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

ASSOCIATED ATTACHMENTS/ENCLOSURES:

Attachment 02.04.03-8AG: Subbasin 26 (Norris Dam) Unit Hydrograph Validation

(33 Pages including Cover Sheet)

# NPG CALCULATION COVERSHEET/CCRIS UPDATE



| REV 0 EDMS/RIMS NO. | EDMS TYPE: | EDMS ACCESSION NO (N/A for REV. 0) |
|---|---|---|
| L58 090216 005 | calculations(nuclear) | L58 091230 042 |

Calc Title: Subbasin 26 (Norris Dam) Unit Hydrograph Validation

| CALC ID | TYPE | ORG | PLANT | BRANCH | NUMBER | CUR REV | NEW REV | REVISION APPLICABILITY |
|---|---|---|---|---|---|---|---|---|
| CURRENT | CN | NUC | GEN | CEB | CDQ000020080066 | 1 | 2 | Entire calc ☒ Selected pages ☐ |
| | | | | | | | | |

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

| UNITS | SYSTEMS | UNIDS |
|---|---|---|
| N/A | N/A | N/A |

| DCN,EDC,N/A | APPLICABLE DESIGN DOCUMENT(S) | CLASSIFICATION |
|---|---|---|
| *See below. | N/A | "E" |

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

| PREPARER ID | PREPARER PHONE NO | PREPARING ORG (BRANCH) | VERIFICATION METHOD | NEW METHOD OF ANALYSIS |
|---|---|---|---|---|
| dstokes | 615-252-4343 | CEB | See Page 7 | ☐ Yes ☒ No |

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

STATEMENT OF PROBLEM/ABSTRACT

Validate existing unit hydrograph for Norris Dam (Subbasin 26) using two 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
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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 090216 005 | calculations(nuclear) | L58 090625 002 |

Calc Title: Subbasin 26 (Norris Dam) Unit Hydrograph Validation

| CALC ID | TYPE | ORG | PLANT | BRANCH | NUMBER | CUR REV | NEW REV | REVISION APPLICABILITY |
|---|---|---|---|---|---|---|---|---|
| CURRENT | CN | NUC | GEN | CEB | CDQ000020080066 | 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 |
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| 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 |

SCB

STATEMENT OF PROBLEM/ABSTRACT

Validate existing unit hydrograph for Norris Dam (Subbasin 26) using two recent flood events.

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

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

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

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

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# NPG CALCULATION COVERSHEET/CCRIS UPDATE



| CALC ID | TYPE | ORG | PLANT | BRANCH | NUMBER | REV |
|---|---|---|---|---|---|---|
| | CN | NUC | GEN | CEB | CDQ000020080066 | 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 |
|---|---|---|---|
| | | | |
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## 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 | |
| A | P | CO | GEN | CEB | UNITGRPH Version 1.0 | |
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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 | CDQ000020080066 |
| Title | Subbasin 26 (Norris Dam) 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. 3) for FLDHYDRO, and Reference 2.3 was revised to reflect the EDMS number of the issued document. Two electronically attached FLDHYDRO output files were replaced with equivalent files generated using current QA Version 1.0 of FLDHYDRO, dated 11/04/2008. Results of FLDHYDRO and this calculation were unaffected by the version change. Significant changes in Revision 1 are noted with a right margin revision bar.<br><br>Pages replaced: 1, 2, 3, 6, 9<br>Pages Added / Deleted: None<br><br>Attachments 2-2 and 2-4 (electronically attached FLDHYDRO output files) were replaced. See page 6 for the listing of file names and their associated attachment numbers.<br><br>Total pages of calculation hardcopy for Revision 1 = 30 pages |
| 2 | This calculation was revised to address the following:<br>• 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.<br><br>• PER 204081- The verification of Rev 1 of the calculation was completed by a TVA Project Engineer with expired qualifications.<br><br>• PER 203872- replace NEDP-2 forms on Pages2 through 5 with the forms from the NEDP-2 Revision in effect at the time of calculations issuance.<br><br>Significant changes in Revision 2 are noted with a right margin revision bar. Administrative changes and typos are excluded.<br><br>Pages Added: 1a & 7a<br>Pages Replaced: 1-7 & 9<br>Total pages of calculation hard copy for Revision 2= 32 |

# NPG CALCULATION TABLE OF CONTENTS

Calculation Identifier: CDQ000020080066 | Revision: 2

## TABLE OF CONTENTS



List of Tables:



List of Figures:



Attachments: see listing of electronic attachments on page 6

**NPG COMPUTER INPUT FILE**
**STORAGE INFORMATION SHEET**

| Document CDQ000020080066 | Rev. 2 | Plant: GEN | |
|---|---|---|---|

Subject: Subbasin 26 (Norris Dam) 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 CDQ000020080066 | Rev. 2 | Plant: GEN | |
| Subject: Subbasin 26 (Norris Dam) Unit Hydrograph Validation | | | |

| Electronic Attachment | Name of File of Folder | File Location |
|---|---|---|
| | **Supporting Spreadsheets** | |
| Attachment 1-1 | Basin 26 FLDHYDRO Works.xls | Attached to PDF |
| Attachment 1-2 | Basin 26 Precipitation Data Processing 2002.xls | Attached to PDF |
| Attachment 1-3 | Basin 26 Precipitation Data Processing 2003.xls | Attached to PDF |
| Attachment 1-4 | Clinch Basin Dam Data.xls | Attached to PDF |
| Attachment 1-5 | GriddedPrecipitationDataAllSubbasins2002.xls | Attached to PDF |
| Attachment 1-6 | GriddedPrecipitationDataAllSubbasins2003.xls | Attached to PDF |
| Attachment 1-7 | Norris Dam Direct Runoff Cal.xls | Attached to PDF |
| Attachment 1-8 | Norris Dam Q & HW.xls | Attached to PDF |
| Attachment 1-9 | NorrisRRR1997Z.xls | Attached to PDF |
| Attachment 1-10 | NorrisRRR1998Z.xls | Attached to PDF |
| Attachment 1-11 | NorrisRRR1999Z.xls | Attached to PDF |
| Attachment 1-12 | NorrisRRR2000Z.xls | Attached to PDF |
| Attachment 1-13 | NorrisRRR2001Z.xls | Attached to PDF |
| Attachment 1-14 | NorrisRRR2002Z.xls | Attached to PDF |
| Attachment 1-15 | NorrisRRR2003Z.xls | Attached to PDF |
| Attachment 1-16 | NorrisRRR2004Z.xls | Attached to PDF |
| Attachment 1-17 | NorrisRRR2005Z.xls | Attached to PDF |
| Attachment 1-18 | NorrisRRR2006Z.xls | Attached to PDF |
| Attachment 1-19 | NorrisRRR2007Z.xls | Attached to PDF |
| | **FLDHYDRO & UNITGRAPH Input & Output Files** | |
| Attachment 2-1 | Basin26ppt2002.dat | Attached to PDF |
| Attachment 2-2 | Basin26ppt2002.out (Revised in Revision 1) | Attached to PDF |
| Attachment 2-3 | Basin26ppt2003.dat | Attached to PDF |
| Attachment 2-4 | Basin26ppt2003.out (Revised in Revision 1) | Attached to PDF |
| Attachment 2-5 | NorrisUG.dat | Attached to PDF |
| Attachment 2-6 | NorrisUG.prm | Attached to PDF |
| | **HEC-HMS File Folders** | |
| Attachment 3 | Basin 26.zip (HEC-HMS project files) | FILEKEEPER No. 311290 |
| | | |

# NPG CALCULATION VERIFICATION FORM

| Calculation Identifier CDQ000020080066 | Revision 2 |
|---|---|

| Method of verification used: | |
|---|---|
| 1. Design Review ☒ | |
| 2. Alternate Calculation ☐ | Verifier [signature] Karl E. Stickley Date 12/11/09 |
| 3. Qualification Test ☐ | |

Comments:

This calculation entitled, "Subbasin 26 (Norris Dam) Unit Hydrograph Validation" was verified by independent design review. The process involved a critical review of the calculation to ensure that it is correct and complete, uses appropriate methodologies, and achieves its intended purpose. The inputs were reviewed and determined to be appropriate inputs for this calculation. The results of the calculation were reviewed and were found to be reasonable and consistent with the inputs provided. Backup files and documents were consulted as necessary to verify data and analysis details found in the calculation.

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

Storm hydrographs in this document were produced by reverse reservoir routing. The resulting hydrographs were averaged and/or smoothed to avoid drastic slope changes in the hydrograph that are typically caused by imperfections in the gaged data. This is an acceptable practice, but the final hydrograph volume should have been checked against the original data to ensure a proper volume balance. This verification process included a check of this volume balance and no notable discrepancies were found.

Subbasin 26, Norris Dam: The inflow hydrographs, obtained by Reverse Reservoir Routing, were averaged and smoothed. When compared to the original reservoir release and storage data, the inflow hydrographs are very close in volume. For the March 2002 storm, the inflow hydrograph is higher by 0.31%. For the February 2003 storm, the inflow hydrograph is lower by 0.07%.

