ASSOCIATED ATTACHMENTS/ENCLOSURES:

Attachment 02.04.03-09D: Wheeler Dam Watershed Unit Hydrograph (Subbasins 53, 57, 59, 60, 61 and 62) CDQ000020080073, Rev. 0

(100 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 091125 001	calculations(nuclear)	NA

Calc Title: Wheeler Dam Watershed (Subbasins 53, 57, 59, 60, 61, and 62) Unit Hydrograph Validation

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC						Entire calc ☐
NEW	CN	NUC	GEN	CEB	CDQ000020080073	NA	0	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
NA	NA	NA

DCN,EDC,N/A	APPLICABLE DESIGN DOCUMENT(S)	CLASSIFICATION
EDCN-22404A (SQN) EDCN-54018A (WBN) EDCN-LATER (BFN)	NA	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
WP Hamilton	615.252.4437	CEB	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
William P. Hamilton William P Hamilton	11/17/09	Karl Stickley Karl E Stickley	11/18/09

VERIFIER SIGNATURE	DATE	APPROVAL SIGNATURE	DATE
Mark Crisp Mark Crisp	11/18/09	K.R. Spates K.R. Spates	11/25/09

WR 11/25/09 PBS 11-25-09

STATEMENT OF PROBLEM/ABSTRACT

Direct validation of hydrographs for Subbasins 53, 57, 59, 60, 61, and 62 in the Wheeler Dam Watershed using recent flood data.

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

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CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	REV
	CN	NUC	GEN	CEB	CDQ000020080073	0

ALTERNATE CALCULATION IDENTIFICATION

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

CATEGORIES

KEY NOUNS (A-add, D-delete)

ACTION (A/D)	KEY NOUN	A/D	KEY NOUN
A	PMF		
A	River		
A	Flood		

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	CN	GEN	CEB	CDQ000020080051	1
A	P	CN	GEN	CEB	CDQ000020080052	0
A	S	CN	GEN	CEB	CDQ000020080053	0
A	S	CN	GEN	CEB	CDQ000020080054	0
A	P	CN	GEN	CEB	CDQ000020080055	2
A	P	EN	WBN	CEB	54018A	
A	P	EN	SQN	CEB	22404A	
A	p	CO	GEN	CEB	FLDHYDRO Version 1.0	

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

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE

PREPARER PHONE NO. | EDMS ACCESSION NO.

NPG CALCULATION RECORD OF REVISION	
CALCULATION IDENTIFIER CDQ000020080073	
Title	Wheeler Dam Watershed (Sub-basins 53, 57, 59, 60, 61, and 62) Unit Hydrograph Validation
Revision No.	DESCRIPTION OF REVISION
0	Total Pages: 99

NPG CALCULATION TABLE OF CONTENTS			
Calculation Identifier: CDQ000020080073	Revision:	0	
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SECTION	TITLE		PAGE

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Note: N/A indicates an electronically attached file(s).

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Table of Tables

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SECTION	TITLE	PAGE

NPG CALCULATION VERIFICATION FORM

Calculation Identifier	CDQ000020080073	Revision 0

Method of verification used:	
1. Design Review ☒	
2. Alternate Calculation ☐	Verifier Mark W. Crisp Date Mark Crisp 01/18/09
3. Qualification Test ☐	

Comments:

The calculation entitled, "Wheeler Dam Watershed (Subbasins 53, 57, 59, 60, 61, and 62) Unit Hydrograph Validation" was verified by an independent verification process. The engineering methods and approaches utilized in this report are correctly applied. The summaries and conclusions, developed from proper hydrologic and hydrualic methodologies, have been verifed and are consistent with proper engineering practices.

NPG COMPUTER INPUT FILE STORAGE INFORMATION SHEET			
Document CDQ000020080073	Rev. 0	Plant: GEN	
Subject: Wheeler Dam Watershed (Sub-basins 53, 57, 59, 60, 61, and 62) 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 list of electronic attachments on the following page.			
☐ Microfiche/eFiche			

Electronic Attachment Number		File Name
1-01		Attachment 1-01-Wheeler Sub-basin Areas and Scaled Unit Hydrographs.xls
1-02		Attachment 1-02-FlintNrChase.xls
1-03		Attachment 1-03-LimestoneNrAthens .xls
1-04		Attachment 1-04-ElkAbvFayetteville.xls
1-05		Attachment 1-05-ElkAtProspect.xls
1-06		Attachment 1-06-Richland Creek.xls
1-07		Attachment 1-07-timsford.xls
1-08		Attachment 1-08-2002_Wheeler_Watershed_Hourly_Precip_Data.xls
1-09		Attachment 1-09-2003_Wheeler_Watershed_Hourly_Precip_Data.xls
1-10		Attachment 1-10-2004_Wheeler_Watershed_Hourly_Precip_Data.xls
1-11		Attachment 1-11-2006_Wheeler_Watershed_Hourly_Precip_Data.xls
1-12		Attachment 1-12 Intentially Omitted
1-13		Attachment 1-13-2009-10-19_Convol-53v5.xls
1-14		Attachment 1-14-2009-10-19_Convol-57v5.xls
1-15		Attachment 1-15-2009-10-19_Convol-59v5.xls
1-16		Attachment 1-16-2009-10-19_Convol-60v5.xls
1-17		Attachment 1-17-2009-10-19_Convol-61v5.xls
1-18		Attachment 1-18-2009-10-19_Convol-62v5.xls
1-19		Attachment 1-19-2009-10-19-53-Base_Flow.xls
1-20		Attachment 1-20-2009-10-19-57-Base_Flow.xls
1-21		Attachment 1-21-2009-10-19-59-Tims Ford Reverse Routing.xls
1-22		Attachment 1-22-2009-10-19-60-Base_Flow.xls
1-23		Attachment 1-23-2009-10-19-61-Base_Flow.xls
1-24		Attachment 1-24-2009-10-19-62-Base_Flow.xls
2-01		Attachment 2-01-UA_53_02052004_A.out
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2-47		Attachment 2-47-UA_62_02052004_A.dat
2-48		Attachment 2-48-UA_62_02052004_B.dat

1 Purpose

The Tennessee Valley Authority's (TVA) Water Management Group has adapted computer codes and data sets developed from flood studies carried out over the past 40 years to develop a dynamic hydrologic model [1] of the Tennessee River upstream of the Wheeler Dam for use in the Probable Maximum Flood (PMF) and dam break analysis for the Sequoyah, Watts Bar, and Browns Ferry Nuclear Plant sites and the planned Bellefonte Nuclear Plant site.

Inputs to the model include hydrographs for the 15 sub-basins developed from design rainfall inputs convoluted with unit hydrographs (UH) developed specifically for each sub-basin. These unit hydrographs were developed by TVA in previous studies utilizing observed rainfall and stream flow and reservoir headwater and discharge data, and they are being validated for the purpose of calculating PMF by checking their performance in reproducing recent floods.

TVA has developed unit hydrographs for the 15 sub-basins that comprise the Wheeler watershed. For 6 of these unit hydrographs, where stream flow and suitable precipitation data was available, their ability to reproduce recent floods was directly validated by assessing their performance in reproducing the floods. For the remaining 9 sub-basins, where stream gage data or suitable precipitation data was not available or the sub-basins empty directly into the Tennessee River, unit hydrographs can be indirectly validated by assessing their ability to replicate calculated stage and stream flows produced with a dynamic hydrologic model.

This calculation (CDQ000020080073) presents the validation of unit hydrographs developed by TVA for Sub-basins 53, 57, 59, 60, 61 and 62 of the Wheeler watershed. These 6 sub-basins are gaged, and therefore their performance can be directly validated. A companion calculation (CDQ000020080072) will assess unit hydrographs for the remaining 9 sub-basins of the Wheeler Watershed [8].

The locations of the sub-basins assessed in this calculation in relation to other relevant features of the Tennessee River Valley are illustrated in Figure 1.

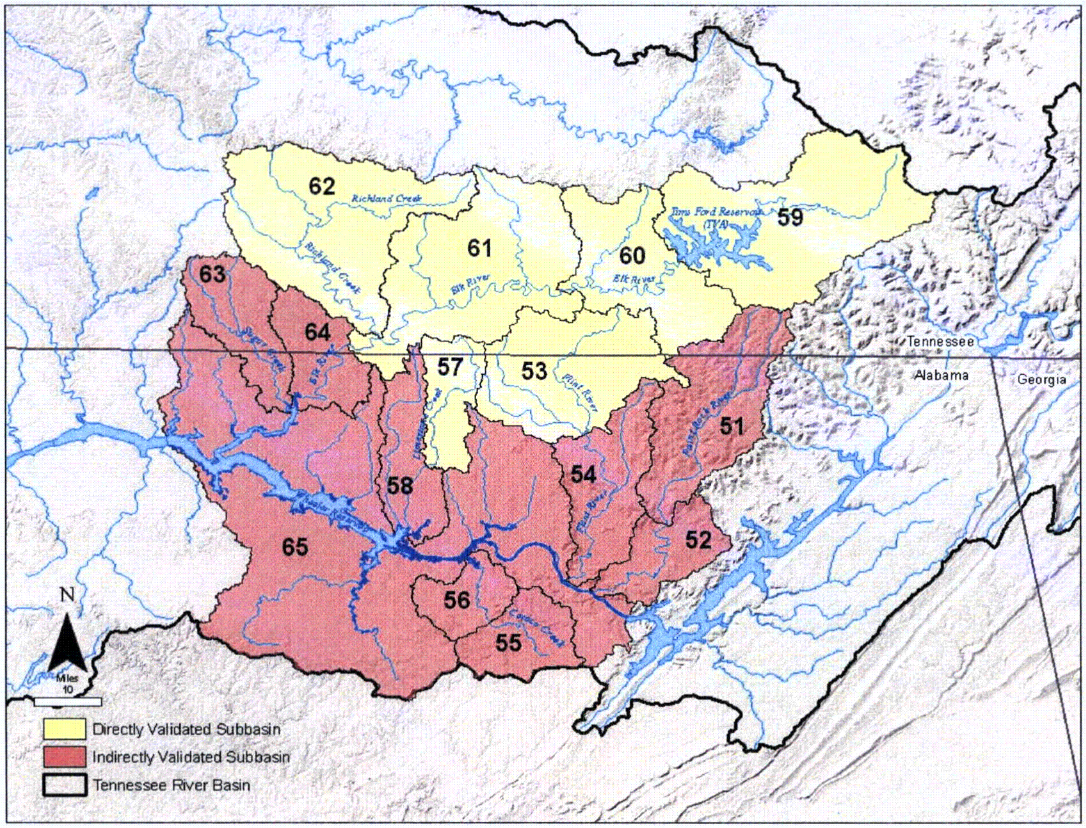

Figure 1: The Wheeler Dam Watershed and the Location of the Six Directly Validated Sub-basins (shown in yellow).

2 References

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2.11. Tennessee Valley Authority. Unit Area 59, Tims Ford Dam, File Book Reference (EDMS No. L58 090611 808)

2.12. Tennessee Valley Authority, Unit Area 60, Elk River Local, Tims Ford to Fayetteville, File Book Reference (EDMS No. L58 090611 809)

2.13. Tennessee Valley Authority, Unit Area 61, Elk River Local, Fayetteville to Prospect, File Book Reference (EDMS No. L58 090611 810)

2.14. Tennessee Valley Authority, Unit Area 62, Richland Creek at Mouth, File Book Reference. (EDMS No. L58 090611 811)

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3 Assumptions

3.1 General Assumptions

None

3.2 Unverified Assumptions

None

4 Introduction

The *unit hydrograph* is used to predict the runoff response at the outlet of a watershed, or sub-basin, 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 [2-4].

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

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

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

Unit Hydrograph theory is applicable under the following conditions [2, 3]:

1. Excess rainfall has constant intensity within the effective duration;
2. Excess rainfall is uniformly distributed over the entire basin;
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 amount of direct runoff (linear response);
5. The surface runoff hydrograph reflects all of the unique physical characteristics and runoff processes in the drainage basin in a given "epoch."

5 Methodology

The methodology followed for unit hydrograph validation follows that described in ANSI/ANS 2.8-1992 [5]. 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 [6]. With regard to verifying runoff models, ANSI/ANS-2.8-1992 indicates 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 [5].

For the purpose of validating the unit hydrographs for the six sub-basins within the Wheeler Dam watershed, the period of record from which the highest two or more floods with suitable precipitation data were selected from 1997 through 2008. This period was targeted because high resolution, radar-based, hourly precipitation data are available for this period as is described in Section 6.6. Furthermore, since the original unit hydrographs were developed from floods that occurred between 1940 and1977 (See Section 6.2.), it was necessary to use recent rainfall and stream flow data to evaluate the possibility that changes in watershed characteristics over the intervening years might have altered the rainfall-runoff response of the watershed to such an extent as to invalidate the original TVA unit hydrograph.

The validation procedure includes the following steps:

1. Screen historical stream flow data to identify significant floods that occurred subsequent to those used to develop the sub-basin unit hydrograph. These more recent floods are used for unit hydrograph validation.
2. Obtain observed hydrograph data for the more recent floods and transfer the flow series to the sub-basin outlet using established hydrologic procedures as necessary (i.e. reverse reservoir routing or stream flow routing and hydrograph separation) to develop the local basin hydrograph.
3. Separate base flow from the local basin hydrograph to obtain the observed direct runoff hydrograph for the basin, and calculate the volume of direct runoff based on hydrograph ordinates.
4. Obtain observed rainfall data for the selected floods and calculate the basin average precipitation for the adopted time step.
5. Convert the observed rainfall series to an effective rainfall series using TVA's API-RI method as implemented in FLDHYDRO [7]. 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. Convolute a direct runoff hydrograph utilizing the TVA unit hydrograph and the effective rainfall series as inputs and compare the resulting simulated hydrograph with the observed direct runoff hydrograph in terms of total volume, and the timing and magnitude of the peak discharge.

6 Design Input Data

The input data necessary for directly validating the 6 unit hydrographs for the Wheeler Watershed, Sub-basins 53, 57, 59, 60, 61 and 62, are summarized below.

- Sub-basin drainage areas comprising the Wheeler Dam Watershed
- Unit hydrograph ordinates and durations
- Flood routing parameters for applicable river reaches
- Observed discharge records from stream flow gages located at or near the outlets of the individual sub-basins
- Observed rainfall data associated with selected floods
- Observed outflows from Tims Ford Dam and corresponding headwater elevations
- The stage-volume relationship for Tims Ford Reservoir

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

6.1 Sub-basin Areas

The Wheeler Dam Watershed is located between Wheeler Dam (Tennessee River Mile (TRM) 274.9) and Guntersville Dam (TRM 349.0) on the Tennessee River in Northern Alabama. The watershed has an area of approximately 5,141 square miles.

The Wheeler Dam Watershed is divided into 15 sub-basins for hydrologic modeling as shown in Figure 2, and as summarized in Table 1. The original unit hydrograph calculations are based on the areas shown in the 4th column of Table 1 labeled "Reference" derived from TVA File Reference Books [9-14]. The difference between the reference areas and the areas recently calculated using Geographic Information System (GIS) software (which are used in this calculation) are presented in Table 1 in the column labeled "% difference." There are some notable differences in areas for individual basins, but the total basin area is essentially the same.

Table 1: Wheeler Reservoir Sub-basin Areas (in square miles).

Basin ID	Sub-basin Name	Area, mi^2		% difference[a]
		GIS	Reference	
51	Paint Rock Creek near Woodville	321.1	320	-0.3
52	Paint Rock Local	138.1	138	-0.1
53	Flint River near Chase	343.1	342	-0.3
54	Flint River Local	224.8	226	0.5
55	Cotaco Creek at Florette	136.2	136	-0.1
56	Cotaco Creek Local	101.1	107	5.7
57	Limestone Creek near Athens	121.3	119	-1.9
58	Limestone Creek Local	157.4	167	5.9
59	Tims Ford Dam	533.2	529	-0.8
60	Elk River Local, Tims Ford to Fayetteville	293.4	298	1.6
61	Elk River Local, Fayetteville to Prospect	490.2	469	-4.4
62	Richland Creek at Mouth	488.0	488	0.0
63	Sugar Creek at Mouth	177.0	177	0.0
64	Elk River Local, Mile 16.5 to Prospect Gage	145.1	167	14.0
65	Wheeler Local (excluding Reservoir)	1380.0	1357	-1.7
Wheeler Lake	Wheeler Surface Area	90.9	100	9.5
	Total	5140.9	5140	0.0

a $\%\text{difference} = \frac{2\times(A_1 - A_2)}{A_1 + A_2}\times 100$ where A is area

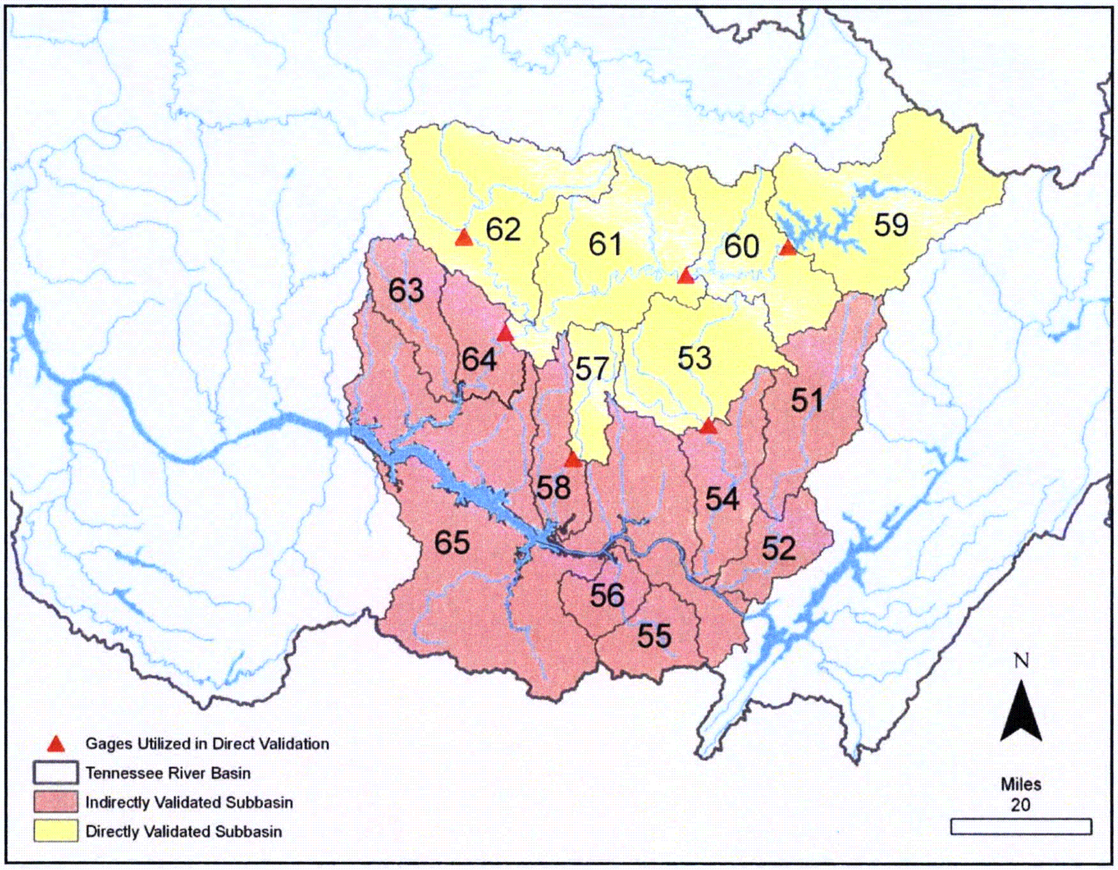

Figure 2: The 15 Wheeler Dam Watershed Sub-basins and the Location of the Gages Utilized in Direct Validation.

6.2 Unit Hydrographs

As described in Section 4, a unit hydrograph is the hydrograph that results from one inch of excess rainfall applied uniformly over a given watershed at a uniform rate during a specified period of time [15]. The unit hydrographs for Sub-basins 53, 57, 59, 60, 61 and 62 are described in the TVA File Books [9-14] and were developed using the methodology proposed by Newton and Vinyard [16] as implemented in the UNITGRAPH computer program [7]. Use of this methodology allows for consideration of possible adjustments in the initial estimate of the time distribution of precipitation excess, and adjustment of the timing and depth of excess precipitation ordinates in the development of the unit hydrograph.

The unit hydrographs for sub-basins 53, 57, 59, 60, 61, and 62 were developed on the basis of the non-reservoir area, with the exception of sub-basin 59 which includes the Tims Ford Reservoir Area, and each catchment (i.e. discounting the reservoir surface area). Because of the differences between historical and GIS-calculated areas (See section 6.1.), the ordinates of each of the unit hydrographs have been adjusted by a linear scale factor to provide a total runoff depth of one inch (as shown in Attachment 1-01 to this calculation). The revised unit hydrographs for Sub-basins 53, 57, 59, 60, 61, and 62 are plotted in Figures 3 – 8.

Key parameters associated with each of the revised TVA unit hydrographs are presented in Table 2. As shown in the final column of the table, the volume of runoff, based on the calculation of area under the unit hydrograph, is one inch for each unit hydrograph as required by theory.

Table 2: TVA Unit Hydrograph Parameters for the Wheeler Watershed Sub-basins.

Subbasin	Effective Duration (hrs)	No. of Ordinates	Qpeak (cfs)	Peak Time (hr)	Area (mi^2)	Vol (ac-ft)	Vol (in)
53	6	11	16,356	12	343.1	18,298.7	1.000
57	4	11	10,618	12	121.3	6,469.3	1.000
59	6	14	17,555	6	533.2	28,437.3	1.000
60	6	14	7,044	18	293.4	15,648.0	1.000
61	6	35	8,874	30	490.2	26,144.0	1.000
62	6	31	11,529	30	488	26,026.7	1.000

A summary of the procedures used by TVA for the development of the unit hydrograph for each sub-basin is presented in the following subsections.

6.2.1 Sub-basin 53 Unit Hydrograph

A unit hydrograph for the Flint River near Chase was developed by the TVA from stream flow and rainfall data from the three following floods [9]:

- January 21, 1954
- March 12, 1963
- March 16, 1973

In addition, the February 13, 1948 flood was simulated using the adopted unit hydrograph.

The three floods were used by TVA to develop a composite six-hour unit hydrograph. Flow routing to the mouth of the Flint River was accomplished with a simple 6-hour lag. The Sub-basin 53 unit hydrograph is shown in Figure 3 and Table 3.

Table 3: Six-hour Unit Hydrograph for Sub-basin 53 (Flint River near Chase).

Time hrs	Flow cfs
0	0
6	146
12	16,356
18	13,348
24	3,225
30	1,978
36	731
42	502
48	381
54	231
60	0
total flow, cfs	36,898
UH duration, hr	6
Drainage area, mi^2	343.1
rainfall depth, in	1.000

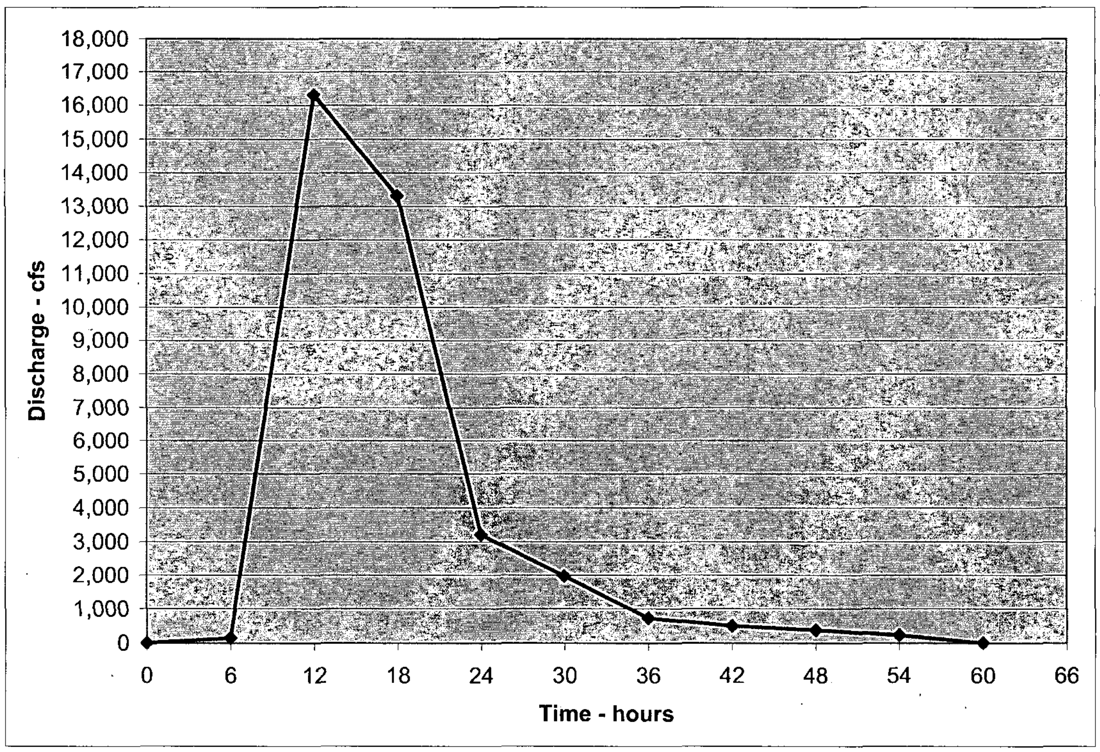

Figure 3: Six-hour Unit Hydrograph for Sub-basin 53 (Flint River near Chase).

The unit hydrograph for Sub-basin 53 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4 and comparing the basin outlet hydrograph with observed stream flow on the Flint River near Chase.

