APPENDIX A

Hydrologic Modeling Methodology

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The goal of this study was to delineate the floodplains in the Pennypack watershed that result from four hypothetical (design) storms: The 25-year, 50-year, 100-year, and 500-year storms. The 100-year and 500-year storms were subsequently mapped in accordance with FEMA requirements.

General Description of the Site

The Pennypack watershed lies in the lower Delaware River Basin in Pennsylvania and discharges into the Delaware River in the City of Philadelphia. Most of the watershed is located in Montgomery County, and a small part is in Bucks and Philadelphia Counties. The watershed area is 56 square miles (Fig. 1), of which approximately 90 % lies upstream of the USGS gauge station at Rhawn Street in Philadelphia.

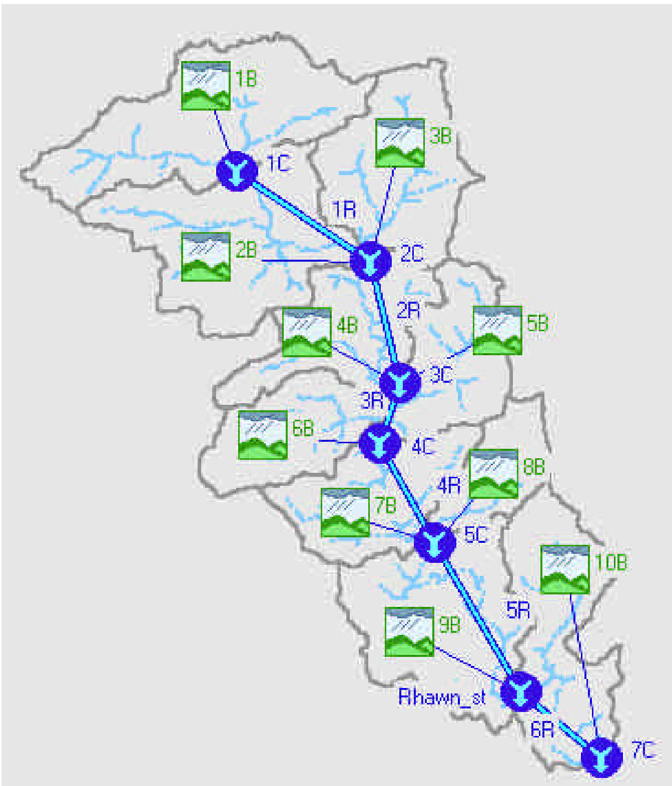


Figure 1: The Pennypack watershed. For hydrologic modeling purposes, the watershed was considered as consisting of 10 primary subbasins (e.g., 4B) and six reaches (e.g., 2R).

The topography of the Pennypack Watershed is characterized by gently rolling hills in the headwaters, and moderately sloping valley in the central part of the watershed, and tidal flats draining to the Delaware River. The elevations over the whole watershed range from 436 feet to less than 10 feet.

The climate of the region is characterized by warm summers and cold winters with moderate intermediate seasons. Winter temperatures rarely drop below 0°F, and summer temperatures do not often rise above 100°F. The mean annual temperature is 54°F and the average annual precipitation is 41.41 inches (at the Northeast Airport), as obtained from the NOAA site http://www.ncdc.noaa.gov/oa/ncdc.html.

The Hydrologic Model

For hydrologic modeling, the U.S. Army Corps of Engineers' (ACOE) software HEC-HMS was used. The watershed was treated as consisting of 10 subbasins, whose areas range from 2.6 to 8.3 $mile^2$ with an average of 5.5 $mile^2$. A curve number was computed for each subbasin based on Land Use Land Cover (LULC) data and soil type data. The outflows from the subbasins were assumed to pass through six Junctions as available from HEC-HMS. The junctions are designated by the symbols C in Figure 1 (e.g., junction 2C). They were connected to each other and to the outlet of the watershed by six reaches (designated by the symbol R in Figure 1, e.g., 3R). The routing of water flow through the reaches was conducted using the Modified Puls method, which required evaluation of the number of subreaches. In this work, the following approach was conducted for each reach.

1- A Hec-RAS model was developed using multiple cross sections at a spacing of 30 – 200 feet.
2- Different flow rates, varying from 100cfs to 30,000 cfs were routed.
3- The cumulative volume of water for each reach was recorded and a storage-outflow table was developed for each reach (see details under the section "reach properties").
4- An average travel time was determined for each reach based on the computational interval of 15 minutes. The number of sub-reaches was then computed.
5- The number of sub-reaches from 4) was allowed to change by $\pm$ 20% in matching simulated hydrographs to observed hydrographs at the USGS station (Rhawn Street).

