Karst Hydrograph Characterization Report

Wolf Run Watershed
Fayette County, Kentucky

Prepared for
Kentucky Division of Water
200 Fair Oaks Lane
Frankfort, KY 40601
and
Lexington-Fayette Urban County Government
Division of Environmental Quality

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Environmental Analysis & Restoration

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I. INTRODUCTION

This report summarizes survey results for the karst hydrograph characterization study in the Wolf Run watershed. The survey was conducted under a Section 319(h) Nonpoint Source Implementation Program Cooperative Agreement (#C9994861-09) awarded by the Commonwealth of Kentucky, Energy and Environment Cabinet, Department for Environmental Protection, Division of Water (KDOW) to Lexington-Fayette Urban County Government (LFUCG) based on an approved work plan. The survey was conducted by Third Rock staff, according to the preapproved *Quality Assurance Project Plan* (QAPP, Third Rock 2011).

The Wolf Run watershed has significant karst development, which must be considered during pollutant loading calculations because it can influence the decision making process during development of the action plan. In particular, local karst deviation from surface watershed boundaries adds drainage area to Wolf Run. Based on dye traces, a substantial fraction of both the Vaughn's Branch and main stem of Wolf Run sub-watersheds are captured by the Prestons (McConnell) Spring Basin (Recker and Meiman, 1990 and Spangler, 1992). During base flow and drier conditions most of the surface water in the karst-influenced fractions of these sub-watersheds is directed to Prestons Spring. During high flow conditions the surface component of the discharge becomes greater as the karst system conduit limits are approached.

To determine the influence of the karst system on the discharge and the nature of the stream hydrograph, simultaneous gaging of the three affected tributaries and a major sinkhole was performed during base flow conditions and during a wet weather event. Temporary water level gages (pressure transducers with data loggers) were installed at each of the five gaging stations. The objective of this study was to improve modeling of the stream flow.

II. METHODS

In order to measure the stream hydrograph of tributaries affected by karst systems, a combination of in-stream flow measurements and temporary water level gages was utilized at six locations as shown in Exhibit 1 and summarized in Table 1. The six gaging locations in the watershed allow for the evaluation of the discharge at the mouth of the watershed (W1), Prestons Spring (W2), Vaughn’s Branch tributary (W4), Wolf Run upstream of Cardinal Run (W6), Wolf Run at the edge of the karst basin (W9), and Big Elm Tributary, which flows into the sinkhole at Picadome (W11). In the event that the capacity of the sinkhole downstream of W11 was exceeded and surface water flowed from Big Elm Tributary into Vaughn’s Branch, this surface flow was also to be measured at W11A.

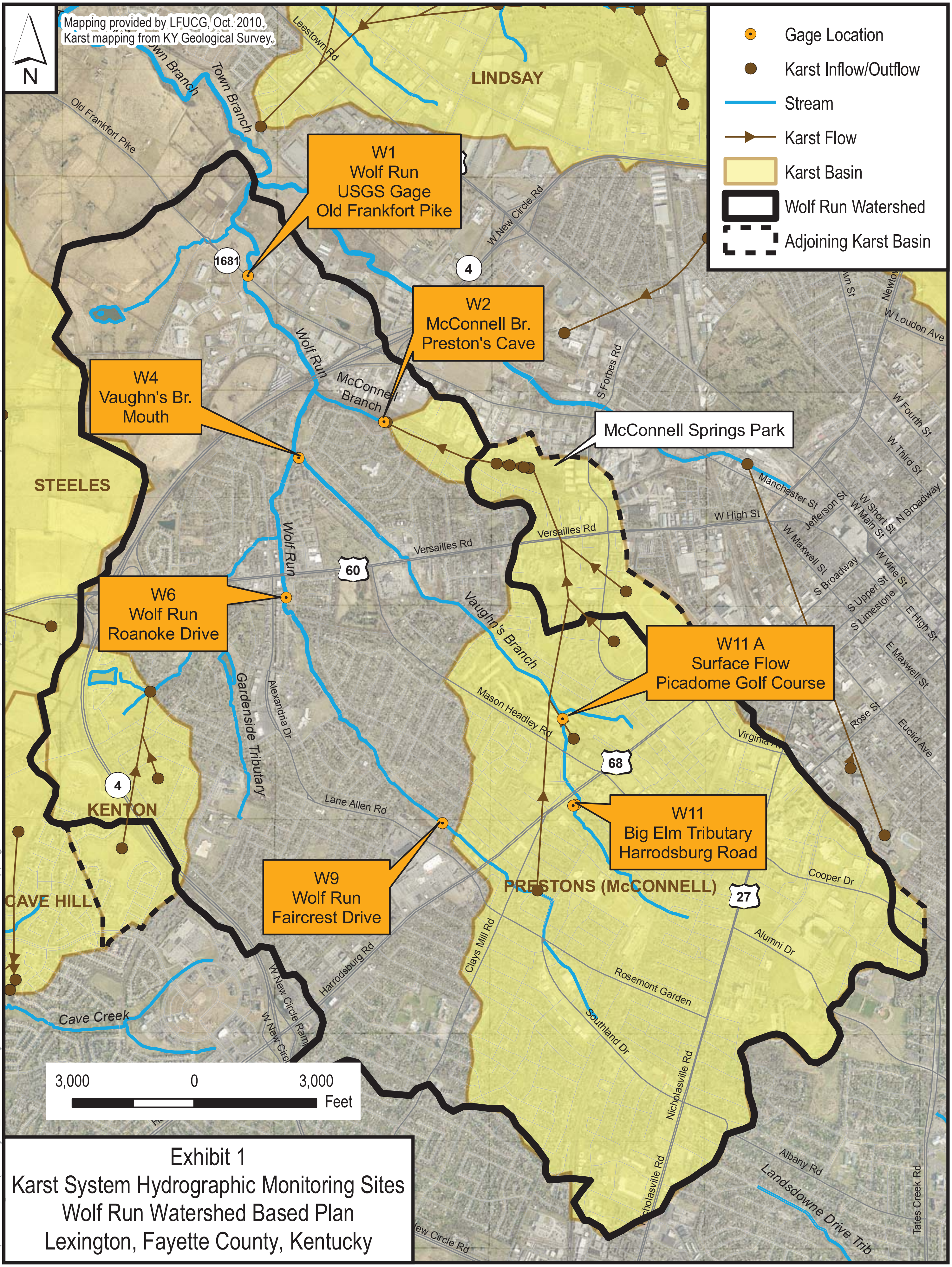


Exhibit 1
Karst System Hydrographic Monitoring Sites
Wolf Run Watershed Based Plan
Lexington, Fayette County, Kentucky

Map Document: (P:\Project_Files\Kentucky\KY10-030_LFUCG_WolfRun\Mapping\GIS\QAPP_Exhibits\Exhibit_1_Karst_System.mxd) 6/20/2012 -- 2:21:32 PM sje

TABLE 1 – MONITORING LOCATIONS

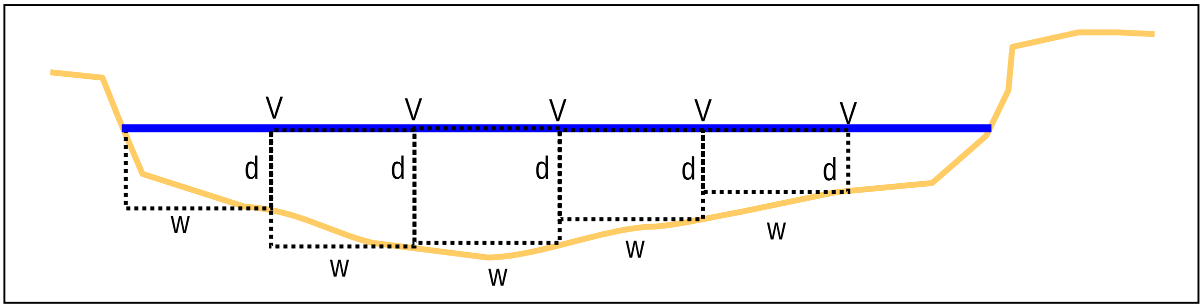
Site Name	Stream	Location	Latitude	Longitude	Upstream Acreage
W01	Wolf Run	Old Frankfort Pike	38.067303	-84.554182	6614[1,2]
W02	McConnell Branch	Prestons Cave	38.057333	-84.542169	418[1]
W04	Vaughn's Branch	Valley Park	38.054904	-84.549624	1966
W06	Wolf Run	Wolf Run Park	38.045274	-84.550661	2234
W09	Wolf Run	Faircrest Dr	38.029954	-84.537091	1024
W11	Big Elm Tributary	Harrodsburg Road	38.031245	-84.526027	581
W11A	Big Elm Tributary	Picadome Golf Course	38.037494	-84.527095	[3]

[1]Includes 402 acres of misbehaved karst in the Town Branch watershed that flow to McConnell Springs.
[2]Includes 121 acres of misbehaved karst in the South Elkhorn watershed that flow to the Kenton Blue Hole.
[3]Site located at confluence with Vaughn's Branch; site flows only under excessive rainfall when the Picadome sinkhole is overwhelmed.

Data loggers were installed on June 13, 2011 and began recording in-stream water levels every five minutes, with the intention to also field measure flow during one base flow event and one wet weather event of at least 1 inch of rainfall by August 2011 if weather conditions allowed. In-situ LevelTROLLs were installed inside PVC pipes attached to firmly anchored stakes or permanent in-stream structures such as trees along the bank. After the loggers were installed, the caps of the PVC pipes were cemented to prevent theft or damage. A BaroTROLL was also installed outside of Third Rock's office to allow readings to be calibrated for barometric pressure. A Rugged-Reader was used to download the loggers at the end of the monitoring period.