6.2.2 Sub-basin 57 Unit Hydrograph

A unit hydrograph for Limestone Creek near Athens was developed by TVA from stream flow and rainfall data from the three following floods [10]:

- January 21, 1954
- March 12, 1963
- March 16, 1973

The three floods were used by TVA to develop a composite four-hour unit hydrograph. Flows were routed to the mouth of Limestone Creek with a simple lag time of 2 hours. The Sub-basin 57 unit hydrograph is shown in Figure 4 and Table 4.

Table 4: Four-hour Unit Hydrograph for Sub-basin 57 (Limestone Creek near Athens).

Time hrs	Flow cfs
0	0
4	815
8	3,111
12	10,618
16	1,885
20	1,223
24	785
28	466
32	379
36	291
40	0
total flow, cfs	19,573
UH duration, hr	4
Drainage area, mi^2	121.3
rainfall depth, in	1.000

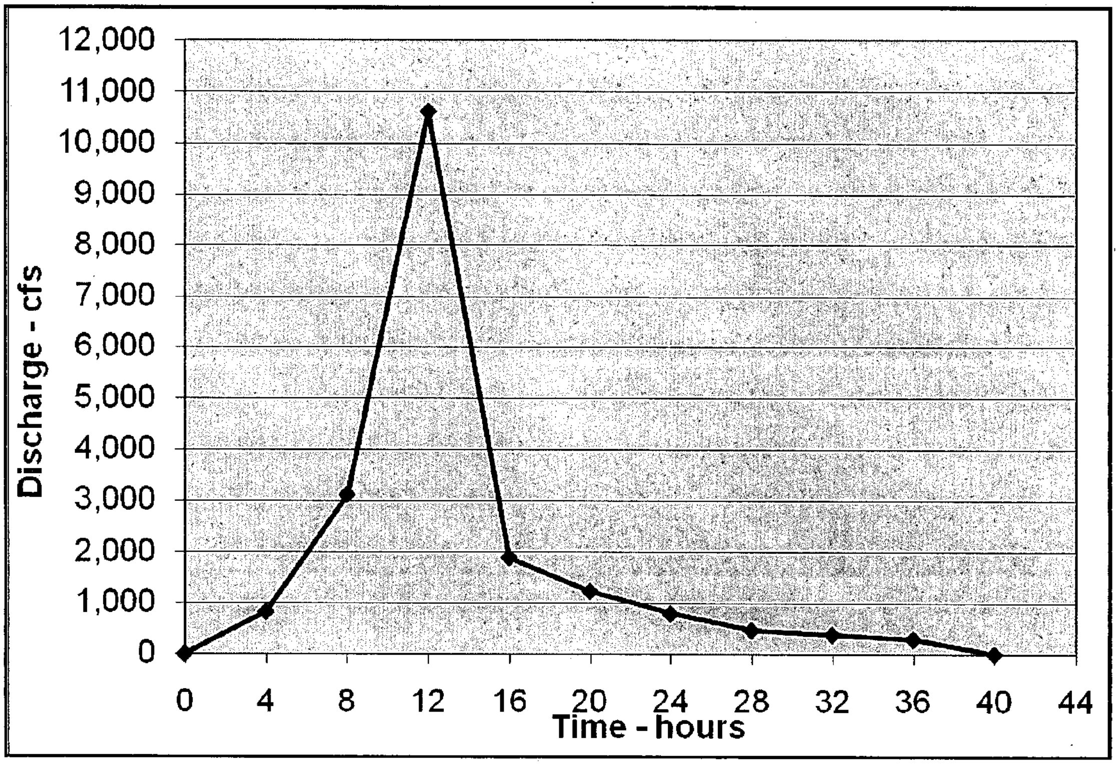

Figure 4: Four-hour Unit Hydrograph for Sub-basin 57 (Limestone Creek near Athens).

The unit hydrograph for Sub-basin 57 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4, and comparing the basin outlet hydrograph with observed stream flow on Limestone Creek near Athens.

6.2.3 Sub-basin 59 Unit Hydrograph

A unit hydrograph for Tims Ford Dam was developed by TVA from reservoir headwater elevation, discharge, volume and rainfall data from the three following floods [11]:

- March 16, 1973
- March 14, 1975
- April 14, 1977

Flood inflows were determined by reverse reservoir routing. Single unit hydrographs were computed for each flood, and a composite six-hour unit hydrograph was adopted based on all three floods. The Sub-basin 59 unit hydrograph is shown in Figure 5 and Table 5.

Table 5: Six-hour Unit Hydrograph for Sub-basin 59 (Tims Ford Dam).

Time hrs	Flow cfs
0	0
6	17,555
12	11,834
18	9,105
24	6,588
30	4,482
36	2,378
42	1,785
48	1,192
54	959
60	725
66	491
72	257
78	0
total flow, cfs	57,351
UH duration, hr	6
Drainage area, mi^2	533.2
rainfall depth, in	1.000

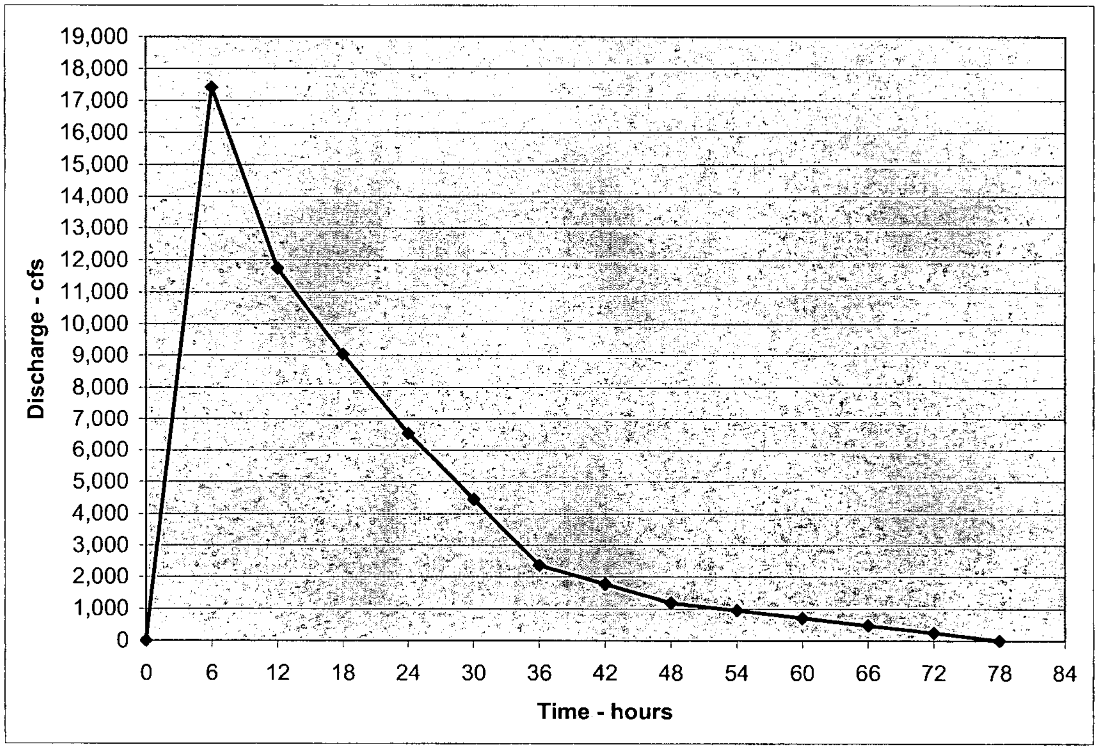

Figure 5: Six-hour Unit Hydrograph for Sub-basin 59 (Tims Ford Dam).

The unit hydrograph for Sub-basin 59 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4, and comparing the basin outlet hydrograph with computed reservoir inflows at Tims Ford Dam.

6.2.4 Sub-basin 60 Unit Hydrograph

A unit hydrograph for Elk River Local, Tims Ford to Fayetteville, was developed by TVA from stream flow and rainfall data from the three following floods [12]:

- March 16, 1973
- March 14, 1975
- April 4, 1977

The following routing equation developed by TVA was used to route the Tims Ford Dam discharges down to Fayetteville (routing period = T = 6 hours) [12]:

$$O(T) = 1.00 \times O(T-1) - 0.25 \times O(T-2) + 0.0625 \times I(T) + 0.125 \times I(T-1) + 0.0625 \times I(T-2)$$

Where O(T) is the outflow for a given time T, and I(T) is the inflow for a given time T. The routed discharge was subtracted from the gaged discharges at Fayetteville to obtain the flow on the local area, Tims Ford to Fayetteville. The three floods were used by TVA to develop a composite six-hour unit hydrograph. The Sub-basin 60 unit hydrograph is shown in Figure 6 and Table 6.

Table 6: Six-hour Unit Hydrograph for Sub-basin 60 (Elk River Local, Tims Ford to Fayetteville).

Time hrs	Flow cfs
0	0
6	2,655
12	4,999
18	7,044
24	6,321
30	4,079
36	2,664
42	1,249
48	909
54	569
60	462
66	354
72	247
78	0
total flow, cfs	31,552
UH duration, hr	6
Drainage area, mi^2	293.4
rainfall depth, in	1.000

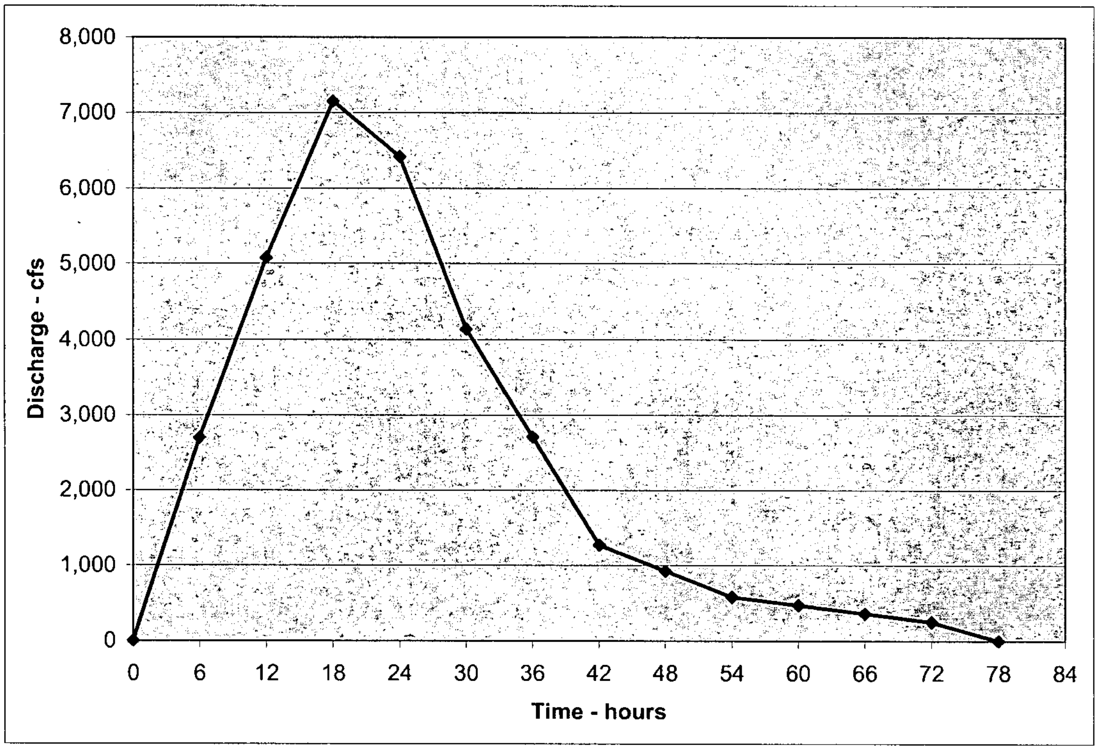

Figure 6: Six-hour Unit Hydrograph for Sub-basin 60 (Elk River Local, Tims Ford to Fayetteville).

The unit hydrograph for Sub-basin 60 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4, and comparing the basin outlet hydrograph with the computed local stream flow on Elk River Local, Tims Ford to Fayetteville.

6.2.5 Sub-basin 61 Unit Hydrograph

A unit hydrograph for Elk River Local, Fayetteville to Prospect was developed by TVA from stream flow and rainfall data from the two following floods [13]:

- February, 1948
- March, 1955

The flood hydrographs for the local area were computed using a preliminary dynamic routing model to route the gaged discharges upstream of Fayetteville down to the Prospect gage and subtracting them along with the Richland Creek discharges at the mouth from the Prospect gaged discharge.

A composite unit hydrograph was computed using the computed 1948 and 1955 flood discharges for the local area.

Subsequent to the unit hydrograph development, routing parameters were determined using results from the dynamic routing model of the Elk River reach from Fayetteville to Prospect. The following equation was used for routing flows from Fayetteville to Prospect for unit hydrograph validation (Routing period = 6 hours) [13]:

$$O(T) = 1.3463 \times O(T-1) - 0.3368 \times O(T-2) - 0.5610 \times O(T-3) + 1.0240 \times O(T-4) - 0.6025 \times O(T-5) + 1.042 \times O(T-6) - 0.0232 \times I(T) + 0.1193 \times I(T-1) + 0.2811 \times I(T-2) - 0.5681 \times I(T-3) + 0.4125 \times I(T-4) - 0.1399 \times I(T-5) - 0.3357 \times I(T-6)$$

Where O(T) is the outflow for a given time T, and I(T) is the inflow for a given time T. Single unit hydrographs were computed for each flood, and a composite six-hour unit hydrograph was adopted based on both floods. The Sub-basin 61 unit hydrograph is shown in Figure 7 and Table 7.

Table 7: Six-hour Unit Hydrograph for Sub-basin 61 (Elk River Local, Fayetteville to Prospect).

Time hrs	Flow cfs
0	0
3	418
6	835
9	1,462
12	2,192
15	3,132
18	4,176
21	5,429
24	6,786
27	8,039
30	8,874
33	8,665
36	8,248
39	6,995
42	6,055
45	5,116
48	4,176
51	3,550
54	3,028
57	2,506
60	2,297
63	1,984
66	1,775
69	1,670
72	1,462
75	1,357
78	1,148
81	1,044
84	940
87	731
90	626
93	418
96	209
99	104
102	0
total flow, cfs	105,447
UH duration, hr	6
Drainage area, mi^2	490.2
rainfall depth, in	1.000

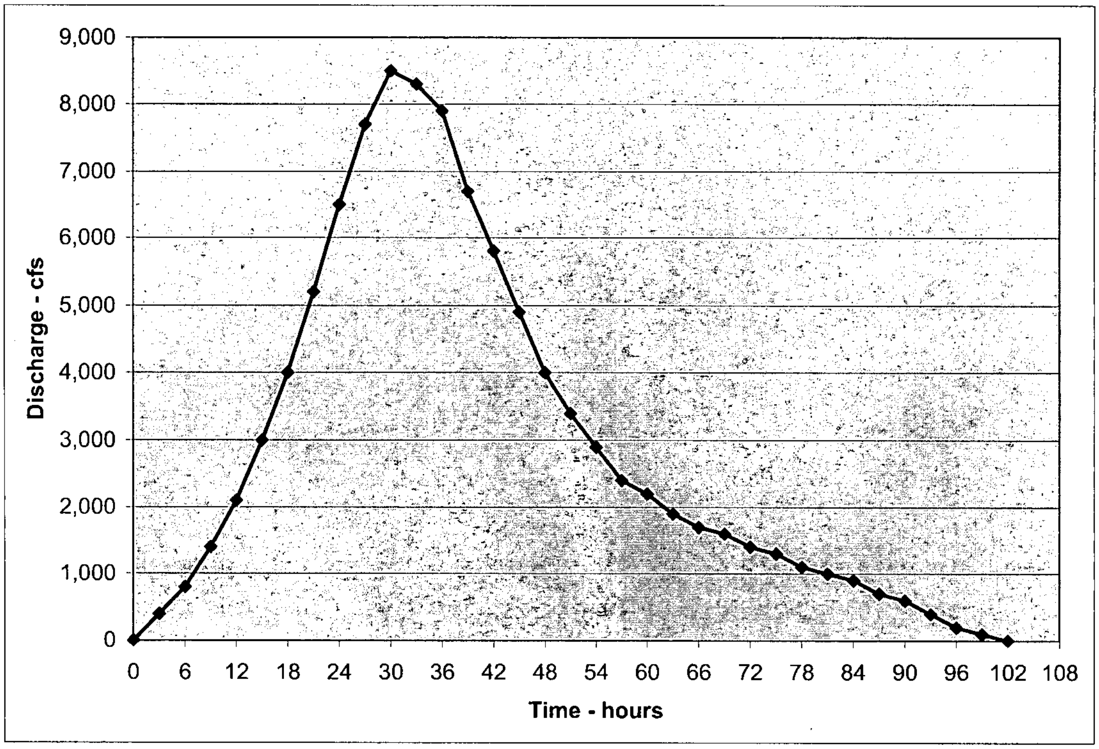

Figure 7: Six-hour Unit Hydrograph for Sub-basin 61 (Elk River Local, Fayetteville to Prospect).

The unit hydrograph for Sub-basin 61 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4, and comparing the basin outlet hydrograph with the computed local flow on Elk River Local, Fayetteville to Prospect.

6.2.6 Sub-basin 62 Unit Hydrograph

A unit hydrograph for Richland Creek at Mouth was developed by TVA from stream flow and rainfall data from the two following floods [14]:

- February 13, 1948
- March 22, 1955

Floods were estimated at the mouth of Richland Creek by routing the gaged flows upstream of Pulaski, Tenn. (mile 30.1) together with estimated local inflows for the reach below Pulaski to the mouth of Richland Creek.

Single unit hydrographs were computed for both floods. The two floods were used by TVA to develop a composite six-hour unit hydrograph. The Sub-basin 62 unit hydrograph is shown in Figure 8 and Table 8.

Table 8: Six-hour Unit Hydrograph for Sub-basin 62 (Richland Creek at Mouth).

Time hrs	Flow cfs
0	0
3	55
6	110
9	165
12	220
15	2,315
18	4,409
21	6,684
24	8,959
27	10,244
30	11,529
33	10,724
36	9,919
39	8,124
42	6,329
45	4,539
48	2,750
51	2,555
54	2,360
57	2,165
60	1,970
63	1,770
66	1,570
69	1,375
72	1,180
75	985
78	790
81	590
84	390
87	195
90	0
total flow, cfs	104,970
UH duration, hr	6
Drainage area, mi^2	488
rainfall depth, in	1.000

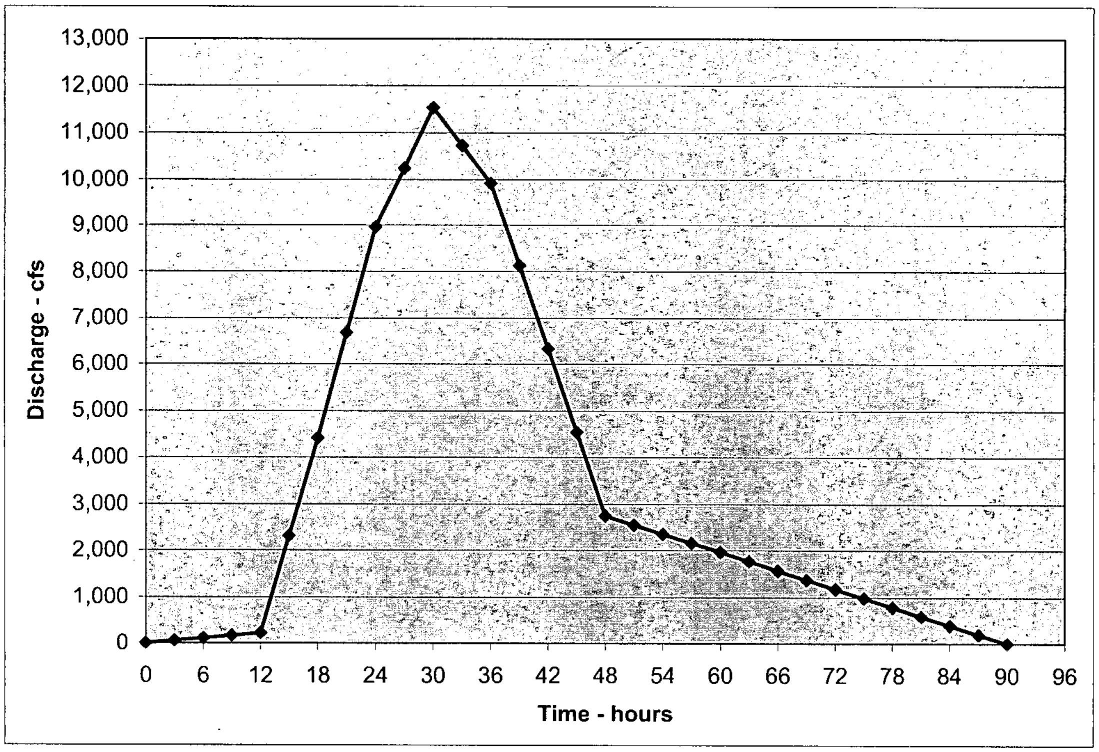

Figure 8: Six-hour Unit Hydrograph for Sub-basin 62 (Richland Creek at Mouth).

The unit hydrograph for Sub-basin 62 is validated in this calculation by utilizing it in simulating the runoff from observed rainfall for two recent storms, as described in Section 4, and comparing the basin outlet hydrograph with estimated stream flow on Richland Creek at Mouth.

6.3 Observed Stream Flow Data

Bihourly observed stream flow data were obtained from TVA or the USGS for the following locations in the Wheeler Watershed:

- Flint River near Chase for January 1997 to February 2008 [17].
- Limestone Creek near Athens for January 1997 to February 2008 [25]
- Elk River above Fayetteville for January 1997 to February 2008 [18].
- Elk River at Prospect for January 1997 to February 2008 [19].
- Richland Creek near Pulaski for January 1997 to February 2008 [24]

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

Data was collected at the USGS gage 03575000 on the Flint River near Chase, Ala. from 1936 until 1994 [20]. Data from this gage were used to develop the unit hydrograph for Sub-basin 53 (Section 6.2.2). TVA provided bihourly discharge measurements from this gage in spreadsheet format for 1997 through 2008; these data are provided as Attachment 1-02 to this calculation. The drainage area above this gage is 343.1 mi^2 [20].

Data has been collected at the USGS gage 03576250 on Limestone Creek near Athens, Ala. since 1939 [21]. Data from this gage were used to develop the unit hydrograph for Sub-basin 57 (Section 6.2.3). The USGS provided bihourly discharge measurements from this gage in an electronic text format for 1997 through 2008; these data are provided as Attachment 1-03 to this calculation. The drainage area above this gage is 121.3 mi^2 [21].

Data has been collected at the USGS gage 03582000 on the Elk River above Fayetteville, Tenn. from 1934 until 1981 [22]. Data from this gage were used to develop the unit hydrograph for Sub-basin 60 (Section 6.2.4). TVA provided bihourly discharge measurements from this gage in spreadsheet format for 1997 through 2008; these data are provided as Attachment 1-04 to this calculation. The drainage area above this gage is 826.6 mi^2 [22].

Data has been collected at the USGS gage 03584600 on the Elk River at Prospect, Tenn. since 1904 [23]. Data from this gage were used to develop the unit hydrograph for Sub-basin 61 (Section 6.2.5). TVA provided bihourly discharge measurements from this gage in spreadsheet format for 1997 through 2008; these data are provided as Attachment 1-05 to this calculation. The drainage area above this gage is 1,804.8 mi^2 [23].

The USGS provided bihourly discharge measurements at the USGS gage 03584020 on Richland Creek near Pulaski in spreadsheet format for 1997 through 2008; these data are provided as Attachment 1-06 to this calculation [24]. Data from this gage were used to develop the unit hydrograph for Sub-basin 62 (Section 6. 2.6). The drainage area above this gage is 366 mi^2; there are an additional 122 mi^2 of drainage area below this gage which is included in the unit hydrograph development [24].

6.4 Observed Dam Outflows and Headwater Elevations

Hourly records of outflow from Tims Ford Dam (including spills and turbine discharges) and hourly headwater elevations were obtained in spreadsheet format and are contained in the tabs labeled "Total Q" and "HW" in the spreadsheet "Attachment 1-07-timsford.xls" which is provided with this calculation as Attachment 1-07.

6.5 Stage-Volume Relationship

The Stage-volume relationship for the Tims Ford reservoir, which is used for reverse reservoir routing, was obtained from Calculation CDQ000020080051 [26]. Table 9 summarizes the data (elevation, volume) used to prepare the stage-volume relationship for Tims Ford reservoir, and Figure 9 illustrates the relationship.