The values of the hydrologic parameters are reported in Tables 1 and 2. These values were obtained in a two step process, where the values computed based on watershed characteristics (such as LULC, soil type, slope) were altered by calibration of the model to the outflow at the Rhawn street USGS station in Philadelphia. In general, the differences between the final and initial values were less than 5% for CN (Table 1) and 20% for the time lags (Table 1) and the travel times in reaches (Table 2).

Table 1: Subbasins Properties

Basin	Area ($mile^2$)	CN	Percent Impervious	Time lag (minute)
1B	8.314	80.53	13.34	126
3B	5.9627	77.93	11.64	116
2B	7.9365	80.03	21.32	122
4B	4.9918	74.3	2.37	95
5B	4.1826	77.45	7.41	102
6B	3.9409	77.7	6.8	85
7B	4.7719	74.92	5.14	98
8B	2.6074	74.97	22.39	128
9B	7.1235	73.13	25.49	145
10B	6.0329	76.71	34.97	182

Table 2: Reach Properties				
Reach ID	Length (feet)	Width (feet)	Slope (ft/ft)	Manning's n
1R	17691	15	0.003	0.035
2R	15963	20	0.0017	0.035
3R	1782	25	0.0047	0.035
4R	16502	25	0.0008	0.035
5R	28211	30	0.0018	0.035
6R	18306	30	0.0008	0.035

Hydrologic Data

The landuse data were obtained from the DVRPC at the 1/2,000 resolution based the year 2000 aerial imagery. The soil type data were obtained from the PASDA website (http://www.pasda.psu.edu/) at the resolution 1/24,000, which is the highest available from NRCS. Streamflow data used for calibration were obtained from the USGS Station 01467048 located approximately at Rhawn Street. The website is http://waterdata.usgs.gov/pa/nwis/uv. Rainfall data of previous storms were obtained from the Philadelphia Water Department. These were NEXRAD Level 111 estimates adjusted to about 24 ground rain gauge readings. The total amounts of rainfall for use in the design storms were obtained from the NOAA website http://hdsc.nws.noaa.gov/hdsc/pfds/. At the location (Lat=40.1; Long=-75.3), the upper 95% confidence gave 6.28, 7.19, 8.18, 10.81, for the 25, 50, 100, and 500 year storms. The temporal distribution of rainfall pulses for the design storms for the area are of the SCS Type II.

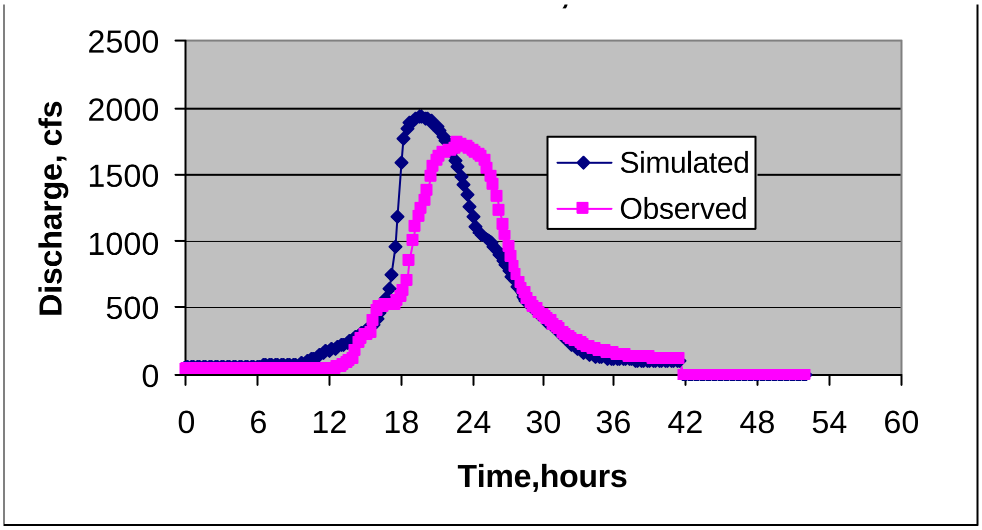
Calibration

Eight storms were used for the calibration. They are listed in Table 3 below along with the total amount of rainfall and the runoff duration. The automatic calibration option in HEC-HMS was not used because it provided a different set of parameters for each storm. We elected to adjust the parameters based on heuristic arguments and to put a special effort on matching the peak value and the time to peak. This resulted in a unique set of parameters, reported in Tables 1 and 2.