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

(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 | CDQ000020080066 | Revision 0 |

| | |
|---|---|
| Method of verification used:<br>1. Design Review ☒<br>2. Alternate Calculation ☐<br>3. Qualification Test ☐ | Verifier Bob Swain Date 2/4/2009 |

Comments:

The calculation entitled, "Subbasin 26 (Norris Dam) 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. All of the comments were minor in nature. Most of the editorial suggestions were adopted in the final document.

The primary issue raised during the verification process was with the original computation of the unit hydrograph. The unit hydrograph had been computed with a version of UNITGRPH that contained a programming error; therefore, the unit hydrograph was recomputed for the 1957 and 1963 floods with the corrected program. The individual unit hydrographs were combined to form a composite unit hydrograph, which was applied to the storms associated with the 2002 and 2003 floods. The resulting flood simulations compared fair to good with the observed floods.

Based on the successful simulation of the March 2002 and February 2003 floods, the calculation supports the conclusion that the unit hydrograph developed for Subbasin 26 has been validated against recent floods.

# 1 Purpose

The TVA's Water Management Group has adapted computer codes and data sets developed from flood studies carried out over the past 40 years to develop a dynamic hydrologic model of the Tennessee River upstream of the Guntersville Dam for use in the Probable Maximum Flood (PMF) and dam break analysis for the proposed Bellefonte Nuclear Power Plant site.

Inputs to the dynamic model include hydrographs for 47 subbasins developed from design rainfall inputs convoluted with unit hydrographs developed specifically for each subbasin. These unit hydrographs were developed by the TVA in previous studies, mostly in the 1970s and early 1980s, utilizing observed rainfall and stream flow and reservoir headwater elevation 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 for the Norris Dam, Subbasin 26, which is located within the Tennessee River watershed as shown in Figure 1.

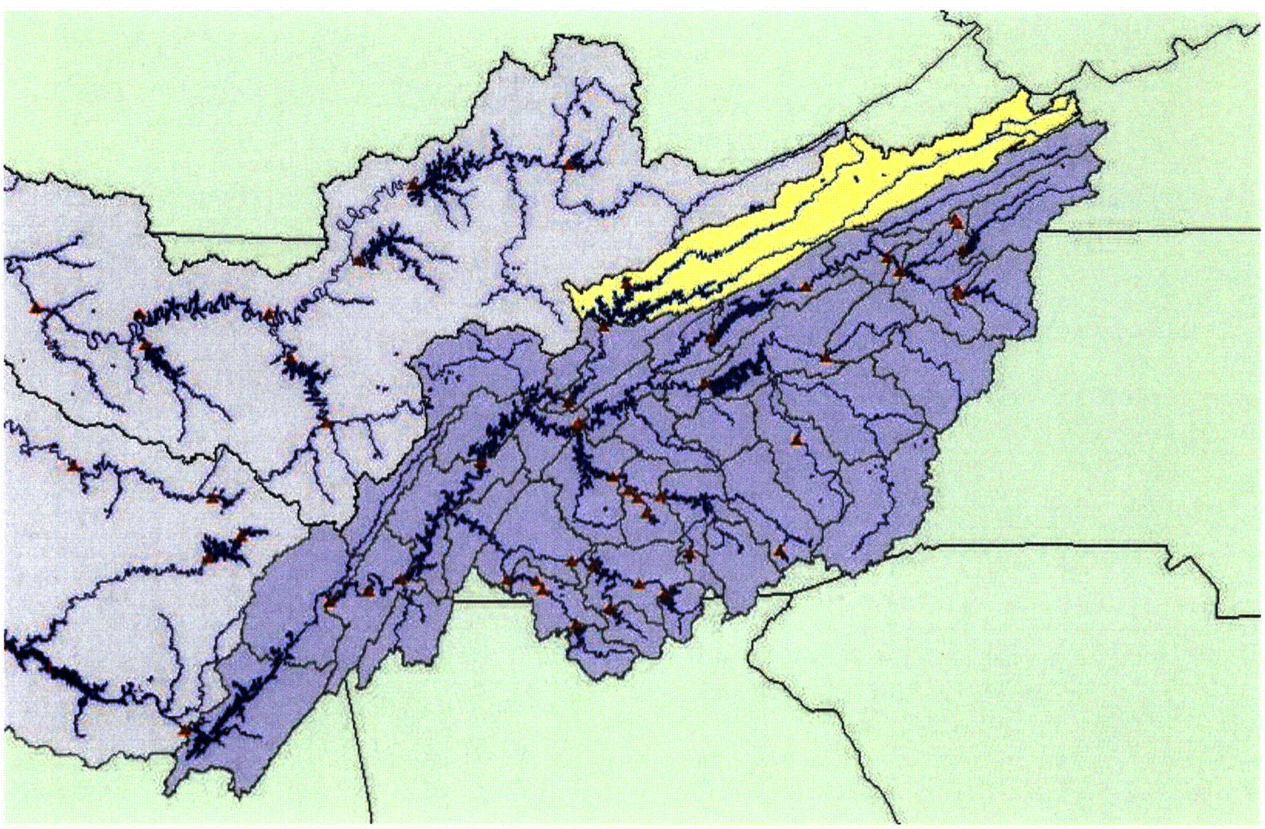


**Figure 1: Location of Norris Dam Subbasin (No. 26) within the Tennessee River watershed**

# 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. Tennessee Valley Authority, *UNITGRPH-FLDHYDRO-TRBROUTE-CHANROUT User's Manual*, Version 1.0, October 2008 (EDMS No. L58 090325 001).
4. American Nuclear Society, American National Standard for Determining Design Basis Flooding at Power Reactor Sites, ANSI/ANS-2.8-1992, 1992.
5. 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.
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 26, Norris Dam, File Book Reference. (EDMS No. L58 090123 800)
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 (EDMS No. L58081030008), Processing and Validation of National Weather Service's NEXRAD Stage III Hourly Precipitation Data for Hydrologic Analysis of TVA Subbasins, Revision 3
11. Tennessee Valley Authority, Bellefonte Nuclear Plant - White Paper, Hydrologic Analysis, Revision 1, July 25, 2008. (EDMS No. L58080730001) FOR INFORMATION ONLY
12. 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)
13. Christopher Zoppou, "Reverse Reservoir Routing of Flood Hydrographs Using Level Pool Routing" *ASCE Journal of Hydrologic Engineering*, Vol. 4 No. 2, April 1999.
14. Linsley, R.K., Kohler, M.A., and J.L. Paulhus, *Hydrology for Engineers*, McGraw-Hill Book Company 1982.

# 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).

The unit hydrograph is used to obtain the stream flow 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 stream flow 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 a specific excess rainfall duration.

# 5 Methodology

The methodology used for unit hydrograph validation follows that described in ANSI/ANS-2.8-1992 (Reference 4). 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 5). 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 26, 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 6.4. Furthermore, since the original unit hydrograph for Subbasin 26 was developed from floods that occurred in 1957 and 1963 (see Section 6.1), it was necessary to use recent rainfall and stream flow data to evaluate the possibility that changes in watershed characteristics over the intervening 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 stream flow data from the 1997-2007 period to identify the two highest flood events. These flood events are used for unit hydrograph validation.
2. Obtain 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 base flow from the local basin hydrograph to obtain the "observed" direct runoff hydrograph for the basin, and calculate the volume of the direct runoff based on the hydrograph ordinates.
4. Obtain observed rainfall data for the selected 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 3). This includes inputting the observed runoff volume obtained in Step 3 to ensure that the effective rainfall volume calculated by FLDHYDRO equals the observed runoff volume.
6. Run HEC-HMS (References 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.

# 6 Design Input Data

The input data necessary for validating the unit hydrograph for the Norris Dam, Subbasin 26, are summarized below.

- Unit hydrograph ordinates and duration
- Observed outflows from Norris Dam and corresponding headwater elevations
- The stage-volume relationship for the reservoir
- Observed rainfall data associated with the selected flood events

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

## *6.1 Unit Hydrograph Ordinates*

The drainage area of the Norris Dam subbasin is given in the TVA File Book References as 2912 $mi^2$ (Reference 8) and was calculated in GIS as 2,912.8 $mi^2$. 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 adjustments to the precipitation excess in the development of the unit hydrograph. The data used to develop the unit hydrograph includes stream flow and precipitation records from the following historical floods:

- January 27 to February 8, 1957
- March 1963

The flood hydrographs used to develop the unit hydrograph for Subbasin 26 were computed by the TVA by lag-routing observed flows at four locations in the upper watershed downstream to Norris Dam and combining them with the inflow from the local area. A unit hydrograph was developed for each storm from the resultant flow series and the effective rainfall (or runoff) using the process of deconvolution. A single composite unit hydrograph was developed from both floods for subsequent modeling tasks. This procedure was duplicated for this calculation using the version of UNITGRAPH validated in 2008 (Reference 3). Input and output files for these runs are provided as Attachments 2-5 and 2-6, respectively.

The resulting composite six-hour 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.