Table 9: Stage – Volume Data for Tims Ford Reservoir [26]

Elevation (feet)	Volume (ac-ft)
860.00	290,000.00
861.00	296,800.00
862.00	303,800.00
863.00	310,900.00
864.00	318,100.00
865.00	325,400.00
866.00	332,900.00
867.00	340,500.00
868.00	348,200.00
869.00	356,000.00
870.00	364,000.00
871.00	372,000.00
872.00	380,200.00
873.00	388,500.00
874.00	396,800.00
875.00	405,300.00
876.00	414,000.00
877.00	422,700.00
878.00	431,700.00
879.00	440,800.00
880.00	450,000.00
881.00	459,400.00
882.00	469,000.00
883.00	478,700.00
884.00	488,600.00
885.00	498,700.00
886.00	509,000.00
887.00	519,400.00
888.00	530,000.00
889.00	540,800.00
890.00	551,700.00
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892.00	573,900.00
893.00	585,200.00
894.00	596,500.00
895.00	608,000.00

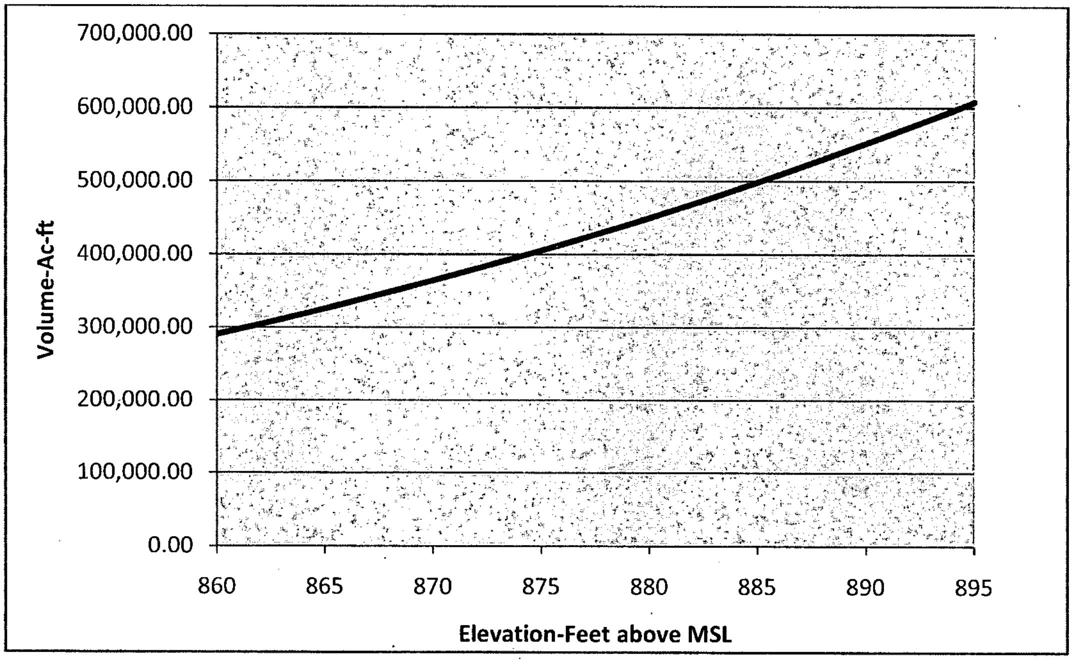

Figure 9: Tims Ford Stage – Volume Relationship [26].

6.6 Observed Rainfall

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

NWS NEXRAD Stage III hourly precipitation data were obtained from the Lower Mississippi River Forecast Center (LMRFC) from January 1997 to April 2008 for unit hydrograph validation. A Microsoft.Net utility was developed to generate radar-based Mean Areal Precipitation (MAPX) time series for each of the sub-basins [27].

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 sub-basin, grouping output into a matrix of MAPX elements arrayed by sub-basin and time (Greenwich Mean Time, GMT). Each column of this matrix is equivalent to an annual hyetograph for each sub-basin in the TVA model.

The results are stored in an Excel spreadsheet for each year of record. The methodology used to process the precipitation data, including resulting sub-basin-averaged hourly values for the 1997 to 2008 period of record, is described elsewhere [27].

Observed average basin rainfall for the February 2004, March 2002 and 2004, May 2003, December 2004 and January 2006 events were obtained from NEXRAD files [26]. The hourly precipitation series developed from NWS-gridded data for use in the calculation are provided in the following spreadsheets:

- Attachment 1-08-2002_Wheeler_Watershed_Hourly_Precip_Data.xls
- Attachment 1-09-2003_Wheeler_Watershed_Hourly_Precip_Data.xls
- Attachment 1-10-2004_Wheeler_Watershed_Hourly_Precip_Data.xls
- Attachment 1-11-2006_Wheeler_Watershed_Hourly_Precip_Data.xls

The hourly precipitation data obtained from the NEXRAD files is indexed in Greenwich Mean Time (GMT). After identifying storms for verification, precipitation data was processed with FLDHYDRO (see Section 7.4). The unit conversion (millimeters to inches) and the conversion of the time base of the precipitation time series to Central Daylight Savings Time (CDT) for the May 2003 event and to Central Standard Time (CST) for the remaining events are carried out in the storm hydrograph convolution files:

- Attachment 1-13-2009-10-19_Convol-53v5.xls
- Attachment 1-14-2009-10-19_Convol-57v5.xls
- Attachment 1-15-2009-10-19_Convol-59v5.xls
- Attachment 1-16-2009-10-19_Convol-60v5.xls
- Attachment 1-17-2009-10-19_Convol-61v5.xls
- Attachment 1-18-2009-10-19_Convol-62v5.xls

7 Computations and Analysis

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

7.1 Determination of Local Inflow Volumes

As noted in Section 5, the unit hydrographs must be validated by comparing the results of simulations with the two highest peaked floods of record with suitable precipitation for the period in which suitable precipitation data are available. Towards this end, peak discharges and associated date of occurrence were identified between 1997 and 2008 based on the bihourly discharge data provided by TVA and USGS (see Section 6.3) for the stream gages located at the outlets of Sub-basins 53, 57, 59, 60, 61, and 62 between 1997 and 2008. Only daily average data is readily available for Sub-basin 57 [21], therefore large storms were first identified with daily average flow data, then further defined with hourly data provided by the Alabama Water Science Center [25]. In addition to the availability of quality NEXRAD data, preference was given to discrete, simple storms (a single peak without complex, multiple peak character spread over many days). Finally, preference was given to storms which, when processed with FLDHYDRO, returned reasonable runoff estimates without the use of a check volume. From these criteria (large storms, available NEXRAD data, and check volume independence), the largest events were identified for each Sub-basin. Table 10 summarizes the storms used in validation for the sub-basins of the Wheeler Watershed.

Table 10: Selection Criteria for Storms Used in Validations for Each Sub-basin

Sub-basin	Date of Peak Event	Peak Discharge	Comment
53 - Flint River Near Chase	12/23/1990	61,000	NEXRAD precipitation data not available.
	2/6/2004	31,297	Selected for validation.
	5/7/2003	25,093	Not selected due to invalid hydrograph data, excess precipitation is in excess of weighted rainfall total.
	1/23/1999	16,022	NEXRAD precipitation data not available.
	3/6/2004	15,664	Selected for validation.
57 - Limestone Creek Near Athens	1/23/1999	16,966	NEXRAD precipitation data not available.
	2/6/2004	15,193	Selected for validation.
	5/6/2003	13,061	Not selected due to complex rainfall and complex stream flow.
	12/7/2004	11,723	Selected for validation.

Sub-basin	Date of Peak Event	Peak Discharge	Comment
	4/3/2000	8,102	Not selected due to complex rainfall, complex stream flow and low peak flow.
	12/9/2004	5,217	Not selected due to complex rainfall, complex stream flow, and low peak.
	1/7/1998	*	NEXRAD precipitation data not available.
	2/22/2003	*	Not selected due to complex stream flow.
	3/6/2004	*	Not selected due to complex stream flow.
	11/24/2004	*	Not selected due to complex stream flow.
	2/5/2004	37,724	Not selected due to unreliable reservoir elevation data on Tims Ford Reservoir used in reverse reservoir routing.
59 - Tims Ford Dam	5/5/2003	31,054	Selected for validation.
	12/5/2004	20,897	Selected for validation
	3/18/2002	**	Not selected due to invalid hydrograph data, excess precipitation is in excess of weighted rainfall total.
	2/6/2004	20,938	Selected for validation
60 - Elk River, Tims Ford Dam To Fayetteville	12/7/2004	17,291	Not selected due to complex rainfall and complex stream flow.
	3/18/2002	16,165	Selected for validation
	1/23/1999	15,092	NEXRAD precipitation data not available.
	12/10/2004	13,367	Not selected due to complex rainfall and complex stream flow.
	1/24/1999	55,038	NEXRAD precipitation data not available.
61 - Elk River Local, Fayetteville to Prospect	2/5/2004	20,297	Selected for validation
	3/15/2002	13,585	Not selected due to complex rainfall.
	1/24/2006	11,461	Selected for validation
	1/23/2002	40,463	NEXRAD precipitation data not available.
62 – Richland Creek @ Mouth	2/6/2004	32,650	Selected for validation
	1/24/2006	26,700	Selected for validation
	2/17/2001	20,100	NEXRAD precipitation data not available.
	12/7/2004	16,105	Not selected due to complex rainfall and complex stream flow.
	3/18/2002	13,938	Not selected due to complex rainfall.
	12/10/2004	11,625	Not selected due to complex rainfall and complex stream flow.
	12/10/2004	11,625	Not selected due to complex rainfall and complex stream flow.

* Peak data not available via internet, no additional research required due to lack of NEXRAD data or complex storm determined by daily average data.

7.2 Development of Flow Series for Unit Hydrograph Validation

An observed flow series is required for the validation of each unit hydrograph, as discussed in Section 5. Two sub-basins (53, 57) considered in this calculation are gaged headwater catchments, and therefore the observed stream flow series can be used directly. Otherwise, hydrograph separation techniques are required, which entails routing observed hydrographs downstream. Routing is carried out in accordance with TVA methodology, as summarized in Figure 10.

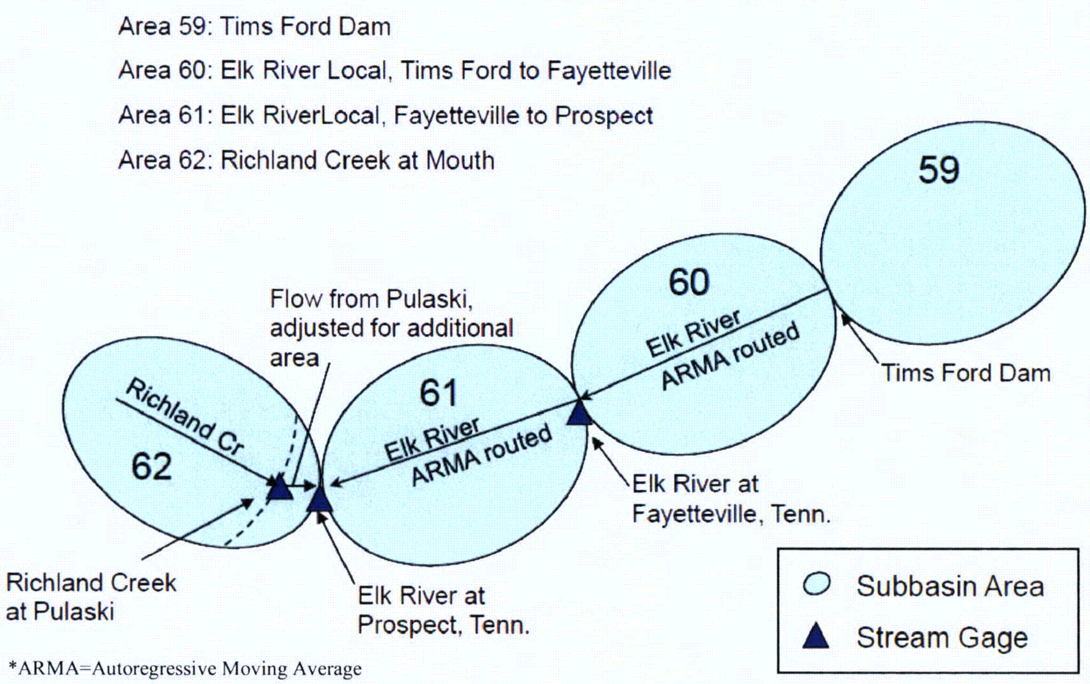

Figure 10: Flow Routing for the Directly Validated Sub-basins along the Elk River

The development of the flow series for the validation of the unit hydrograph for each of the sub-basins within the Wheeler Dam watershed is discussed in the following sections.

7.2.1 Sub-basin 53 Outflow Hydrograph Development

Sub-basin 53 is a headwater catchment, so the observed hydrograph for the Flint River near Chase can be used for validation of the unit hydrograph with no additional processing. Bihourly flow data for the validation events were provided by TVA. This data is presented in the spreadsheet "Attachment 1-19-2009-10-19-57-Base_Flow.xls" included as Attachment 1-19 to this calculation.

7.2.2 Sub-basin 57 Outflow Hydrograph Development

Sub-basin 57 is a headwater catchment, so the observed hydrograph for Limestone Creek near Athens can be used for validation of the unit hydrograph with no additional processing. Bihourly flow data for the validation events were provided by TVA. This data is presented in the spreadsheet "Attachment 1-20-2009-10-19-57-Base_Flow.xls" included as Attachment 1-20 to this calculation.

7.2.3 Sub-basin 59 Outflow Hydrograph Development

The reservoir inflow hydrograph for Sub-basin 59, Tims Ford Dam, must be computed. The reservoir inflow hydrograph for Sub-basin 59 is obtained from the observed headwater and outflows from Tims Ford Dam and changes in storage within Tims Ford Reservoir by reverse reservoir routing, which consists of solving the continuity equation for the reservoir, which can be stated as [28]:

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

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

This equation can be written using a finite-difference scheme as follows, where the term t-Δt refers to the preceding time step [28]:

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

Using the records of outflow and headwater for Tims Ford Dam and the stage-volume relationship for the reservoir (enumerated in Section 6.4), reverse reservoir routing was performed for the May 2003 and the December 2004 flood events. This calculation is presented in the spreadsheet "Attachment 1-21-2009-10-19-59-Tims Ford Reverse Routing.xls," provided as Attachment 1-21 to this calculation.

Fluctuations in the estimated inflow can occur when the water surface elevation of the reservoir is changing slowly, and surface elevations are measured at discrete height intervals (i.e., to the nearest hundredth foot). This is demonstrated in Figure 11 for the May 2003 flood.

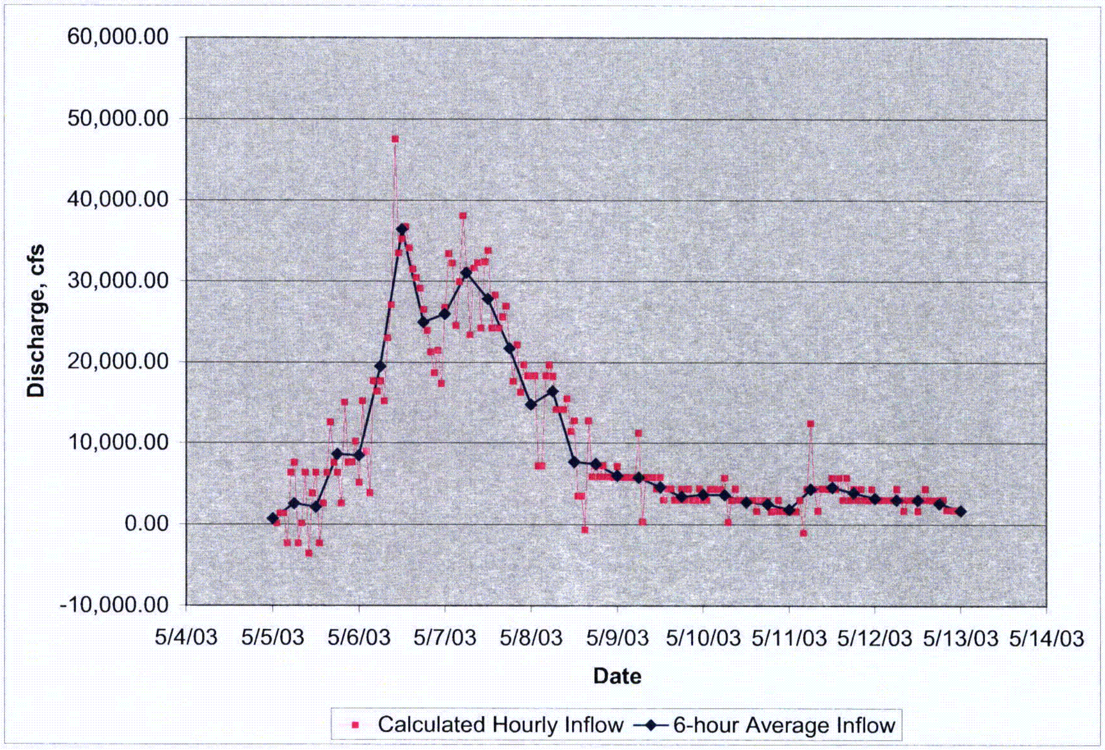

Figure 11: Calculated Tims Ford Reservoir Inflow Hydrograph for May 2003

In Figure 11, the pink line with square markers illustrates the reservoir inflow series calculated by reverse reservoir routing (RRR). The fluctuations in calculated inflows illustrated in Figure 11. These fluctuations are dampened and negative flow values must be removed through hydrograph smoothing. Hydrograph smoothing is performed by averaging the RRR hourly flow values over a period of 6 hours, as shown by the heavy dark line with diamond markers in Figure 11.

7.2.4 Sub-basin 60 Outflow Hydrograph Development

The observed flow on the Elk River between Tims Ford and Fayetteville includes local inflow from Sub-basin 60 and stream flow coming down from the Tims Ford Dam discharge (Sub-basin 59). To obtain the flow series for the validation of the local inflow unit hydrograph for Sub-basin 60, the observed flow at Tims Ford Dam (Sub-basin 59) is routed downstream and subtracted from the observed flow at Fayetteville [18]. TVA developed an ARMA routing model for routing flows from Tims Ford Dam to Fayetteville [12]. (See Section 6.2.5.):

$$O(T) = 1.00 \times O(T-1) - 0.25 \times O(T-2) + 0.0625 \times I(T) + 0.125 \times I(T-1) + 0.0625 \times I(T-2)$$

The remaining flow is the contribution from Sub-basin 60. Figures 12 and 13 illustrate the hydrograph separation for Sub-basin 60 for the 2002 and 2004 floods. Calculations in support of these figures can be found in the spreadsheet "Attachment 1-22-2009-10-19-60-Base_Flow.xls: provided as Attachment 1-22 to this calculation.

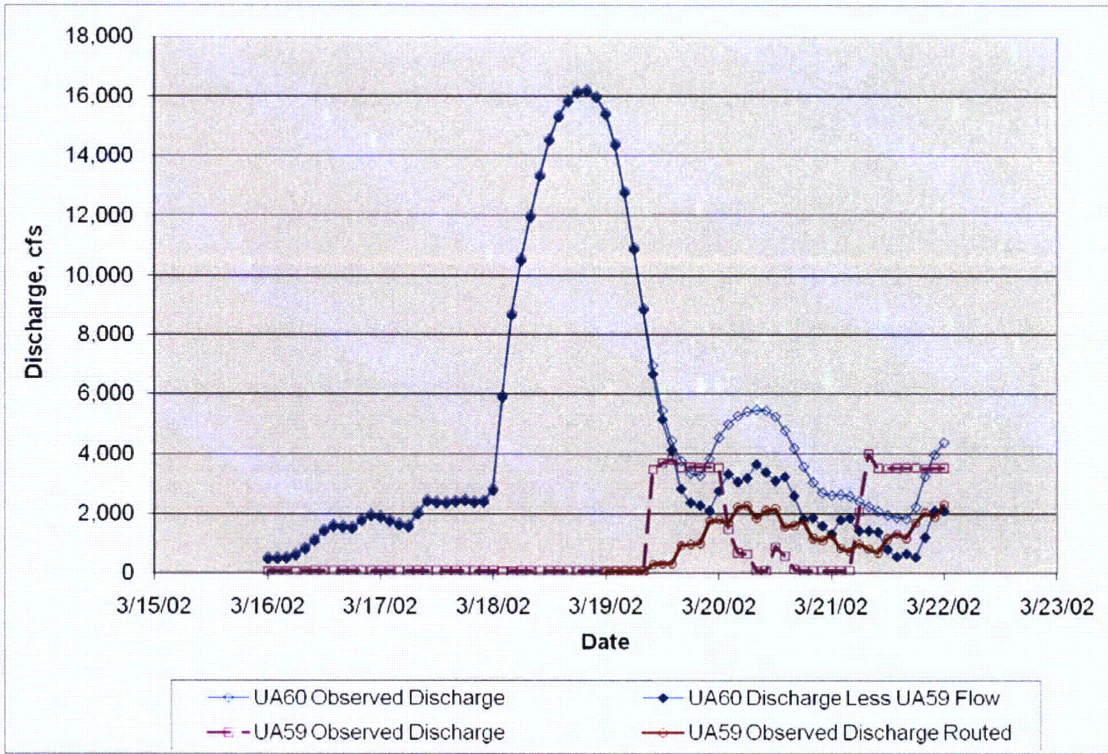

Figure 12: Observed Flow Series for Sub-basin 60, Elk River above Fayetteville, March 2002

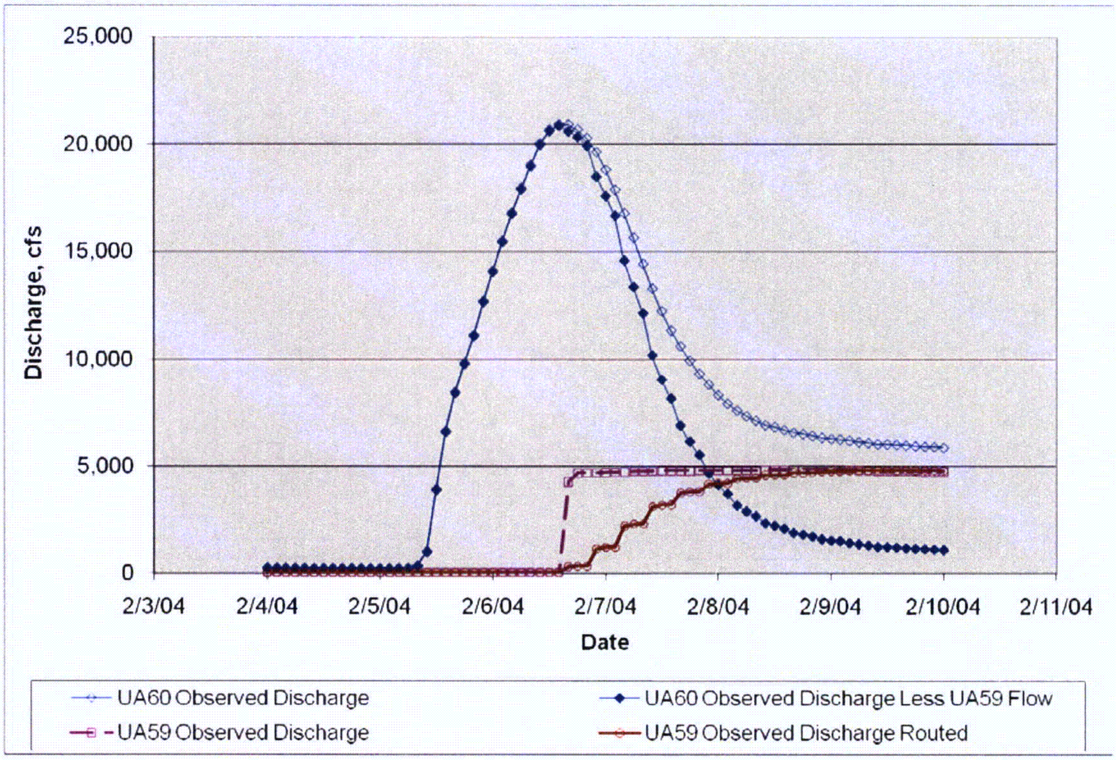

Figure 13: Observed Flow Series, Sub-basin 60, Elk River above Fayetteville, February, 2004

7.2.5 Sub-basins 61 and 62 Outflow Hydrograph Development

The observed flow on the Elk River between Fayetteville and Prospect includes local inflow from Sub-basins 61 and 62 and stream flow coming down from Sub-basins 59 and 60. In the development of local inflows for Sub-basin 62, applicable stream flow data was available for a stream gage located at Pulaski, approximately 16 miles northwest of the Richland Creek mouth. The stream gage at Pulaski has a drainage area of 366 square miles; the entire Richland Creek Basin has a drainage area of 488 square miles. The stream flow data from the Pulaski gage was used as a shaping tool in creating the storm hydrograph for Sub-basin 62. An excess precipitation was determined from the Pulaski gage information. The excess precipitation value was adjusted, based on the observed weighted rainfall ratio between the 366 square mile area captured by the Pulaski gage and the 488 square mile area that is inclusive of the entire Richland Creek Drainage Area. The volume of runoff was proportionally increased based on the increase in contributing area and the observed weighted rainfall. The flow volume observed at the Pulaski gage ($V_{Pulaski}$) is multiplied by the ratio of drainage areas ($A_{62,total}/A_{Pulaski}$), corrected for the variation in precipitation over the ungaged drainage area ($A_{62,total} - A_{Pulaski}$) using the equation below:

$$V_{62,total} = V_{Pulaski} \times \frac{A_{62,total}}{A_{Pulaski}} \times \frac{(A_{62,total} - A_{Pulaski}) \times \frac{P_{62}}{P} + A_{Pulaski}}{A_{62,total}}$$

In the equation above, P_{62} is the weighted NEXRAD precipitation for the entire Sub-basin, and P is the weighted NEXRAD precipitation in the ungaged drainage area within Sub-basin 62 (below Pulaski).

Observations of the historical relationship between the storm hydrograph for Richland Creek at Pulaski and the routed storm hydrograph for Richland Creek at mouth were made and incorporated into the development of the storm hydrographs for Unit Area 62. These observations included peak magnitude, peak time, lag time, and shape. These trends were then applied to more recent storms to account for potential changes in the basin characteristics. These techniques include lagging the gage information to the mouth 16 hours to account for travel time from Pulaski to the mouth, and maintaining the width ratio at both 50^{th} & 75^{th} percentile of the peak discharge. The peak discharge was slightly increased to account for local contributing rainfall. Local contribution for the basin area between the Pulaski Gauge and the Richland Creek mouth was primarily accounted for in the leading leg of the storm hydrographs.