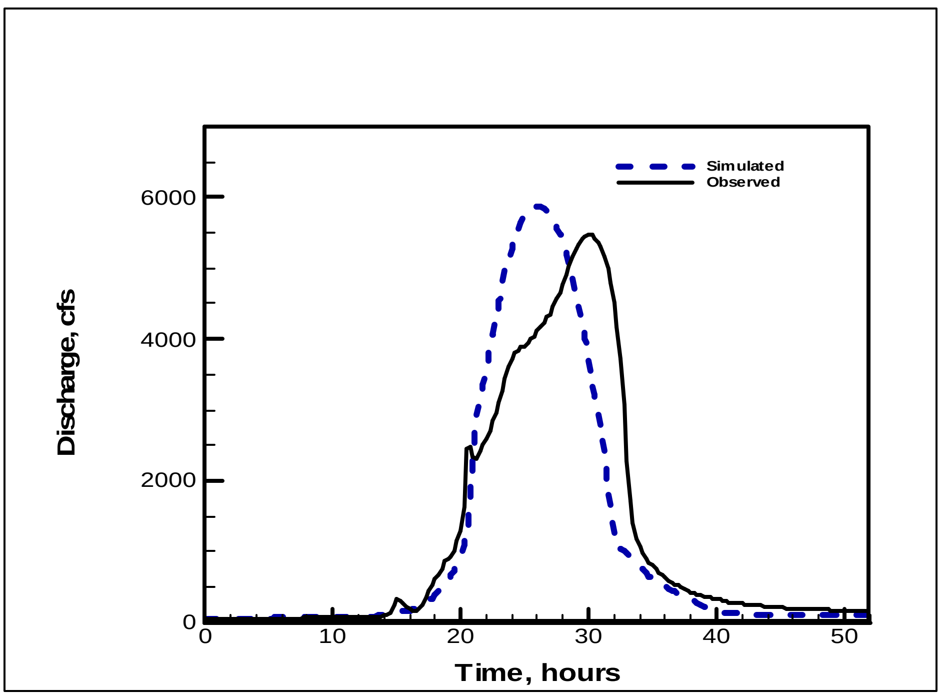
Table 3: Rainfall Events Used for Calibration		
#	Date	Total Rainfall (inch)
1	October 08, 96	2.00
2	October 16, 96	3.46
3	September, 99 (1)	7.03
4	November, 99	1.12
5	December, 99	1.65
6	March, 2002	1.15
7	May, 2002	1.50
8	June, 2002	1.62

(1): Hurricane Floyd

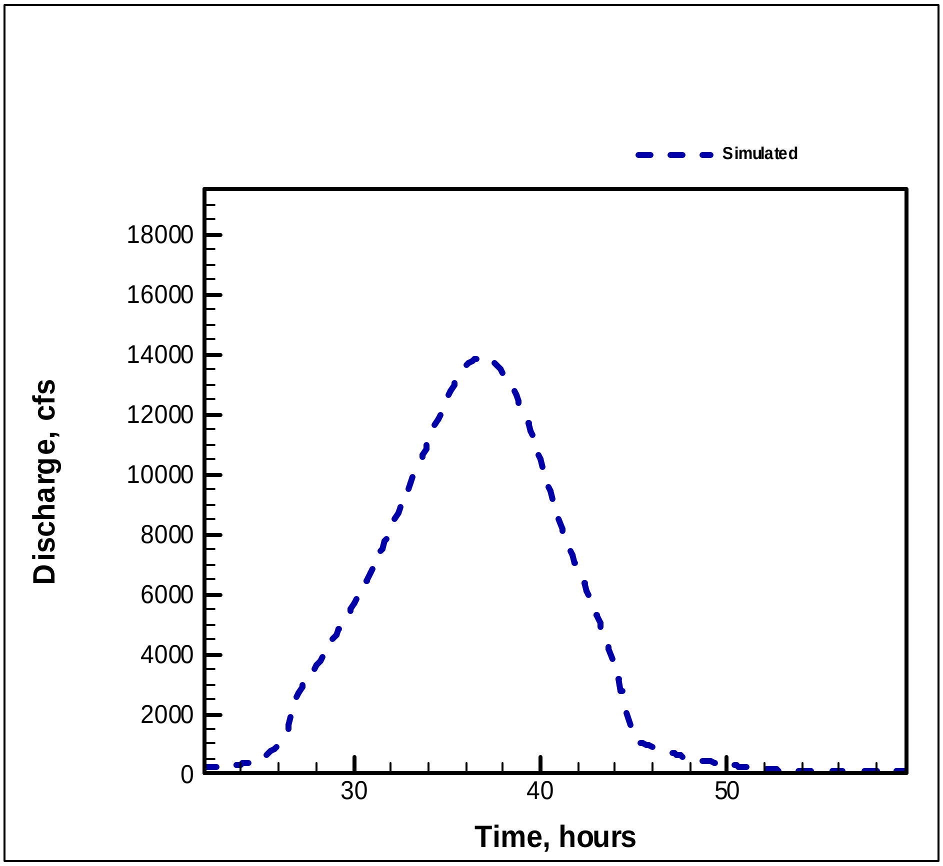
The graphs below show the comparison between predicted (or simulated) runoff and those observed.