Stream flow (Q) was calculated using two variables, flow area (A) and water velocity (V), according to the equation: $Q = AV$. Flow measurements were conducted according to the KDOW's *Measuring Stream Discharge Standard Operating Procedure* (KDOW 2010b). A Marsh McBirney Flo-Mate Portable Flowmeter was used with a top-setting wading rod to measure the flow. Because the velocity is variable across a stream cross-section, the flow area and velocity were measured in specified intervals across the stream, as shown in Figure 2. The velocity and depth and width measurements were recorded in a bound field book, and flow measurements were calculated in the office according to the equations specified in KDOW 2010b. For the wet weather event, flow measurements were performed by two teams of surveyors circulating to each of the five gaging points. The goal was to measure flow at each of the points at a minimum of every thirty minutes during the storm event, continuing until well past the hydrograph peak.

FIGURE 1 – MEASUREMENT OF STREAM FLOW THROUGH SUB-SECTIONAL MEASUREMENTS



Note: Stream cross-section showing intervals where water depth and velocity are measured. Flow will be calculated for each "box" (flow area for each box is d * w) and summed to obtain the flow for the entire stream.

Due to the difficulty of coordinating monitoring for a rain event greater than 1 inch, loggers recorded data from June 13 until December 2, 2011. Because the caps were cemented in place to prevent theft, loggers could not be downloaded until after the wet event was monitored. During a wet weather event of 1.94 inches of precipitation on November 28, as recorded at the Bluegrass airport (www.wunderground.com), two measurements were made at each location except W01. Three measurements were recorded at W06. More measurements could not be made during the event because of the time required to make each measurement. Although fewer measurements were made during a single wet weather event than expected, more events were measured than initially planned. In total, flow was measured during 11 monitoring events conducted during the period of data logger recording.

Because the higher flow levels were under-represented in the measured stream flow dataset, flows for higher stages were calculated using using a resistance equation. Hydrogeomorphic assessment data including longitudinal profiles, cross-sectional areas, and pebble counts were utilized to predict flow across the range of recorded depths using Manning's equation in *RiverMorph*, a stream assessment software. Flows were predicted at 0.1 ft intervals over the logger measured depth range for the measured cross-section using slope measured from the longitudinal profile data and using the limerinos equation with the D84 pebble size as input for the roughness value.

Measured stream flows and *RiverMorph* calculated flows were used to develop discharge ratings using simple stage-discharge relations following Rantz *et al.,* 1983. These rating curves were then used to convert the full range of logger stage measurements to stream flows.

III. RESULTS

A. Stream Flow Measurements

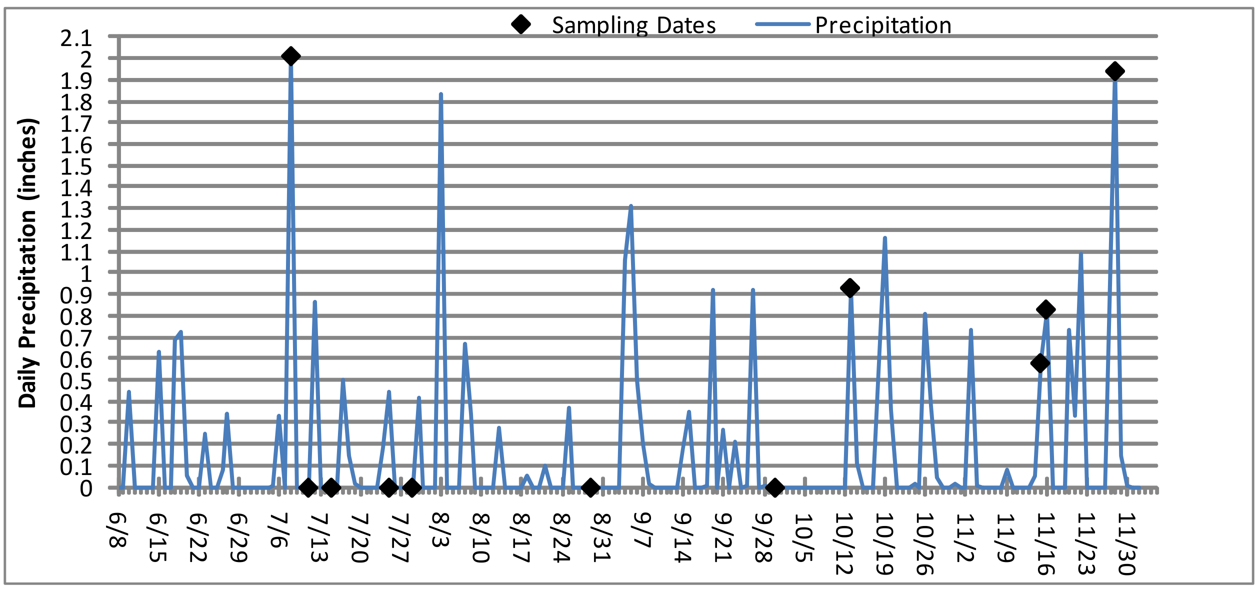
Stream flow measurements were performed on 11 days as shown in Table 2. Six monitoring events were conducted during base flow while five events measured stream flow during precipitation. Two events were conducted during storms where more than 1" of daily rainfall was recorded at the Bluegrass airport. The monitoring dates in relation to the daily precipitation are shown in Figure 2. Precipitation was recorded on 62 of the 185 days in which the data loggers were deployed, or 34% of the days in the monitoring period. Of the 62 days in which precipitation was recorded, only 8 had over 1" of rainfall.

TABLE 2 – MONITORING DATES AND DAILY RAINFALL

Date	Daily Rainfall (in)	Comments
7/8	2.01	Measured during precipitation
7/11	0	Base flow
7/15	0	Base flow
7/25	0.44	Base flow, measured prior to precipitation
7/29	0	Base flow
8/29	0	Base flow
9/30	0	Base flow
10/13	0.93	Measured during precipitation
11/15	0.58	Measured during precipitation
11/16	0.83	Measured during precipitation
11/28	1.94	Measured during precipitation

NOTE: Precipitation values based on KLEX weather station data from http://www.wunderground.com.

FIGURE 2 – PRECIPTATION DURING MONITORING PERIOD



NOTE: Precipitation values based on KLEX weather station data from http://www.wunderground.com.

The monitoring times and measured flows at each site are shown in Table 3. A total of 66 flow measurements were recorded at the seven sites, with 10 or more measurements recorded at each site. Only two flow measurements were recorded at W11A, which only flows when the capacity of the sinkhole at the mouth of the Big Elm Tributary is exceeded and the water crosses several golf course fairways to drain into Vaughn's Branch. On July 8, stream velocities were too fast to allow for safe measurement conditions at all but two sites. Pooled or no flow events were also recorded when observed. Because the times for most events indicate the time at which grab sampling was conducted, the actual flow measurement times can vary by up to 30 minutes from the times indicated in Table 3. In addition, due to daylight savings time adjustments, data logger times after 2 AM on November 6 are one hour behind field recorded times.

TABLE 3 – MEASURED STREAM FLOW

<table>
<tr><th>Date</th><th colspan="7">Time*</th><th colspan="7">Measured Stream Flow (cfs)</th></tr>
<tr><th>Site</th><th>W01</th><th>W02</th><th>W04</th><th>W06</th><th>W09</th><th>W11</th><th>W11A</th><th>W01</th><th>W02</th><th>W04</th><th>W06</th><th>W09</th><th>W11</th><th>W11A</th></tr>
<tr><td>7/8/2011</td><td>10:08</td><td>10:43</td><td>11:21</td><td>12:24</td><td>11:30</td><td>11:38</td><td rowspan="8">N/A</td><td>36.2</td><td>15.6</td><td>Too Fast</td><td>Too Fast</td><td>Too Fast</td><td>Too Fast</td><td rowspan="8">N/A</td></tr>
<tr><td>7/11/2011</td><td>9:30</td><td>10:05</td><td>10:25</td><td>11:35</td><td>11:15</td><td>12:00</td><td>7.8</td><td>4.2</td><td>0.4</td><td>1.6</td><td>0.4</td><td>0.6</td></tr>
<tr><td>7/15/2011</td><td>9:35</td><td>9:35</td><td>10:30</td><td>9:50</td><td>9:35</td><td>10:00</td><td>6.3</td><td>3.9</td><td>1.7</td><td>1.1</td><td>0.1</td><td>0.2</td></tr>
<tr><td>7/25/2011</td><td>10:15</td><td>10:50</td><td>11:20</td><td>12:30</td><td>11:05</td><td>11:35</td><td>6.3</td><td>4</td><td>2.8</td><td>3.1</td><td>2</td><td>1.6</td></tr>
<tr><td>7/29/2011</td><td>9:35</td><td>10:20</td><td>11:00</td><td>12:10</td><td>10:45</td><td>10:30</td><td>1.9</td><td>1.4</td><td>Pooled</td><td>0.26</td><td>Pooled</td><td>0.05</td></tr>
<tr><td>8/29/2011</td><td>9:23</td><td>9:46</td><td>10:38</td><td>11:35</td><td>10:20</td><td>11:00</td><td>1.1</td><td>0.8</td><td>0.03</td><td>0.2</td><td>0.01</td><td>No flow</td></tr>
<tr><td>9/30/2011</td><td>9:39</td><td>10:11</td><td>11:25</td><td>13:20</td><td>11:15</td><td>11:45</td><td>10.9</td><td>2.4</td><td>0.4</td><td>1.1</td><td>0.12</td><td>0.14</td></tr>
<tr><td>10/13/2011</td><td>14:00</td><td>13:10</td><td>12:25</td><td>12:00</td><td>13:40</td><td>12:15</td><td>69.9</td><td>8.6</td><td>13.3</td><td>0.04</td><td>39.6</td><td>1.9</td></tr>
<tr><td>11/15/2011</td><td>8:30</td><td>9:00</td><td>9:30</td><td>8:17</td><td>8:40</td><td>9:10</td><td>9:10</td><td>12.3</td><td>4.8</td><td>0.9</td><td>3.1</td><td>0.5</td><td>1.5</td><td>No flow</td></tr>
<tr><td>11/16/2011</td><td>9:35</td><td>11:10</td><td>11:50</td><td>13:00</td><td>11:05</td><td>12:00</td><td>12:00</td><td>47.9</td><td>16.8</td><td>5</td><td>12.1</td><td>6.2</td><td>4.8</td><td>No flow</td></tr>
<tr><td rowspan="3">11/28/2011</td><td rowspan="3">N/A</td><td>11:15</td><td>11:35</td><td>9:45</td><td>10:10</td><td>10:20</td><td>10:55</td><td rowspan="3">N/A</td><td>38.8</td><td>61.7</td><td>106.6</td><td>46.5</td><td>34.9</td><td>29.8</td></tr>
<tr><td>13:30</td><td>13:45</td><td>12:20</td><td>12:45</td><td>12:55</td><td>13:10</td><td>39.3</td><td>52.4</td><td>91.9</td><td>43.4</td><td>22.7</td><td>29.5</td></tr>
<tr><td colspan="2">N/A</td><td>14:00</td><td colspan="3">N/A</td><td colspan="2">N/A</td><td>65.22</td><td colspan="3">N/A</td></tr>
<tr><td colspan="8">Maximum Flow</td><td>69.9</td><td>39.3</td><td>61.7</td><td>106.6</td><td>46.5</td><td>34.9</td><td>29.8</td></tr>
<tr><td colspan="8">Minimum Flow</td><td>1.05</td><td>0.8</td><td>0.03</td><td>0.04</td><td>0.01</td><td>0.05</td><td>0</td></tr>
</table>