To obtain the flow series for the validation of the local inflow unit hydrograph for Sub-basin 61, the observed flow at Fayetteville (which includes flows from Sub-basins 59 and Sub-basin 60) is routed downstream and subtracted from the observed flow at Prospect [19]. TVA developed an ARMA routing model for routing flows from Fayetteville to Prospect [13]. (See Section 6.2.5.):

$$O(T) = 1.3463 \times O(T-1) - 0.3368 \times O(T-2) - 0.5610 \times O(T-3) + 1.0240 \times O(T-4) - 0.6025 \times O(T-5) + 1.042 \times O(T-6) - 0.0232 \times I(T) + 0.1193 \times I(T-1) + 0.2811 \times I(T-2) - 0.5681 \times I(T-3) + 0.4125 \times I(T-4) - 0.1399 \times I(T-5) - 0.3357 \times I(T-6)$$

The volume determined above represents the portion of the total gaged flow at the Prospect gage attributable to Sub-basin 62, after the subtraction of the routed flow from Fayetteville. The remaining volume represents the portion of total flow attributable to Sub-basin 61. Figures 14 and 15 illustrate the development of flow series for Sub-basin 61 while Figures 16 and 17 represent the development of flow series for Sub-basin 62. Data to support these figures can be found in the following spreadsheets:

- "Attachment 1-23-2009-10-19-61-Base_Flow.xls"
- "Attachment 1-24-2009-10-19-62-Base_Flow.xls"

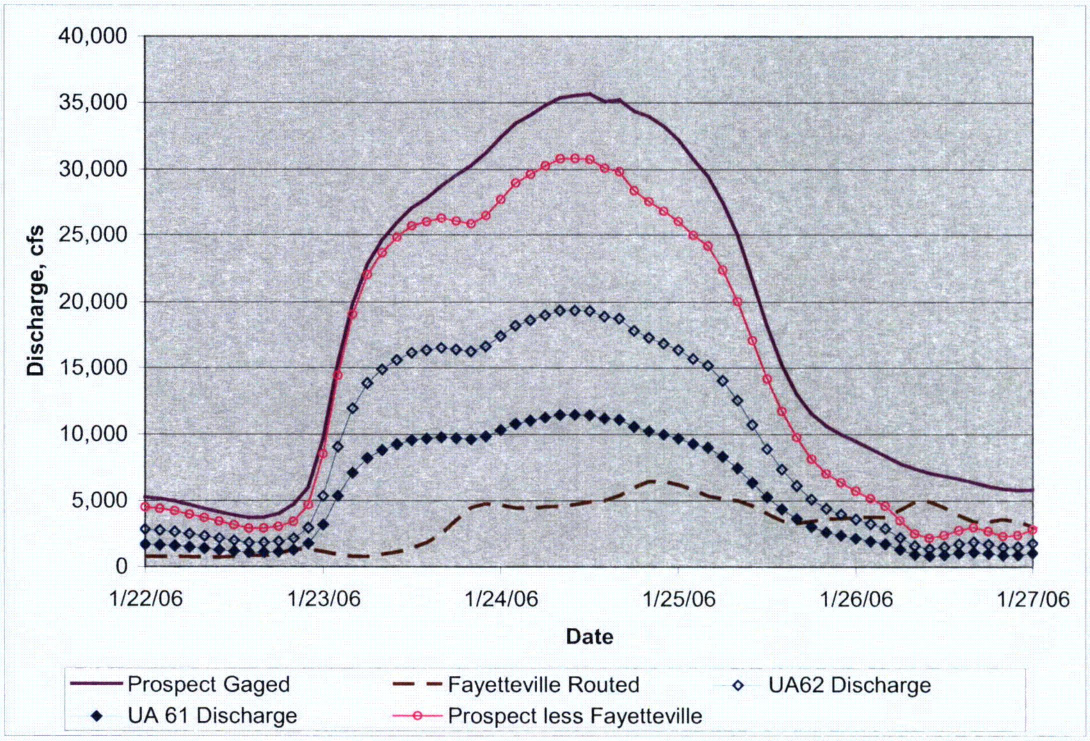

Figure 14: Observed Flow Series, Sub-basin 61, Elk River at Prospect, January, 2006

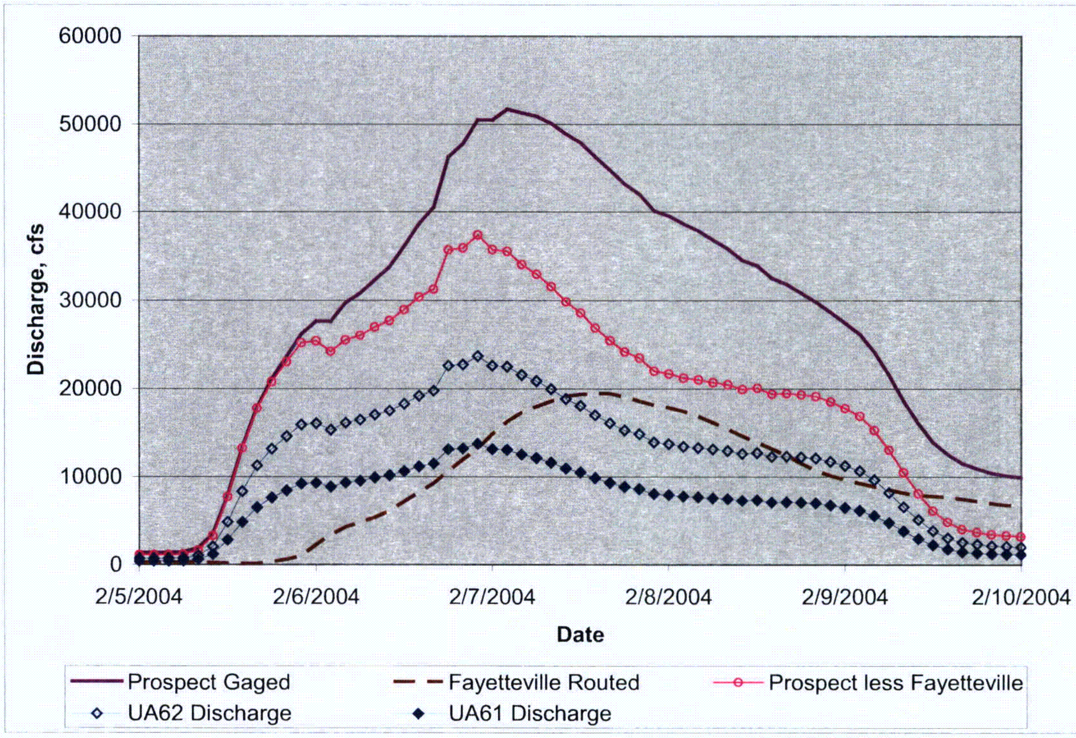

Figure 15: Observed Flow Series, Sub-basin 61, Elk River at Prospect, February, 2004

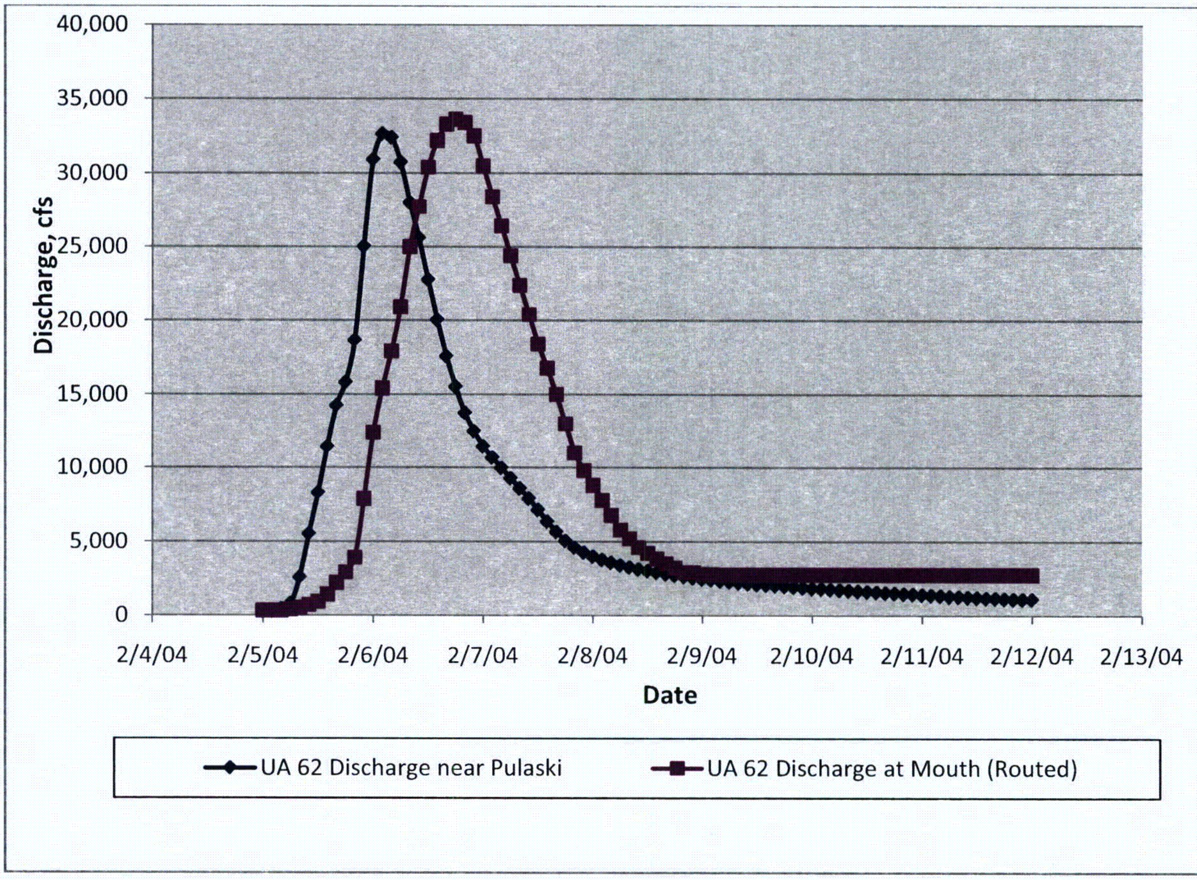

Figure 16: Observed Flow Series, Sub-basin 62, Richland Creek at Mouth, February, 2004

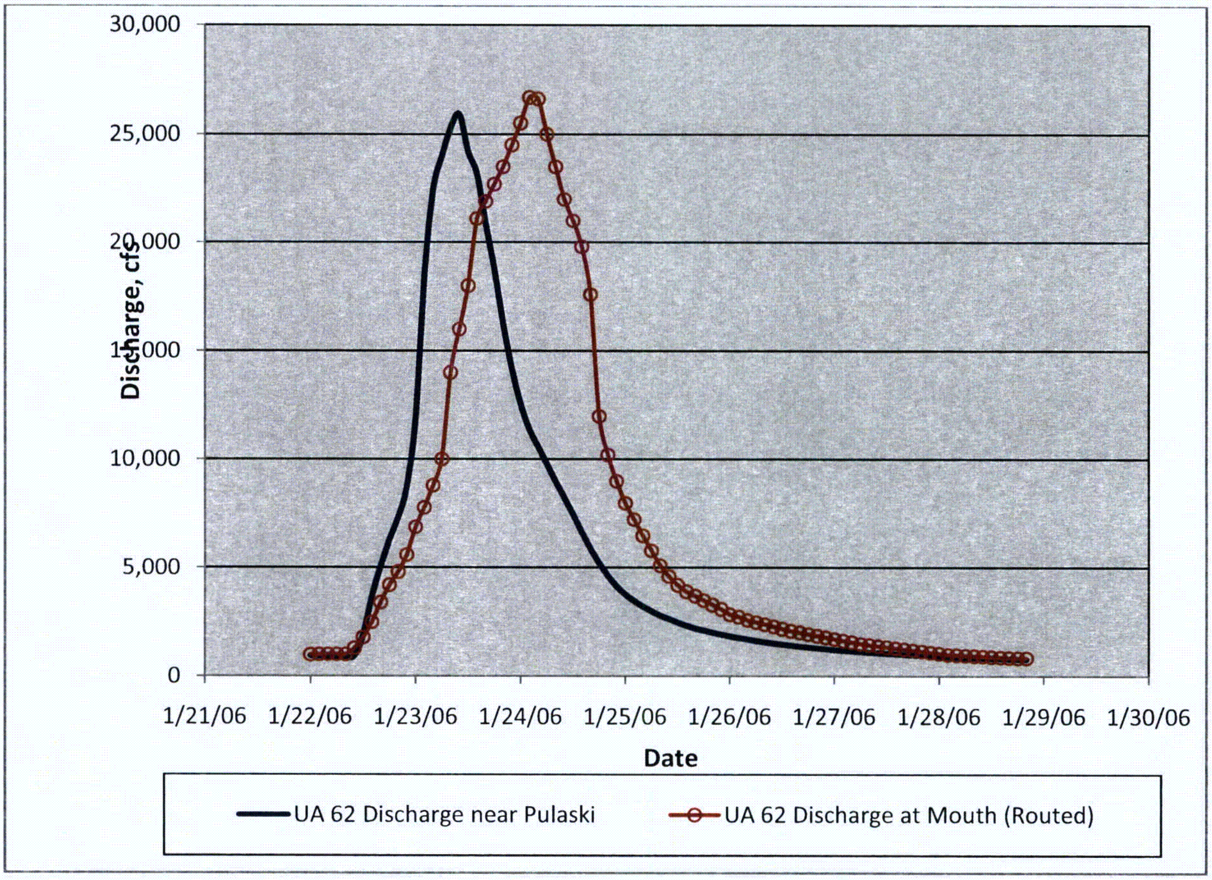

Figure 17: Observed Flow Series, Sub-basin 62, Richland Creek at Mouth, January, 2006

7.3 Base Flow Separation and Calculation of Direct Runoff

Base flow separation is required to determine an estimate of direct runoff associated with the rainfall event. The direct runoff volume is used as the effective rainfall volume in FLDHYDRO, as described in Section 7.4. For this calculation, the base flow is drawn from the starting point of runoff to a point on the receding limb of the hydrograph after the time of peak discharge, using a simple, constant slope approach. The constant slope is determined from the difference in discharge at the beginning and end of the storm, divided by the duration of the storm in hours [15].

Table 11 presents a summary of the change in discharge, constant slope, and duration of each storm for the Sub-basins considered in this calculation. The separation of base flow from direct runoff for each of the simulations is presented graphically in Figures 18 to 29.

For the Sub-basins considered in this calculation, it is possible to determine direct runoff volume by the numerical integration of the hydrographs. Direct runoff volume, V, is calculated from period average flow rate, Q, and the length of the period, Δt, as:

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

For complex storms, it was necessary to separate direct runoff into parts corresponding to separated periods of rainfall to provide a better estimate of excess rainfall than would be obtained for a single calculation of cumulative runoff (see Section 7.4). The December 2004 storm was only storm that was separated.

Direct runoff volume calculations are summarized in Table 11 and are presented in detail in the following spreadsheets, provided as the indicated attachments:

"Attachment 1-19-2009-10-19-53-Base_Flow.xls"
"Attachment 1-20-2009-10-19-57-Base_Flow.xls"
"Attachment 1-21-2009-10-19-59-Tims Ford Reverse Routing.xls"
"Attachment 1-22-2009-10-19-60-Base_Flow.xls"
"Attachment 1-23-2009-10-19-61-Base_Flow.xls"
"Attachment 1-23-2009-10-19-62-Base_Flow.xls"

Table 11: **Summary of Direct Runoff Calculation for Each Flood**

Sub-basin		Drainage Area	Start	Discharge at Start	End	Discharge at End	Peak	Discharge at Peak
		mi²		cfs		cfs		cfs
53	Flint River Near Chase	343.06	2/5/2004 6:00	267	2/8/2004 6:00	1,734	2/6/2004 14:00	31,297
		343.06	3/5/2004 16:00	1,123	3/7/2004 20:00	1,765	3/6/2004 14:00	15,664
57	Limestone Creek Near Athens	121.31	2/5/2004 6:00	154	2/8/2004 8:00	618	2/6/2004 8:00	15,253
		121.31	12/5/2004 20:00	256	12/18/2004 18:00	954	38328.08333	11,723
59	Tim's Ford Dam	533.22	5/5/2003 0:00	700	5/11/2003 0:00	1,848	5/7/2003 6:00	31,054
		533.22	12/5/2004 20:00	1,800	12/10/2004 8:00	1,900	12/7/2004 8:00	19,061
60	Elk River, Tim's Ford Dam To Fayetteville	293.36	3/17/2002 22:00	2,370	3/19/2002 18:00	2,360	3/18/2002 20:00	16,167
		293.36	2/5/2004 6:00	195	2/8/2004 14:00	2,066	2/6/2004 14:00	20,938
61	Elk River Local, Fayetteville to Prospect	490.23	2/5/2004 6:00	538	2/9/2004 20:00	1,584	2/6/2004 22:00	17,268
		490.23	1/22/06 16:00	1,087	1/26/06 6:00	1,305	1/24/06 10:00	11,557
62	Richland Creek @ Mouth(Routed)	487.97	2/5/2004 4:00	315	2/9/2004 12:00	2,720	2/6/2004 18:00	33,630
		487.97	1/22/2006 8:00	1,010	1/26/2006 20:00	1,875	1/24/2006 2:00	26,677

Table 11 Continued: Summary of Direct Runoff Calculation for Each Flood

Sub-basin		Duration	Discharge Change	Slope	Rising Duration	Recession Duration	Surface Runoff	Time Interval	Excess Precip
		hr	cfs	cfs/hr	hr	hr	cfs	hr	in
53	Flint River Near Chase	72	1,467	20.38	32	40	313,434	2	2.83
		52	642	12.35	22	30	122,783	2	1.11
57	Limestone Creek Near Athens	74	464	6.27	26	48	150,143	2	3.84
		70	698	9.98	30	40	158,671	2	4.05
59	Tim's Ford Dam	144	1,147	7.97	54	90	258,634	6	4.51
		108	100	0.92	36	72	109,052	6	1.90
60	Elk River, Tim's Ford Dam To Fayetteville	44	-10	-0.23	22	22	178,289	2	1.88
		80	1,871	23.39	32	48	379,483	2	4.01
61	Elk River Local, Fayetteville to Prospect	110	1,046	9.51	40	70	392,876	2	2.48
		86	218	2.54	42	44	264,246	2	1.67
62	Richland Creek @ Mouth(Routed)	104	2,405	23.12	38	66	570,530	2	3.62
		108	865	8.01	42	66	463,876	2	2.95

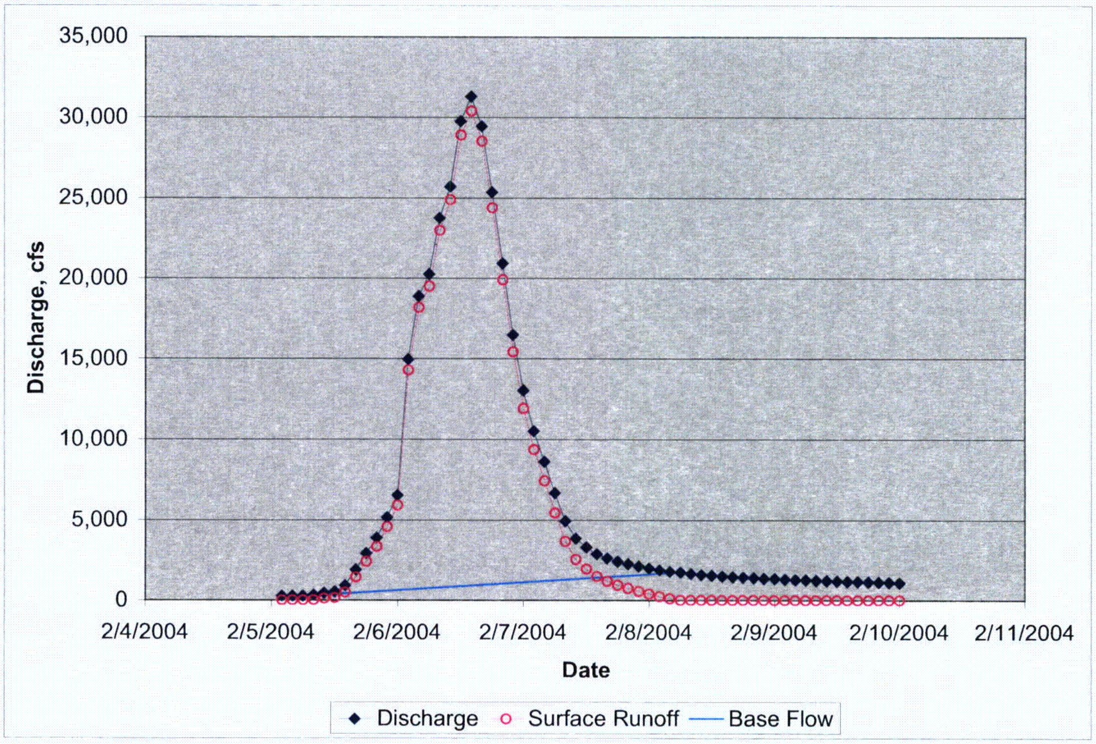

Figure 18: Base Flow Separation, Sub-basin 53, Flint River near Chase, February 2004

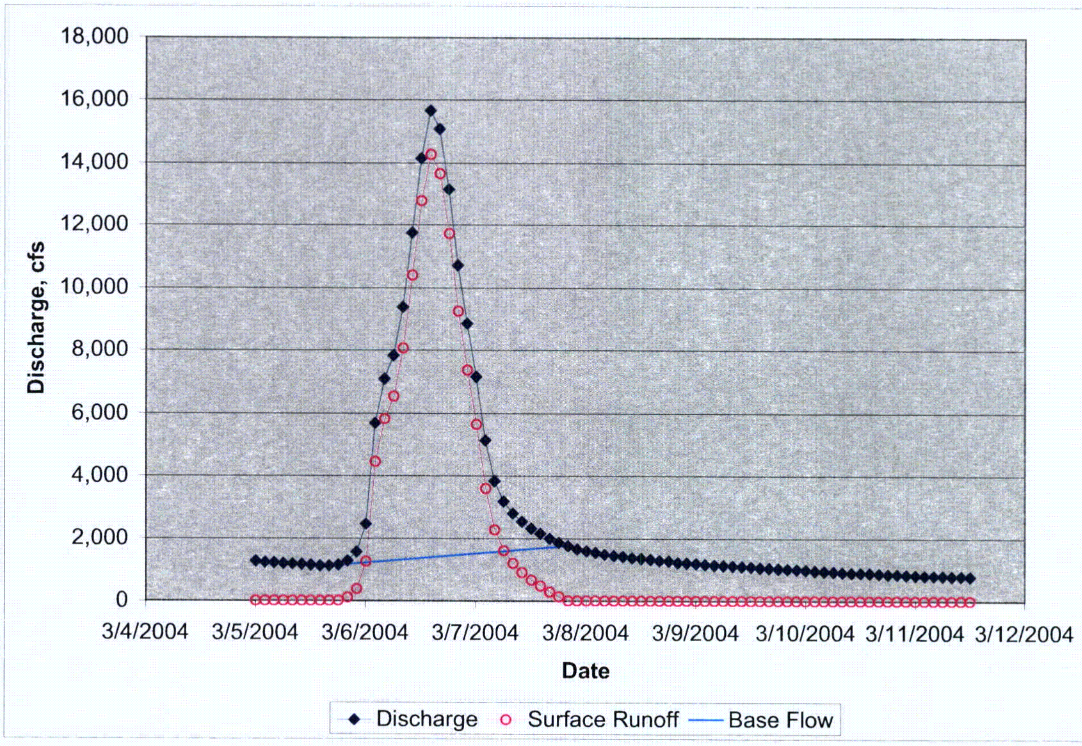

Figure 19: Base Flow Separation, Sub-basin 53, Flint River near Chase, March 2004

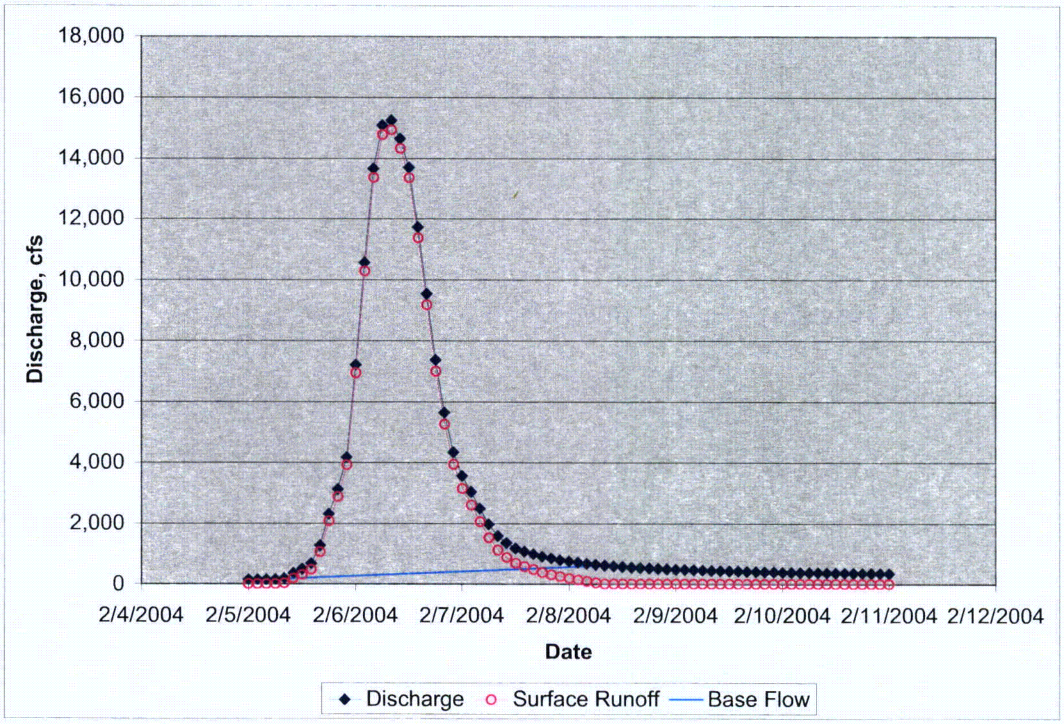

Figure 20: Base Flow Separation, Sub-basin 57, Limestone Creek near Athens, February 2004