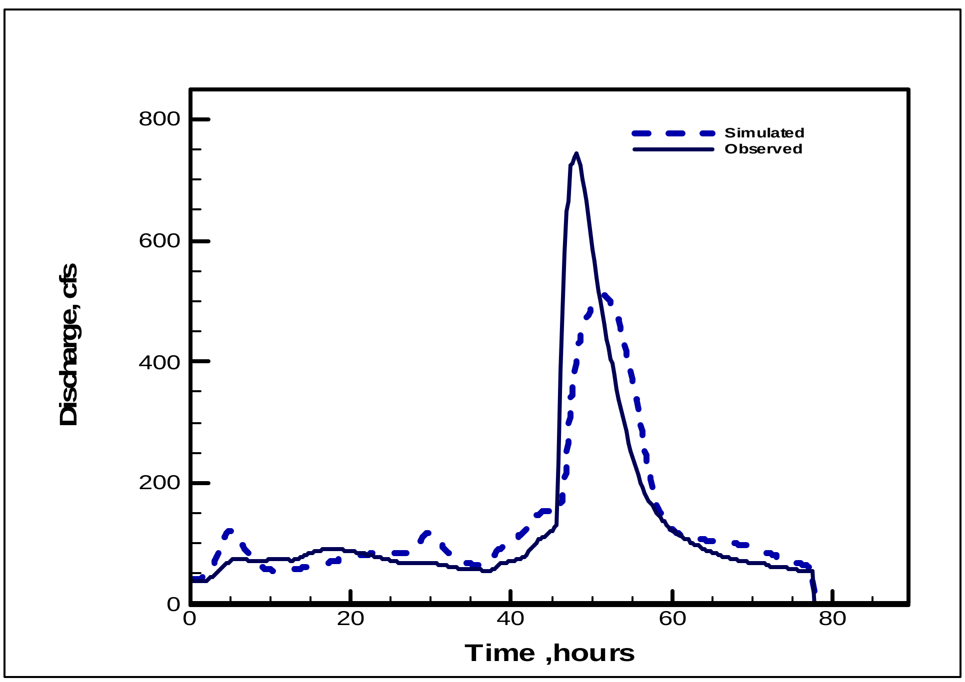
Storm 1 October 08, 96



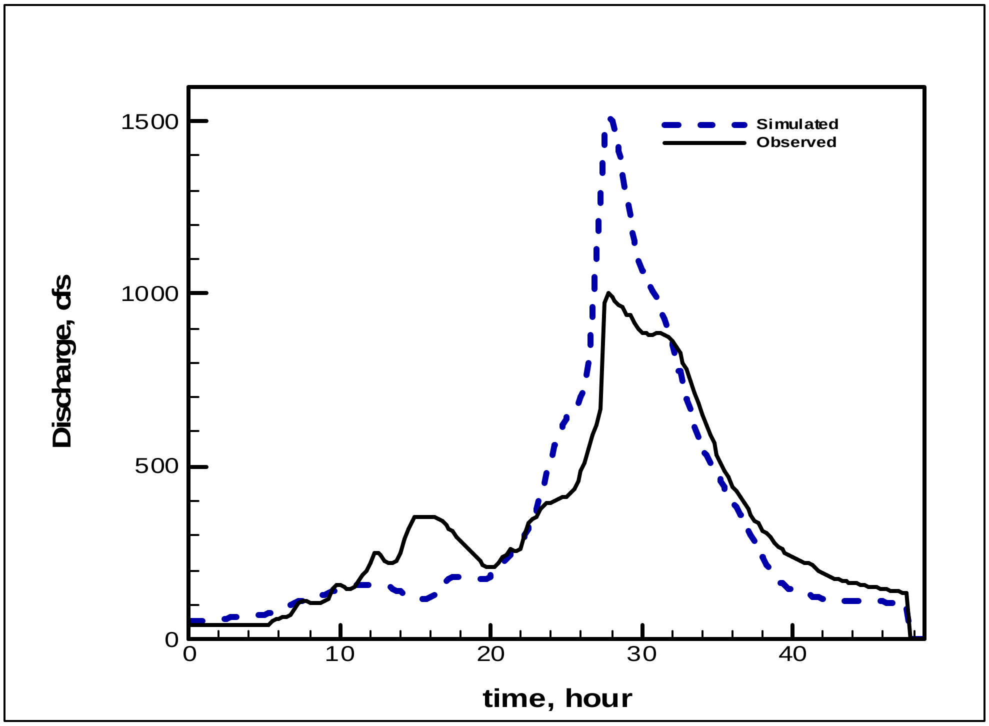