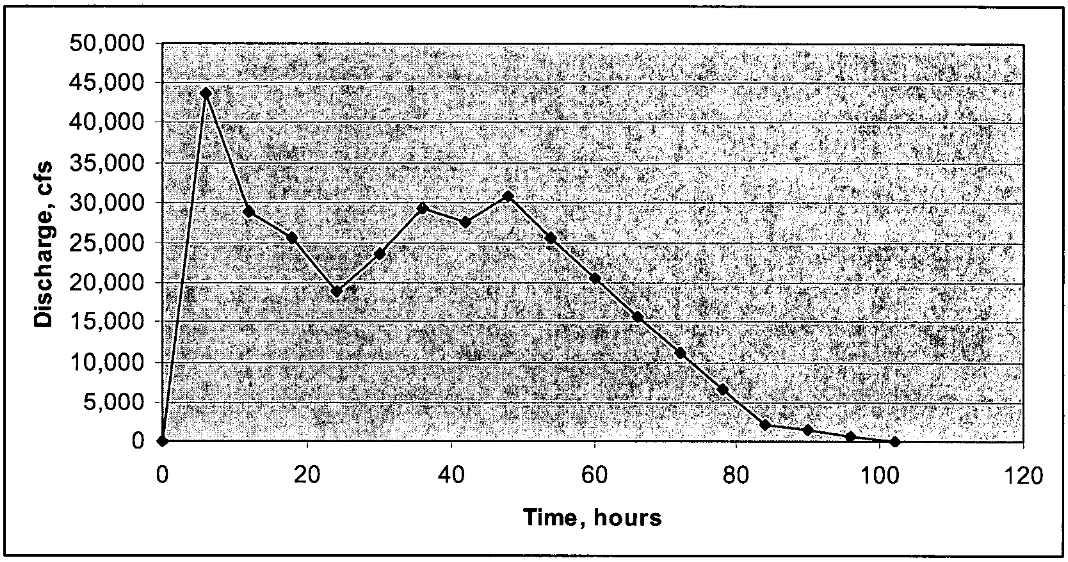



**Figure 2: Six-hour unit hydrograph for Subbasin 26 (Norris Dam)**

**Table 1: Six-hour unit hydrograph ordinates for the Norris Dam subbasin**

| Hour | Q, cfs | Qave, cfs (1) | Volume, acft (2) | |
|---|---|---|---|---|
| 0 | 0 | 21,887 | 10,853 | |
| 6 | 43,773 | 36,363 | 18,031 | |
| 12 | 28,952 | 27,276 | 13,525 | |
| 18 | 25,600 | 22,329 | 11,072 | |
| 24 | 19,058 | 21,410 | 10,616 | |
| 30 | 23,761 | 26,573 | 13,177 | |
| 36 | 29,385 | 28,463 | 14,114 | |
| 42 | 27,540 | 29,168 | 14,463 | |
| 48 | 30,796 | 28,275 | 14,020 | |
| 54 | 25,753 | 23,232 | 11,520 | |
| 60 | 20,711 | 18,190 | 9,020 | |
| 66 | 15,669 | 13,421 | 6,655 | |
| 72 | 11,172 | 8,924 | 4,425 | |
| 78 | 6,675 | 4,427 | 2,195 | |
| 84 | 2,178 | 1,815 | 900 | |
| 90 | 1,452 | 1,089 | 540 | |
| 96 | 726 | 363 | 180 | |
| 102 | 0 | 0 | 0 | |
| Total volume | | | 155,306 | acft |
| Basin area | | | 2,912.8 | $mi^2$ |
| Runoff depth (3) | | | 1.000 | inches |

**Notes:**

1) $Q_{ave} = 0.5(Q_t + Q_{t+6})$

2) $Volume = Qave \frac{ft^3}{\sec} * 3600 \frac{\sec}{hr} * 6hr * \frac{1acft}{43560 ft^3}$

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

## *6.2 Observed Outflows and Headwater Elevations*

Hourly records of outflow from Norris Dam (including spills and turbine discharges) and hourly headwater elevations obtained from the TVA are contained on the tabs "Total Q" and "HW" of the spreadsheet "Norris Dam Q & HW.xls," provided with this calculation as Attachment 1-8.

## 6.3 Stage-Volume Relationship

The stage-volume relationship for the Norris Dam reservoir, which is used for reverse reservoir routing, was obtained from TVA in the spreadsheet "Clinch Basin Dam data.xls" (Attachment 1-4). This file includes stage-volume data of all dams in the upstream watershed. The stage-volume curve for the Norris Reservoir is plotted in Figure 3.

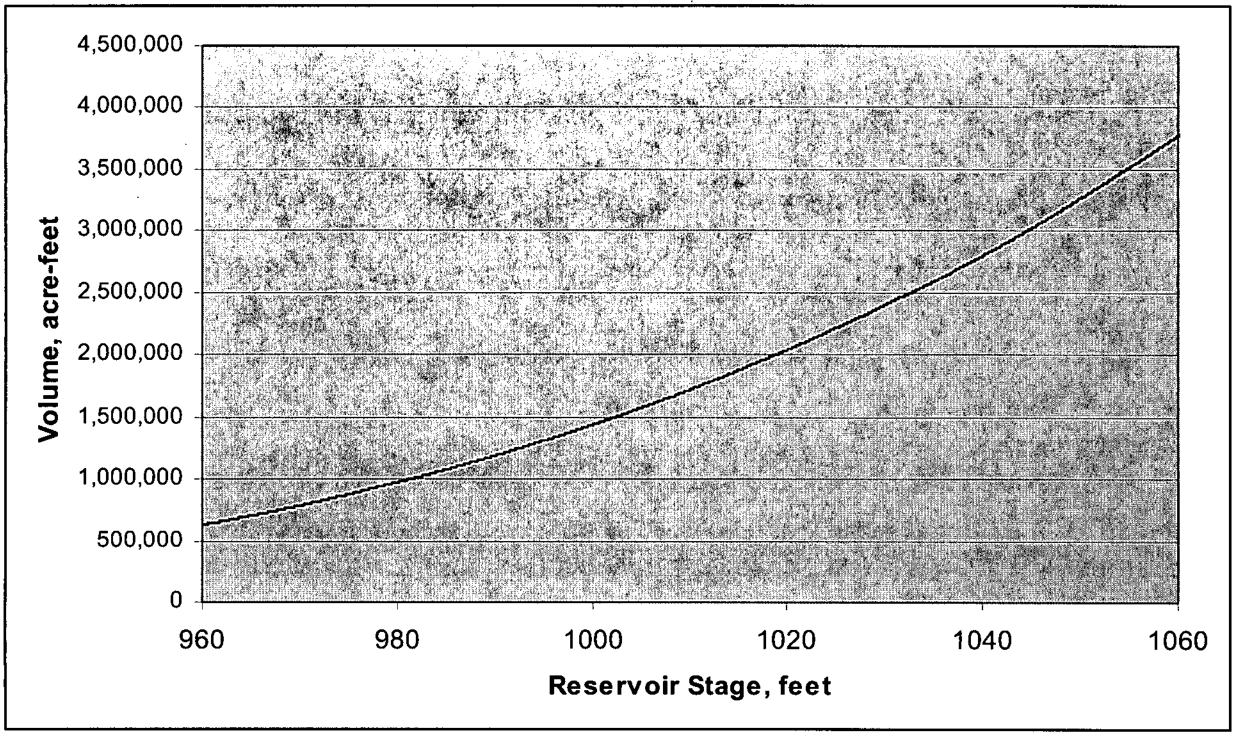



**Figure 3: Stage-volume curve for the Norris Reservoir**

## 6.4 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.

# 7 Computations and Analyses

Computations required for the development of the hydrologic models used in the validation of the TVA unit hydrograph for the Norris Dam watershed are presented in the following sections of this calculation.

## *7.1 Flood Events for Unit Hydrograph Validation*

As noted in Section 5, the unit hydrograph developed by the TVA must be verified by comparing the simulated and observed hydrographs for the two highest peaked floods recorded for the period in which suitable precipitation data are available.

For this calculation, the suitable precipitation data is the gridded hourly rainfall data for the period from 1997 to 2007, obtained from the U.S. National Weather Service (NWS) Lower Mississippi River Forecast Center (LMRFC).

The observed stream flow time series to be used for comparison with the simulated flows were obtained for the same period from reverse reservoir routing (RRR) utilizing observed headwater elevation and dam outflow data, as described in Section 7.2. The largest storms within each year were identified from a plot of the RRR-derived hydrograph and the precipitation data were checked for the period coinciding with (and preceding) the storm period to ensure that there were no missing blocks of data.

The spreadsheets used for the reverse reservoir routing are provided as Attachments 1-9 through 1-19 for the period from 1997 to 2007. Results of the review of the rainfall and reservoir inflow time series are summarized in Table 2, and ordered by rank. Based on the ranking and the analysis of the reservoir inflow and rainfall time series, the following two storm/flood events were selected for unit hydrograph validation:

- March 12 2002, 00:00 hrs to March 27, 2002, 00:00 hrs, the "March 2002" storm
- February 10, 2003 00:00 hrs to February 22, 2003 00:00 hrs, the "February 2003" storm

Note that the top-ranked storm in the series, which occurred in 1998, was not used for validation because the complexity of the rainfall pattern and the multiple-peaked hydrograph made the separation of base flow and the correlation of runoff with rainfall highly unreliable.

