Basin Average Excess Precipitation between Subbasins 47A and 47B

Effective rainfall, or excess precipitation, is the input to the linear basin model that is converted into direct runoff at the basin outlet via convolution with the unit hydrograph. The amount of excess can be developed from observed rainfall by application of a loss function which incorporates the hydrologic abstractions of evaporation and transpiration, interception, depression storage, and infiltration (Reference 3). The amount of excess precipitation, or direct runoff, produced by a given storm is dependent on the soil and land use characteristics, state of the basin at the beginning of the storm, and the characteristics of the storm (Reference 14 and Reference 16). Storm characteristics related to excess rainfall generation include precipitation intensity, total rainfall amount, and spatial and temporal distribution of rainfall across the watershed (although use of the unit hydrograph method precludes incorporating the spatial distribution of rainfall into the analysis of storm runoff). The state of the basin encompasses antecedent soil moisture conditions, the amount of depression storage remaining in the watershed after recent rains, and vegetation-related concerns like evapotranspiration and interception.

The TVA utilizes the FLDHYDRO computer program (Reference 4) to estimate excess precipitation from a given rain storm for use with the UH for runoff prediction. Reference 4 provides detailed information concerning the operation of the FLDHYDRO program. The TVA created this program to implement the Antecedent Precipitation Index (API)/Runoff Index (RI) methodology developed by the United States Weather Bureau (USWB) and described in Reference 14 and Reference 16. In this method, antecedent precipitation data are used to define the basin state at the beginning of the storm through the API. Seasonal, empirical relationships (the RI component) are employed to account for expected seasonal variation in runoff resulting from observed seasonal variations in evapotranspiration.

7.5.1 FLDHYDRO Operation

Direct runoff is equivalent to excess precipitation. The sum of direct runoff volume produced by Subbasins 47A and 47B during the May 2003 and March 1973 floods is provided in Table 8. For each flood, direct runoff volume needs to be partitioned into contributions from Subbasin 47A and 47B and distributed across the duration of the flood.

The FLDHYDRO program can be used to partition a known total excess precipitation (or direct runoff) volume across two sub-watersheds (Reference 4). In this method of operation, the total volume of excess precipitation, or direct runoff, for the two subbasins is given to FLDHYDRO as the CHKVOL value in the input file. Rainfall during the flood and antecedent rainfall are also provided to FLDHYDRO for each subbasin in the input file. FLDHYDRO then calculates a distribution of excess precipitation for each subbasin so that the CHKVOL value, representing the sum of excess precipitation in both subbasins, is satisfied. As part of this operation, FLDHYDRO preserves unique antecedent conditions (API) for each subbasin by maintaining the relative relationships between the initial API values calculated for each subbasin and the API employed for each subbasin to generate the output excess precipitation.

7.5.2 FLDHYDRO Input and Output

FLDHYDRO input files were developed for the March 1973 and the May 2003 floods. The input file for each flood contains basin average rainfall during the flood for each subbasin, antecedent rainfall for each subbasin, and the total volume of direct runoff (i.e. the CHKVOL value) for the two subbasins. NWS basin average rainfall data were used for the 2003 flood. Reference 12 provides basin average rainfall values for each subbasin for the 1973 flood; Attachment 1- 9 and Attachment 1- 10 provide the calculations required to prepare the 1973 flood rainfall values for the FLDHYDRO input file. The CHKVOL values for each flood are listed in brackets in the "Direct Runoff Volume from Subbasins 47A and 47B"column of Table 8. Figure 13 through Figure 20 display the cumulative rainfall and runoff and the time series of rainfall and runoff obtained from FLDHYDRO for Subbasins 47A and 47B for both floods. Table 9 provides a summary of excess precipitation volumes obtained from FLDHYDRO for each subbasin.

Because the CHKVOL values were obtained by subtracting the difference between rainfall and excess precipitation across the reservoir surface and because FLDHYDRO operation was required to obtain the estimate of excess precipitation used to calculate the difference, an iterative process was used to determine the CHKVOL value. In this process, FLDHYDRO was run with water budget area direct runoff volume (see Table 8) to obtain an initial estimate of excess precipitation. Then, the additional direct runoff volume for the reservoir (i.e. the difference between rainfall and excess precipitation over the reservoir surface area) was calculated. An initial estimate of the direct runoff from Subbasins 47A and 47B was calculated and FLDHYDRO rerun with this estimate as the CHKVOL value as the third step. Steps two and three were repeated until approximately the same total depth of excess precipitation (i.e. the same CHKVOL value) was obtained for the reservoir surface and for Subbasins 47A and 47B. FLDHYDRO input and output files are enclosed as Attachment 2- 1 through Attachment 2-6. Attachment 1- 11 contains a summary of the FLDHYDRO output for each flood and each subbasin.

Table 9: Selected FLDHYDRO Inputs and Resulting Excess Precipitation Volumes

Flood	FLDHYDRO Input File	CHKVOL Value from Table 8 (inches per 644.0 mi^2)	Subbasin	Subbasin Area (mi^2)	Basin-Average Rainfall (inches per subbasin area)	Excess Precipitation from FLDHYDRO (inches per subbasin area)	Total Excess Precipitation from FLDHYDRO (inches per 644.0 mi^2)	Difference Between CHKVOL and Total Excess Precipitation from FLDHYDRO (%)
March 1973	B47_1973.dat	4.47	47A	545.7	7.48	4.50	4.51	0.9
			47B	98.3	7.71	4.56		
May 2003	B47_2003.dat	4.66	47A	545.7	7.96	4.63	4.71	1.1
			47B	98.3	8.56	5.18		