Storm 2 October 18, 96



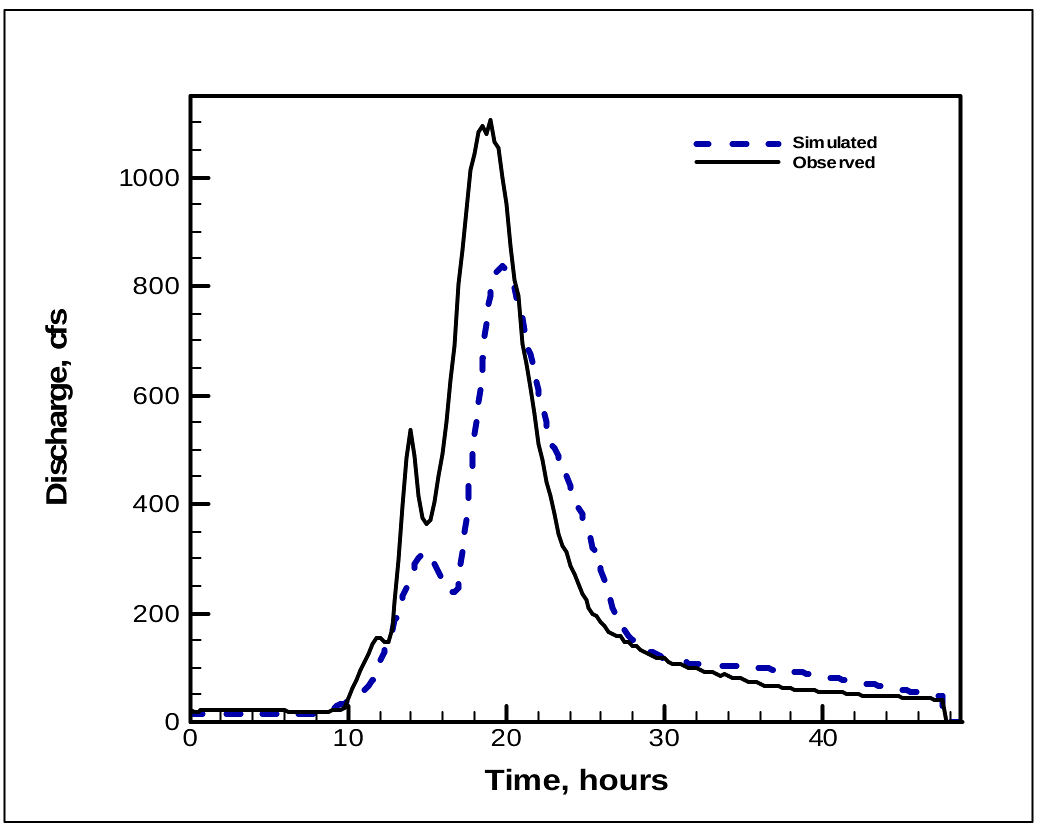
Storm 3 September 99 (Floyd)