*Field times corrected for daylight savings time. For correspondent data logger times after 2 AM on November 6, add one hour.
NOTE: NA indicates the site was not measured at this time.

B. Logger Stage Data

Data loggers were deployed at five sites for 185 days from June 13 to December 2, 2011. Pressure readings were recorded at five-minute intervals over this period for a total of over 49,500 measurements at each site. These pressure readings were merged with logger measurements of barometric pressure to generate the depth of water above the sensor at each site. Field measurements of the data logger sensor depth from the lowest point in the stream were recorded in order to calculate the stream depth. Data was then plotted and reviewed to eliminate noise from the dataset.

Table 4 provides a summary of the logger data for each site. The depth of the logger from the stream bottom ranged from 1 to 3 inches due to the logger construction and the location of the installation within the stream. Review of the data indicated that results were valid at minimum depths ranging from 3.0 to 5.28 inches. At these depths, only 20 to 51% of the measurements recorded over the period were valid for a given site. Based on comparison of maximum logger depths to field cross-sectional measurements, out of channel flooding occurred only at W06, Wolf Run at Roanoke Drive, and W11, Big Elm Tributary, during the monitoring period.

TABLE 4 – DATA LOGGER SUMMARY

Site	Site Description	Logger Type	Depth of Sensor from Bottom (ft)	Depth of Valid Data (ft)	% Valid	Maximum Depth Recorded (ft)	Top of Bank (ft)	Time Difference from USGS Gage (min)
W01	Wolf Run at Mouth	USGS	N/A	0.00	100%	5.56	N/A	0
W02	McConnell Branch	LevelTROLL	0.23	0.43	20%	1.04	1.5	+2
W04	Vaughn's Br at Mouth	LevelTROLL	0.21	0.25	29%	3.76	4.1	+1
W06	Wolf Run at Roanoke Dr	LevelTROLL	0.08	0.27	51%	4.24	3.0	+3
W09	Wolf Run at Faircrest Dr	LevelTROLL	0.15	0.31	21%	2.03	2.2	0
W11	Big Elm Tributary	LevelTROLL	0.25	0.44	38%	4.58	4.1	0

Charts showing the valid logger measurements for the duration of the monitoring period are found in Appendix A.

C. Stage-Discharge Rating Curves

Measured stream flows and *RiverMorph* calculated flows were used to develop discharge ratings using simple stage-discharge relations following Rantz *et al*., 1983. Rating curves were developed using the equation for simple stage-discharge relations,

Q = p (G-e)^N

where

Q = Stream flow (cfs);
G = Gage height of the water surface (ft);
e = mathematical constant to preserve logarithmic linearity;
p = constant equal to flow (cfs) when (G- e) equals 1.0 ft; and
N = slope of the rating curve.

The final equations developed for each site are shown in Table 5, as well as the coefficients of determination (R^2 values) associated with the field measured flows and the *RiverMorph* calculated flows for each site. For some locations, different rating curves are used based on the depth of the water in order to improve the fit of the curve to the data. R^2 values were calculated by the following equation:

$$R^2 = 1 - \left(\frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2} \right)$$

where

f is the modeled value
y is the field measured or *RiverMorph* calculated values

R^2 values are used to indicate the goodness of fit of a curve to a given dataset and range from 0 to 1, with a value of 1.0 indicating a perfect fit. As expected for calculated values, the stage-discharge rating curves had good fits for the *RiverMorph* calculated flows,, with R^2 ranging from 0.942 to 0.999. Field measured flows had much poorer fits, with R^2 values ranging from 0.051 to 0.880.

TABLE 5 – STAGE-DISCHARGE RATING CURVE SUMMARY

Site	Depth Range (ft)	Stage-Discharge Rating Curve Equation	R^2 RiverMorph Flows	R^2 Field Measured Flows
W02	0.43 – 1.04	Q = 36(Stage + 0.09)^2.90	0.942	0.87
W04	0.25 – 1.00	Q = 41(Stage - 0.07)^2.3	0.954	0.823
	1.00 – 3.76	Q = 23.44(Stage + 0.1)^2.21		
W06	0.27 – 0.85	Q = 46(Stage - 0.17)^1.9	0.997	0.694
	0.85 – 4.24	Q = 52(Stage - 0.17)^2.21		
W09	0.31 – 1.00	Q = 35(Stage - 0.0)^2.7	0.995	0.051
	1.00 - 2.03	Q = 54(Stage - 0.2)^1.9		
W11	0.44 – 2.50	Q = 15.71(Stage - 0.2)^1.7	0.999	0.88
	2.50 - 4.58	Q = 12.4(Stage - 0.2)^2.0		

Lack of agreement between the rating curves and the field measured flows may in part be due to the flashiness of the stream, the low number of measurements associated with valid logger data, and the variance within the recorded times of measurement. Table 6 indicates the variation in the data logger depth measurements over a period one hour before and after each recorded measurement time. While loggers are relatively stable during base flows with a maximum variance of 0.11 ft, most of the logger data associated with these measurements is not valid. During precipitation events, logger measurements varied up to 1.11 ft within an hour of the measurement time.

The stage-discharge rating curves for each site, *RiverMorph* flows and field measured flows are shown in Figures 3 through 7 below.

TABLE 6 – VARIATION IN GAGE DEPTHS WITHIN ONE HOUR OF RECORDED MEASUREMENT TIMES

Date	Event Type	Variation in Gage Depths (ft)					
		W02	W04	W06	W09	W11	Maximum
7/8/2011	Precipitation	0.25					0.25
7/11/2011	Base Flow	0.02	0.07	0.03	0.02	0.11	0.11
7/15/2011	Base Flow	0.08	0.02	0.01	0.02	0.02	0.08
7/25/2011	Base Flow	0.02	0.11	0.1	0.09	0.09	0.11
7/29/2011	Base Flow	0.02	0.02	0.01	0.02	0.02	0.02
8/29/2011	Base Flow	0.02	0.02	0.01	0.02	0.01	0.02
9/30/2011	Base Flow	0.03	0.02	0.02	0.1	0.02	0.1
10/13/2011	Precipitation	0.03	0.38	0.78	0.82	1.11	1.11
11/15/2011	Precipitation	0.02	0.04	0.03	0.02	0.08	0.08
11/16/2011	Precipitation	0.04	0.04	0.4	0.1	0.15	0.4
11/28/2011	Precipitation	0.03	0.18	0.14	0.07	0.08	0.18
11/28/2011	Precipitation	0.02	0.29	0.3	0.23	0.18	0.3
11/28/2011	Precipitation			0.2			0.2
Minimum		0.02	0.02	0.01	0.02	0.01	
Maximum		0.25	0.38	0.78	0.82	1.11	

NOTE: Variation was assessed based on maximum and minimum depths with one hour before and after the recorded measurement time.