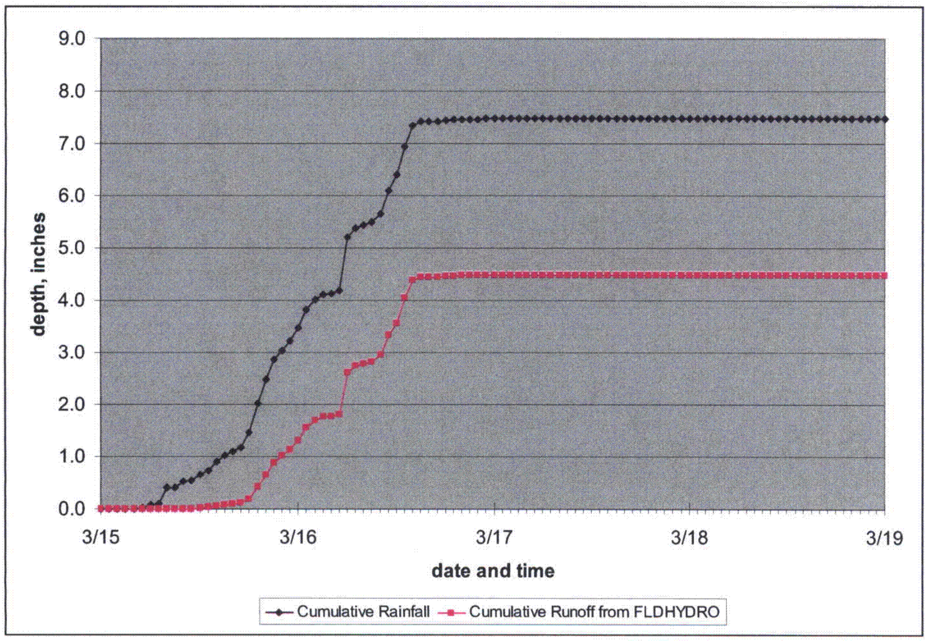

Figure 13: Subbasin 47A Cumulative Rainfall and Runoff for the March 1973 Storm

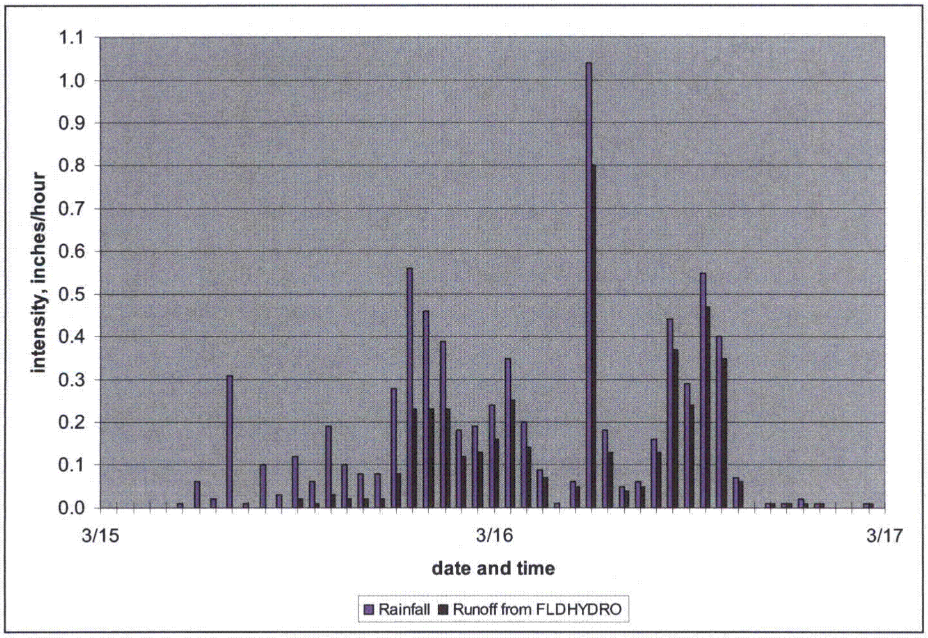

Figure 14: Subbasin 47A Rainfall and Runoff Time Series for the March 1973 Storm

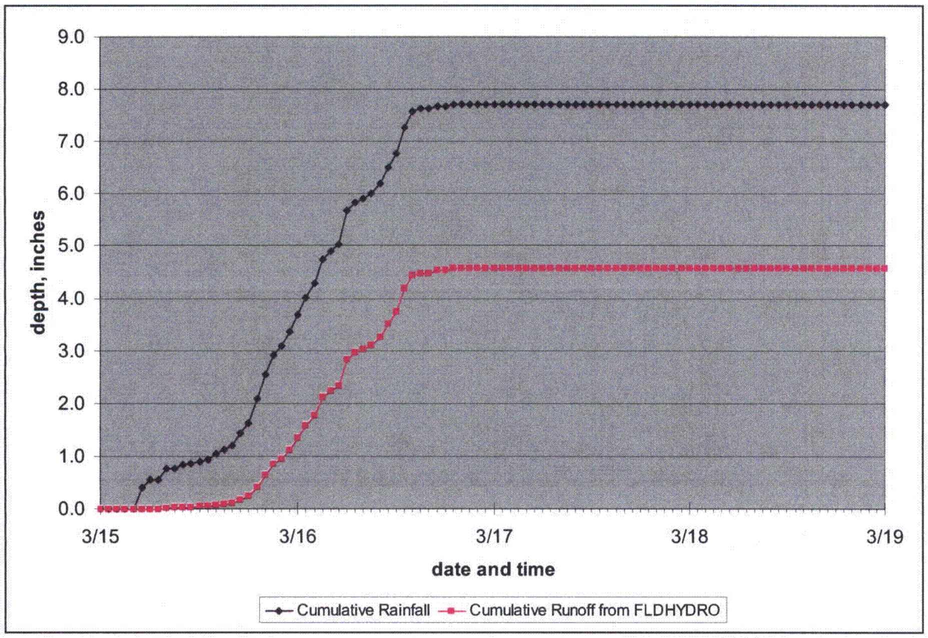

Figure 15: Subbasin 47B Cumulative Rainfall and Runoff for the March 1973 Storm

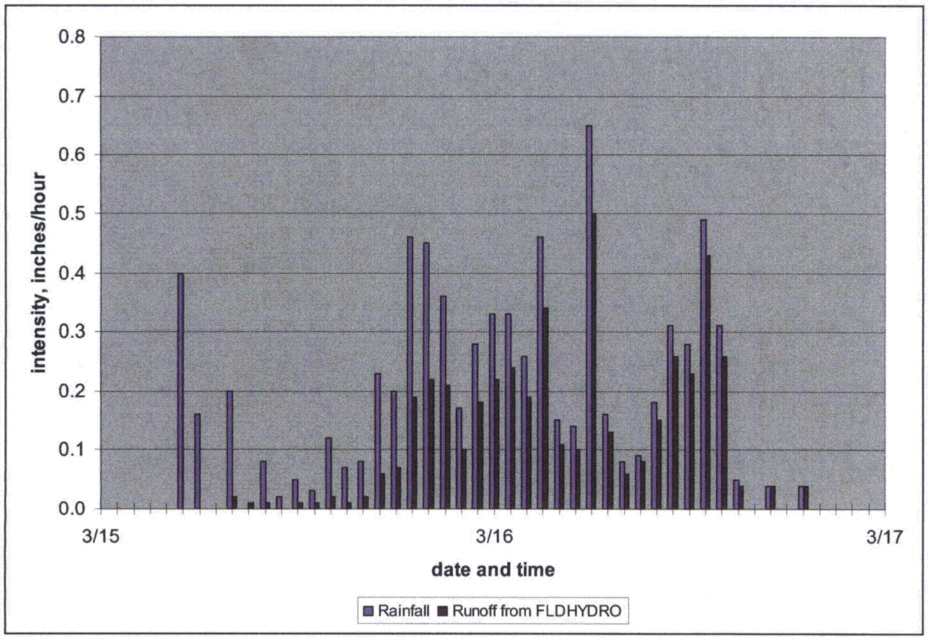

Figure 16: Subbasin 47B Rainfall and Runoff Time Series for the March 1973 Storm

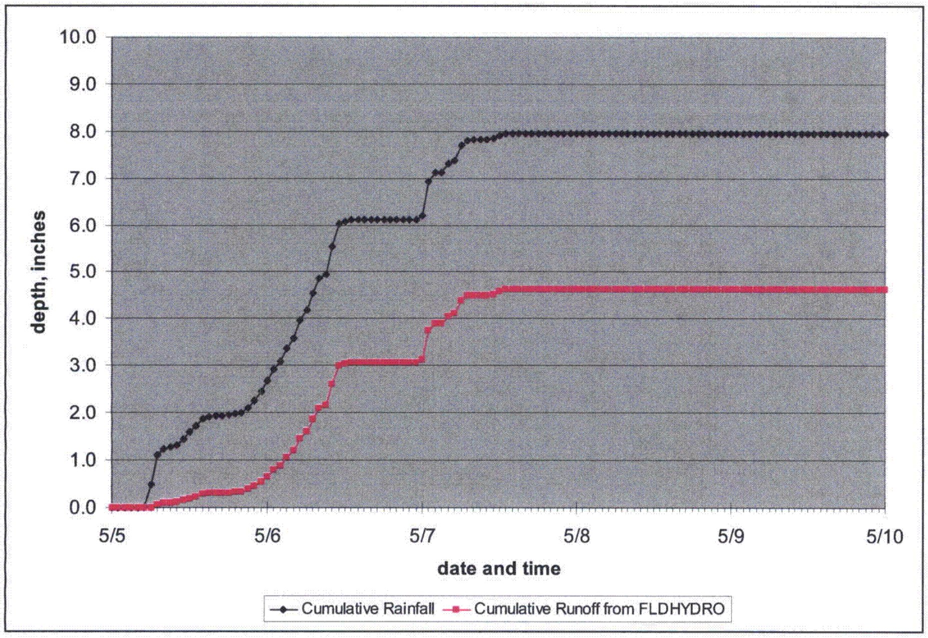

Figure 17: Subbasin 47A Cumulative Rainfall and Runoff for the May 2003 Storm

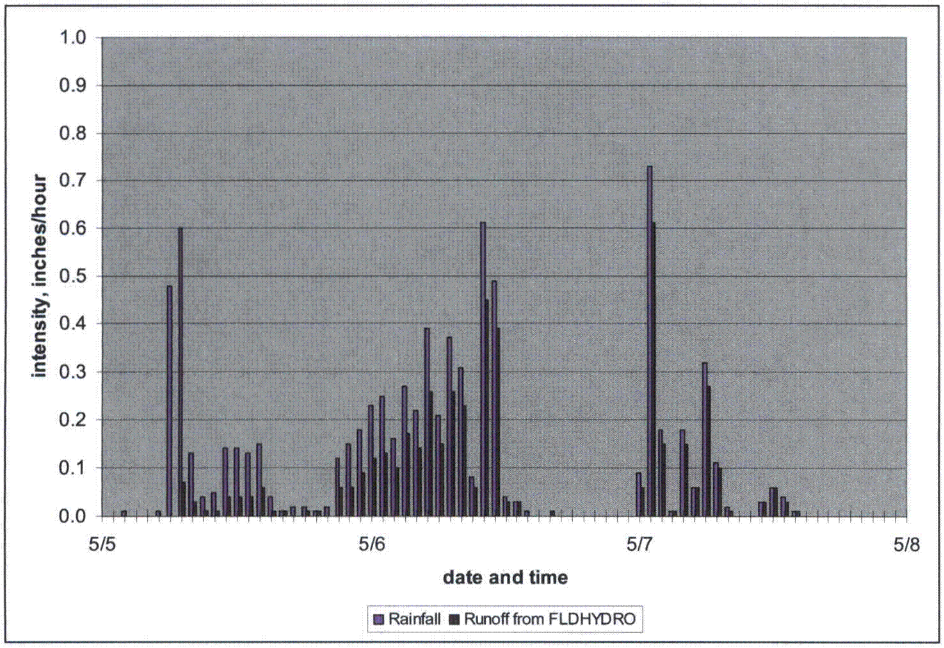

Figure 18: Subbasin 47A Rainfall and Runoff Time Series for the May 2003 Storm

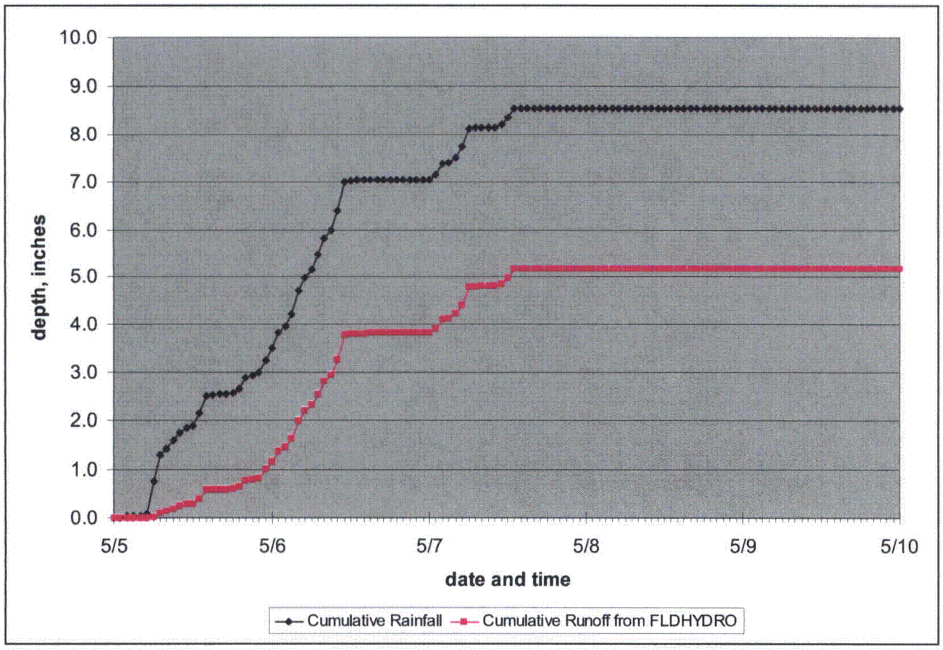

Figure 19: Subbasin 47B Cumulative Rainfall and Runoff for the May 2003 Storm

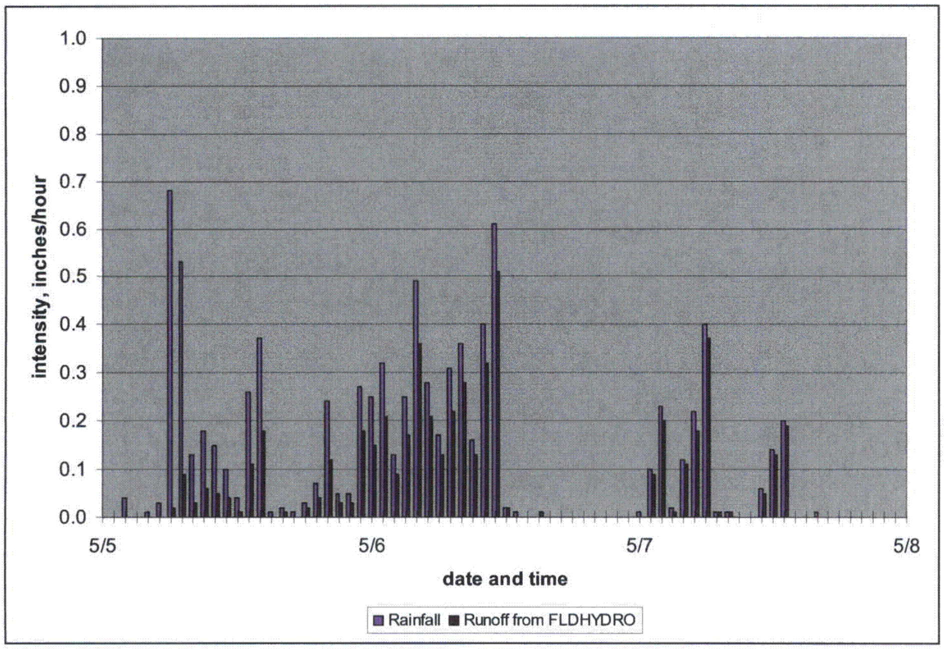

Figure 20: Subbasin 47B Rainfall and Runoff Time Series for the May 2003 Storm

7.6 Calculation of the Subbasin 47A and 47B Initial Inflow Hydrographs

Local direct runoff hydrographs were calculated for the March 1973 and May 2003 floods for Subbasins 47A and 47B via convolution of the excess precipitation obtained from FLDHYDRO and the unit hydrographs presented in Section 6.2. Convolution