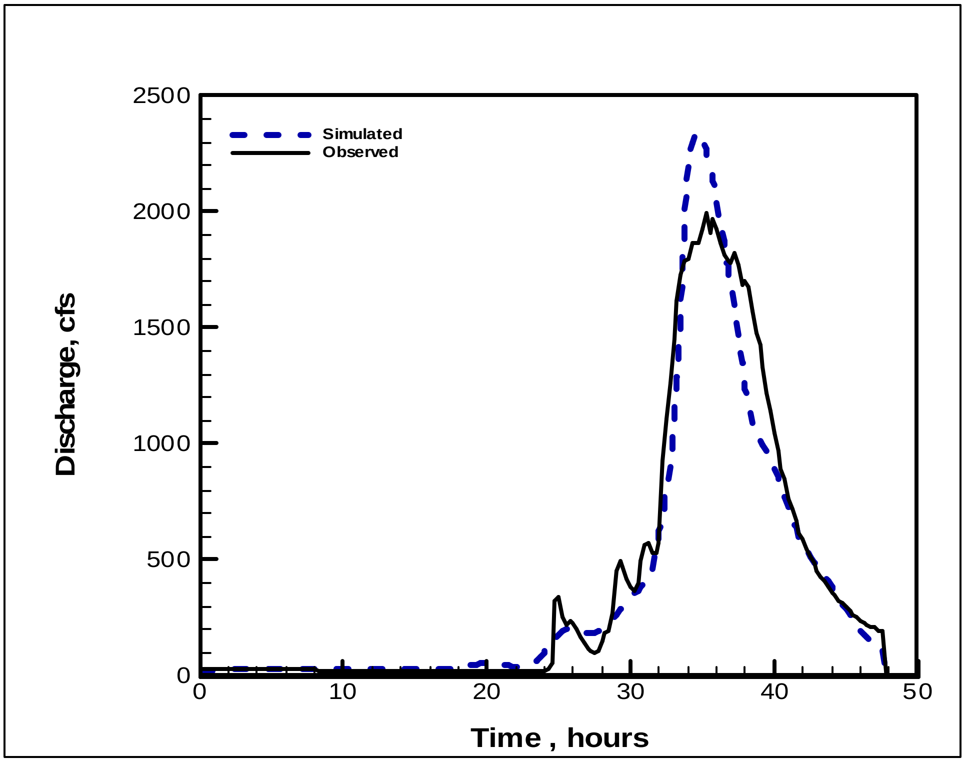
Storm 4 November 99



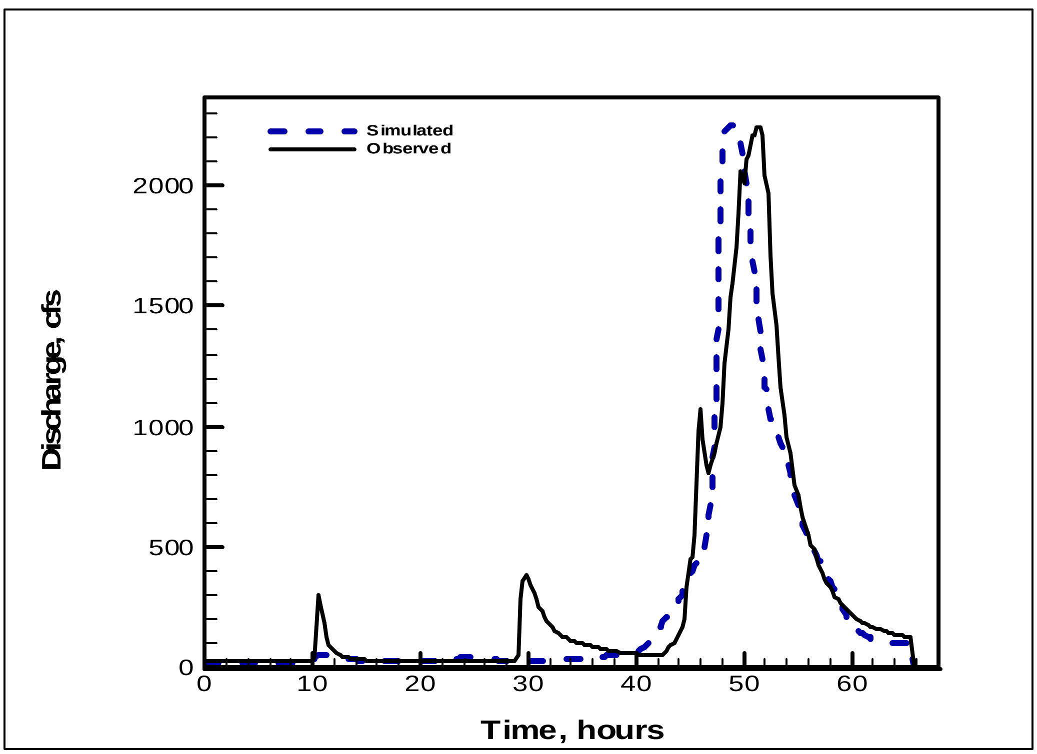
Storm 5 December, 99



Storm 6 March, 2002



Storm 7 May, 2002



Storm 8 June, 2002

Reach Properties

Reach One		
Discharge (cfs)	Volume (Acre-foot)	Travel Time (hour)
100	27.42	2.52
250	51.42	2.05
500	94.69	1.81
1000	191.09	1.75
2000	422.08	2.23
4000	914.35	2.57
7000	1398.22	2.27
10000	1835.37	2.09
15000	2593.17	1.96
20000	3369.15	1.9
25000	4102.78	1.85
30000	4786.73	1.81

Reach Two		
Discharge (cfs)	Volume (Acre-foot)	Travel Time (hour)
100	26.71	2.99
250	37.93	1.72
500	53.86	1.23
1000	80.72	0.93
2000	166.91	0.95
4000	347.12	0.93
7000	655.66	1.01
10000	996.55	1.09
15000	1481.48	1.08
20000	1823.04	1.02
25000	2158.92	0.97
30000	2511.59	0.96

Reach Three		
Discharge (cfs)	Volume (Acre-foot)	Travel Time (Hour)
100	11.49	1.32
250	15.15	0.71
500	20.5	0.48
1000	31.44	0.37
2000	87.98	0.49
4000	259.84	0.56
7000	572.1	0.68
10000	827.52	0.73
15000	1257.24	0.83

20000	1492.83	0.76
25000	1809.15	0.76
30000	1926.97	0.68

Reach Four		
Discharge (cfs)	Volume (Acre-foot)	Travel Time (Hour)
100	39.28	4.03
250	58.65	2.57
500	82.91	1.88
1000	121.26	1.4
2000	186.73	1.08
4000	341.1	1
7000	588.5	0.99
10000	813.91	0.96
15000	1205.42	0.92
20000	1463.39	0.83
25000	1739.85	0.78
30000	2001.36	0.75

Reach Five		