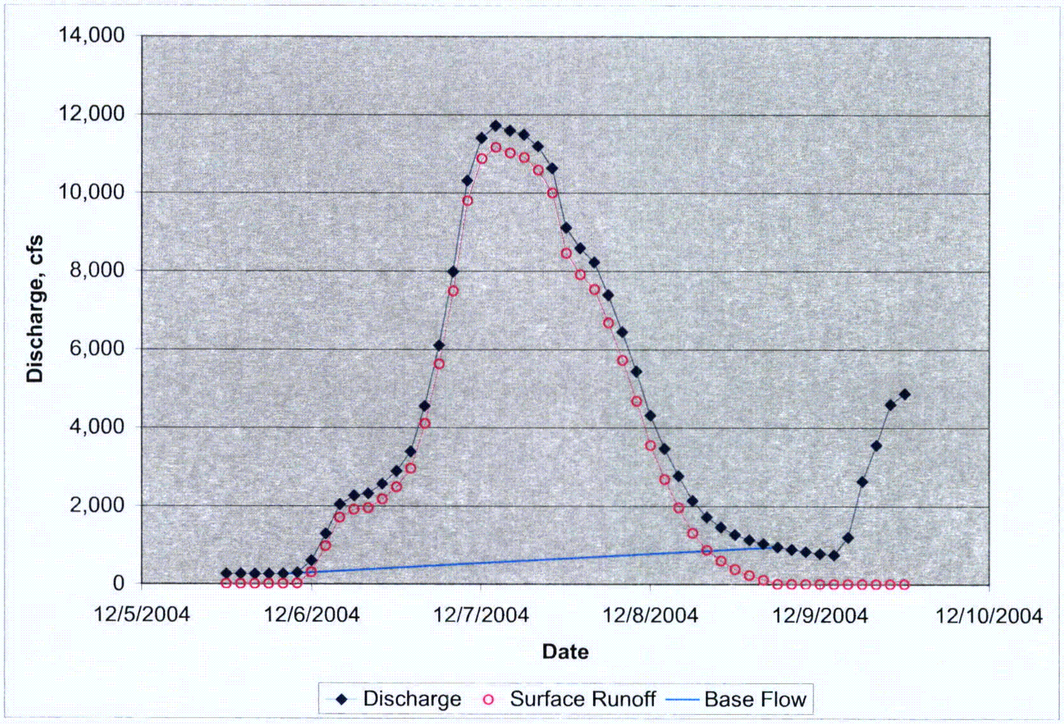

Figure 21: Base Flow Separation, Sub-basin 57, Limestone Creek near Athens, December 2004

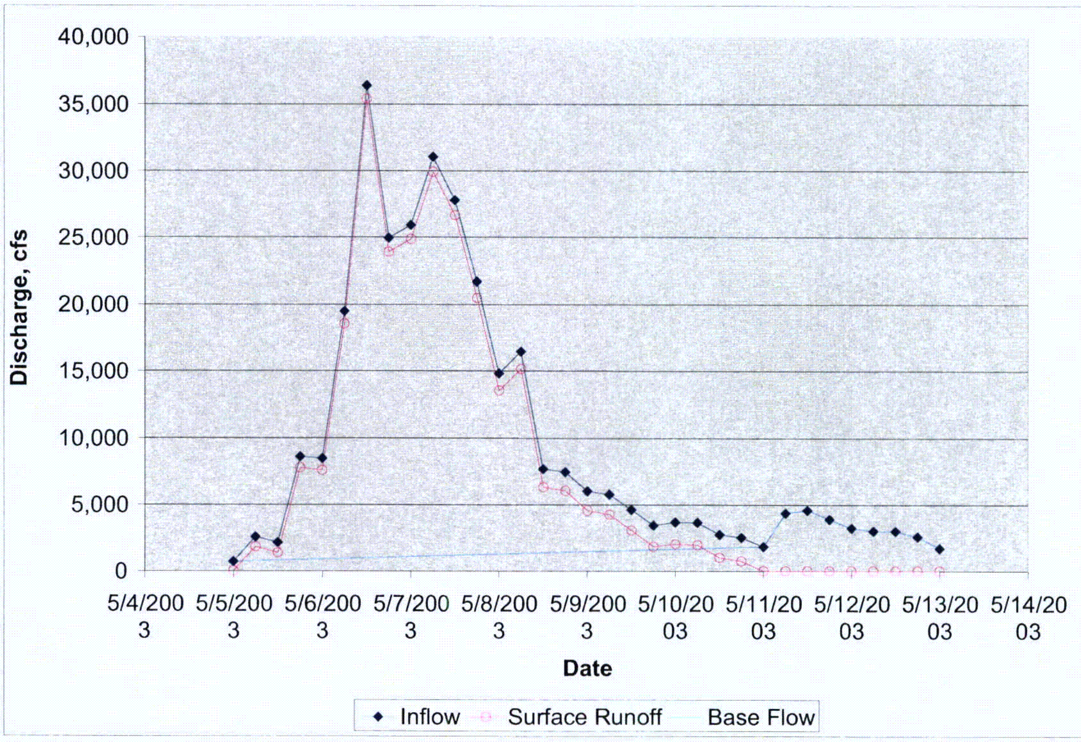

Figure 22: Base Flow Separation, Sub-basin 59, Tims Ford Dam, May 2003

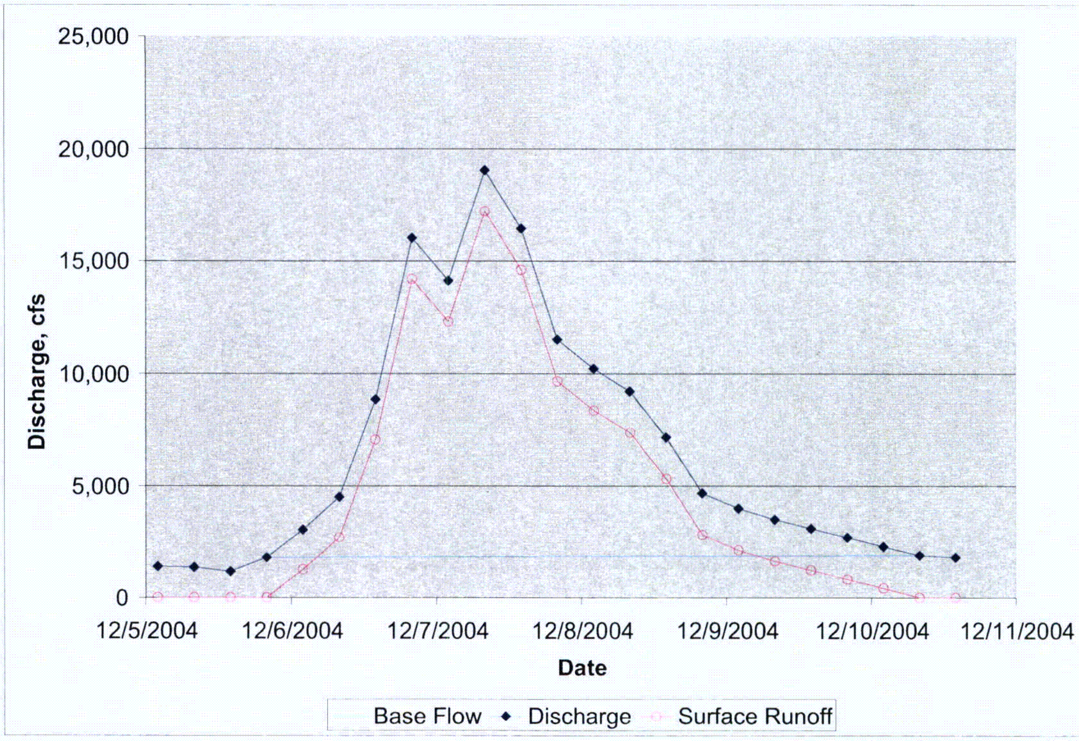

Figure 23: Base Flow Separation, Sub-basin 59, Tims Ford Dam, December 2004

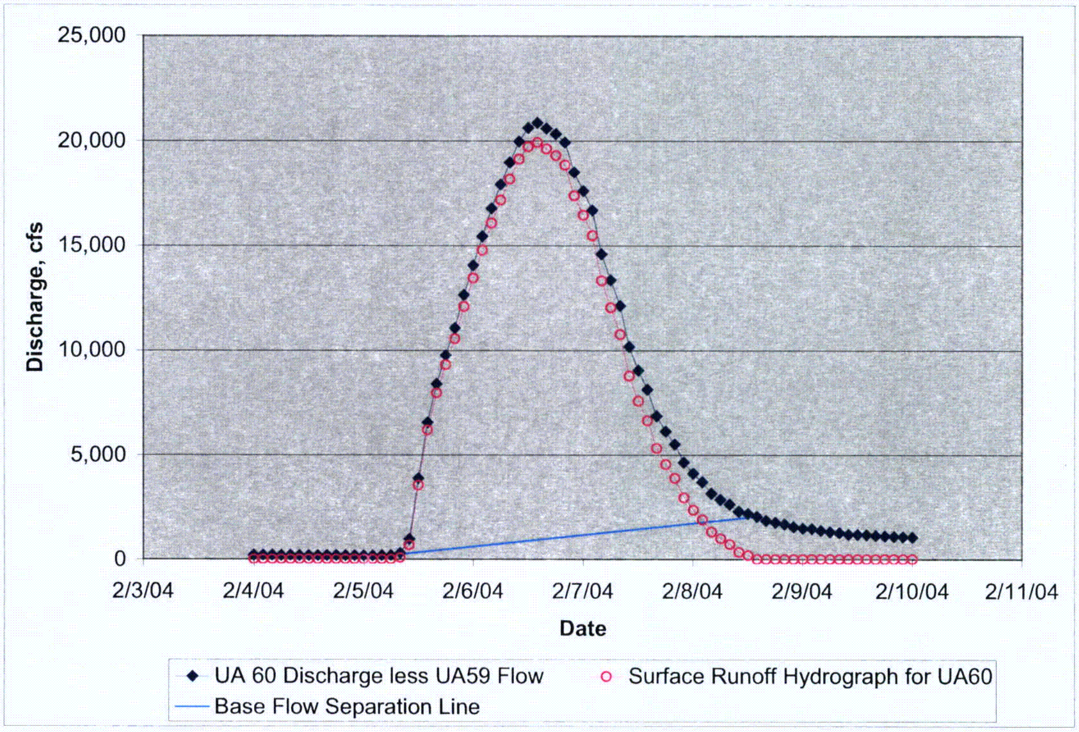

Figure 24: Base Flow Separation, Sub-basin 60, Elk River Local, Tims Ford to Fayetteville, March 2002

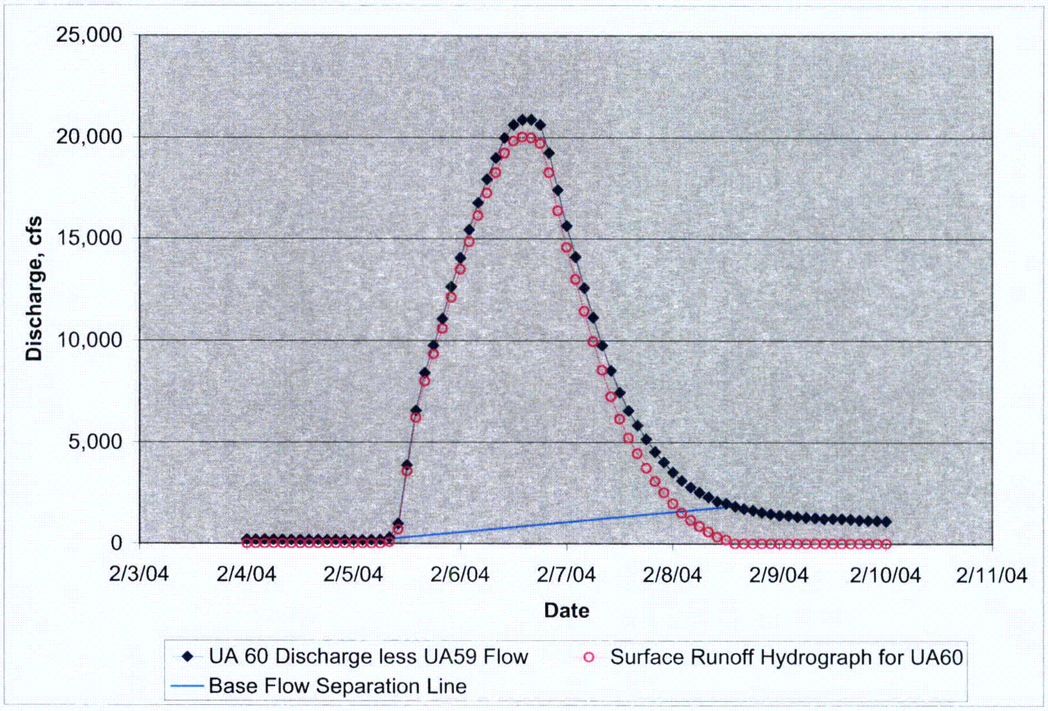

Figure 25: Base Flow Separation, Sub-basin 60, Elk River Local, Tims Ford to Fayetteville, February 2004

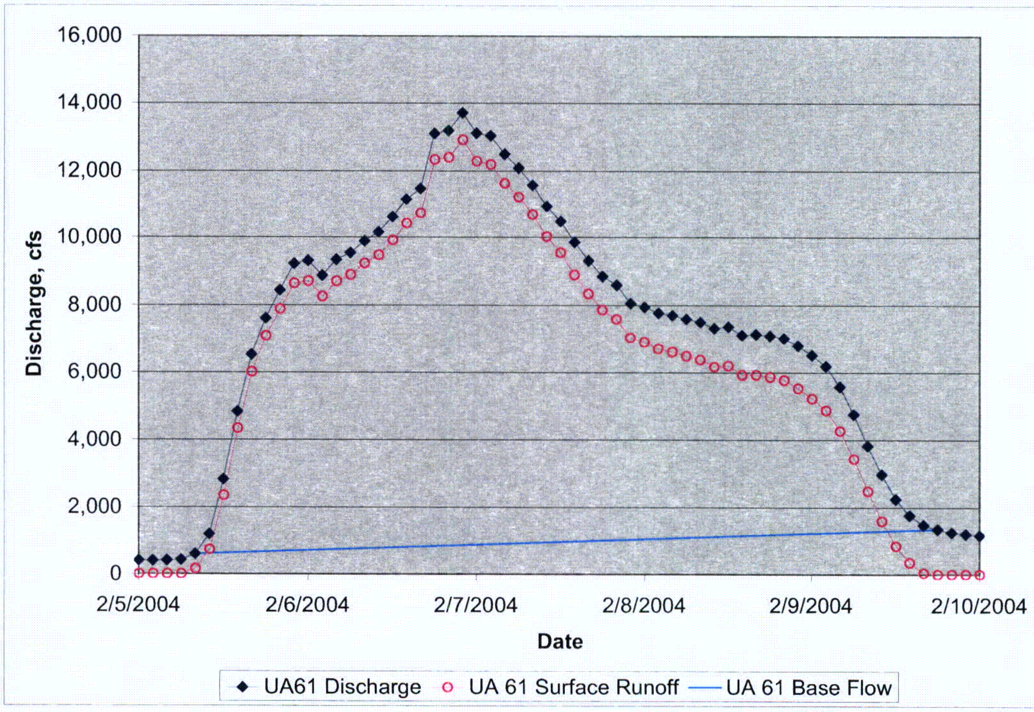

Figure 26: Base Flow Separation, Sub-basin 61, Elk River Local, Fayetteville to Prospect, February 2004

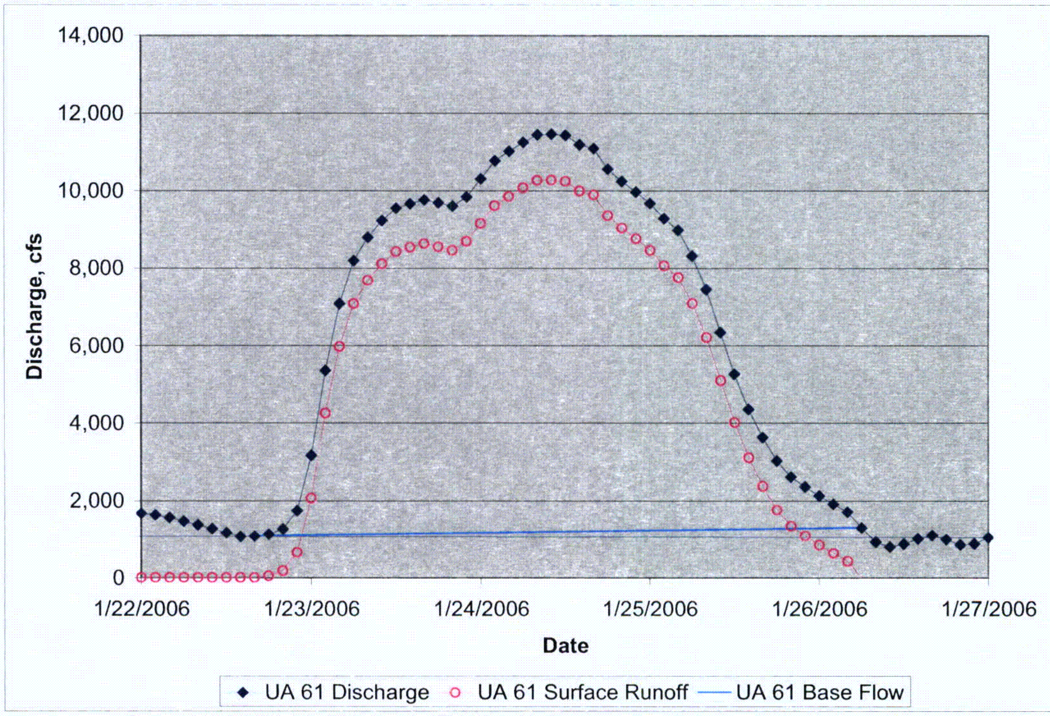

Figure 27: Base Flow Separation, Sub-basin 61, Elk River Local, Fayetteville to Prospect, January 2006

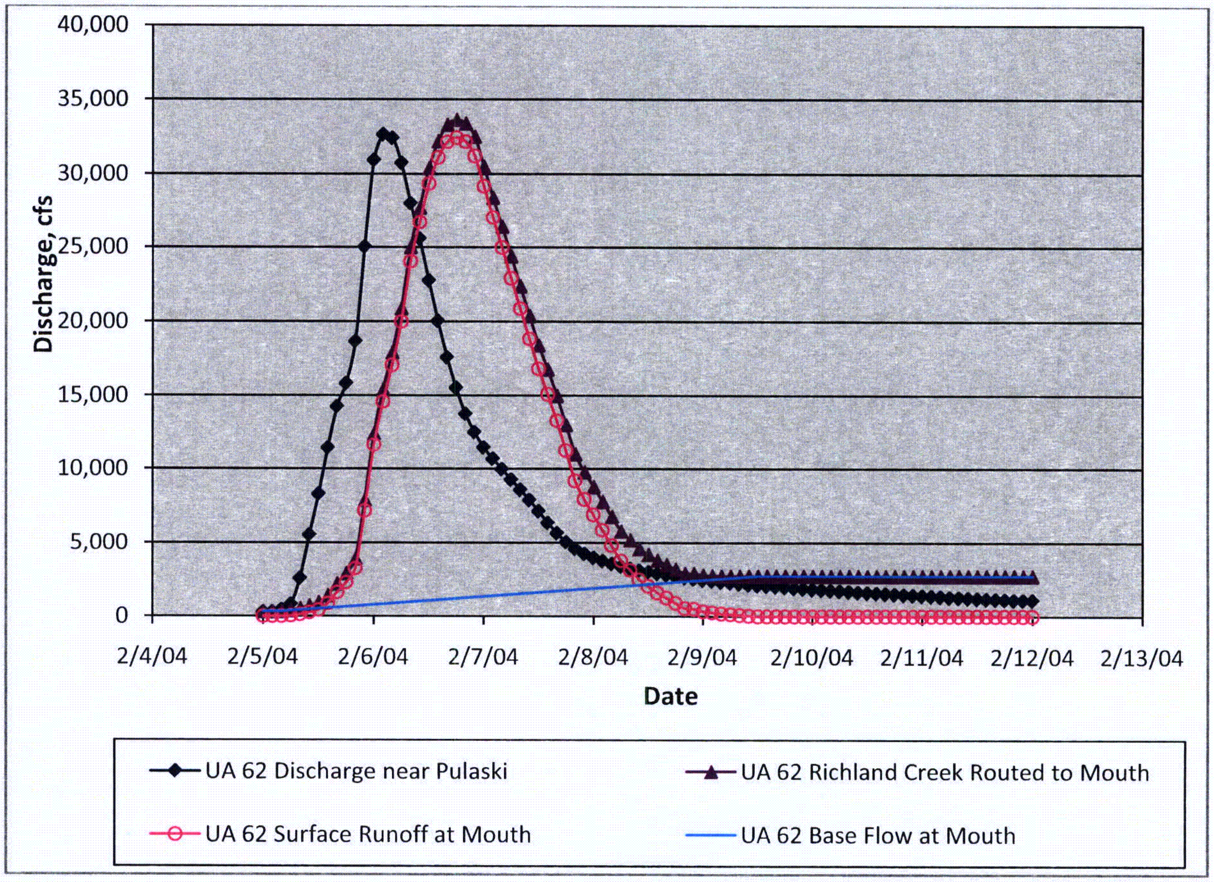

Figure 28: Base Flow Separation, Sub-basin 62, Richland Creek @ Mouth, February 2004

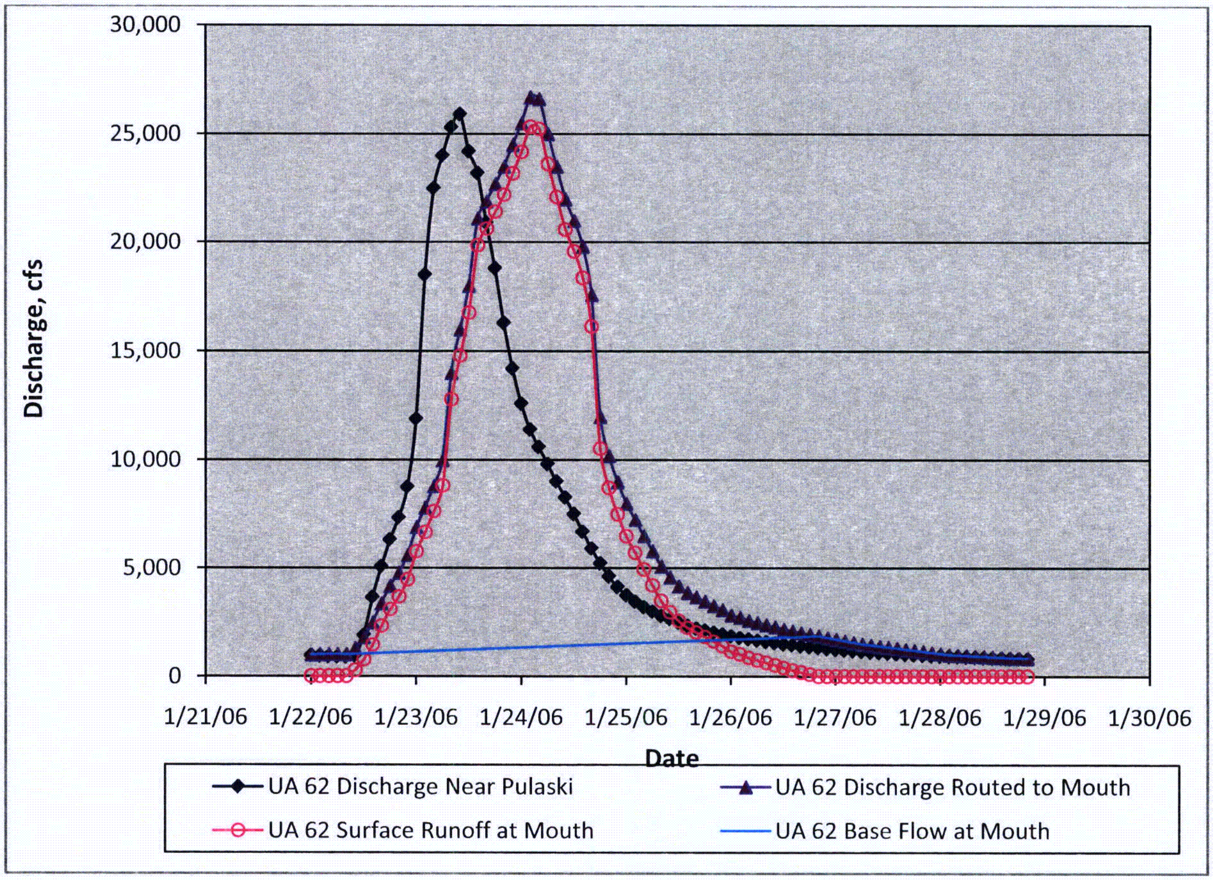

Figure 29: Base Flow Separation, Sub-basin 62, Richland Creek @ Mouth, Jan. 2006

7.4 Calculation of Effective Precipitation

The effective (or excess) rainfall hyetograph is the input to the basin model that is converted into direct runoff at the basin outlet. This is developed from the observed rainfall hyetograph by the application of a loss rate function which accounts for the hydrologic abstractions of evaporation and transpiration, interception, depression storage, and infiltration [4].