calculations were completed in spreadsheets, and excess precipitation values were aggregated to time intervals that matched the duration of the unit hydrograph. Table 10 identifies the worksheet, within the spreadsheet provided as Attachment 1- 12, that contains the calculations for each flood.

Table 10: Matrix Identifying Pertinent Calculation Worksheets within Attachment 1- 12

Flood	Subbasin	Worksheet Name (see Attachment 1- 12)	
		Excess Precipitation Aggregation	Convolution
March 1973	47A	47A 1hr to 6hr ppt 1973	Convolution 47A 1973
	47B	47B 1hr to 4hr ppt 1973	Convolution 47B 1973
May 2003	47A	47A 1hr to 6hr ppt 2003	Convolution 47A 2003
	47B	47B 1hr to 4hr ppt 2003	Convolution 47B 2003

Flood hydrographs were calculated for the March 1973 and May 2003 floods by adding base flow to the direct runoff values obtained by convoluting excess precipitation and the subbasin unit hydrograph. Total base flow volume for the budget area is provided for each flood in Table

7. Total base flow volume was partitioned into a base flow volume for each subbasin using the ratio of the subbasin area to the water budget area. Subbasin base flow volume was then converted into a constant base flow discharge corresponding to the direct runoff interval by dividing the base volume by the time base of the