FIGURE 3 – MCCONNELL BRANCH AT PRESTON'S CAVE (W02) STAGE-DISCHARGE RATING CURVE

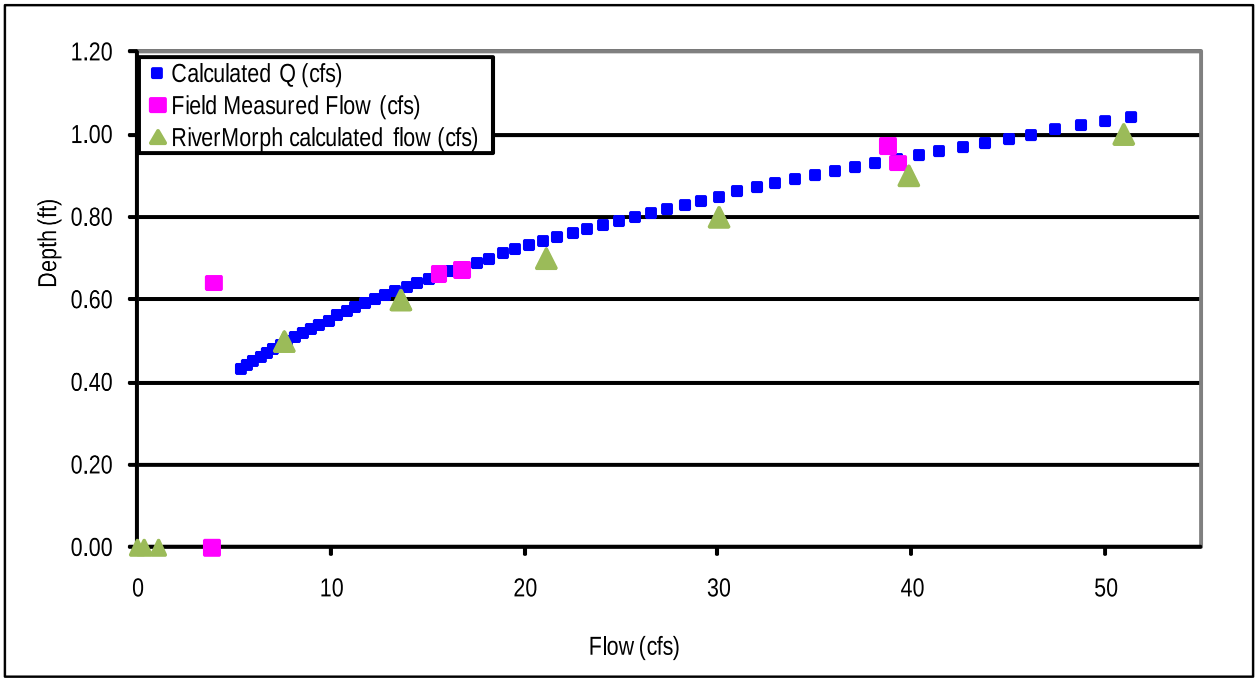


FIGURE 4 – VAUGHN'S BRANCH AT MOUTH (W04) STAGE-DISCHARGE RATING CURVE

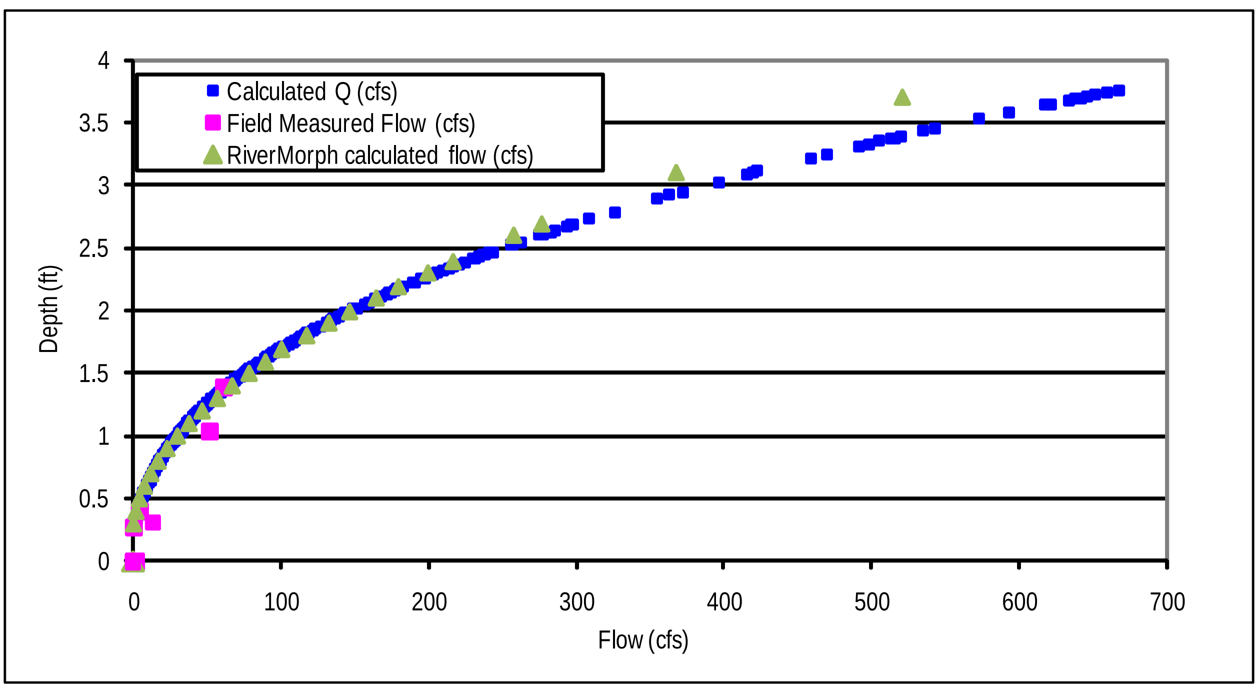


FIGURE 5 – WOLF RUN AT ROANOKE DRIVE (W06) STAGE-DISCHARGE RATING CURVE

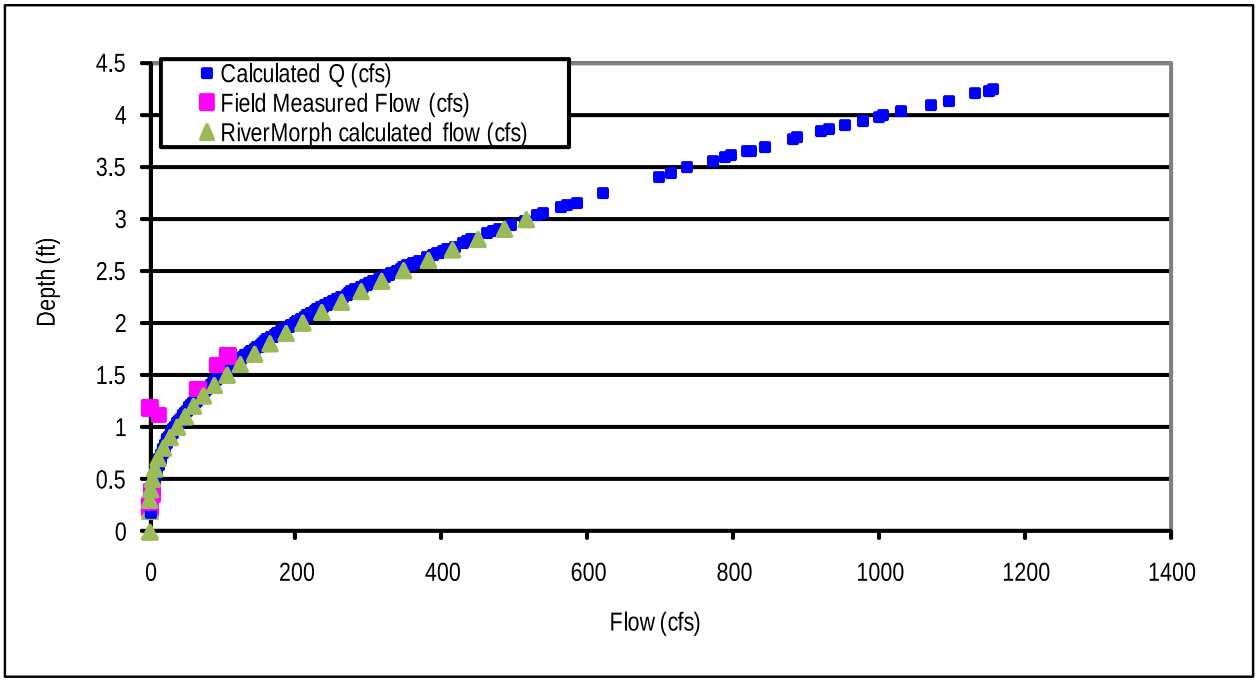


FIGURE 6 – WOLF RUN AT FAIRCREST DRIVE (W09) STAGE-DISCHARGE RATING CURVE

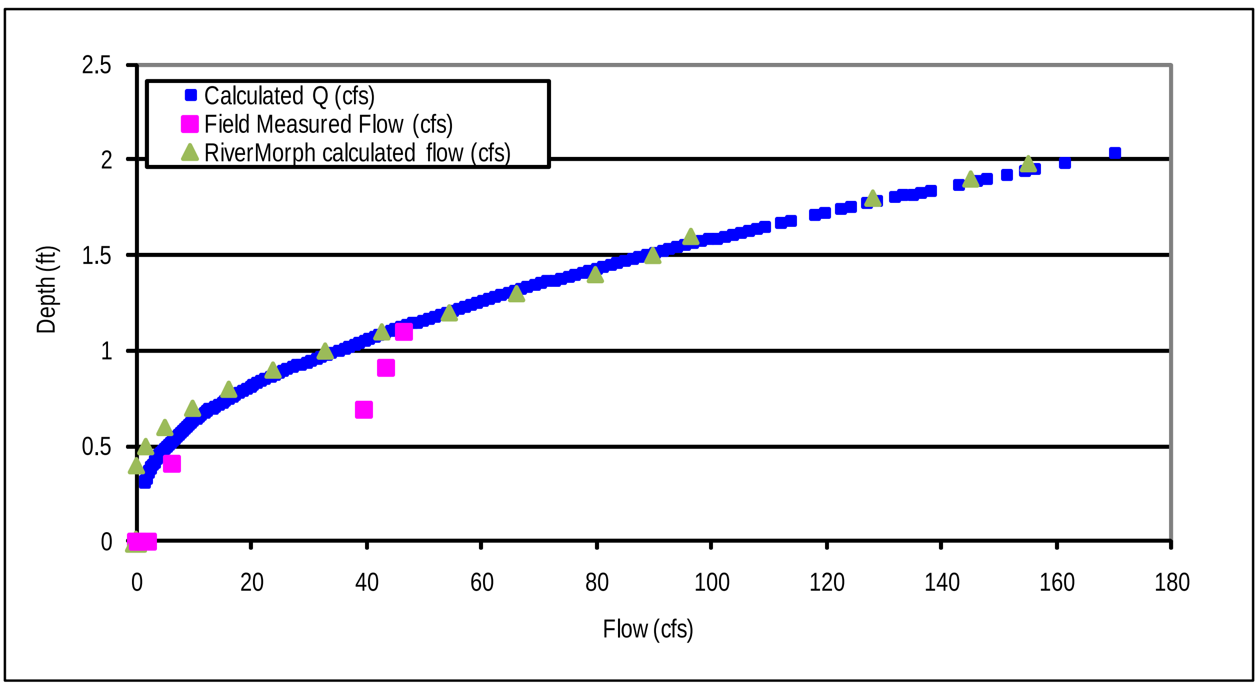
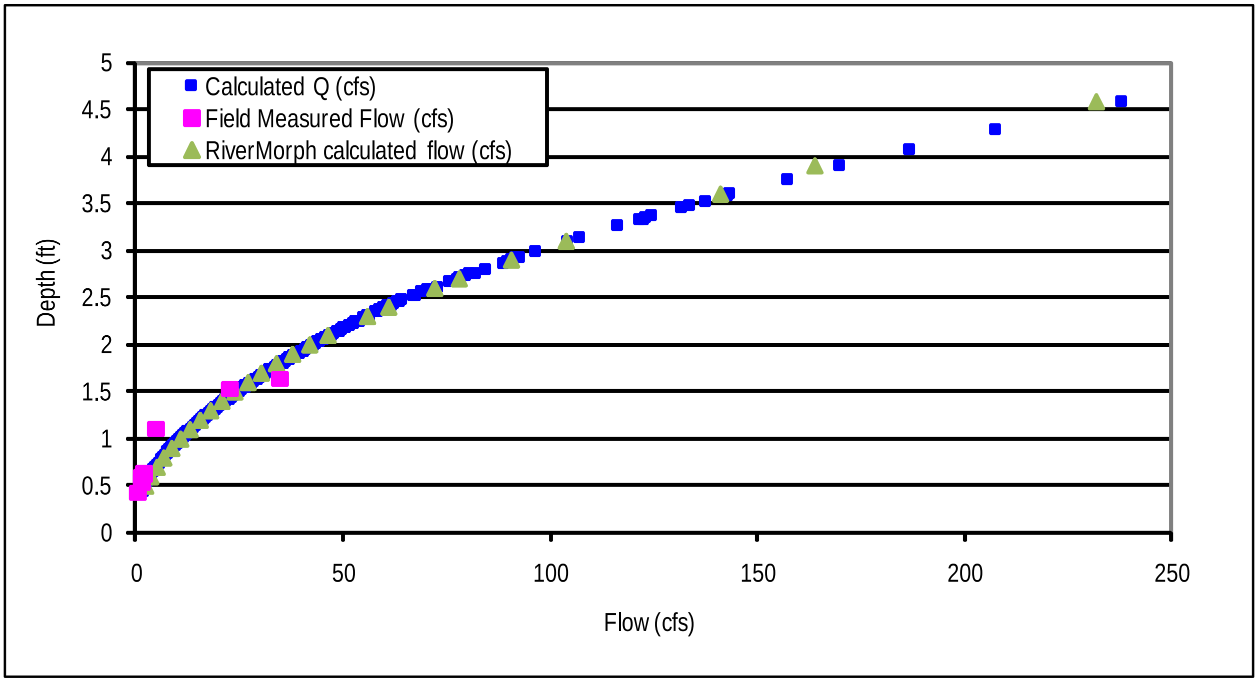


FIGURE 7 – BIG ELM TRIBUTARY (W11) STAGE-DISCHARGE RATING CURVE



D. Stream Flow

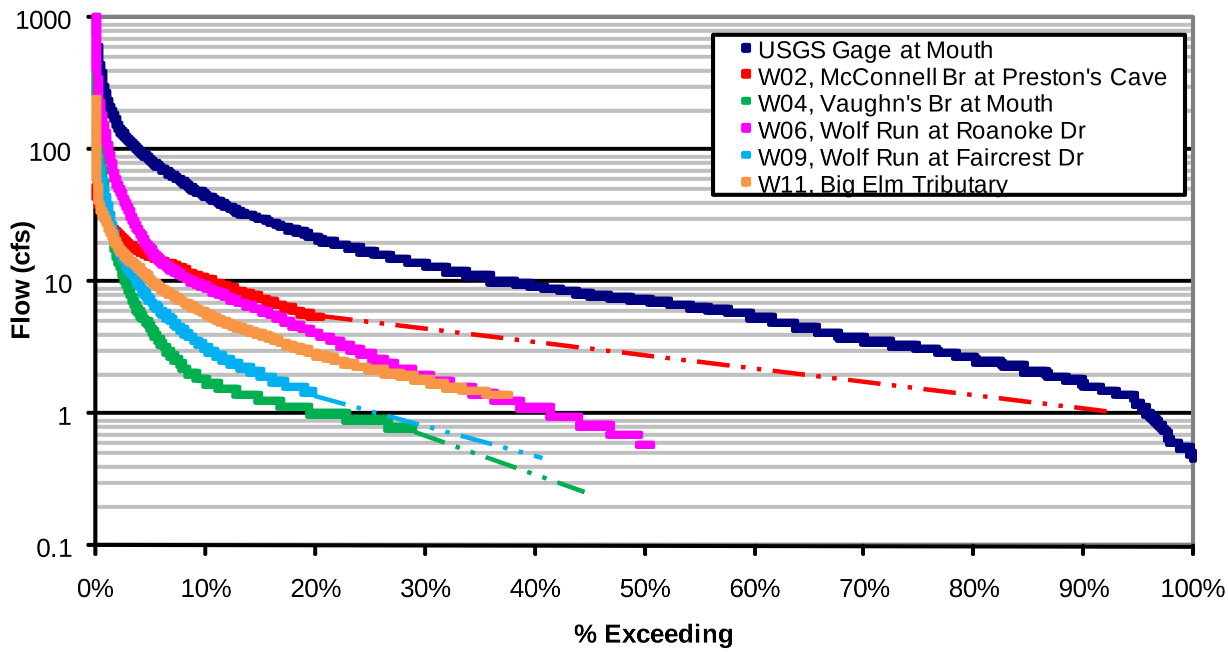
The stage-discharge rating curves were utilized to convert the data logger depth measurements into flows for each site. The results for the monitoring period are shown in the charts in Appendix B.

Table 7 and Figure 8 summarize the stream flow data in a flow duration curve, which indicates the percentage of time a given flow was exceeded for the monitoring period. These results indicate the flashiness of streams throughout the watershed and the range of flow values that occur at the sites. The maximum flows calculated at each site are 1150 cfs at the USGS gage at the mouth of the watershed, 51 cfs at McConnell Branch at Preston's Cave, 668 cfs at the mouth of Vaughn's Branch, 1157 cfs at Wolf Run at Roanoke Drive, 170 cfs at Wolf Run at Faircrest Drive, and 238 cfs at the Big Elm Tributary. In Figure 8, the solid lines indicate the flows based on valid logger data; dotted lines are projections beyond the valid logger data based on field measured flow observations under dry weather conditions.