**Table 2: Annual peak discharges in Subbasin 26 from 1997 through 2007**

| Year | Date | Qp, cfs, from RRR | | Comments |
|---|---|---|---|---|
| | | 1-hour peak | 3-point avg | |
| 1998 | 19-Apr | 101,389 | 101,172 | Did not use due to rainfall complexity |
| 2003 | 16-Feb | 105,848 | 97,791 | Utilized for validation |
| 2002 | 19-Mar | 86,847 | 83,502 | Utilized for validation |
| 1997 | 3-Mar | 54,391 | 53,192 | |
| 2004 | 7-Mar | 63,838 | 44,255 | |
| 1999 | 28-Feb | 115,051 | 41,981 | |
| 2007 | 16-Apr | 40,275 | 37,689 | |
| 2000 | 3-Apr | 47,036 | 37,631 | |
| 2001 | 16-Feb | 41,207 | 37,178 | |
| 2006 | 9-Apr | 39,282 | 36,192 | |
| 2005 | 4-Apr | 30,295 | 27,849 | |

## *7.2 "Observed" Basin Hydrographs*

The available stream flow data are the observed outflows from Norris Dam. For the purpose of unit hydrograph validation, it is necessary to use this reservoir outflow time series along with changes in reservoir storage to calculate reservoir inflows using reverse reservoir routing. The reservoir inflow series can then be used as the "observed" hydrograph for comparison with the flood hydrograph obtained from convolution of the TVA unit hydrograph with excess rainfall.

Reverse reservoir routing consists of solving the continuity equation for the reservoir, which can be stated as (Reference 13):

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

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

Equation 2 can be written using a centered finite-difference scheme as follows, where the terms t+Δt and t-Δt refer to the following and preceding time steps, respectively (Reference 13):

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

Using the records of outflow and headwater elevation for Norris Dam, provided by the TVA as recorded in the spreadsheet "Norris Dam Q & HW.xls" (Attachment 1-8), and the stage-volume relationship for the reservoir obtained from the TVA for the dams within the Clinch River watershed in the spreadsheet "Clinch Basin Dam Data.xls" (Attachment 1-4), reverse reservoir routing was performed for the March 2002 and February 2003 events. These spreadsheets are attached to this calculation as:

- NorrisRRR2002Z.xls (Attachment 1-14)
- NorrisRRR2003Z.xls (Attachment 1-15)

Fluctuations in the estimated inflow can occur when the water surface elevation of the reservoir is changing slowly and surface elevations are measured at discrete height intervals (i.e., to the nearest hundredth foot). A three-point moving average technique was used to smooth the fluctuations in the hydrographs resulting from the reverse reservoir routing calculations.

The resultant inflow hydrographs are plotted in Figures 4 and 5.

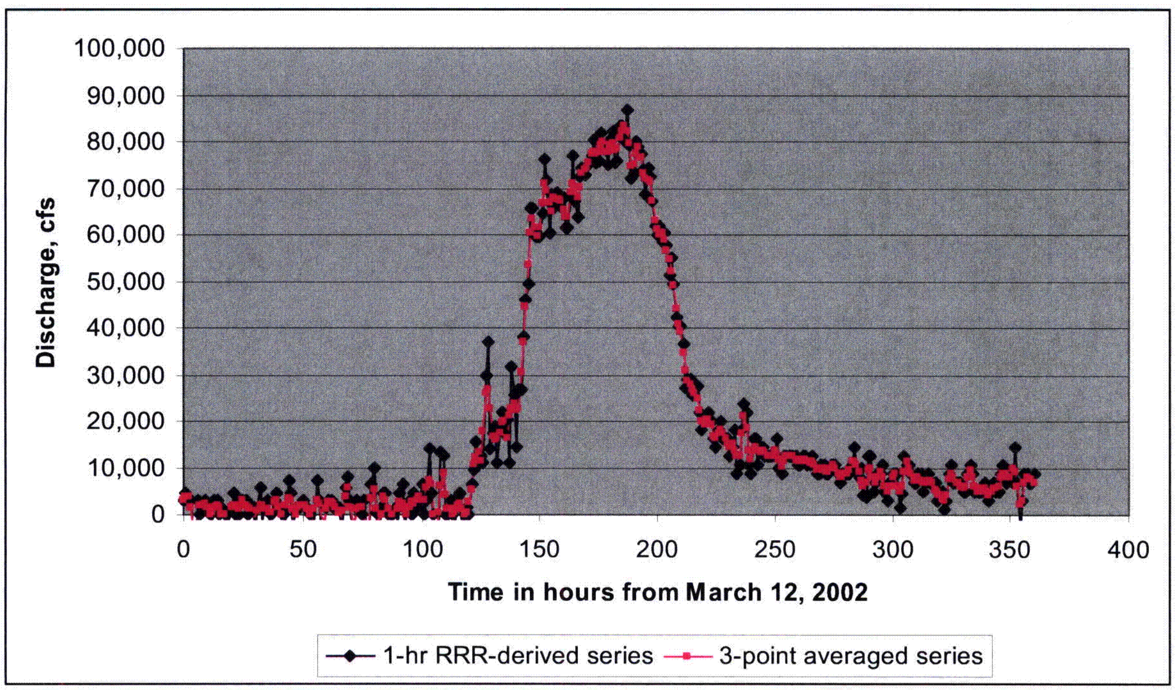



**Figure 4: Norris Dam reservoir inflow hydrograph for March 2002 flood**

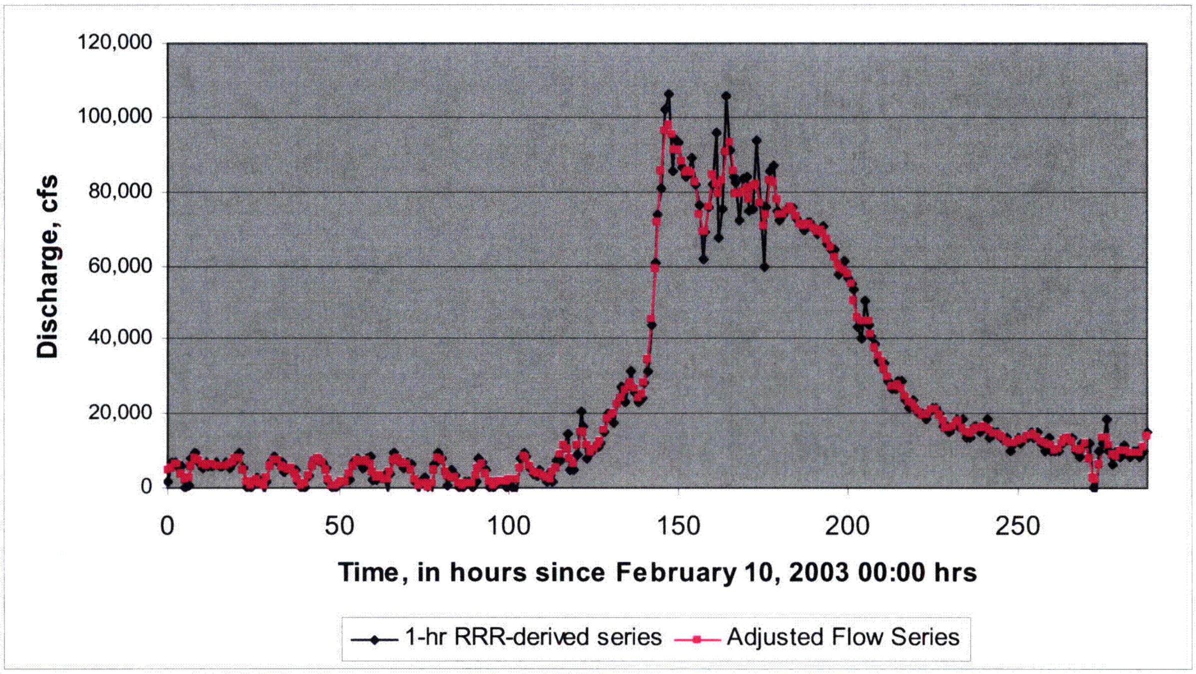



**Figure 5: Norris Dam reservoir inflow hydrograph for February 2003 flood**

## *7.3 Base Flow Separation & Direct Runoff Calculation*

Base flow separation is required to determine an estimate of direct runoff associated with the rainfall event. The observed direct runoff volume is used to adjust, if necessary, the effective rainfall volume computed by FLDHYDRO, as described in Section 7.5.

For this calculation, the base flow is drawn from the starting point of runoff to a point on the receding limb of the hydrograph N days after the time of peak discharge, where N is the area of the watershed, in square miles, raised to the one-fifth power per the criterion proposed by Linsley et al (Reference 14). For the Norris Dam watershed, with a drainage area of 2,912.8 square miles, N is calculated as 4.93 days or 118 hours (see Table 3).