Discharge (cfs)	Volume (Acre-foot)	Travel Time (Hour)
100	88.95	9.94
250	130.46	5.95
500	228.48	5.28
1000	360.36	4.21
2000	457.72	2.52
4000	769.35	2.19
7000	1306.06	2.13
10000	1794.46	2.08
15000	2677.56	2.07
20000	3209.88	1.86
25000	3534.6	1.64
30000	4592.11	1.78

Reach Six		
Discharge (cfs)	Volume (Acre-foot)	Travel Time (Hour)
100	186.45	21.45
250	195.57	9.02
500	210	4.92
1000	238.66	2.82
2000	301.58	1.77
4000	474.16	1.4
7000	786.51	1.32

10000	1210.83	1.42
15000	1904.16	1.48
20000	2368.76	1.39
25000	2602.68	1.22
30000	2989.46	1.17

Channel routing – Number of sub-reaches calculation					
Reach ID	Length (ft)	Ave. Travel-Time (hr) [(1)]	Selected Trav-Time (hr) [(2)]	Corresponing-Flow(cfs) [(3)]	No. of Sub-Reaches [(4)]
1	18180	2.0675	2.25	250-25000	6
2	15320	1.24	1	500-30000	3
3	4165	0.6975	0.75	2000-30000	2
4	16689	1.4325	1	2000-30000	3
5	28227	3.4708	2	4000-30000	5
6	19329	4.115	1.5	2000-30000	4

[(1)] HEC-RAS ‘travel time ave.’ averaged over the 12 flow rates (100 cfs to 30,000 cfs).
[(2)] Travel time based on the most likely flow rates involved during a 100 yr flood.
[(3)] The flow rate for which the selected travel time values are reasonable.
[(4)] Number of Sub-Reaches= (Selected Travel Time / 1.5) / (Time interval) where:
1.5 = Ratio of wave velocity / average flow velocity; time interval =0.25 hrs. (15 min.)