TABLE 7 – PERCENTAGE OF TIME STREAM FLOWS (CFS) EXCEEDED

Site	Max	5%	10%	15%	20%	30%	40%	50%	70%	100%
USGS	1150	83	45	30	22	14	9.2	7.3	3.8	0.46
W02	51	16	10	7.4	5.4	-	-	-	-	-
W04	668	4.7	1.9	1.3	1.0	-	-	-	-	-
W06	1157	17	9.3	6.3	4.1	2.0	1.1	0.58	-	-
W09	170	7.3	3.2	1.9	-	-	-	-	-	-
W11	238	10	5.7	4.0	2.9	1.8	-	-	-	-

FIGURE 8 – RELATIONSHIP BETWEEN FLOWS OVER THE MONITORING PERIOD



NOTE: Dotted lines indicate inferences beyond the valid data logger data based on field measurements.

Because precipitation data was not recorded in the watershed, the rainfall intensity and lag time could not be calculated for storm events. Also, because base flow data was not valid at some sites, the time to peak and the recovery rate could not be calculated for all sites. Therefore, the time to peak was calculated for the USGS gage for the 15 precipitation events in which the peak flow at the USGS gage was greater than 200 cfs. For the other sites, the time from the hydrographic rise at the USGS gage to the peak flow at each of sites was calculated in order to have some comparison of the relative peak times. Although the November 28-29 precipitation event had a peak flow of 501 cfs at the USGS gage, this event was not evaluated due to prolonged and intermittent rainfall over several days.