Results for the March 2002 and February 2003 flood events are plotted on Figures 6 and 7, respectively. Base flow separation calculations are carried out in the spreadsheet "Norris Dam Direct Runoff Calc.xls," provided as Attachment 1-7 to this calculation.

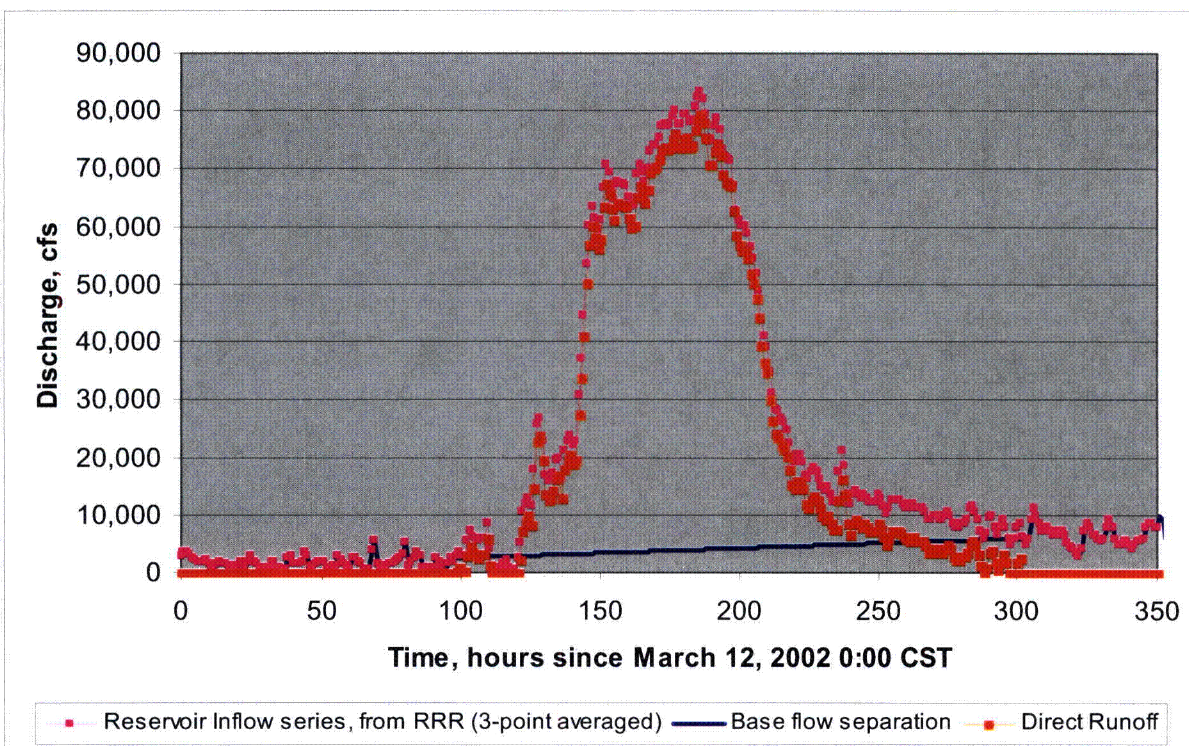



**Figure 6: Norris Dam base flow separation for the March 2002 flood**

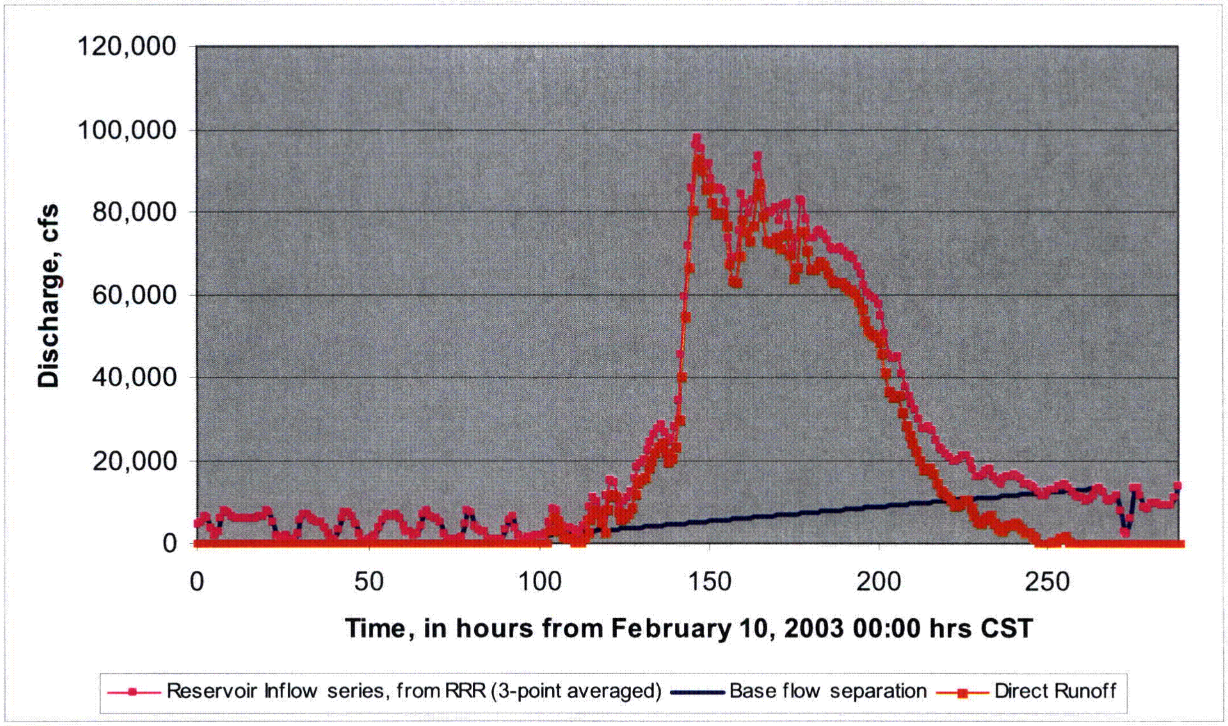



**Figure 7: Norris Dam base flow separation for the February 2003 flood**

Base flow was removed from the inflow hydrographs to obtain the direct runoff hydrograph. The total volume of direct runoff is obtained by numerical integration of the hydrograph (see Attachment 1-7) and is used in adjusting the effective rainfall volume, as described in Section 5.

The direct runoff volume calculation is summarized in Table 3.

**Table 3: Direct runoff volume calculations for the March 2002 and February 2003 events**

| Storm/Flood Event | Starting Hour of direct RO (1) | Peak Hour of direct RO (1) | End Hour of Direct Runoff (2) | Total Runoff Volume, acft (3) | Runoff Depth, inches (4) |
|---|---|---|---|---|---|
| March 2002 | 96 | 186 | 304 | 450,426 | 2.90 |
| February 2003 | 100 | 147 | 265 | 427,835 | 2.75 |

1) by observation of hydrograph, arbitrary zero hour for storm isolation (see Attachment 1-4)

2) End hour = Peak hour + N expressed in hours (see text)

3) By integration of hydrograph after base flow separation

4) Depth = 12 "/ft x Volume in acft/640 acres/mi$^2$/2912.8 mi$^2$

## 7.4 Observed Basin Average Rainfall

Observed average basin rainfall for the March 2002 and February 2003 storms were obtained from Reference 10 (see spreadsheets "GriddedPrecipitationDataAllSubbasins2002.xls" and "Gridded-PrecipitationDataAllSubbasins2003.xls", provided as Attachments 1-5 and 1-6). The hourly and daily precipitation series developed from NWS gridded data for 2002 and 2003 for use in FLDHYDRO are provided in the spreadsheets "Basin 26 Precipitation Data Processing 2002.xls" and "Basin 26 Precipitation Data Processing 2003.xls" (Attachments 1-2 and 1-3, respectively) along with adjustments from Greenwich Mean Time to Central Time and conversion from millimeters to inches.

## 7.5 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 3). The FLDHYDRO program was developed by the TVA to implement the API/RI methodology developed by the USWB, as described in Reference 3. In brief, the method uses the Antecedent Precipitation Index (API) for a given day, which is calculated on the basis of a recession constant normally reported to range from 0.85 to 0.98 (Reference 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 precipitation location and season. The RI is then used to obtain precipitation losses for each increment of rainfall. The use of the loss function is discussed in the TVA White Paper (Reference 11), and the methodology is described in detail in Kohler and Linsley's publication (Reference 12).