direct runoff for each subbasin. These calculations are summarized in Table 11. Flood hydrographs for Subbasins 47A and 47B for the March 1973 and May 2003 floods will be used by the TVA as initial SOCH model inputs.

Table 11: Subdivision of Base Flow Volume between Subbasins

Flood	Budget Area Base Flow Volume from Table 7 (cf)	Subbasin				
		Subbasin	Area mi^2	Base Flow Volume (cf)	Direct Runoff Time Base (hours)	Constant Base Flow Discharge (cfs)
March 1973	1,235,520,000	47A	545.71	1,046,933,463	183	1589
		47B	98.3	188,586,537	148	354
May 2003	693,522,000	47A	545.71	587,664,618	67	812
		47B	98.3	105,857,382	172	171

7.6.1 Subbasin 47A Initial Inflow Hydrographs

A six-hour time step was used in the convolution of the Subbasin 47A unit hydrograph with the corresponding excess precipitation for the March 1973 and May 2003 floods to calculate direct runoff. The initial inflows for each flood were estimated as the calculated direct runoff plus the constant baseflow discharge from Table 11. The FLDHYDRO output for these floods provides excess precipitation values for one-hour intervals; these values were aggregated to six-hour intervals prior to convolution. The resulting Subbasin 47A inflow hydrographs are shown in Figure 21 and Figure 22 for the March 1973 and May 2003 floods.