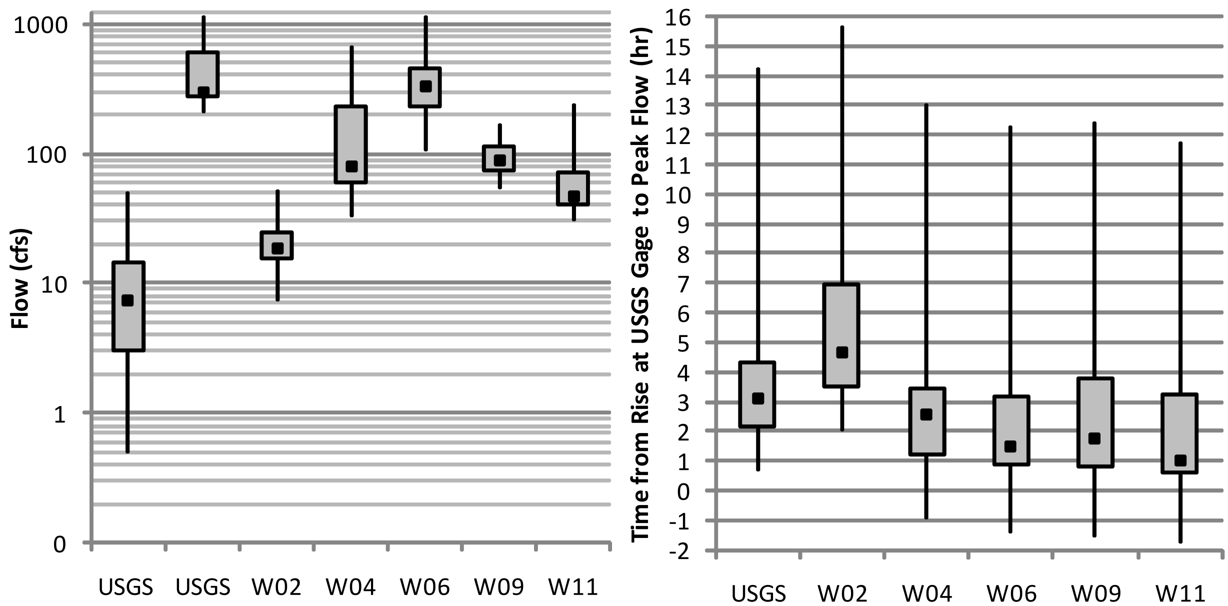
The results of this evaluation are shown in Table 8 and Figure 9. Results indicate that the time to peak for the USGS gage ranged from 0.7 to 14.3 hours depending on the rainfall intensity and duration and peak flow level. The median time to peak of 3.1 hours indicates a flashy watershed with dramatic flushing events, including a jump from 1.9 cfs to 1150 cfs in just 2.6 hours. The McConnell Branch site (W02) did not peak until some 1.6 hours after the USGS gage peak when comparing medians, indicating a slower response from the groundwater system. All other sites peaked before the USGS gage, as expected, with Vaughn's Branch typically peaking after Wolf Run at Roanoke Drive.

TABLE 8 – RELATIONSHIP BETWEEN PEAK FLOWS AND HYDROGRAPHIC RISE AT WOLF RUN USGS SITE

Date	Base Flow (cfs)*	Peak Flow (cfs)						Time from Hydrographic Rise at USGS to Peak Flow (hr)					
	USGS	USGS	W02	W04	W06	W09	W11	USGS	W02	W04	W06	W09	W11
6/19/2011	8.5	258	16	60	104	53	32	3.1	4.5	1.5	1.3	0.9	0.8
7/5/2011	1.4	207	7	32	243	98	40	4.1	3.8	2.7	2.0	1.9	1.5
7/7/2011	3.1	580	18	283	585	138	143	0.7	2.3	-0.9	-1.4	-1.6	-1.8
7/8/2011	24	767	51	299	475	100	79	5.3	4.4	3.4	3.1	4.1	3.2
7/12/2011	8.5	287	19	80	198	74	47	5.4	6.5	3.8	3.3	3.4	3.3
7/24/2011	2.9	243	11	37	441	120	64	14.3	15.7	13.0	12.3	11.6	11.8
8/3/2011	1.9	1150	27	668	1157	162	238	2.6	3.2	1.0	0.8	12.4	0.5
8/7/2011	5.3	290	11	81	222	75	61	2.2	2.5	0.6	0.3	-0.1	0.0
8/8/2011	8.5	404	16	117	408	72	42	1.8	2.0	0.3	-0.3	0.1	-0.1
9/4/2011	0.5	855	20	520	1029	170	133	2.0	4.7	1.4	1.1	0.8	0.8
9/26/2011	5.3	298	23	60	251	56	30	3.9	7.3	3.4	0.9	1.2	1.0
10/19/2011	40	339	30	80	262	80	47	2.4	5.1	1.7	1.5	1.0	0.9
10/26/2011	7.3	298	16	66	331	89	46	4.0	9.3	3.5	3.3	3.0	3.3
11/16/2011	20	218	20	47	143	76	32	2.1	12.3	2.6	2.3	1.8	1.6
11/22/2011	50	606	38	177	370	107	59	4.5	6.0	4.8	4.8	4.8	4.8
Maximum	50	1150	51	668	1157	170	238	14.3	15.7	13.0	12.3	12.4	11.8
Median	7.3	298	19	80	331	89	47	3.1	4.7	2.6	1.5	1.8	1.0
Minimum	N/A							0.7	2.0	-0.9	-1.4	-1.6	-1.8

*Flow just before hydrographic rise.

FIGURE 9 – SUMMARY OF PEAK FLOWS AND TIMING OF HYDROGRAPHIC RISE DURING SELECTED STORM EVENTS



As indicated in Figure 9, at the mouth of the Wolf Run watershed, as measured by the USGS gage, stream flows ranged from 0.46 cfs to 1150 cfs. The median flow at the site was 7.3 cfs, but only 3.8% of the flows exceeded 100 cfs. This indicates an extremely flashy stream system with a quick rise and fall during storm events due to numerous upstream factors including a high percentage of impervious surface and geological factors.

McConnell Branch (W02), which receives most of its flow from Prestons Cave and the upstream McConnell Springs groundwater sources, exhibits the most gradual rise and fall of all the monitoring locations. The low maximum calculated flow of 51 cfs is due to the flow restriction created by the size of the cave opening. Based on field measurements, McConnell Branch comprises an increasingly greater portion of the total flow at the mouth of the watershed as the time since the last precipitation event increases. During field measurements on August 29 when the flow at the mouth of the watershed was measured at 1.1 cfs, which is near the lowest observed over the monitoring period, the flow at McConnell Branch was 0.8 cfs.

At Roanoke Drive (W06), peak flows for Wolf Run were found to approach or exceed the peak flows at the mouth of the watershed. However, without the additional flow inputs from Vaughn's Branch and McConnell Branch, flows exceeding 100 cfs only occurred during 1.1% of monitoring period. The flow is also much lower during median flows, at 0.58 cfs.

Further upstream at Faircrest Drive (W09) just upstream of the confluence with Spring Branch, the flows at Wolf Run are much lower, reaching a maximum of 170 cfs, but only 15% of flows exceed 1.9 cfs. The site was pooled during field measurements on July 29, indicating that no flow is present during extended dry weather conditions. A known karst window is located upstream at Southbend Drive. On August 29, a measured flow of 0.03 cfs was observed entering this window, with no flow downstream. The measured flow at W09 at this time was 0.01 cfs. Thus, the base flow of Wolf Run at Roanoke Drive is reduced due to the karst re-direction in the upstream area. It is suspected that peak flows are also reduced in this watershed area due to the karst system, but this study was not able to determine the degree of reduction. The wide, bedrock structure of many of the streams upstream of this location may also contribute to increased evaporation during dry weather conditions.

Although Vaughn's Branch (W04) reached a maximum flow of 668 cfs, only 20% of the flows were greater than 1.0 cfs. Of the sites assessed in the watershed, Vaughn's Branch had the most measurements below this low level. Vaughn's Branch was pooled on July 29, indicating that no flow is present during periods of extended dry weather. The flashiness and frequent dry or low flow conditions are due to numerous factors, including redirection of the flow of the Big Elm tributary into the Picadome sinkhole during base flow conditions, high percentage of impervious surface in the headwaters, and the possibility of other karst features within the subwatershed area.

Big Elm Tributary (W11), in the headwaters of the watershed, was routinely the first site to reach peak flow, as might be expected due to its small watershed area. However, flow levels between 1 and 10 cfs were sustained longer than other sites with larger watershed areas (Vaughn's Branch, Wolf Run at Faircrest Drive) and the peak flows appear suppressed, most likely due to the restriction of flows at the Picadome sinkhole. The site does go dry during prolonged dry periods, as shown by the August 29 sampling in which no water was present in the stream.

IV. DISCUSSION AND CONCLUSIONS

Although one of the objectives of this study was to quantify the portion of flow diverted from the surface water system into the karst system under dry and wet weather conditions, the data generated in this study was not sufficient for that purpose. The data does however indicate that the flow regime in the Wolf Run watershed is dynamic and exhibits a flashy response to storm events. Due in part to the karst influence, but also due to the high percentage of impervious surface in the watershed, streams were found to dry out throughout the headwaters in response to extended dry weather periods. Storm events also indicate that large portions of the flow are diverted into the karst system. This influence is particularly evident when comparing storm event hydrographs at the monitoring sites. Hydrographs of the September 4-6 storm event, the November 15-16 event, and the November 27-29 event are shown in Figures 10 through 12 respectively.

During the November 15-16 and November 27-29 storm events, the Picadome sinkhole was monitored for surface flows across the golf course fairways into Vaughn's Branch. No surface flow was observed during the November 15-16 storm event, shown in Figure 10, in which flow levels reached a maximum of 32 cfs at the Big Elm Tributary site (W11). On November 28, however, surface flow was field measured twice at 10:55 AM and 1:10 PM, measuring 29.8 cfs and 29.5 cfs at the confluence of the Big Elm Tributary and Vaughn's Branch. These surface flow measurements correspond to data logger flow readings of 32 and 30 cfs, respectively, at the Big Elm Tributary. These measurements indicate that almost all flow is following the surface flow route into Vaughn's Branch under conditions when surface flow is present. McConnell Branch (W02) reached maximum levels of 46 cfs in response to these karst groundwater flows. This seems to indicate that when the karst conduit's flow capacity is maximized, through upstream inputs such as Wolf Run at Southbend Drive or through the maximized capacity at the spring outlets, water begins to back up at the Picadome sinkhole until the flood levels are sufficient to allow for the bypass across to Vaughn's Branch. Once the groundwater system has additional capacity to accept additional flow input, floodwaters begin to decline at the Picadome sinkhole.

Upstream view of Big Elm Tributary monitoring site during March 9, 2011 storm event.

Panoramic view of Picadome Sinkhole flooding during storm event on March 9, 2011. The sinkhole is located to the right with water traveling from the Big Elm tributary (left), across to Vaughn's Branch (distant center).