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

- Hourly and daily precipitation gage readings
- Flags and indices to relate each non-recording gage record to a recording gage record for interpolation
- Thiessen coefficients to weight gage records for the calculation of basin average precipitation depths (not used for gridded precipitation data)
- Depth of runoff for the period of rainfall

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

- NARFE = 1 to obtain a printout of flood hydrographs only
- NRI = 1 for the number of Rainfall Indices to be used per basin
- NCPTS = 1 for the number of sites for surface runoff volume check (set to zero for the NORO runs)
- NSUBW = 1 for the number of sub-watersheds (each subbasin is run separately)
- NREC = 1 for the number of recorders (run using only gridded precipitation data as one "recorder"
- NSTNS = 1 for total number of stations (i.e. no non-recording stations used )
- STAB = 1 for all stations are in the same API area
- ITDGR = 0 for the hour at which each gage is read
- BEGDR = the starting date (March 16, 2002 or February 14, 2003, 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 Norris Dam subbasin is within the NE zone, (see Fig. 8)
- NSPW = 1 for number of rainfall stations for each subwatershed (for gridded data there are no Thiessen weighting factors)
- NUMVOL = number of watersheds above surface runoff volume check point
- CHKVOL = the volume of surface runoff in inches, which is calculated from outflow hydrographs after baseflow separation; when CHKVOL is greater than zero, the final runoff index is adjusted if necessary to provide a volume equal to CHKVOL.

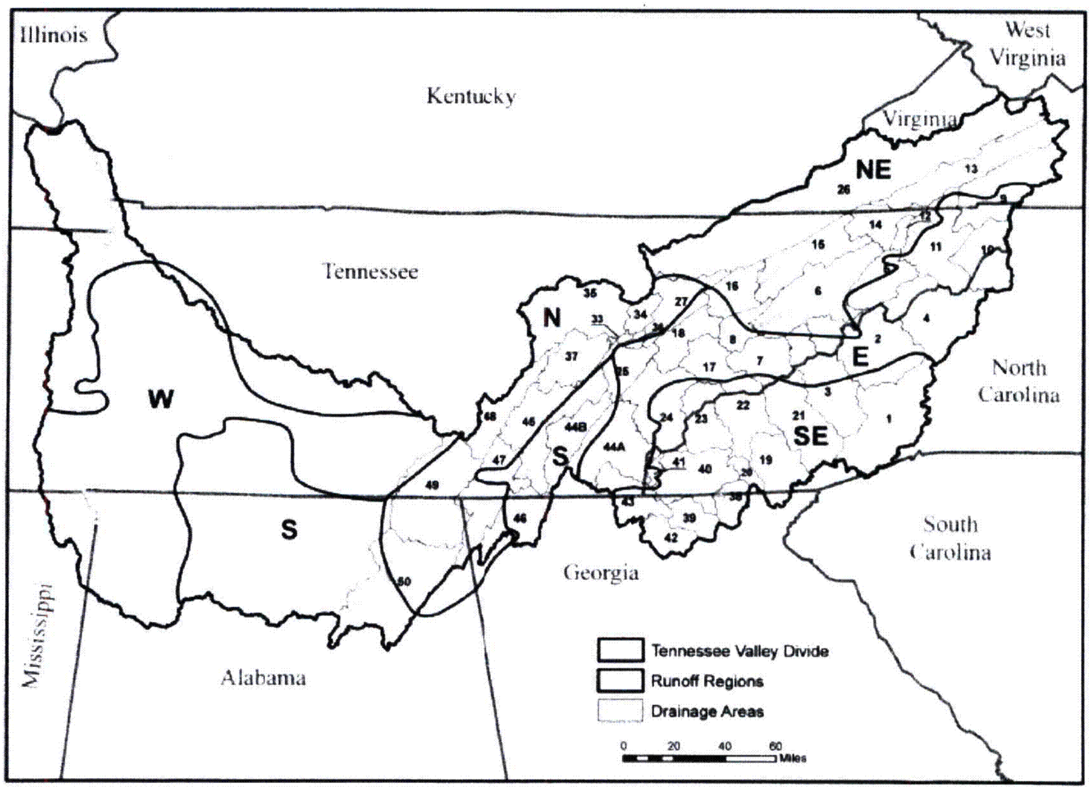



**Figure 8: Runoff regions for application of TVA FLDHYDRO program**

Data processing to obtain daily antecedent rainfall depths and hourly storm depths and convert the gridded precipitation data to the format required for use in FLDHYDRO was carried out in "Basin 26 Precipitation Processing 2002.xls" and "Basin 26 Precipitation Data Processing 2003.xls" (Attachments 1-2 and 1-3).

The antecedent rainfall days used for the March 2002 and February 2003 simulations are presented in Table 4. The hourly basin average rainfall depths are reproduced in Table 5 in the 10F8.0 FORTRAN format used by the FLDHYDRO program.

Input data and parameters for running FLDHYDRO to get effective basin average rainfall for the Norris Dam model were written to the following files:

- Basin26ppt2002.dat (Attachment 2-1)
- Basin26ppt2003.dat (Attachment 2-3)

Output (echoing input) is provided in the following files:

- Basin26ppt2002.out (Attachment 2-2)
- Basin26ppt2003.out (Attachment 2-4)

**Table 4: Daily basin average rainfall depths used in API calculations for March 2002 and February 2003 events**

| Date | Daily Rainfall Depth, inches | | Date | Daily Rainfall Depth, inches |
|---|---|---|---|---|
| 2/16/2002 | 0.046 | | 1/17/2003 | 0.000 |
| 2/17/2002 | 0.002 | | 1/18/2003 | 0.000 |
| 2/18/2002 | 0.000 | | 1/19/2003 | 0.000 |
| 2/19/2002 | 0.005 | | 1/20/2003 | 0.000 |
| 2/20/2002 | 0.304 | | 1/21/2003 | 0.000 |
| 2/21/2002 | 0.000 | | 1/22/2003 | 0.000 |
| 2/22/2002 | 0.000 | | 1/23/2003 | 0.000 |
| 2/23/2002 | 0.000 | | 1/24/2003 | 0.000 |
| 2/24/2002 | 0.000 | | 1/25/2003 | 0.000 |
| 2/25/2002 | 0.000 | | 1/26/2003 | 0.000 |
| 2/26/2002 | 0.060 | | 1/27/2003 | 0.000 |
| 2/27/2002 | 0.000 | | 1/28/2003 | 0.000 |
| 2/28/2002 | 0.000 | | 1/29/2003 | 0.000 |
| 3/1/2002 | 0.000 | | 1/30/2003 | 0.000 |
| 3/2/2002 | 0.358 | | 1/31/2003 | 0.008 |
| 3/3/2002 | 0.019 | | 2/1/2003 | 0.019 |
| 3/4/2002 | 0.000 | | 2/2/2003 | 0.000 |
| 3/5/2002 | 0.000 | | 2/3/2003 | 0.077 |
| 3/6/2002 | 0.000 | | 2/4/2003 | 0.621 |
| 3/7/2002 | 0.000 | | 2/5/2003 | 0.000 |
| 3/8/2002 | 0.000 | | 2/6/2003 | 0.170 |
| 3/9/2002 | 0.190 | | 2/7/2003 | 0.020 |
| 3/10/2002 | 0.000 | | 2/8/2003 | 0.000 |
| 3/11/2002 | 0.002 | | 2/9/2003 | 0.158 |
| 3/12/2002 | 0.112 | | 2/10/2003 | 0.118 |
| 3/13/2002 | 0.067 | | 2/11/2003 | 0.000 |
| 3/14/2002 | 0.000 | | 2/12/2003 | 0.000 |
| 3/15/2002 | 0.000 | | 2/13/2003 | 0.000 |

**Table 5: Hourly basin average rainfall depths used for modeling excess precipitation (runoff) in FLDHYDRO (FORTRAN format, i.e. reading horizontally, left to right)**

| Hourly rainfall depths, in inches, starting 3/16/2002 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.000 | 0.000 | 0.000 | 0.000 | 0.024 | 0.215 | 0.171 | 0.103 | 0.022 | 0.000 |
| 0.006 | 0.008 | 0.003 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 | 0.014 | 0.017 | 0.059 | 0.131 | 0.242 | 0.274 | 0.304 |
| 0.224 | 0.139 | 0.064 | 0.008 | 0.006 | 0.010 | 0.006 | 0.005 | 0.008 | 0.015 |
| 0.095 | 0.143 | 0.170 | 0.177 | 0.261 | 0.245 | 0.243 | 0.208 | 0.191 | 0.204 |
| 0.189 | 0.127 | 0.105 | 0.091 | 0.050 | 0.023 | 0.054 | 0.023 | 0.006 | 0.001 |
| 0.002 | 0.002 | 0.002 | 0.001 | 0.002 | 0.001 | 0.002 | 0.001 | 0.001 | 0.001 |
| 0.001 | 0.000 | 0.001 | 0.000 | 0.000 | 0.001 | 0.001 | 0.003 | 0.000 | 0.002 |
| 0.000 | 0.000 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.024 | 0.100 | 0.061 | 0.015 | 0.005 |
| 0.004 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

| Hourly rainfall depths, in inches, starting 2/14/2003 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.007 | 0.046 | 0.075 |
| 0.087 | 0.061 | 0.028 | 0.008 | 0.017 | 0.039 | 0.077 | 0.091 | 0.076 | 0.088 |
| 0.110 | 0.111 | 0.102 | 0.042 | 0.031 | 0.015 | 0.015 | 0.017 | 0.013 | 0.015 |
| 0.030 | 0.032 | 0.052 | 0.031 | 0.084 | 0.121 | 0.117 | 0.117 | 0.121 | 0.125 |
| 0.105 | 0.044 | 0.026 | 0.031 | 0.046 | 0.138 | 0.228 | 0.231 | 0.192 | 0.186 |
| 0.172 | 0.108 | 0.056 | 0.008 | 0.003 | 0.008 | 0.024 | 0.012 | 0.001 | 0.007 |
| 0.010 | 0.007 | 0.010 | 0.018 | 0.009 | 0.025 | 0.038 | 0.027 | 0.013 | 0.008 |
| 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.001 |
| 0.001 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.002 | 0.000 | 0.000 |
| 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.004 | 0.002 | 0.000 | 0.000 | 0.001 |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.002 |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.007 | 0.006 | 0.002 | 0.001 | 0.001 | 0.000 | 0.001 | 0.009 | 0.008 | 0.012 |
| 0.013 | 0.011 | 0.008 | 0.018 | 0.022 | 0.021 | 0.012 | 0.001 | 0.000 | 0.000 |