Effective rainfall is obtained from observed rainfall data with the FLDHYDRO program [7]. The FLDHYDRO program was developed by TVA to implement the API/RI methodology developed by the United States Weather Bureau (USWB) [3, 29]. 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 [4, page 101]. A recession constant of 0.9 is assumed for this calculation. The API is used to obtain a Runoff Index (RI) that has been determined for the Tennessee River Valley region as a function of precipitation, location, and season. The RI is then used to obtain precipitation losses for each increment of rainfall.

The use of the loss function is discussed in the TVA White Paper [1], and the methodology is described in detail in the Kohler and Linsley publication [29]. Input to FLDHYDRO is via a column delimited batch file. Input includes:

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

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

- NARFE = 1 to obtain a printout of flood hydrographs only
- NRI = 1 for the number of Rainfall Indices to be used per basin
- NCPTS = 1 for the number of sites for surface runoff volume check (set to zero if a runoff check volume is not supplied)
- NSUBW = 1 for the number of sub-watersheds (each sub-basin is run separately)
- NREC = 1 for the number of recorders (run using only gridded precipitation data as one "recorder")
- NSTNS = 1 for total number of stations (i.e. no non-recording stations used)
- STAB = 1 when all stations are in the same API area
- ITDGR = 0 for the hour at which each gage is read
- BEGDR = The starting date (entered in MMDDYY format)
- BEGTR = Time at which the first hour of rainfall has been recorded (between 01 to 24)
- NHR = The number of hourly readings for the storm
- SHRAIN = The time series of hourly rainfall readings (in 10F8.0 format) obtained from processing of NWS gridded rainfall
- NDRAPI = The number of days of antecedent rainfall listed before the storm
- API = The initial API at the beginning of the antecedent daily rainfall series (setting this value to 1.0 is sufficient when a month of data is used because the initial condition has negligible impact on the final API for a sufficiently long series)
- APRAIN = The time series of daily rainfall readings (in 10F8.0 format) obtained from the sum of hourly rainfall data for approximately one month prior to the start of the hourly rainfall
- BAREA = The sub-basin area in square miles
- APITYPE = The API zone with SE = 1, E = 2, NE = 3, N = 4, W = 5, and S = 6. The Wheeler Dam watershed sub-basins are within the S and W zones (see Figure 30).

- NSPW = 1 for number of rainfall stations for each sub-watershed (for gridded data there are no Thiessen weighting factors)
- NUMVOL = Number of watersheds above surface runoff volume check point
- CHKVOL = The volume of surface runoff in inches (calculated from outflow hydrographs after base flow separation); when CHKVOL is greater than zero, the final runoff index is adjusted, if necessary, to provide a volume equal to CHKVOL

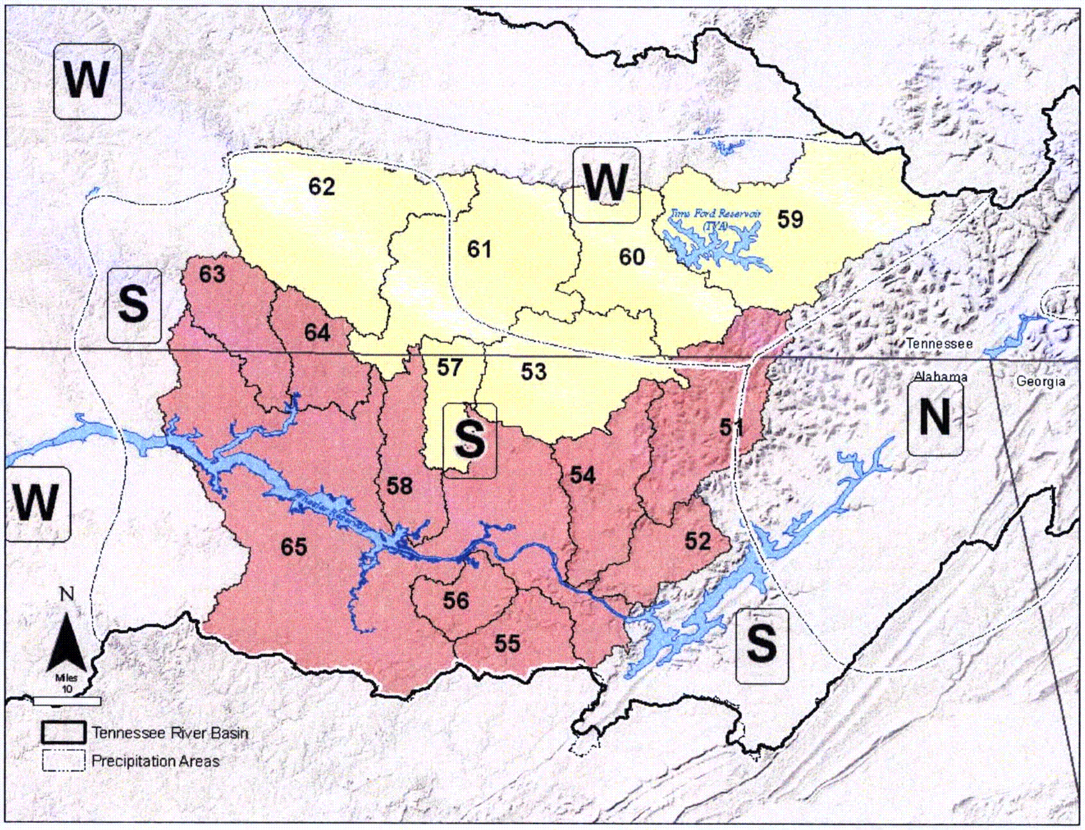

Figure 30: Runoff Regions for Application of the TVA FLDHYDRO Program

FLDHYDRO gives the option of two different methods to compute the time sequence of excess precipitation, the *antecedent rainfall method* and the *check volume method*. The Antecedent Rainfall (API) method, calculates the API using the rainfall data for a period (30 to 40 days) prior to the storm event under consideration. When the antecedent rainfall method is used, a starting API value for the storm event to be analyzed is either specified or calculated. The check volume method computes the time sequence of excess precipitation, independently of antecedent precipitation, so that the total volume of excess precipitation matches the calculated direct runoff volume. By using the check volume method, antecedent rainfall is no longer a user-defined input to the model, but becomes an initial estimate in an optimization procedure. In selecting storms to use for verification, preference was given to storms for which the API and check volume methods returned similar values for excess precipitation.

Input data and parameters for running FLDHYDRO to get effective basin average rainfall for the six sub-basins of the Wheeler Watershed for the simulation periods were written to the following batch input files, included as attachments to this calculation. Input (*.dat) and output (*.out) files with the subscript A represent files run using the check volume method to compute excess precipitation. Files with the subscript 'B' represent files using the API method.

The following FLDHYDRO input files are provided as attachments:

UA_53_02052004_A.dat
UA_53_02052004_B.dat
UA_53_03052004_A.dat
UA_53_03052004_B.dat

UA_57_05052003_A.dat
UA_57_05052003_B.dat
UA_57_02052004_A.dat
UA_57_02052004_B.dat
UA_57_12052004_A.dat
UA_57_12052004_B.dat

UA_59_12052004_A.dat
UA_59_12052004_B.dat
UA_59_02052004_A.dat
UA_59_02052004_B.dat

UA_60_03172002_A.dat
UA_60_03172002_B.dat
UA_60_02052004_A.dat
UA_60_02052004_B.dat
UA_60_12052004_A.dat
UA_60_12052004_B.dat

UA_61_01222006_A.dat
UA_61_01222006_B.dat
UA_61_02052004_A.dat
UA_61_02052004_B.dat

UA_62_03162002_A.dat
UA_62_03162002_B.dat
UA_62_02052004_A.dat
UA_62_02052004_B.dat
UA_62_12052004_A.dat
UA_62_12052004_B.dat

The corresponding FLDHYDRO output files are provided as attachments:

UA_53_02052004_A.out
UA_53_02052004_B.out
UA_53_03052004_A.out
UA_53_03052004_B.out

UA_57_05052003_A.out
UA_57_05052003_B.out
UA_57_02052004_A.out
UA_57_02052004_B.out
UA_57_12052004_A.out
UA_57_12052004_B.out

UA_59_12052004_A.out
UA_59_12052004_B.out
UA_59_02052004_A.out
UA_59_02052004_B.out

UA_60_03172002_A.out
UA_60_03172002_B.out
UA_60_02052004_A.out
UA_60_02052004_B.out
UA_60_12052004_A.out
UA_60_12052004_B.out

UA_61_01222006_A.out
UA_61_01222006_B.out
UA_61_02052004_A.out
UA_61_02052004_B.out

UA_62_03162002_A.out
UA_62_03162002_B.out
UA_62_02052004_A.out
UA_62_02052004_B.out
UA_62_12052004_A.out
UA_62_12052004_B.out

The output for each basin provides an echo of data input and tabulated cumulative rainfall and effective rainfall (runoff) depths. The cumulative effective rainfall depth series were converted to incremental time series for use in convolution calculations (Attachment 1-13 to Attachment 1-18).

The incremental and cumulative precipitation and excess rainfall depths for the two validation runs for each of the sub-basins are plotted in Figures 31 to 36. The convolution of data inputs into storm flows is described in the next section.

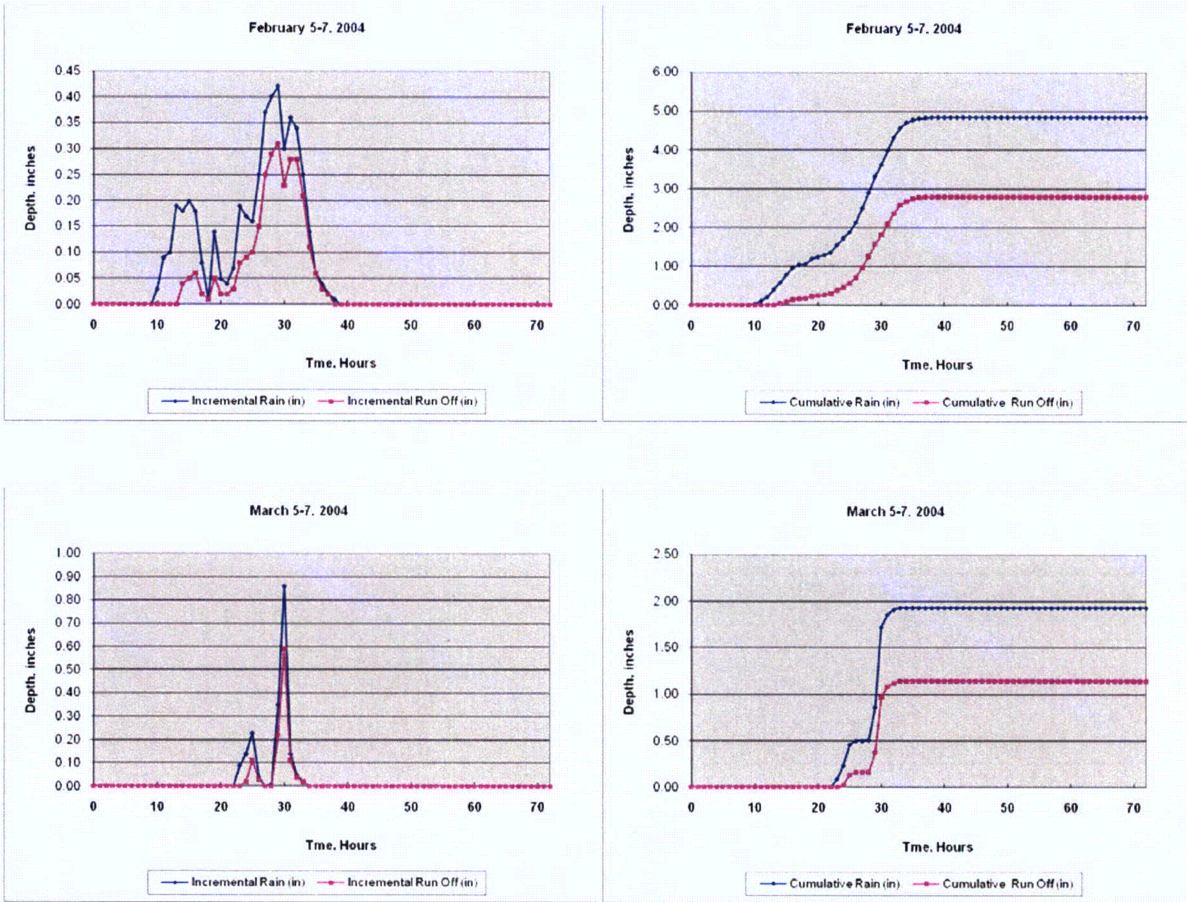

Figure 31: FLDHYDRO-derived Precipitation and Runoff Inputs for Sub-basin 53

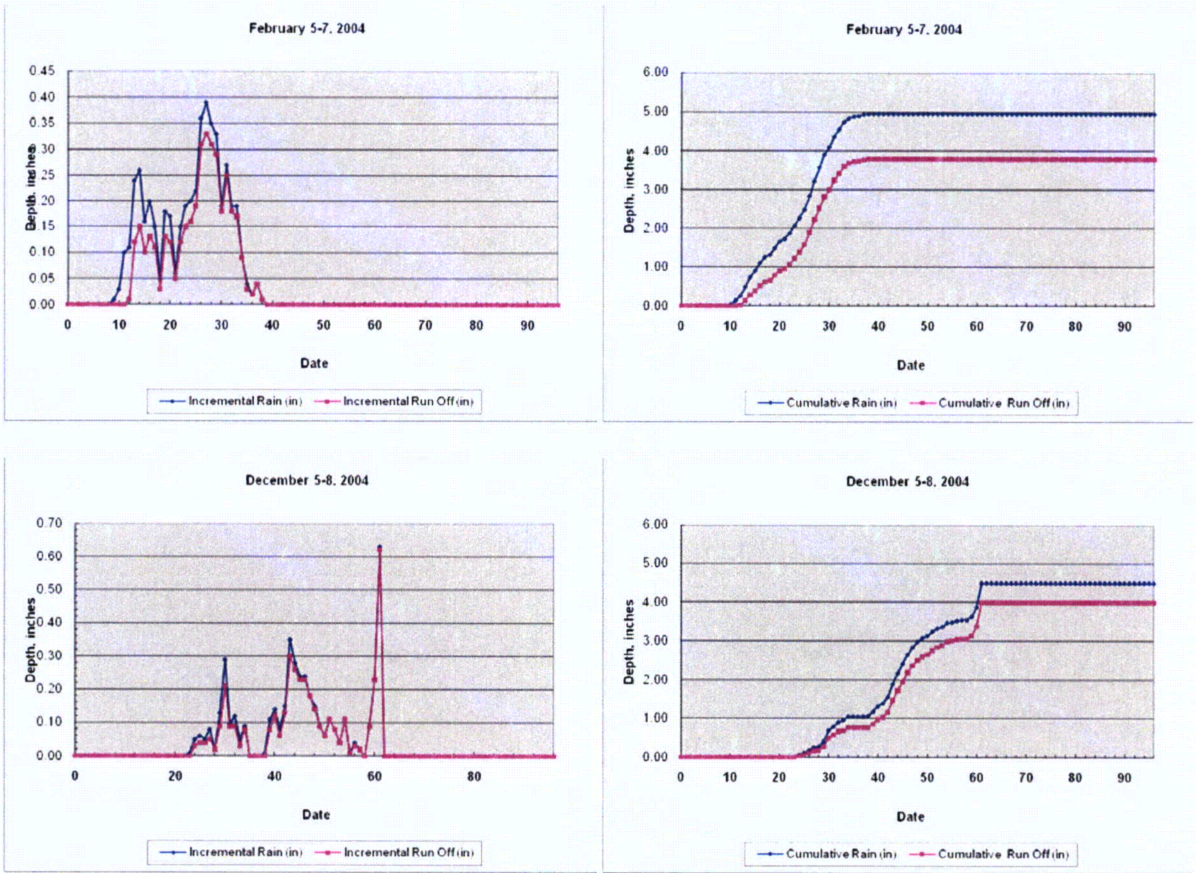

Figure 32: FLDHYDRO-derived Precipitation and Runoff Inputs for Sub-basin 57

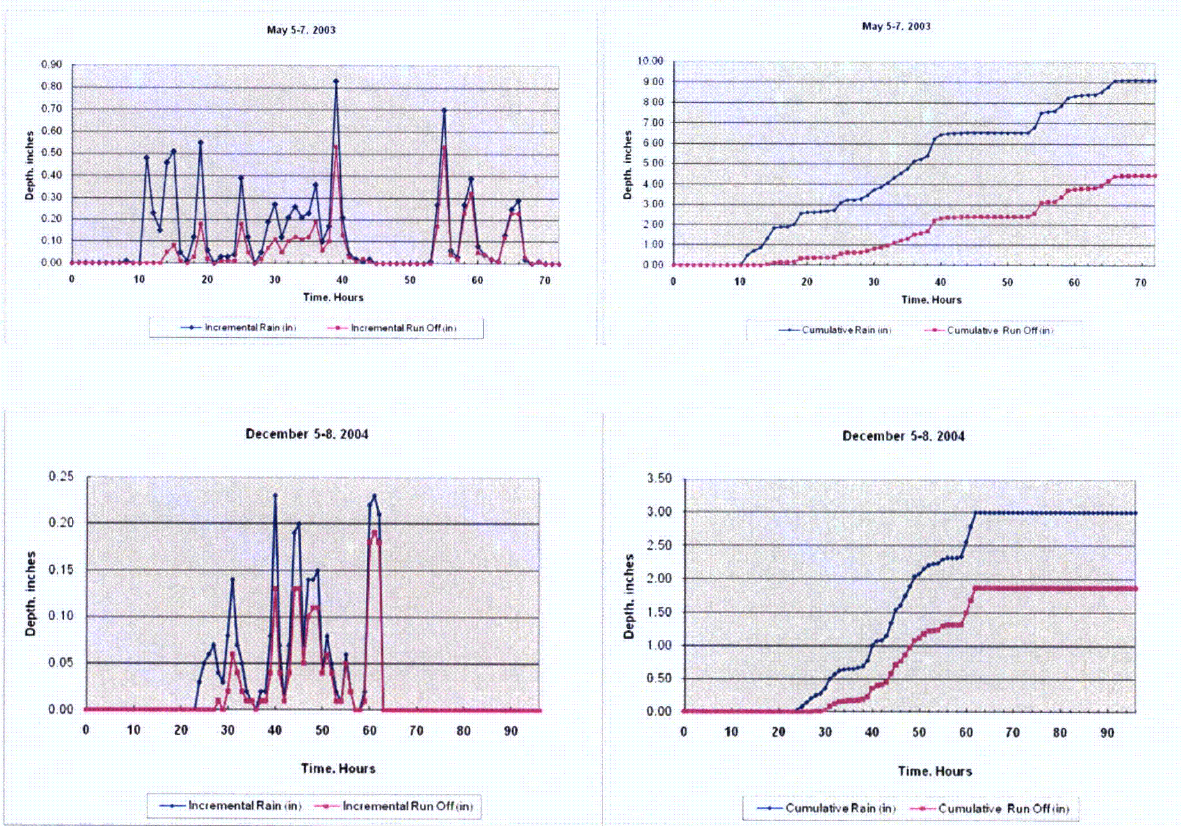

Figure 33: FLDHYDRO-derived Precipitation and Runoff Inputs for Sub-basin 59

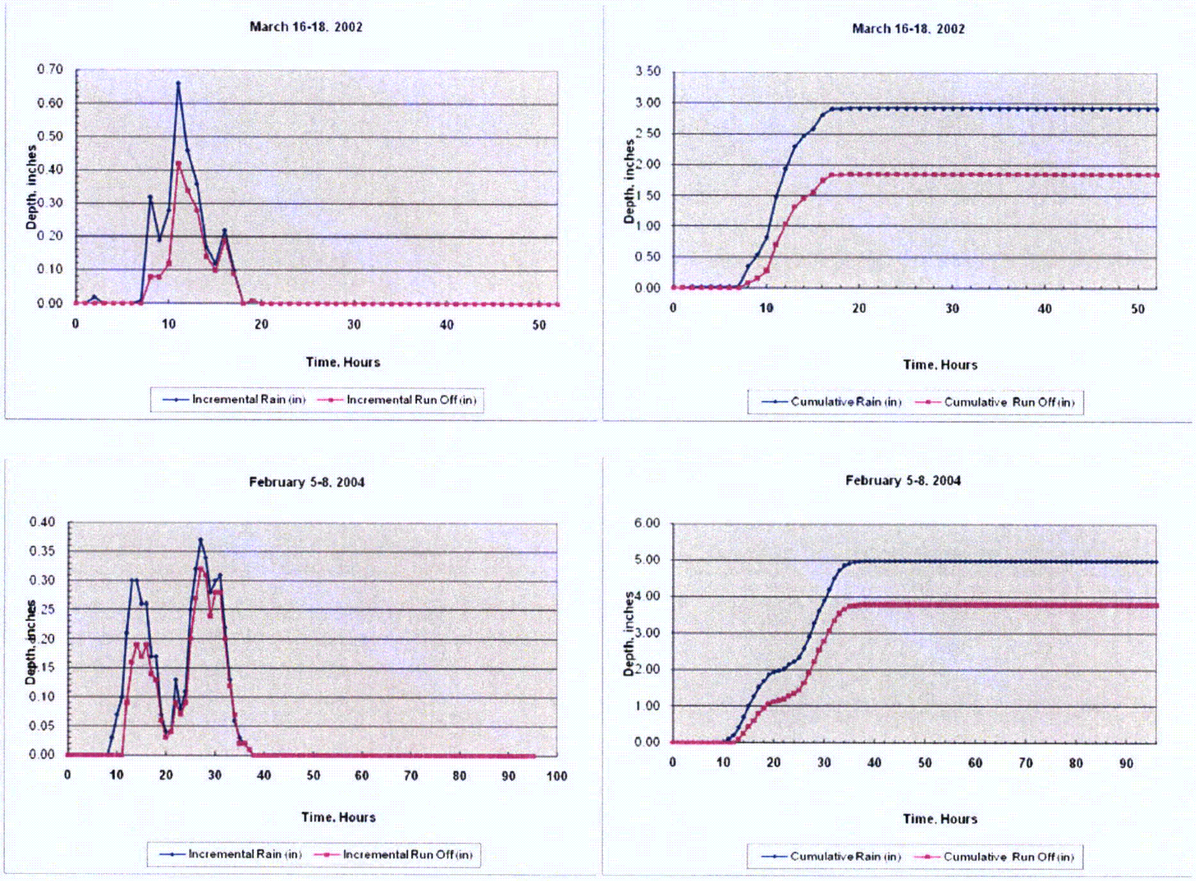

Figure 34: FLDHYDRO-derived Precipitation and Runoff Inputs for Sub-basin 60

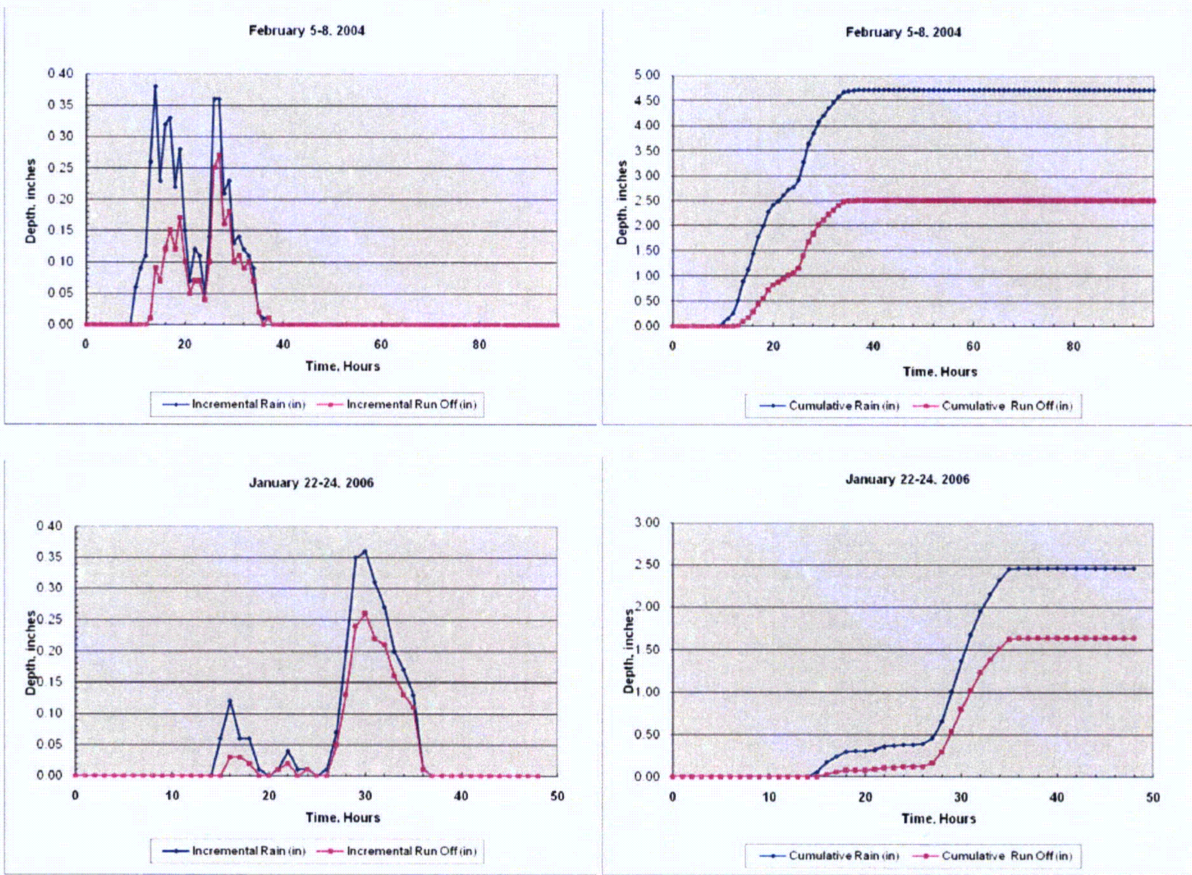

Figure 35: FLDHYDRO-derived Precipitation and Runoff Inputs for Sub-basin 61

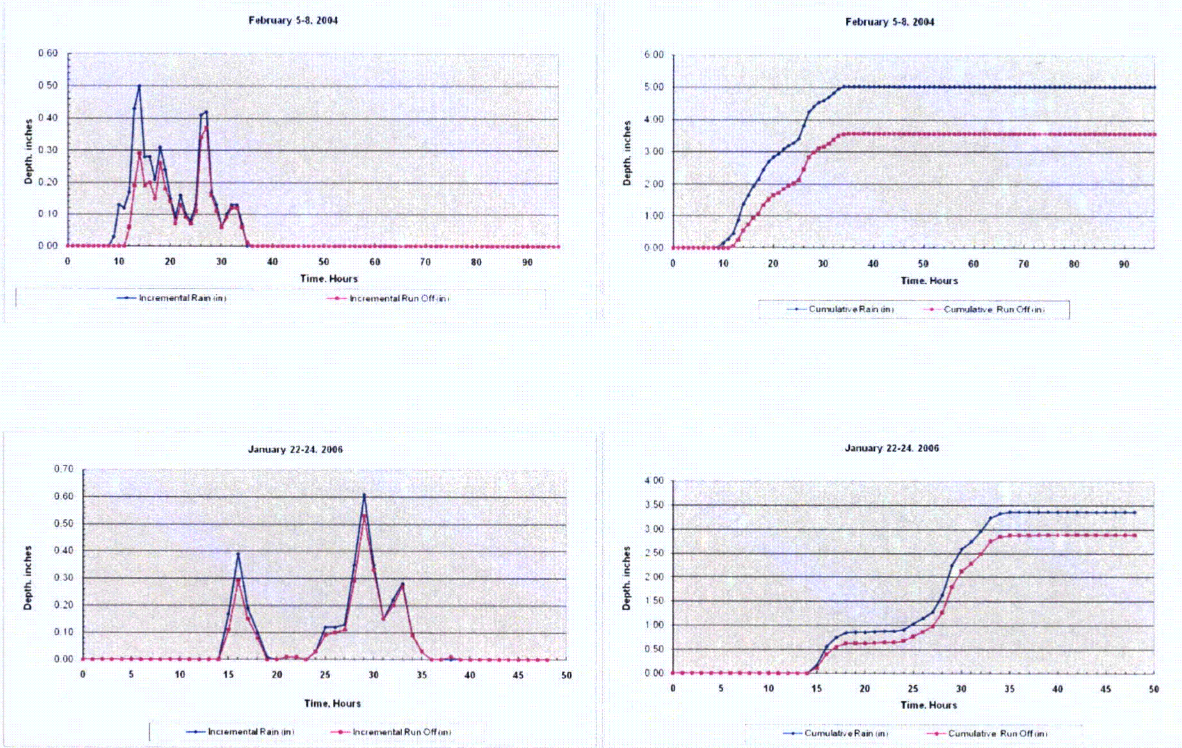

Figure 36: FLDHYDRO-derived Precipitation and Runoff Inputs for Sub-basin 62

7.5 Simulations of Runoff Using Recent Precipitation Events

The unit hydrographs developed by TVA were tested using recent precipitation events to assess their ability to reproduce observed gage data for the six sub-basins in the Wheeler watershed. Data for each simulation are provided as electronic attachments to this calculation as indicated.