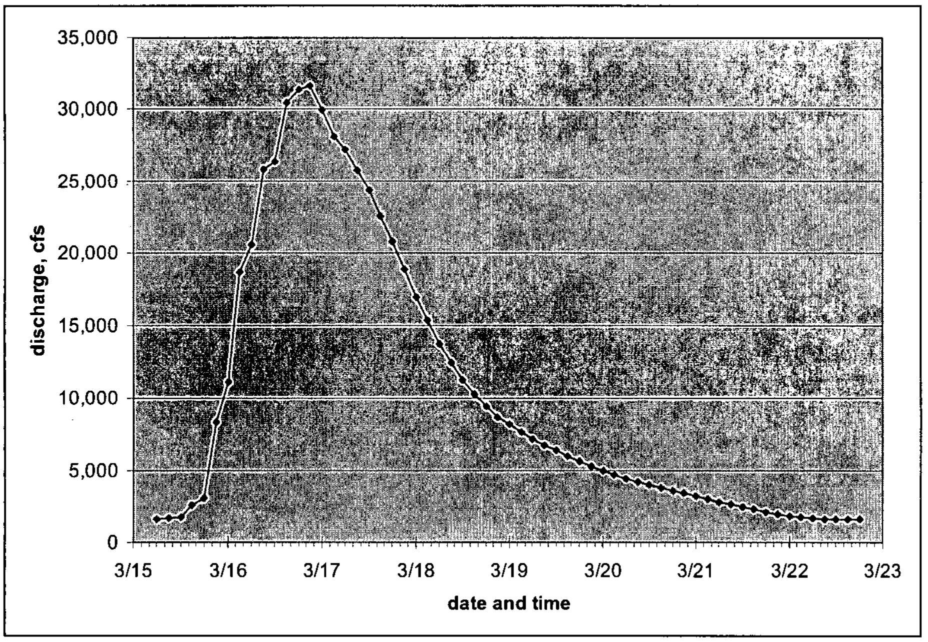

Figure 21: Initial Inflow Hydrograph for Subbasin 47A for the March 1973 Flood

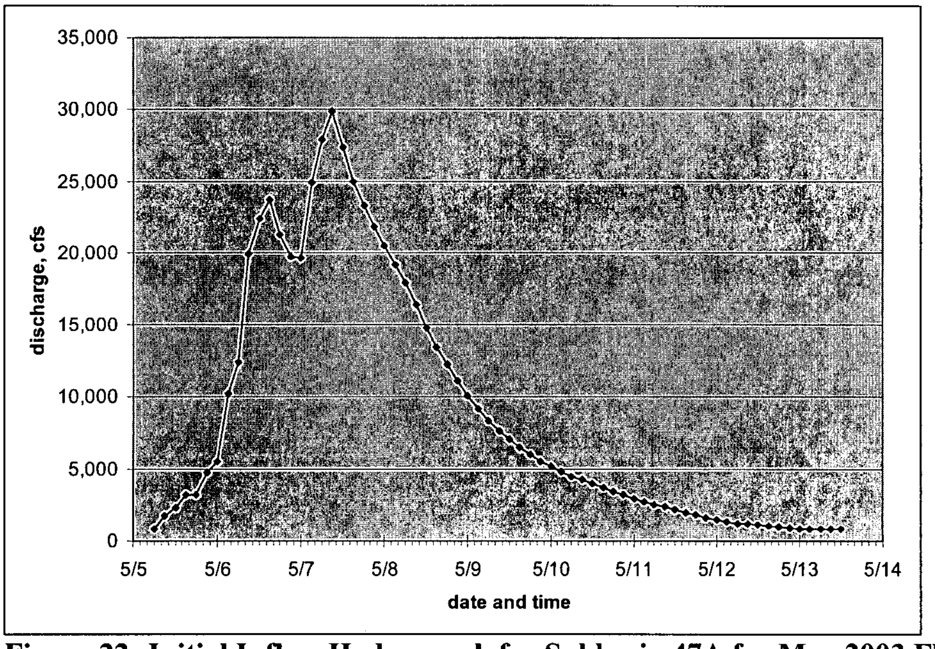

Figure 22: Initial Inflow Hydrograph for Subbasin 47A for May 2003 Flood

7.6.2 Subbasin 47B Initial Inflow Hydrographs

The unit hydrograph for Subbasin 47B has a four-hour duration. Consequently, a four-hour time step was used in the convolution of the Subbasin 47B unit hydrograph with the corresponding excess precipitation for the March 1973 and May 2003 floods. Excess precipitation values were aggregated to four-hour intervals prior to convolution. Base flows, estimated for each flood in Table 11, were added to the direct runoff produced from the convolution calculation to estimate initial inflows from Subbasin 47B. Figure 23 and Figure 24 display the Subbasin 47B inflow hydrographs for the March 1973 and May 2003 floods.

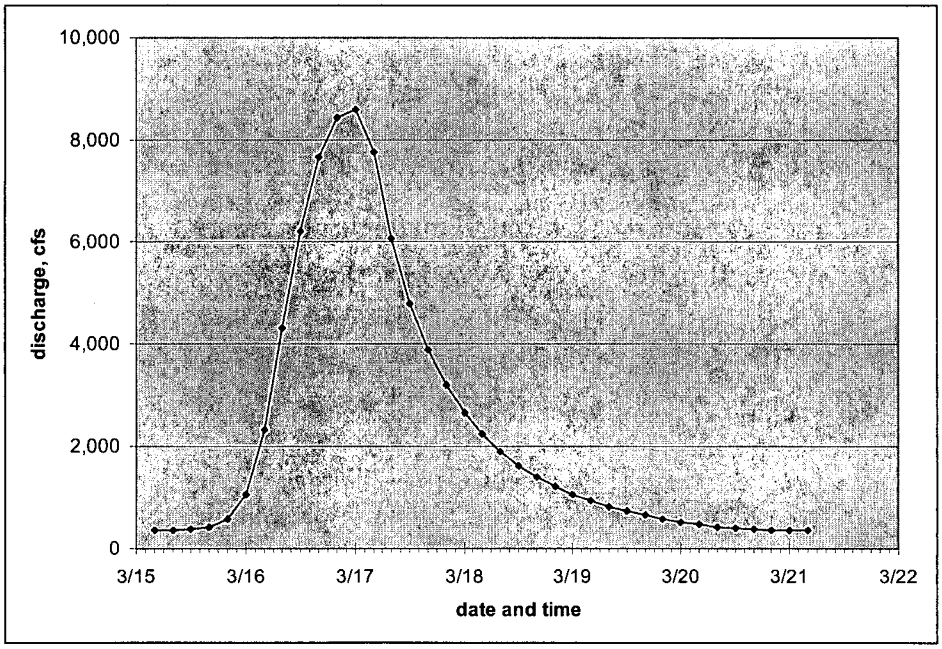

Figure 23: Initial Inflow Hydrograph for Subbasin 47B for the March 1973 Flood

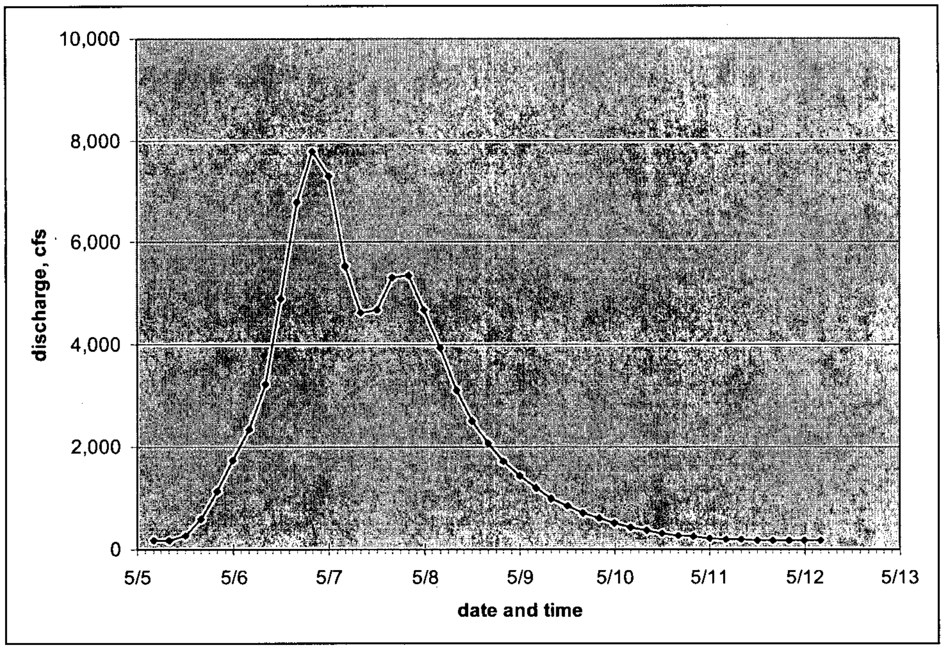

Figure 24: Initial Inflow Hydrograph for Subbasin 47B for the May 2003 Flood

7.7 Water Balance Confirmation

Table 12 provides a comparison of the total flow, direct runoff, and base flow volumes calculated for the water budget area (see Sections 7.3 and 7.3.2) and the sum of total flow, direct runoff, and base flow volumes provided by the initial inflow hydrographs for Subbasin 47A, Subbasin 47B, and Nickajack Reservoir. These volumes match within two percent. The small discrepancy in calculated volumes is due to the slight change to direct runoff volume introduced by FLDHYDRO operation as shown in Table 9 and due to the fact that the unit hydrograph volume does not exactly match one inch as shown in Table 2 and Table 3. Attachment 1- 12 provides these calculations.