Figures 9 and 10 provide a plot of the cumulative precipitation and rainfall based on FLDHHDYRO output for the 2002 and 2003 events, as shown on the tabs "2002" and "2003" of spreadsheet "Basin 26 FLDHYDRO Work.xls" (Attachment 1-1). The *incremental* effective basin average rainfall time series, which appear in the last column of each the two tables in the spreadsheet, were copied for input to HEC-HMS using the Time-Series Data Manager (Reference 6).

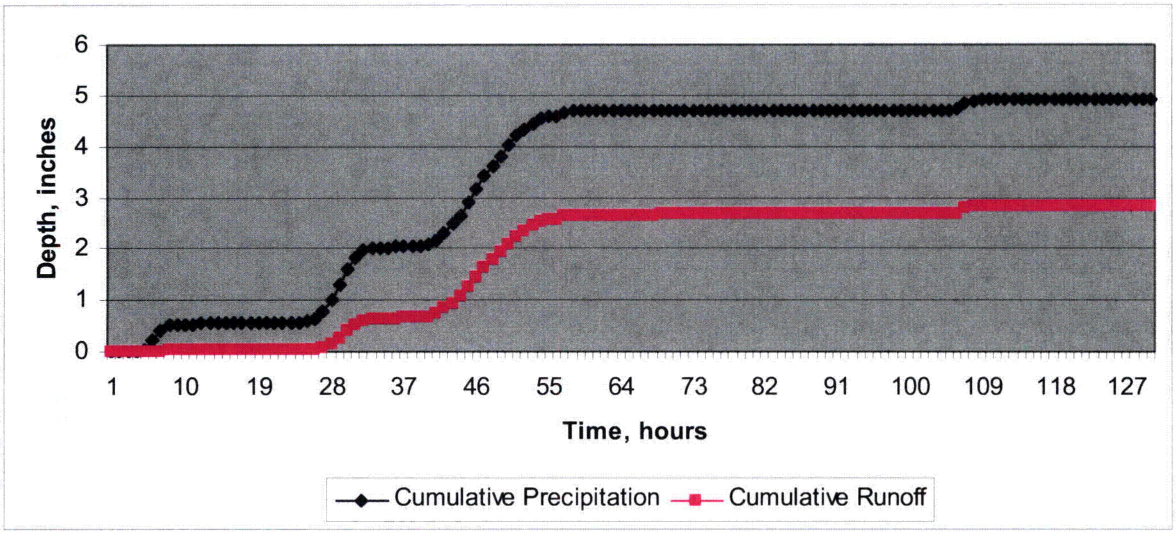



**Figure 9: Cumulative observed and effective basin average precipitation for the March 2002 event**

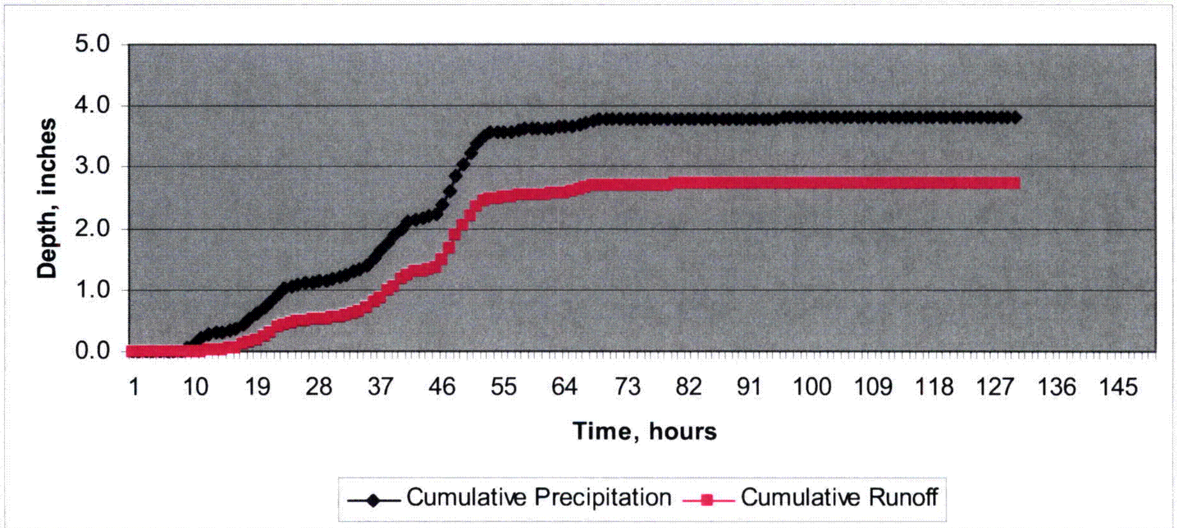



**Figure 10: Cumulative observed and effective basin average precipitation for the February 2003 event**

## 7.6 HEC-HMS Flood Simulations

A HEC-HMS project file (Basin26.hms) was developed for testing the unit hydrograph developed by the TVA for the Norris Dam subbasin for the March 2002 and February 2003 storm events. This project file has been compressed into a zip file, "Basin 26.zip," to preserve the folder structure and has been stored in FILEKEEPER (Attachment 3).

The following basin models were developed within the project folder:

- Norris Dam 2002
- Norris Dam 2003

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 Standard Time for this calculation):

- Precipitation Gage "EffMarch2002" with hourly data incremental depths
- Precipitation Gage "EffFebrurary2003" with hourly data incremental depths
- Discharge Gage "RRRMarch2002" with hourly direct runoff discharge in cfs
- Discharge Gage "RRRFebruary203" with hourly direct runoff discharge in cfs

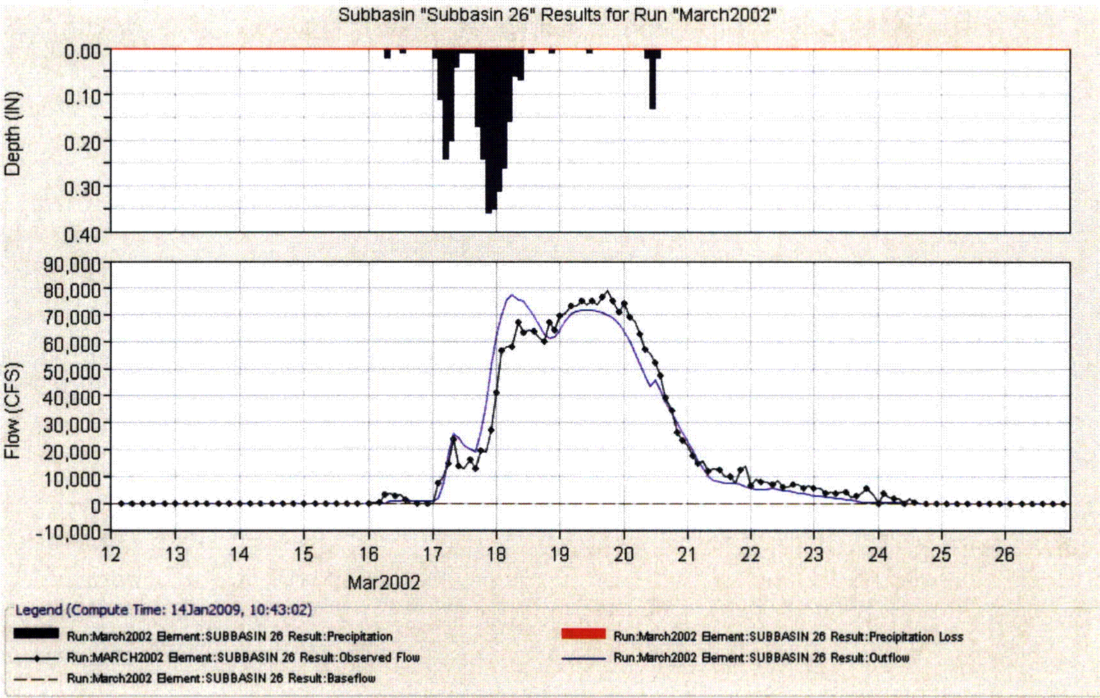
Note that instead of inputting observed basin average precipitation and utilizing a loss function for the subbasin, the effective basin average rainfall (or runoff) output from FLDHYDRO was utilized as "precipitation data."