Upstream view of flow path and erosion from Big Elm Tributary to Vaughn's Branch due to storm event on November 28, 2011

FIGURE 10 – STREAM FLOWS DURING NOVEMBER 15-16 STORM EVENT

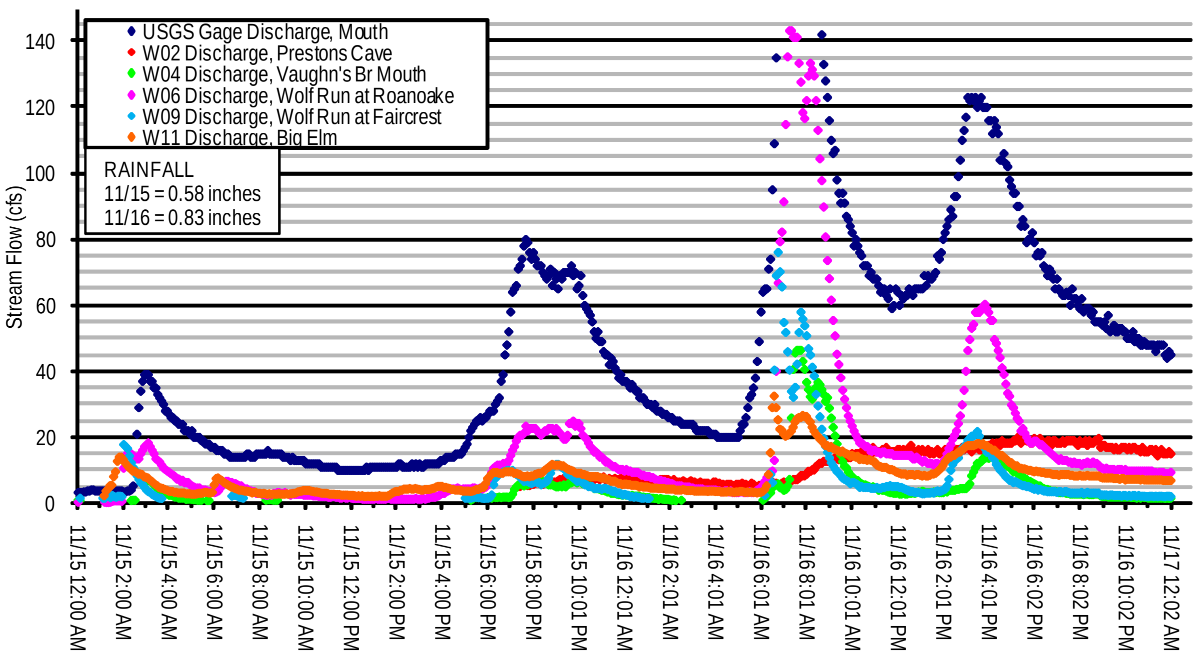
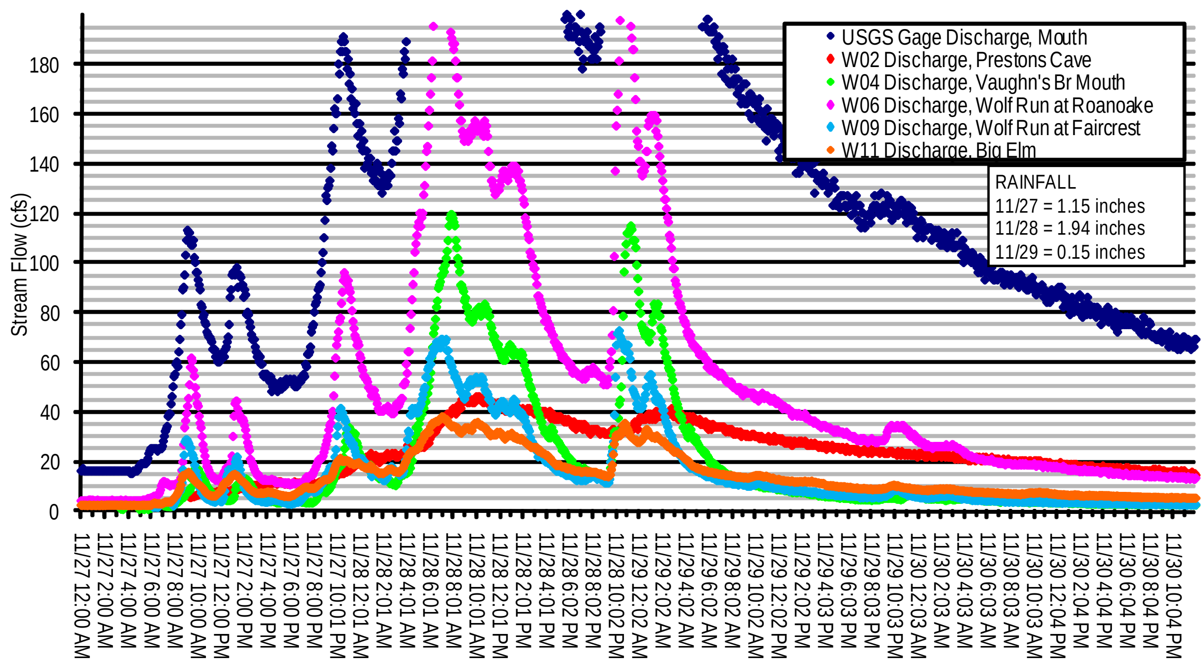
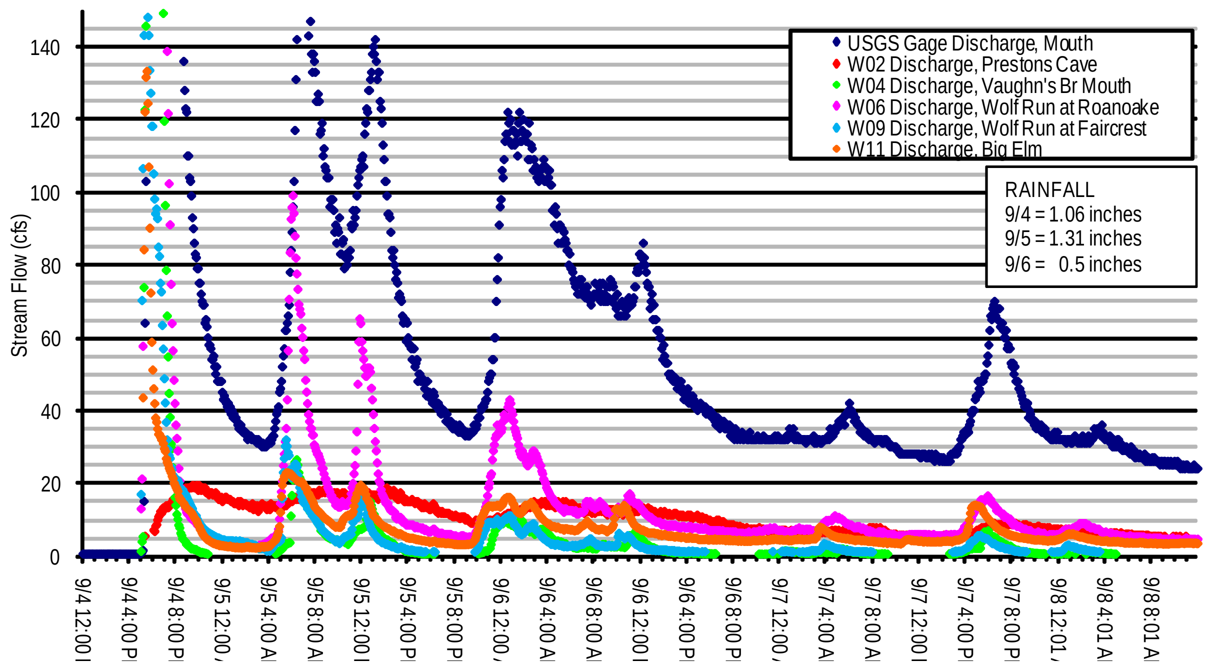


FIGURE 11 – STREAM FLOWS DURING NOVEMBER 27-29 STORM EVENT



These multiple inputs into the karst system cause higher flow levels at McConnell Branch to be sustained for longer periods of time while also suppressing the peak flows and lengthening both the rising and falling limbs of the hydrographs in the headwater areas of Wolf Run and the Big Elm Tributary. Interestingly, when rainfall intensity is particularly high, as in the September 4-6 event shown in Figure 12, surface flows may quickly peak before the karst system is inundated, with the rise in the karst system occurring several hours after the initial hydrographic rise.

FIGURE 12 – STREAM FLOWS DURING SEPTEMBER 4-6 STORM EVENT



Another finding of this study is that flow levels at the USGS gage on Wolf Run at Old Frankfort Pike is not a particularly good indicator of flow levels elsewhere in the watershed. McConnell Branch's contribution to the total flow at the mouth of the watershed tends to increase as the overall flow decreases. During storm events individual sites were found to peak prior to or after hydrographic rise at the USGS gage. Future studies focused on evaluating the stream response times in relation to rainfall patterns within the watershed would improve hydrologic modeling of the watershed.

The results of this study have implications for monitoring, pollutant source identification and loading calculations, and locations for Best Management Practices (BMPs).

In regard to monitoring, the results of this study have several implications. Because of the short time period of hydrographic rise during storm events, organizers of monitoring studies conducted at sites throughout the watershed should utilize multiple groups of samplers in order to ensure the samples are captured during the hydrographic rise at all sites. For dry weather monitoring, samplers should first observe whether flow is present in headwaters of the watershed as well as downstream of known karst inputs such as the swallet at Southbend Drive. Such observations are important for understanding the source area represented by the sample, since upstream surface streams may enter the karst system rather than continuing to downstream sites.