Table 12: Water Balance Confirmation

Volume Balance			
Flood		March 1973 (acre-ft)	May 2003 (acre-ft)
Water Budget Totals (644.0 mi^2)	**Total Flood Flow** (from water budget)	185,455	178,923
	Base Flow (straight-line separation)	28,364	15,921
	Direct Runoff (water budget total flood flow with base flow removed)	157,091	163,002
Sum of Volumes from Initial Inflow Hydrographs for Subbasins 47A, 47B, and Nickajack Reservoir (644.0 mi^2)	**Total Flood Flow** (base flow plus direct runoff)	187,794	181,709
	Base Flow (straight-line separation)	28,364	15,919
	Direct Runoff (from convolution of unit hydrograph and excess precipitation)	159,430	165,790
Volume Balance	**Total Flood Flow**	1.26 %	1.56 %
	Base Flow	0.00 %	0.01 %
	Direct Runoff	1.49 %	1.71 %
Subbasin and Reservoir Initial Inflow Hydrograph Totals			
Subbasin 47A (545.7 mi^2)	Total Flood Flow	155,919	149,184
	Base Flow	24,034	13,489
	Direct Runoff	131,885	135,695
Subbasin 47B (98.3 mi^2)	Total Flood Flow	28,264	29,620
	Base Flow	4,329	2,430
	Direct Runoff	23,935	27,189
Nickajack Reservoir (16.3 mi^2 included in Subbasin 47A)	Additional Direct Runoff	3,610	2,905

7.8 SOCH Model Input

Four time series were provided for use in the SOCH model for the March 1973 and the May 2003 validation runs. These inputs are as follows:

- Total direct runoff for Subbasin 47A,
- Total direct runoff for Subbasin 47B,
- Losses and runoff for Subbasin 47A,
- Losses and runoff for Subbasin 47B.

The time series were developed in spreadsheets in Attachment 1-1 through Attachment 1-3. Plots of the component time series are provided as Figures 5 through 8 in Sections 7.3.

7.9 SOCH Model Output and Unit Hydrograph Validation

The component time series presented in Section 7.3 of this calculation were used as inputs to a SOCH model of the reach of the Tennessee River between Chickamauga and Nickajack Dams. Additional inputs to the model include observed discharge series for the South Chickamauga Creek and outflow from Chickamauga Dam as upstream boundary conditions. (See Figure 1.)

For the March 1973 event, simulated and observed water surface elevations were compared at eight gage locations: TRM 471.0, 467.6, 465.5, 464.2, 454.1, 449.9, 444.1, and 441.3. For the May 2003 event, simulated and observed water surface elevations were compared at two gage locations: TRM 471.0 and 464.2. Simulated and observed discharges at TRM 424.7 were compared for both historic floods.

As described in Calculation CDQ000020080040 Rev 0 (Reference 17), local inflows to Nickajack Reservoir from Subbasin 47A and 47B were combined with the observed data (Chickamauga observed discharge and tailwater elevation, Nickajack observed discharge and headwater elevation, and the South Chickamauga Creek observed discharge) for the March 1973 and May 2003 events and reasonably reproduced the observed elevations at gage locations along the reservoir for the historic floods. Additionally, the shape is similar with the model conservatively predicting elevation and discharge, a desirable conservative feature in a predictive flood model. These comparisons are shown in Figures 25 through 28. As a result, the unit hydrographs developed for basins 47A and 47B were validated and deemed adequate for use in developing flood inflows for other events, including PMF. Data and simulation results for the aforementioned figures are provided in Attachments 4-1 and 4-2.

TVA

Calculation No. CDQ000020080060	Rev: 2	Plant: GEN	Page: 46
Subject: Nickajack Dam Local Watershed		Prepared	HLSS
(Subbasins 47A and 47B) Unit Hydrograph Validation		Checked	BH

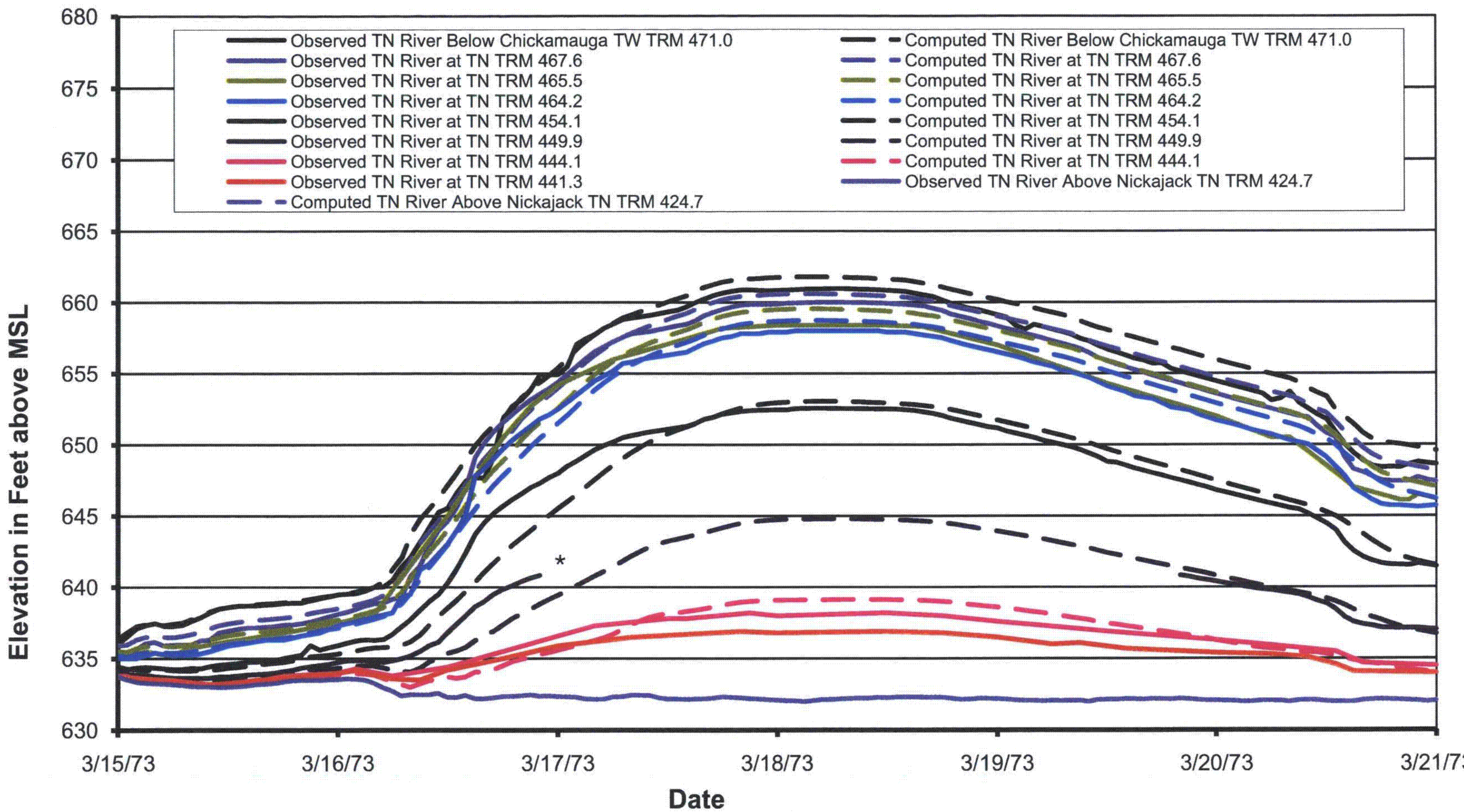

Figure 25: Observed and Simulated Stage Hydrographs for the Tennessee River between Chickamauga and Nickajack Dams, March 1973