The discharge gage time series ("observed flow series") were developed from reverse reservoir routing utilizing observed outflow and stage data collected by the TVA, with base flow removed from each flow series as described in Section 7.3.

The unit hydrograph for the Norris Dam subbasin was input to HEC-HMS as a "user-specified" hydrograph with the Paired Data Manager as "TVAUH."

A two-hour time step was utilized in the model (set in the Control Specifications file). HEC-HMS automatically adjusts the duration of the 6-hour unit hydrograph for the two hour time step (Reference 6). The simulated hydrographs are compared to the observed flow series for the 2002 and 2003 floods in Figures 11 and 12, respectively, which were obtained from the HEC-HMS Graphical User Interface.

In these figures, the simulated hydrographs at the subbasin outlet are shown as solid blue lines and the observed flow series are shown as the heavy dotted black lines. The effective rainfall time series is shown as the inverted histogram at the top of each figure. HEC-HMS also provides a Summary Table with lumped output data, which is shown at the bottom of the figure. Discharge values other than the maximum value must be obtained from Time Series output.




Project: Basin26
Simulation Run: March2002 Subbasin: Subbasin 26

| | | | |
|---|---|---|---|
| Start of Run: | 12Mar2002, 00:00 | Basin Model: | Norris Dam 2002 |
| End of Run: | 27Mar2002, 00:00 | Meteorologic Model: | March2002 |
| Compute Time: | 14Jan2009, 10:43:02 | Control Specifications: | March2002 |

Volume Units: (•) IN ( ) AC-FT

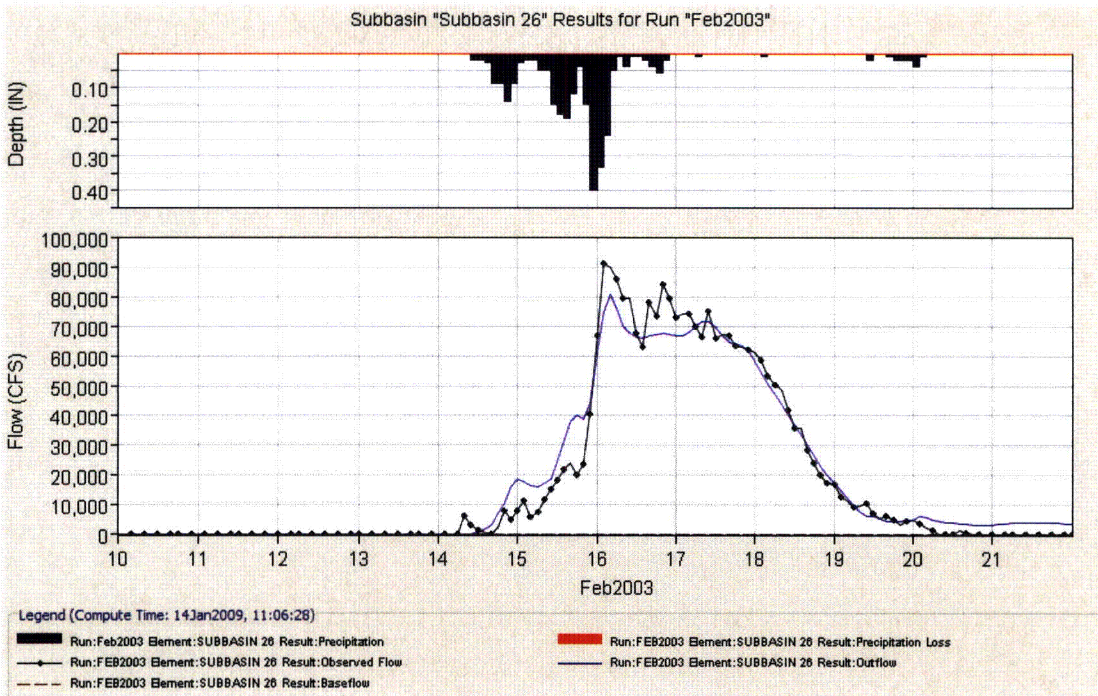
**Computed Results**

| | | | |
|---|---|---|---|
| Peak Discharge : | 77728.5 (CFS) | Date/Time of Peak Discharge : | 18Mar2002, 06:00 |
| Total Precipitation : | 2.85 (IN) | Total Direct Runoff : | 2.85 (IN) |
| Total Loss : | 0.00 (IN) | Total Baseflow : | 0.00 (IN) |
| Total Excess : | 2.85 (IN) | Discharge : | 2.85 (IN) |

**Observed Hydrograph at Gage RRR March2002**

| | | | |
|---|---|---|---|
| Peak Discharge : | 79385.00 (CFS) | Date/Time of Peak Discharge : | 19Mar2002, 18:00 |
| Avg Abs Residual : | 2607.29 (CFS) | | |
| Total Residual : | -0.05 (IN) | Total Obs Q : | 2.90 (IN) |

**Figure 11: HEC-HMS results for Subbasin 26 for the March 2002 flood**




Project: Basin26

Simulation Run: Feb2003 Subbasin: Subbasin 26

| | | | |
|---|---|---|---|
| Start of Run: | 10Feb2003, 00:00 | Basin Model: | Norris Dam 2003 |
| End of Run: | 22Feb2003, 00:00 | Meteorologic Model: | February2003 |
| Compute Time: | 14Jan2009, 11:06:28 | Control Specifications: | February2003 |

Volume Units: ⦿ IN ◯ AC-FT

Computed Results

| | | | |
|---|---|---|---|
| Peak Discharge : | 80900.8 (CFS) | Date/Time of Peak Discharge : | 16Feb2003, 04:00 |
| Total Precipitation : | 2.87 (IN) | Total Direct Runoff : | 2.84 (IN) |
| Total Loss : | 0.00 (IN) | Total Baseflow : | 0.00 (IN) |
| Total Excess : | 2.87 (IN) | Discharge : | 2.84 (IN) |

Observed Hydrograph at Gage RRR February2003

| | | | |
|---|---|---|---|
| Peak Discharge : | 91233.00 (CFS) | Date/Time of Peak Discharge : | 16Feb2003, 02:00 |
| Avg Abs Residual : | 2971.35 (CFS) | | |
| Total Residual : | 0.08 (IN) | Total Obs Q : | 2.76 (IN) |

**Figure 12: HEC-HMS results for Subbasin 26 for the February 2003 flood**

Referring to Figure 11, the hydrograph simulated for the March 2002 flood event compares fairly well with the observed hydrograph obtained from reverse reservoir routing in terms of overall shape and the timing of peak discharge. The simulation could be marginally improved by isolating the precipitation bursts for separate FLDHYDRO runs, but the selection of the point on the observed hydrograph at which to start the recession curve for separating the runoff into two parts is problematic in that case. Because the simulation produces reasonable results as is, the extra analysis was considered unnecessary.

Referring to Figure 12, the February 2003 simulation resulted in a basin outflow hydrograph that compares reasonably well with the observed hydrograph obtained from reverse reservoir routing in terms of the overall shape of the hydrograph and the timing of the multiple peak discharges. The timing of the simulated and observed peaks match within one hour for this case, with the simulated value of 80,900 cfs about 11% below the peak determined from reverse reservoir routing. Part of the difference between the observed and simulated hydrographs can be explained by possible spurious peaks associated with the routing process, with additional differences resulting from the complex nature of the storms with separate bursts of rainfall. The simulation is judged to be quite good considering the complexity of the rainfall pattern of three separate bursts.

# 8 Summary and Conclusions

The purpose of this calculation was to validate the existing unit hydrograph for the Norris Dam watershed (Subbasin 26) by using it to simulate runoff response to rainfall inputs for two recent flood events in the watershed.

Gridded precipitation data was obtained from the NWS and basin average precipitation depths were calculated. The excess rainfall available for runoff was calculated with the TVA's FLDHYDRO program, which uses relationships between rainfall and runoff established for the Tennessee River valley region based on antecedent moisture conditions (API), the week of the year, and the location. For this calculation, the program option for adjusting the effective basin average rainfall hyetograph to match the observed direct runoff volume was used.

The unit hydrograph for Subbasin 26 and the estimated excess rainfalls, determined as described above, were then used in HEC-HMS to simulate the March 2002 and February 2003 floods, resulting in fair to good matches between simulated and observed hydrographs.

Based on the successful simulation of the March 2002 and February 2003 events, it is concluded that the unit hydrograph developed by the TVA for the Norris Dam watershed (Subbasin 26) has been validated for current watershed conditions. Considering that the unit hydrograph developed from historical flood events (1957 and 1963) has been demonstrated in this calculation to be valid for events occurring in 2002 and 2003, it is concluded that the unique physical characteristics and runoff processes of the drainage basin remain the same as at the time of unit hydrograph development. Therefore, the unit hydrograph for Subbasin 26, tabulated in Table 1 and plotted in Figure 2, adequately describes the response of the watershed to rainfall, and is valid for use in hydrologic studies to determine the Probable Maximum Flood (PMF) at the proposed Bellefonte Nuclear Power Plant site.