A description of each simulation is provided in the following subsections. Modeling considerations specific to each basin are discussed, graphical output of simulations are presented, and the results for each sub-basin are reported. All results are summarized in Section 7.6.

7.5.1 Sub-basin 53 Simulation

The unit hydrograph developed by the TVA for the Flint River near Chase (UA 53) was validated in the Microsoft Excel file "2009-10-19_Convol-53v5.xls" (Attachment 1-13). Graphical output is presented in Figures 37 and 38 for the simulation of the following two storms:

- February 5, 2004
- March 5, 2004

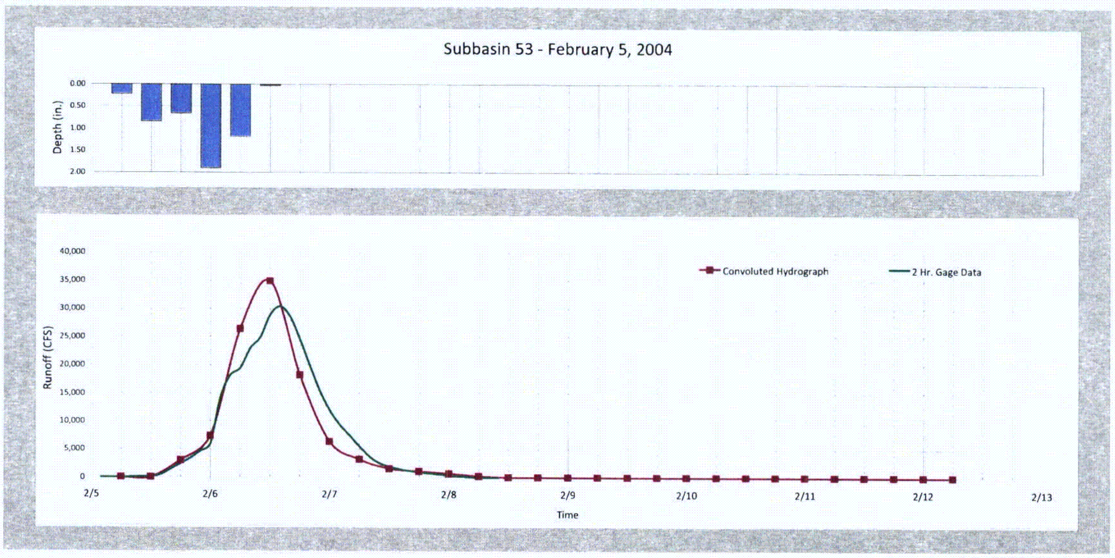

Figure 37: Simulation of Sub-basin 53 Runoff for February 2004 Storm

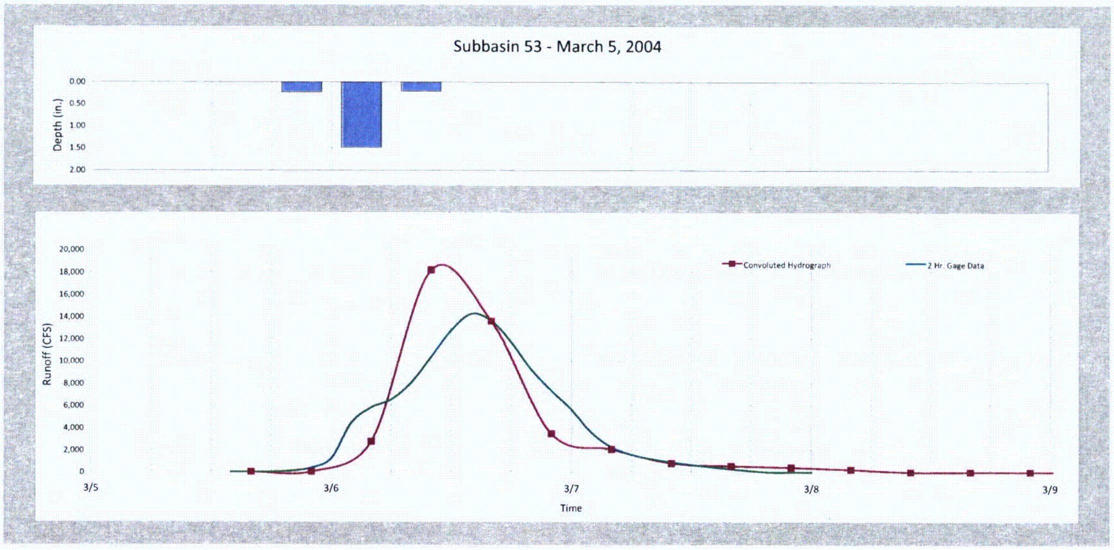

Figure 38: Simulation of Sub-basin 53 Runoff for March 2004 Storm

<u>Simulation of the February 5, 2004 Flood:</u>

The February 2004 observed flow series for Sub-basin 53, shown in the heavy solid (green) line on Figure 37, is taken from gage records and therefore can be considered reliable. The simulated hydrograph, shown in the heavy (red) line with square data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a reasonably good approximation of the observed hydrograph.

The peak of the simulated hydrograph occurs approximately 2 hours before the observed peak, and the simulated excess rainfall volumes (2.79 in.) match closely the observed excess rainfall (2.83 in.). The magnitude of the simulated peak discharge is approximately 15% higher than the observed peak, providing a conservative estimation of the peak flow.

<u>Simulation of the March 5, 2004 Flood:</u>

The March 2004 observed flow series for Sub-basin 53, shown in the heavy solid (green) line on Figure 38, is taken from gage records and therefore can be considered reliable. The simulated hydrograph, shown in the heavy (red) line with square data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a reasonably good fit to the observed hydrograph.

Similar to the February 2004 flood, the peak of the simulated hydrograph for the March, 2004 storm occurs approximately 3 hours prior to the observed peak. Simulated excess rainfall volumes (1.14 in.) are slightly greater than the observed excess rainfall (1.11 in.), but overall in good agreement. The magnitude of the simulated peak discharge is approximately 27% higher than the observed peak.

While both simulations adequately reproduce the overall shape of the storm hydrograph, neither are sensitive enough to reproduce the subtle changes in the observed hydrograph caused by slight changes in rainfall intensity. For instance, both observed data sets display shoulders in the rising limb in response to changes in rainfall intensity; these shoulders are not reproduced in the simulation.

Based upon the generally good reproduction of hydrograph shape and the overestimation of peak flows, it is concluded that the unit hydrograph developed by TVA for Sub-basin 53 (Flint River near Chase) provides a reliable simulation of runoff response to excess rainfall inputs. The floods used in the development of the original unit hydrographs were significantly larger than the two floods selected for this calculation; therefore, overestimation of the peak is reasonable.

7.5.2 Sub-basin 57 Simulation

The unit hydrograph developed by TVA for Limestone Creek near Athens (UA 57) was validated in the Microsoft Excel file "2009-10-19_Convol-57v5.xls" (Attachment 1-14). Graphical output is presented in Figures 39 and 40 for the simulation of the following two storms:

- February 5, 2004
- December 5, 2004

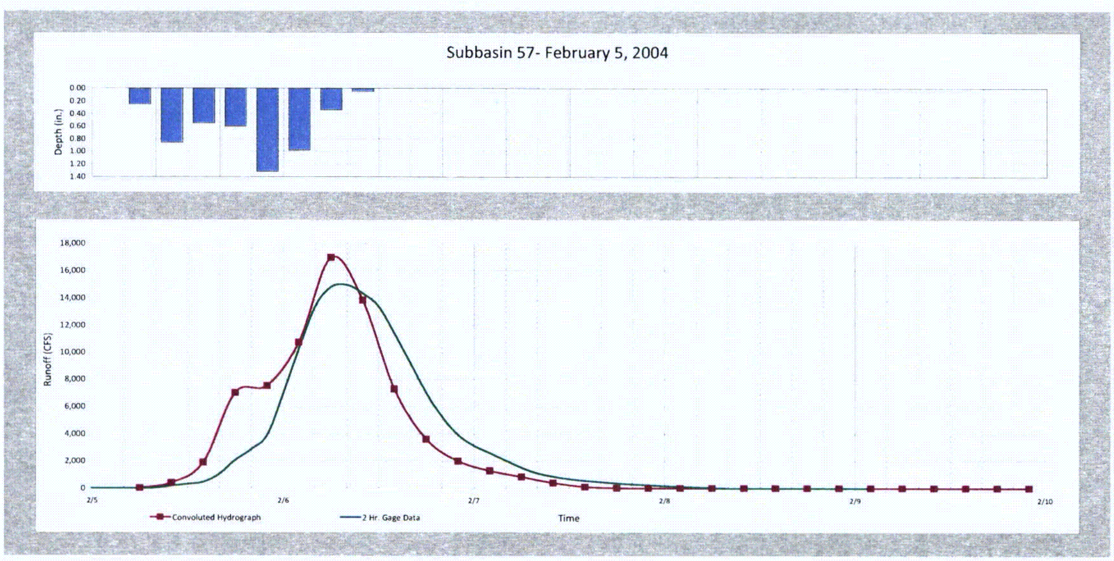

Figure 39: Simulation of Sub-basin 57 Runoff for February 2004 Storm

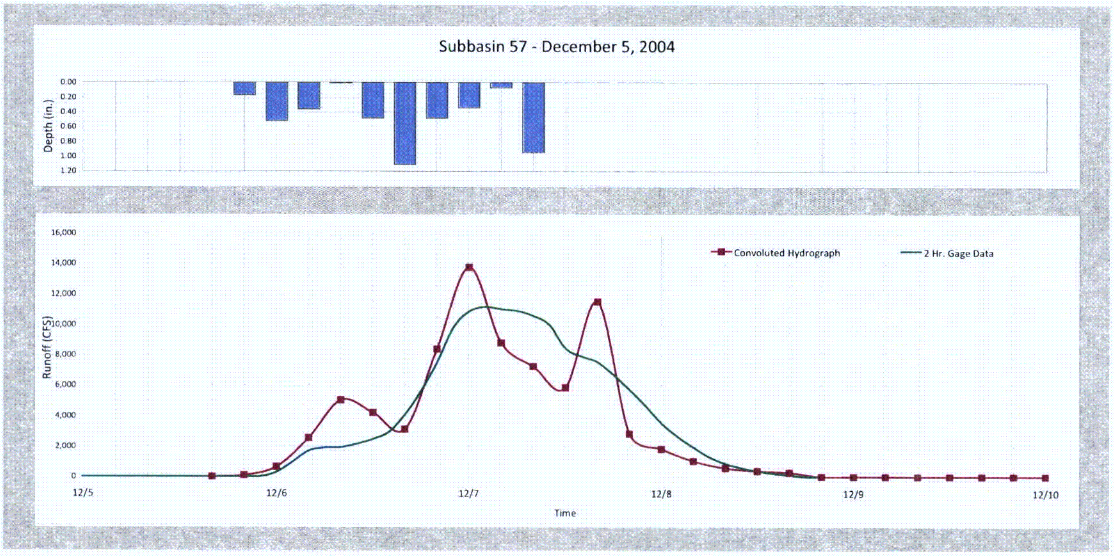

Figure 40: Simulation of Sub-basin 57 Runoff for December 2004 Storm

<u>Simulation of the February 5, 2004 Flood:</u>

The February 2004 observed flow series for Sub-basin 57, shown in the heavy solid (green) line on Figure 39, is taken from gage records and therefore can be considered reliable. The simulated hydrograph, shown in the heavy (red) line with square data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a reasonably good fit to the observed hydrograph.

The February 5, 2004 storm was a long, somewhat complex storm with gentle variations in rainfall intensity. The peak runoff predicted from this flood is approximately 14% greater than the observed peak, and occurs approximately 2 hours before the observed peak. Simulated excess rainfall volumes (3.78 in.) are slightly less than the observed excess rainfall (3.84 in.), but overall in good agreement overall. The simulation predicts a pronounced shoulder in the rising limb in response to a local maxima in rainfall and results from the difficulty of estimating the runoff from separate bursts of rainfall.

<u>Simulation of the December 5, 2004 Flood:</u>

The December 5, 2004 observed flow series for Sub-basin 57, shown in the heavy solid (green) line on Figure 40, is taken from gage records and therefore can be considered reliable. The simulated hydrograph, shown in the heavy (red) line with square data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph shown in the plot above the hydrograph. The general shape of the observed data is reproduced by the simulated hydrograph; the predicted peak discharge occurs approximately 2 hours before the observed peak discharge; and simulated excess rainfall volumes (3.99 in.) are slightly less than the observed excess rainfall (4.05 in.), but overall in good agreement. However, there are apparent differences in the magnitude of the response of the simulation and the observed data to rainfall across the watershed.

The December 5, 2004 storm is fairly complex, with three separate periods of increased rainfall intensity, followed by extended periods of lesser rainfall intensity. The simulation predicts pronounced runoff peaks following each of the more intense rainfall periods, suggesting a "flashy" watershed that responds quickly to excess precipitation. The observed data for the December 5, 2004 storm indicate a more attenuated response to rainfall, with a single broad peak lagging the most intense rain period.

The magnitude of the predicted maximum peak runoff is approximately 23% higher than observed maximum peak; however, this is misleading, given the shape and duration of the peak event. In addition, the simulation predicts peaks following local rainfall maximas that are not observed in the gage data. In all cases, simulated peaks exceed observed peaks, providing a conservative estimate of peak runoff.

It seems clear that the unit hydrograph developed by TVA performs best when rainfall inputs occur continuously and without oscillation in intensity. While the unit hydrograph for Sub-basin 57 predicts more "flashy" behavior during complex storms, for simple storms, it provides generally good simulation of runoff response to rainfall.

7.5.3 Sub-basin 59 Simulation

The unit hydrograph developed by TVA for Tims Ford Dam (UA 59) was validated in the Microsoft Excel file "2009-10-19_Convol-59v5.xls" (Attachment 1-15). Graphical output is presented in Figures 41 and 42 for the simulation of the following two storms:

- May 5, 2003
- December 5, 2004

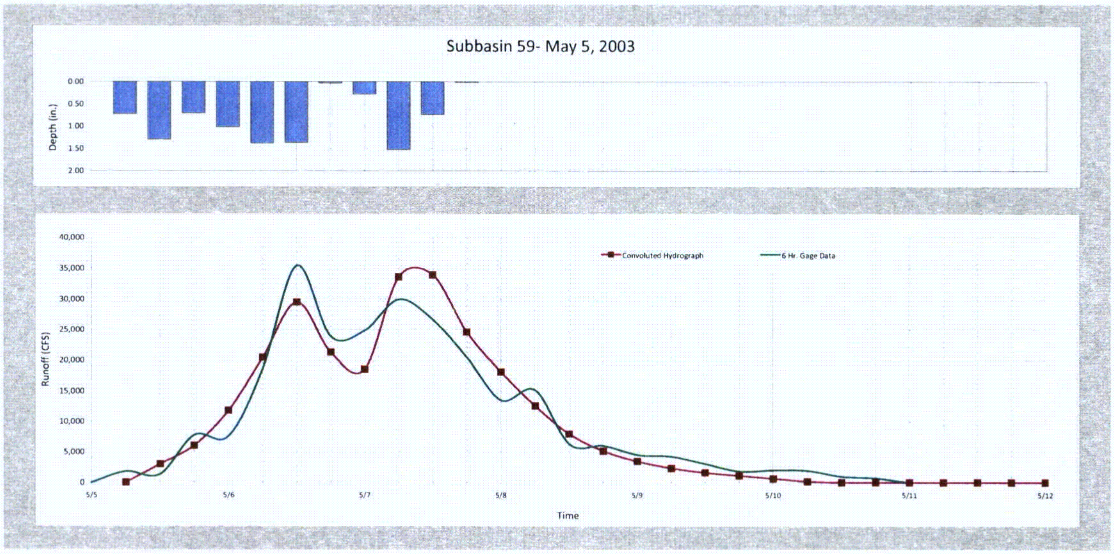

Figure 41: Simulation of Sub-basin 59 Runoff for May 5 2003 Storm

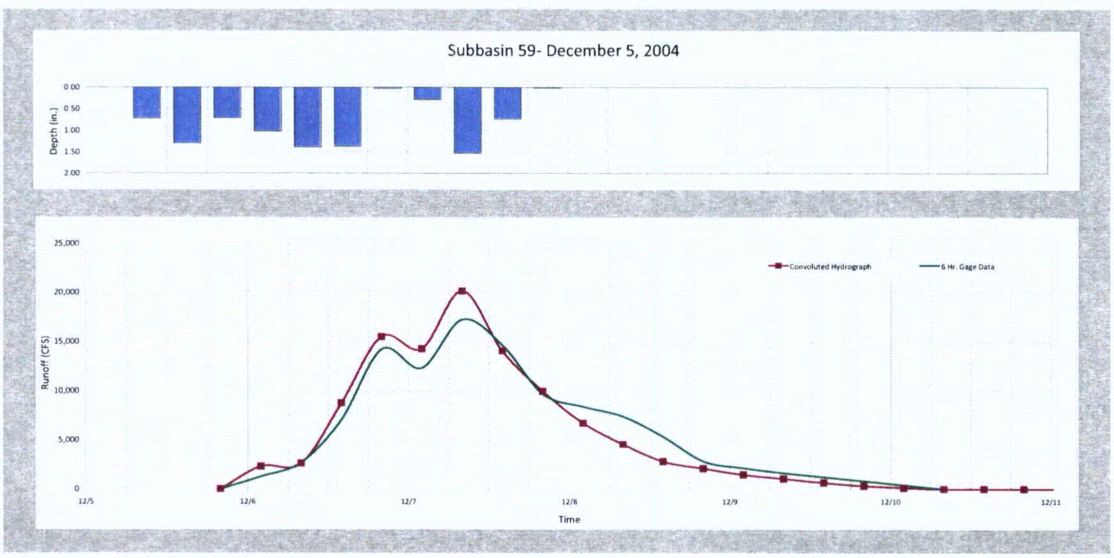

Figure 42: Simulation of Sub-basin 59 Runoff for December 2004 Storm

Simulation of the May 5, 2003 Flood:

The May 5, 2003 observed flow series for Sub-basin 59, shown in the heavy solid (green) line on Figure 41, is developed from reverse reservoir routing Tims Ford Dam discharges and then averaging hourly data points over a six-hour period to smooth out fluctuations. The quality of the observed flow series is thus dependant on the quality of the routing procedure and the degree to which the smoothing process reflects reservoir behavior. The simulated hydrograph, shown in the heavy (red) line with square data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a good fit to the observed hydrograph.

The simulation accurately predicts the complex peaking behavior for Sub-basin 59, with the initial peak occurring concurrently with the observed peak, and the subsequent peak occurring about 3 hours after the second observed peak. In addition, the predicted initial peak flow is underpredicted by 17% while the second peak is over predicted by 17%. Simulated excess rainfall volumes (4.46 in.) are slightly less than the observed excess rainfall (4.51 in.), but overall in good agreement.

Simulation of the December 5, 2004 Flood:

The December 5, 2004 observed flow series for Sub-basin 59, shown in the heavy solid (green) line on Figure 42, is developed from reverse reservoir routing Tims Ford Dam discharges and then averaging hourly data points over a six-hour period to smooth out fluctuations. The quality of the observed flow series is thus dependant on the quality of the routing procedure and the degree to which the smoothing process reflects reservoir behavior. The simulated hydrograph, shown in the heavy (red) line with circle data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a reasonable fit to the observed hydrograph. Similar to the May, 2003 flood, the simulation of the December 2004 flood accurately predicts the complex peaking behavior of Sub-basin 59. Both the initial and subsequent peaks occur concurrent to their respective observed peaks, and peak flows are overpredicted by 9% and 17% respectively. Simulated excess rainfall volumes (1.87 in.) are slightly less than the observed excess rainfall (1.90 in.), but overall in good agreement.

The simulations of the response of Sub-basin 59 to excess rain are generally good. It is concluded that the unit hydrograph developed by TVA for Sub-basin 59 (Tims Ford Dam) provides a reliable simulation of runoff response to excess rainfall inputs.