***NOTE: data not available for these time periods.**

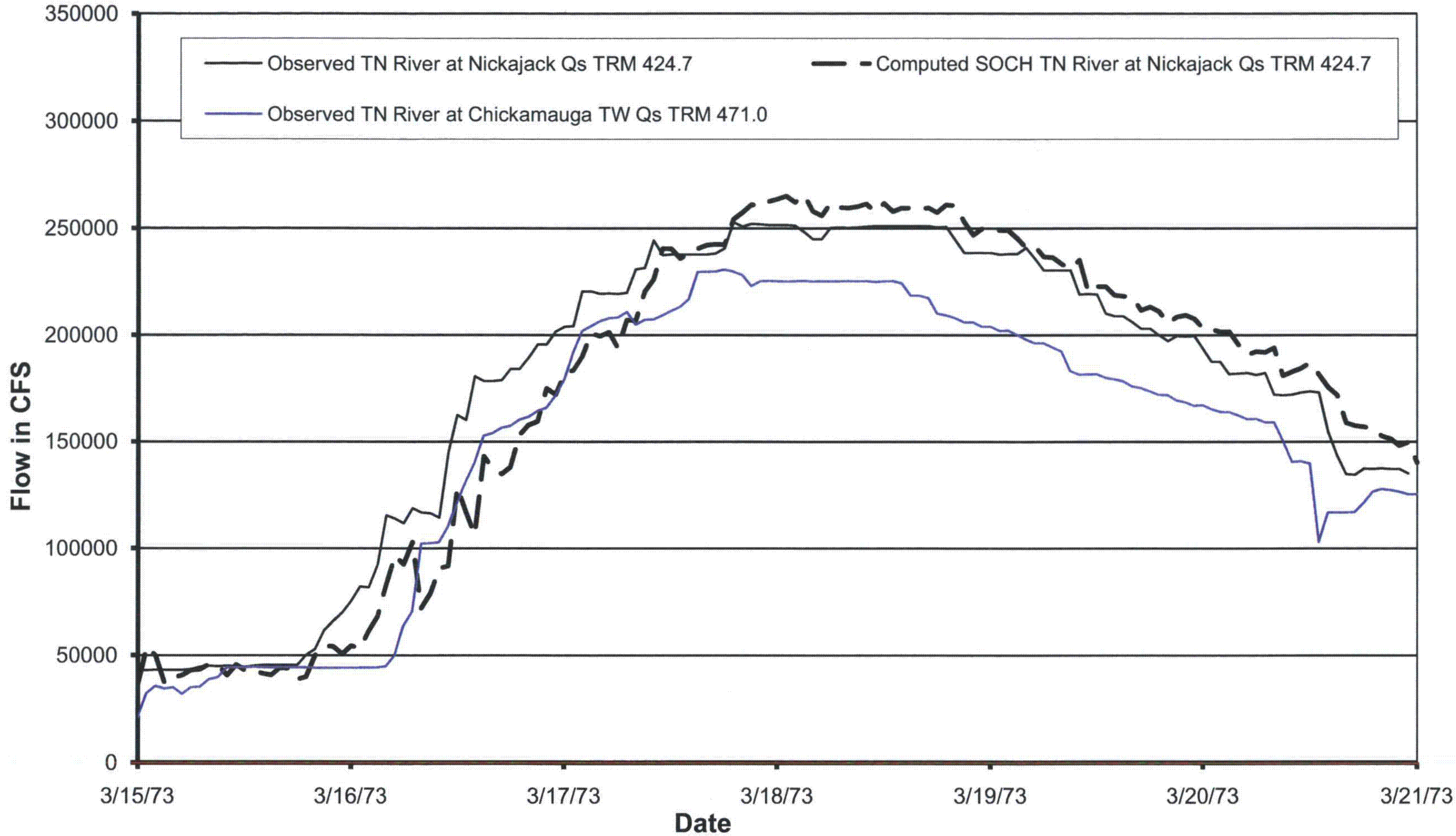

Figure 26: Observed and Simulated Discharge Hydrographs for Nickajack Dam, March 1973

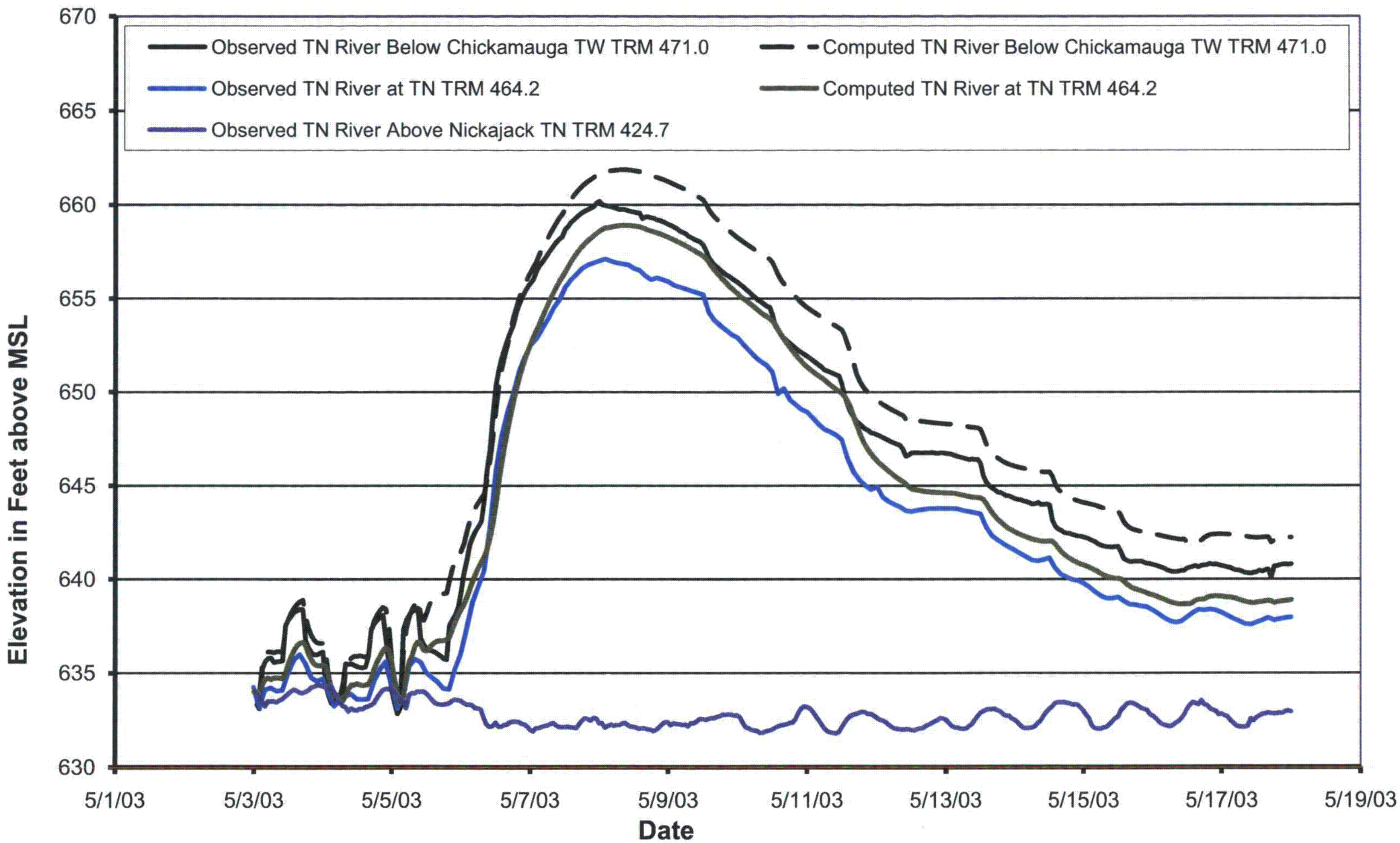

Figure 27: Observed and Simulated Stage Hydrographs for the Tennessee River between Chickamauga and Nickajack Dams, May 2003