7.5.4 Sub-basin 60 Simulation

The unit hydrograph developed by TVA for the Elk River, Tims Ford Dam to Fayetteville (UA 60) was validated in the Microsoft Excel file "2009-10-19_Convol-60v5.xls" (Attachment 1-16). Graphical output is presented in Figures 43 and 44 for the simulation of the following two storms:

- March 16, 2002
- February 5, 2004

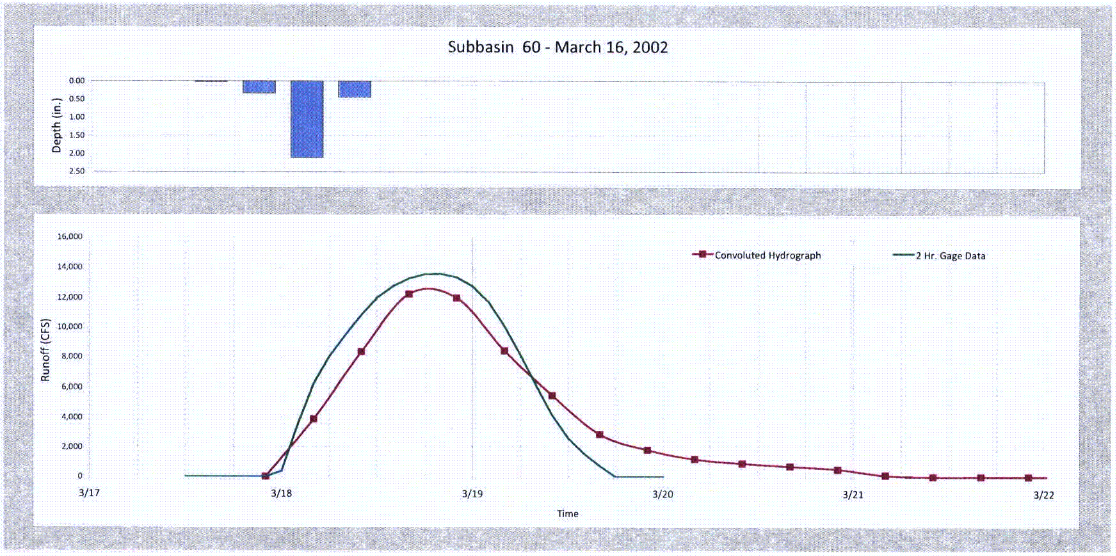

Figure 43: Simulation of Sub-basin 60 Runoff for March 2002 Storm

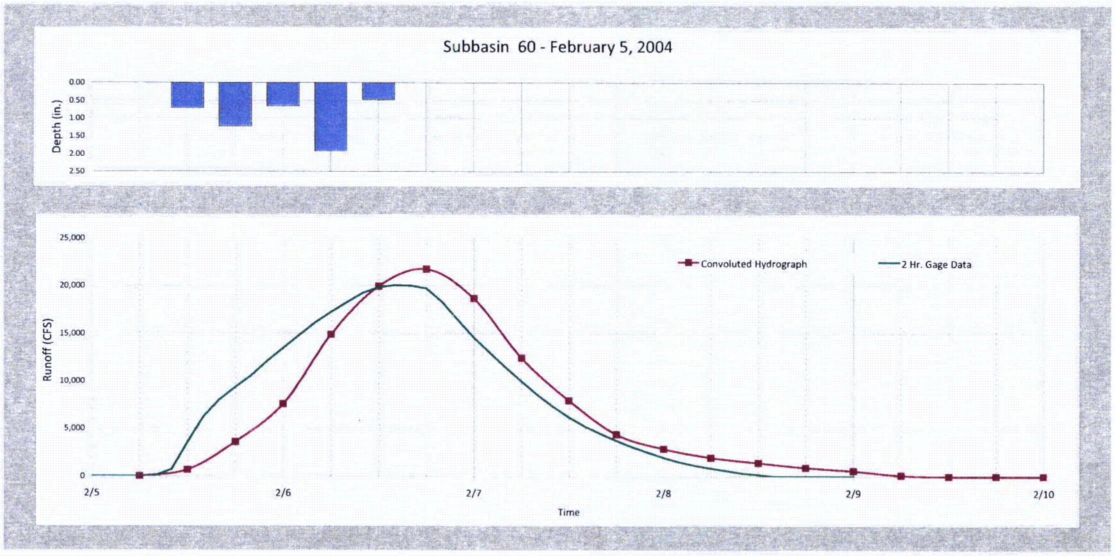

Figure 44: Simulation of Sub-basin 60 Runoff for February 2004 Storm

<u>Simulation of the March 16, 2002 Flood:</u>

The March 16, 2003 observed flow series for Sub-basin 60, shown in the heavy solid (green) line on Figure 43, was developed by routing the observed flow series at Tims Ford Dam downstream to Fayetteville using ARMA routing parameters provided by TVA, followed by subtraction from the observed flow series on the Elk River near Fayetteville. The reliability of this local hydrograph depends on how well the flood routing procedure simulates the actual translation of the flood wave downstream. The simulated hydrograph, shown in the heavy (red) line with square data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a good fit to the observed hydrograph. Although the simulation generally under-predicts runoff during the storm event, the difference is approximately 11% which is acceptable given the assumptions inherent in the development of the observed flow series. The simulated and observed peak flow occur concurrently, and simulated (1.85 in.) and excess (1.90 in.) rainfall volumes are in good agreement.

Simulation of the February 5, 2004 Flood:

Like the March 2003 storm, the February 5, 2004 observed flow series for Sub-basin 60, shown in the heavy solid (green) line on Figure 44, was developed by routing the observed flow series at Tims Ford Dam downstream to Fayetteville using ARMA routing parameters provided by TVA, followed by subtraction from the observed flow series on the Elk River near Fayetteville. The reliability of this local hydrograph is a function of the accuracy of the translation of the flood wave downstream. The simulated hydrograph, shown in the heavy (red) line with square data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is also a good fit to the observed hydrograph. The simulation slightly overpredicts (9%) peak flow and lags the observed peak location by approximately 2 hours. While it generally reproduces the overall shape of the observed flood, the convolution under-predicts the flows during the rising limb of the storm. The simulated (1.85 in.) and excess (1.90 in.) rainfall volumes are in good agreement.

For both runs, the timing and magnitude of the peak of the two hydrographs agree quite closely with the observed values, validating the routing procedure developed by TVA. Based on these results it is concluded that the unit hydrograph for Sub-basin 60 provides a reliable simulation of runoff response to excess runoff.

7.5.5 Sub-basin 61 Simulation

The unit hydrograph developed by TVA for the Elk River Local, Fayetteville to Prospect (UA 61) was validated in the Microsoft Excel file "2009-10-19_Convol-61v5.xls" (Attachment 1-17). Graphical output is presented in Figures 45 and 46 for the simulation of the following two storms:

- February 5, 2004
- January 22, 2006

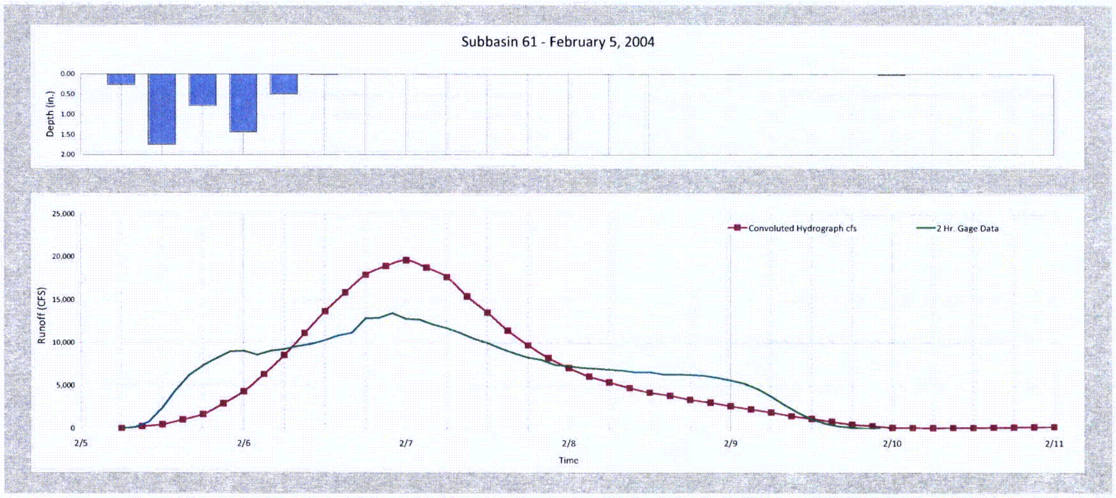

Figure 45: Simulation of Sub-basin 61 Runoff for February 5, 2004 Storm

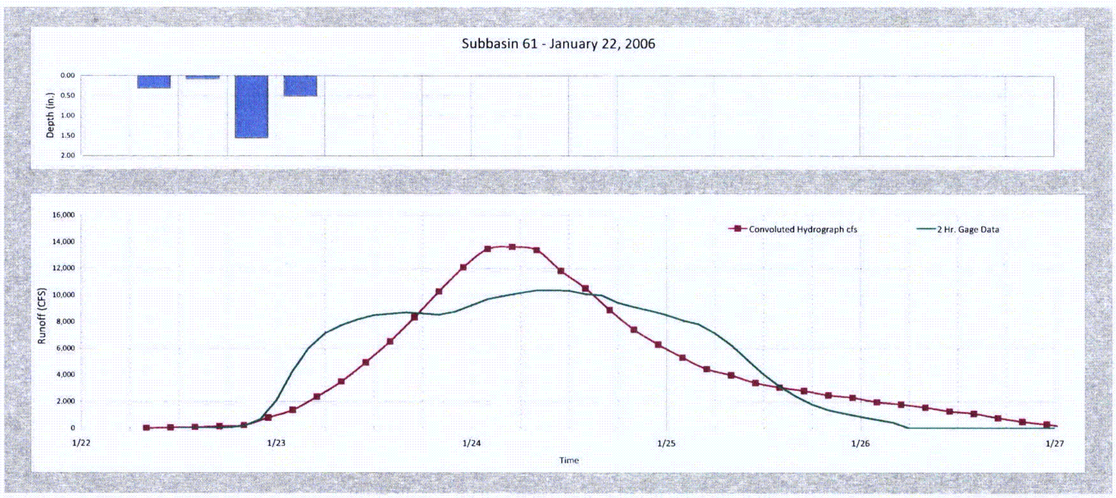

Figure 46: Simulation of Sub-basin 61 Runoff for January 22, 2006 Storm

<u>Simulation of the February 5, 2004 Flood:</u>

The February 5, 2004 observed flow series for Sub-basin 61 is shown in the heavy solid (green) line on Figure 45. The data is taken from gage records, subtracting routed flows from Sub-basins 60 and 62, and therefore can be considered reliable. The simulated hydrograph, shown in the heavy (red) line with circle data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph shown in the plot above the hydrograph.

The simulated hydrograph for the February 5, 2004 storm reproduces the overall shape of the observed hydrograph reasonably well with only mild under-prediction in the rising and falling limbs. The occurrence of simulated and peak flows is concurrent, but the magnitude of the simulated peak runoff exceeds the observed peak flow by approximately 41%. This overprediction of the peak is expected given that the storm used to produce the simulated hydrograph is significantly smaller than the storm used to produce the original unit hydrograph.

While there are significant differences in simulated shape and predicted peak runoff for the two storm events considered for this sub-basin, the predicted peak runoff flows occur at approximately the same time as the observed peak flows, and the magnitudes of the predicted peak flows are always greater than the observed. Therefore, the unit hydrograph developed by TVA for Sub-basin 61 (Elk River Local, Fayetteville to Prospect) provides a conservative simulation of runoff response to excess rainfall inputs during the most critical periods of the flood.

Simulation of the January 22, 2006 Flood:

The January 22, 2006 observed flow series for Sub-basin 61 is shown in the heavy solid (green) line on Figure 46. The data is taken from gage records, subtracting routed flows from Sub-basins 60 and 62, and therefore can be considered reliable. The simulated hydrograph, shown in the heavy (red) line with circle data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph shown in the plot above the hydrograph.

The simulated hydrograph for the January 22, 2006 does not reproduce the overall shape of the observed hydrograph as well as the February 5, 2004; however, it is a reasonable representation with only mild under-prediction in the rising and falling limbs. The occurrence of simulated and peak flows is near concurrent, but the magnitude of the simulated peak runoff exceeds the observed peak flow by approximately 26%. This overprediction of the peak is expected given that the storm used to produce the simulated hydrograph is significantly smaller than the storm used to produce the original unit hydrograph

While there are significant differences in simulated shape and predicted peak runoff for the two storm events considered for this sub-basin, the predicted peak runoff flows occur at approximately the same time as the observed peak flows, and the magnitudes of the predicted peak flows are always greater than the observed. Therefore, the unit hydrograph developed by TVA for Sub-basin 61 (Elk River Local, Fayetteville to Prospect) provides a conservative simulation of runoff response to excess rainfall inputs during the most critical periods of the flood.

7.5.6 Sub-basin 62 Simulation

The unit hydrograph developed by TVA for Richland Creek at Mouth (UA 62) was validated in the Microsoft Excel file "2009-10-19_Convol-62v5.xls" (Attachment 1-18). Graphical output is presented in Figures 47 and 48 for the simulation of the following two storms:

- January 22, 2002
- February 5, 2004

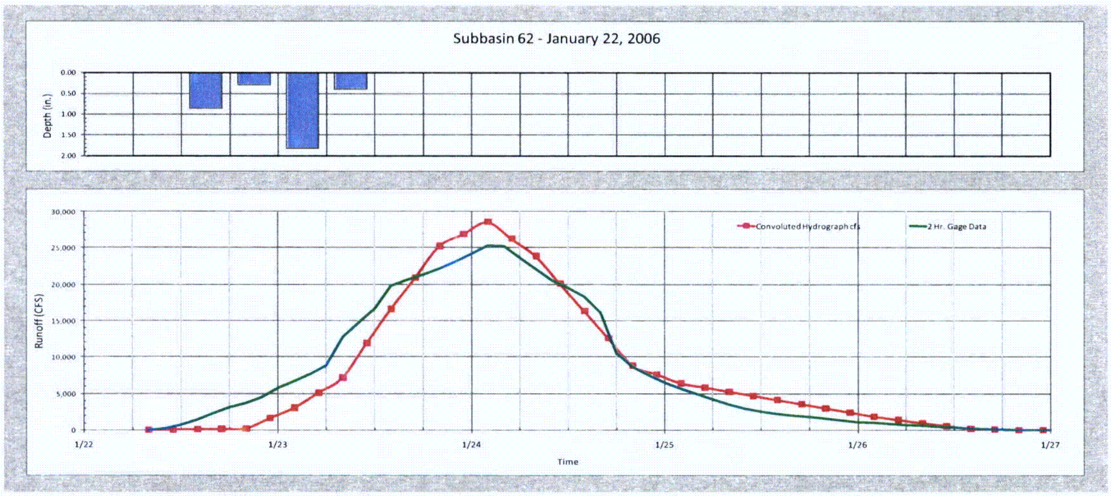

Figure 47: Simulation of Sub-basin 62 Runoff for January 2006 Storm

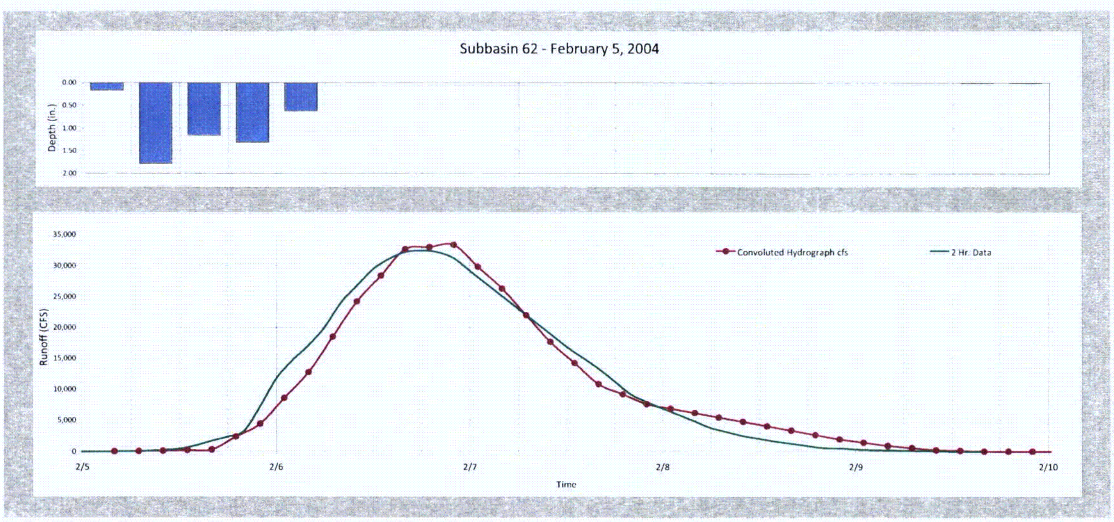

Figure 48: Simulation of Sub-basin 62 Runoff for February 2004 Storm

Simulation of the January 22, 2006 Flood:

The January 2006 observed flow series for Sub-basin 62, shown in the heavy solid (green) line on Figure 47, is taken from upstream gage data routed to the mouth of Richland Creek; therefore, it is considered reliable. The simulated hydrograph, shown in the heavy (red) line with circle data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a reasonably good fit to the observed hydrograph. Observed and predicted peak runoff values differ by approximately 10% and both predicted and observed peaks occur concurrently. The simulated hydrograph slightly under-predicts the rising limb.

Simulation of the February 5, 2004 Flood:

The February 2004 observed flow series for Sub-basin 62, shown in the heavy solid (green) line on Figure 48, is taken from upstream gage data routed to the mouth of Richland Creek; therefore, it is considered reliable. The simulated hydrograph, shown in the heavy (red) line with circle data points, was produced from the convolution of the TVA unit hydrograph with the excess rainfall hyetograph (shown in the plot above the hydrograph) and is a reasonably good fit to the observed hydrograph. The simulation over-predicts the observed peak runoff by 2% and the predicted peak occurs approximately 4 hours after the observed peak runoff.

Both simulated hydrographs for Sub-basin 61 reasonable reproduce the timing, peak flows, and shape of the observed flow series. Therefore, the unit hydrograph developed by TVA provides a reasonable simulation of runoff response to excess rainfall inputs.

7.6 Summary of Simulation Results

A summary of the findings from simulations of runoff response to excess rainfall for the individual sub-basins of the Wheeler Watershed is provided in Table 12.

Table 12: Summary of Simulations of Runoff Response to Excess Rainfall

Unit Area	Date	Overall Shape	Predicted (observed) volume, in.	Occurance of Simulated Peak[a]	Simulated Peak Magnitude[b]
53 Flint River near Chase	2/5/2004	Decent representation of shape; slight overestimation of peak flow. Simulation is less sensitive to storm intensity than gage.	2.79 (2.83)	+2	+15%
	3/5/2004	Simulated hydrograph is narrower than observed data, with steeper slope in rising limb. Peak arrives early and overpredicts peak flow.	1.14 (1.11)	+3	+27%
57 Limestone Creek Near Athens	2/5/2004	Good estimate of peak location; convolution is more sensitive to changing rainfall intensity than gage.	3.78 (3.84)	-2	+14%
	12/5/2004	Convolution is considerably more sensitive to changing rainfall intensity than gage. Simulated hydrograph is "flashy" compared to observed data for complex storm.	3.99 (3.84)	+2	+23%
59 Tims Ford Dam	5/5/2003	Good representation of twin peaks; Simulation does not reproduce smaller peaks in rising and falling limbs.	4.46 (4.51)	Concurrent -3	-17% (1st peak) +17% (2nd peak)
	12/5/2004	Good representation of twin peaks. Good estimate of peak location and slight overestimate of peak flows. Broad hump in receding limb is not reproduced in convolution.	1.87 (1.90)	Concurrent Concurrent	+9% (1st peak) +17% (2nd peak)
60 Elk River Local, Tims Ford Dam to Fayetteville	3/16/2002	Good simulation of peak location with slight underprediction of peak flow. Long tail of convoluted hydrograph is not reflected in observed data.	1.85 (1.88)	+2	-11%
	2/5/2004	Generally good representation of shape, although peak slightly trails observed data. Long tail in observed data is reproduced; underprediction of rising limb.	3.79 (3.81)	-2	-9%
61 Elk River Local, Fayetteville to Prospect	2/5/2004	Reasonable simulation of the overall shape with only mild under-prediction in rising and falling limbs. Concurrent peaks.	2.91 (3.06)	Concurrent	+41%
	1/22/2006	Reasonable simulation of overall shape with only mild under-prediction of rising and falling limbs. Near concurrent peaks.	1.56 (1.64)	+3	+26%
62 Richland Creek at Mouth	2/5/2004	Good simulation of overall shape, rising and falling limbs, and volume. The simulated peak occurs approximately 4 hours after the observed data.	3.57 (3.62)	+4	+2%
	1/22/2006	Generally good; Simulated hydrograph is skewed towards later times (over-prediction late in the event, under-prediction early in the event).	2.88 (2.99)	Concurrent	+10%

a hours before (+) or after (-) observed peak

b percent above (+) or below (-) observed peak

8 Summary and Conclusions

Following NRC requirements, the unit hydrographs developed by TVA for six of the 15 sub-basins within the Wheeler Dam watershed were directly validated by simulating runoff for the highest two floods with suitable precipitation data from the period between 1997 and 2008.

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

Qualitative and quantitative assessments of the success of the simulations in duplicating observed stream flow series are provided in Table 12.

In general, good agreement between simulated and observed flows was obtained for the headwater catchments of the Flint River and Limestone Creek (Sub-basins 53 and 57). For headwater basins, it is only necessary to remove base flow from the observed flow series to compare observed and simulated local hydrographs.

Excellent agreement between simulated and observed local inflow hydrographs was achieved for Tims Ford Dam. This Sub-basin required reverse reservoir routing to develop an inflow hydrograph before a comparison with the simulated inflow series was possible.

In general, good agreement between the simulated and observed local inflow hydrographs was also obtained for the Elk River Local, Tims Ford Dam to Fayetteville (Sub-basin 60), Elk River Local, Fayetteville to Prospect (Sub-basin 61), and Richland Creek at Mouth (Sub-basin 62). All of these Sub-basins required stream flow routing and hydrograph separation to convert the observed in-stream hydrographs to local inflow hydrographs before a comparison with the simulated inflow series could be made. The peaks for the simulated hydrographs in sub-basin 61 were moderately overpredicted; this is expected given that the storms used in simulation are significantly smaller than the storm used in the original unit hydrograph development.

Based on the preceding discussion, it is concluded that the unit hydrographs for the six sub-basins of the Wheeler Dam watershed (Sub-basins 53, 57, 59, 60, 61, 62) have each been validated against two recent floods. Considering that the unit hydrographs were developed from floods from the 1970s and earlier, and have been demonstrated in this calculation to be valid for events that occurred in more recent years, it is concluded that watershed characteristics and runoff processes have remained relatively stationary. It is also concluded that each of the unit hydrographs accurately describes the response of its catchment and is adequate for application to design storm events.

In almost all cases of discrepancies between observed and simulated storm hydrographs (where the "observed" or synthesized hydrographs are reliable), the problems may plausibly be attributed to uncertainties in the modeling of rainfall excess values with FLDHYDRO. Since the unit hydrographs have been demonstrated to provide a reasonable response to a unit of excess rainfall (i.e. good estimates of peak discharge, good timing of peaks, shape of hydrograph especially with respect to timing and the duration of rising and falling limbs), these unit hydrographs are valid for use in hydrologic studies to determine the Probable Maximum Flood (PMF) at the TVA Nuclear Plant sites (see Section 1).

8.1 Validated Unit Hydrographs

The six unit hydrographs developed by TVA from basins with observed, gaged stream flow data and gridded precipitation data were validated in this calculation for two recent floods. The quality of the simulation for each sub-basin is a function of the quality of the routing procedure and the complexity of the storm. For simple storms, unit hydrographs prepared in the 1970s were able to reasonably reproduce observed flood events. Complex storms and complicated routing lead to greater uncertainty in the accuracy of observed floods, however given the inherent uncertainty in hydrograph separation, reasonable simulations of observed floods were obtained. The key parameters associated with the unit hydrographs validated in this calculation are summarized in Table 19. The ordinates for all six unit hydrographs are summarized in Table 13 - 18 and are provided in spreadsheet form as Attachment 1-01 to facilitate use in subsequent modeling efforts.

Table 13 Validated Unit Hydrograph Ordinates for Sub-basin 53

Sub-basin 53 6-Hour Unit Hydrograph	
Time hrs	Flow cfs
0	0
6	146
12	16356
18	13348
24	3225
30	1978
36	731
42	502
48	381
54	231
60	0

Table 14 Validated Unit Hydrograph Ordinates for Sub-basin 57

Sub-basin 57 4-Hour Unit Hydrograph	
Time hrs	Flow cfs
0	0
4	815
8	3111
12	10618
16	1885
20	1223
24	785
28	466
32	379
36	291
40	0

Table 15 Validated Unit Hydrograph Ordinates for Sub-basin 59

Sub-basin 59 6-Hour Unit Hydrograph	
Time hrs	Flow cfs
0	0
6	17555
12	11834
18	9105
24	6588
30	4482
36	2378
42	1785
48	1192
54	959
60	725
66	491
72	257
78	0

Table 16 Validated Unit Hydrograph Ordinates for Sub-basin 60

Sub-basin 60 6-Hour Unit Hydrograph	
Time hrs	Flow cfs
0	0
6	2655
12	4999
18	7044
24	6321
30	4079
36	2664
42	1249
48	909
54	569
60	462
66	354
72	247
78	0

Table 17 Validated Unit Hydrograph Ordinates for Sub-basin 61

Sub-basin 61 6-Hour Unit Hydrograph	
Time hrs	Flow cfs
0	0
3	418
6	835
9	1462
12	2192
15	3132
18	4176
21	5429
24	6786
27	8039
30	8874
33	8665
36	8248
39	6995
42	6055
45	5116
48	4176
51	3550
54	3028
57	2506
60	2297
63	1984
66	1775
69	1670
72	1462
75	1357
78	1148
81	1044
84	940
87	731
90	626
93	418
96	209
99	104
102	0

Table 18 Validated Unit Hydrograph Ordinates for Sub-basin 62

Sub-basin 62 6-Hour Unit Hydrograph	
Time hrs	Flow cfs
0	0
3	55
6	110
9	165
12	220
15	2315
18	4409
21	6684
24	8959
27	10244
30	11529
33	10724
36	9919
39	8124
42	6329
45	4539
48	2750
51	2555
54	2360
57	2165
60	1970
63	1770
66	1570
69	1375
72	1180
75	985
78	790
81	590
84	390
87	195
90	0

8.2 Validated Routing Parameters

The routing equations and methods utilized by the TVA in modeling stream flow in the Wheeler Dam watershed have been validated by use in the models described in the body of this report and are suitable for appropriate, joint use with the unit hydrographs in subsequent hydrologic studies to determine the Probable Maximum Flood (PMF) at the TVA Nuclear Plant sites (see Section 1). The routing parameters are summarized in Table 19.

Table 19: Routing Parameters used in Hydrologic Modeling of the Wheeler Dam Watershed (Directly Validated Unit Hydrographs)

Unit Area	Stream	Reach	ARMA Routing Coefficients
60	Elk River	Tims Ford Dam to Fayetteville Stream Gage	O(T) = 1.00 × O(T–1) – 0.25 × O(T–2) + 0.0625 × I(T) + 0.125 × I(T–1)+0.0625 × I(T–2)
61	Elk River	Fayetteville to Prospect Stream Gage	O(T) =1.3463 x O(T-1)-0.3368 x O(T-2)-0.5610 x O(T-3) + 1.0240 x O(T-4) - 0.6025 x O(T-5) + 1.042 x O(T-6)- 0.0232 x I(T) + 0.1193 x I(T-1) + 0.2811 x I(T-2) – 0.5681 x I(T-3) + 0.4125 x I(T-4) - 0.1399 x I(T-5) – 0.3357 x I(T-6)