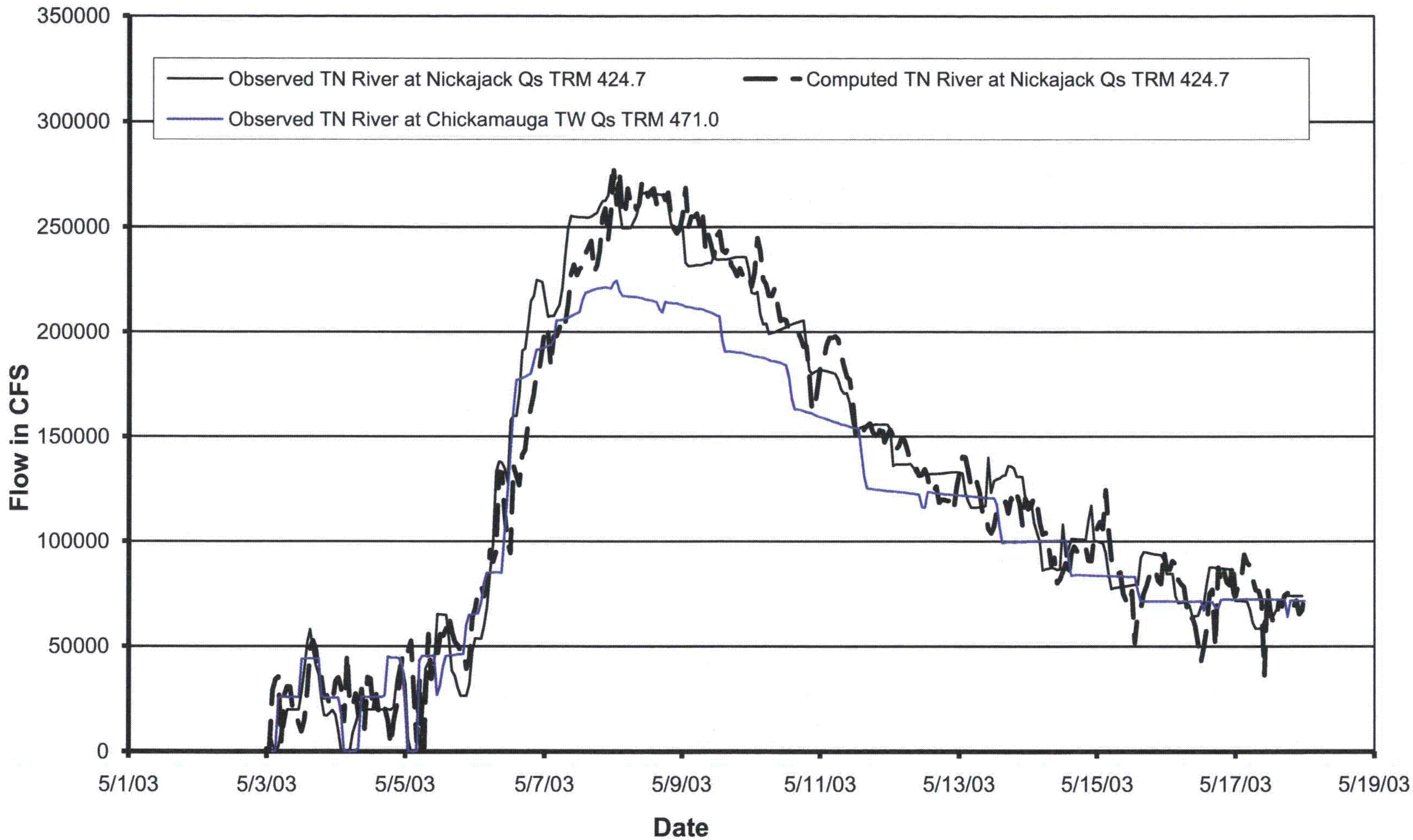

Figure 28: Observed and Simulated Discharge Hydrographs at Nickajack Dam, May 2003

8 Conclusions

Unit hydrographs for subbasins 47A and 47B for the simulation of local inflow to the Tennessee River between Chickamauga and Nickajack Dam were developed by TVA previously. In compliance with NRC requirements, the unit hydrographs were indirectly validated in this calculation for two events: the floods of March 1973 and May 2003.

The usual procedure for validating local unit hydrographs is to use them to develop flow series for observed rainfall inputs and compare them with check series developed from reverse reservoir routing and hydrograph separation, as required. Because of the mild slopes and significant backwater on the main stem of the Tennessee River, however, reverse reservoir routing cannot be used to develop inflow series for Nickajack Reservoir. Therefore, it was necessary to validate the unit hydrographs indirectly. Local runoff hydrographs were developed from observed rainfall series for use as input to the SOCH model simulation of the reach of the Tennessee River between Chickamauga and Nickajack Dam for the two validation runs.

8.1 Unit Hydrograph Validation

The original unit hydrographs in Section 6.2 for Subbasins 47A and 47B were indirectly validated for the March 1973 and May 2003 floods in this calculation and are provided in Table 13 and Table 14 (Attachment 4-3). Since the stage and discharge hydrographs simulated in the SOCH model runs utilizing local inputs developed with the unit hydrographs conservatively predict observed data, it is concluded that the original unit hydrographs adequately describe the response of the local catchment areas between the reservoirs and are valid for use in hydrologic studies to determine the PMF.

Table 13: Validated 6-hour Unit Hydrograph Ordinates for Subbasin 47A

Time (hours)	Discharge (cfs)
0	0
3	4,520
6	7,366
9	9,059
12	7,366
15	6,194
18	6,194
21	6,194
24	6,194
27	6,026
30	5,943
33	5,441
36	4,855
39	4,352
42	3,934
45	3,515
48	3,097
51	2,762
54	2,344
57	2,093
60	1,925
63	1,758
66	1,590
69	1,423
72	1,339
75	1,256
78	1,172
81	1,088
84	1,004
87	921
90	837
93	753
96	670
99	628
102	586
105	544
108	502
111	460
114	419
117	377
120	335
123	293
126	251
129	209
132	167
135	126
138	84
141	42
144	0

Table 14: Validated 4-hour Unit Hydrograph Ordinates for Subbasin 47B

Time (hours)	Discharge (cfs)
0	0
4	124
8	671
12	2,038
16	3,000
20	2,137
24	1,566
28	1,243
32	974
36	780
40	636
44	507
48	422
52	348
56	283

Time (hours)	Discharge (cfs)
60	239
64	199
68	164
72	129
76	109
80	89
84	70
88	55
92	40
96	25
100	15
104	10
108	5
112	0