For pollutant loading calculations and source identifications, storm event data should be interpreted with caution, as the flow level and concentrations can vary greatly based on the time during which a site was sampled. Efforts to normalize flows and concentrations across multiple events will improve accuracy of conclusions drawn from such data. Also, loading and source identification efforts in the headwaters of Wolf Run and Vaughn's Branch are complicated by the loss of flow to the karst system.

Results also indicate that Best Management Practices to improve the warmwater aquatic habitat in the Wolf Run Watershed should target improving the flow regime, as well as other factors identified by other studies. Frequent dry periods impair the ability of a stream to support aquatic life, as do increased occurrence of scouring events in the watershed. Best Management Practices to increase base flow, as well as measures to increase infiltration, storage, or re-direction of stormwater runoff should aid the survival of aquatic life.

However, because of the difficulty in restoring base flow in heavily karst areas, efforts to improve the health of the aquatic ecosystem may best be focused in areas with lesser karst influences since these areas have one less potential source of impairment. For instance, flow levels on McConnell Branch are sustained through drought periods, and high velocities are restricted by the size of the cave outlet. With a healthy hydrologic regime for this reach, efforts targeted to improve the stream and riparian habitat or eliminate identified pollutant sources improve the likelihood of success due to these measures. Other areas with reduced karst influence include Cardinal Run, Gardenside Tributary, and the lower portions of Wolf Run and Vaughn's Branch. All areas in the watershed would benefit from efforts to capture or infiltrate stormwater.

BMP efforts may also be utilized to address erosion and flooding on the Picadome Golf Course due to capacity limits at the Picadome sinkhole. Severe erosion is currently occurring on the Big Elm Tributary and Vaughn's Branch due to no clear channel for water to bypass the Picadome sinkhole during storm flows. Restoration of a channel from Big Elm Tributary to Vaughn's Branch may reduce erosion and golf course maintenance due to flooding.

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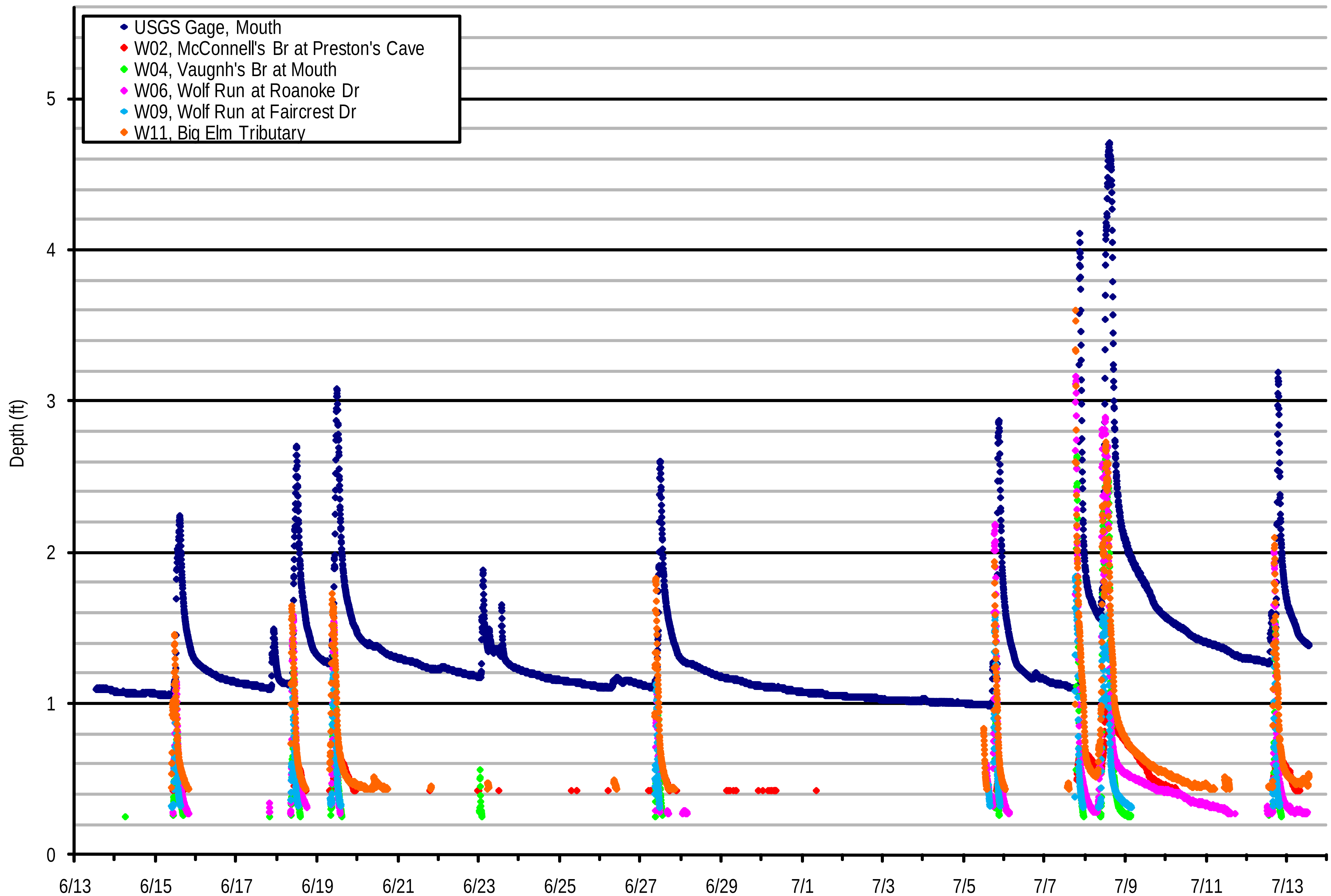
APPENDICES

APPENDIX A – STREAM DEPTH CHARTS



USGS Gage, Mouth
W02, McConnell's Br at Preston's Cave
W04, Vaugnh's Br at Mouth
W06, Wolf Run at Roanoke Dr
W09, Wolf Run at Faircrest Dr
W11, Big Elm Tributary
Depth (ft)
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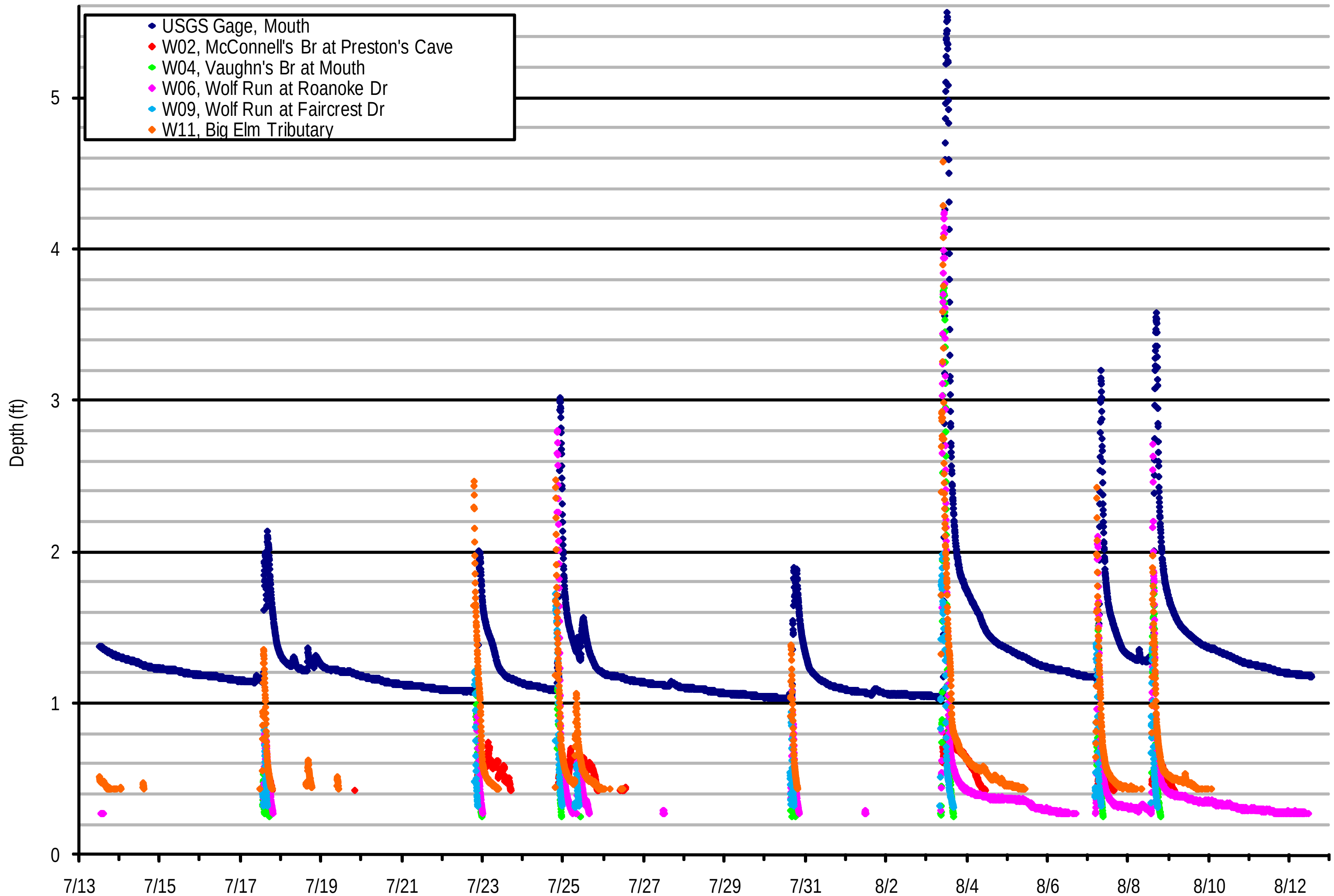

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W09, Wolf Run at Faircrest Dr
W11, Big Elm Tributary
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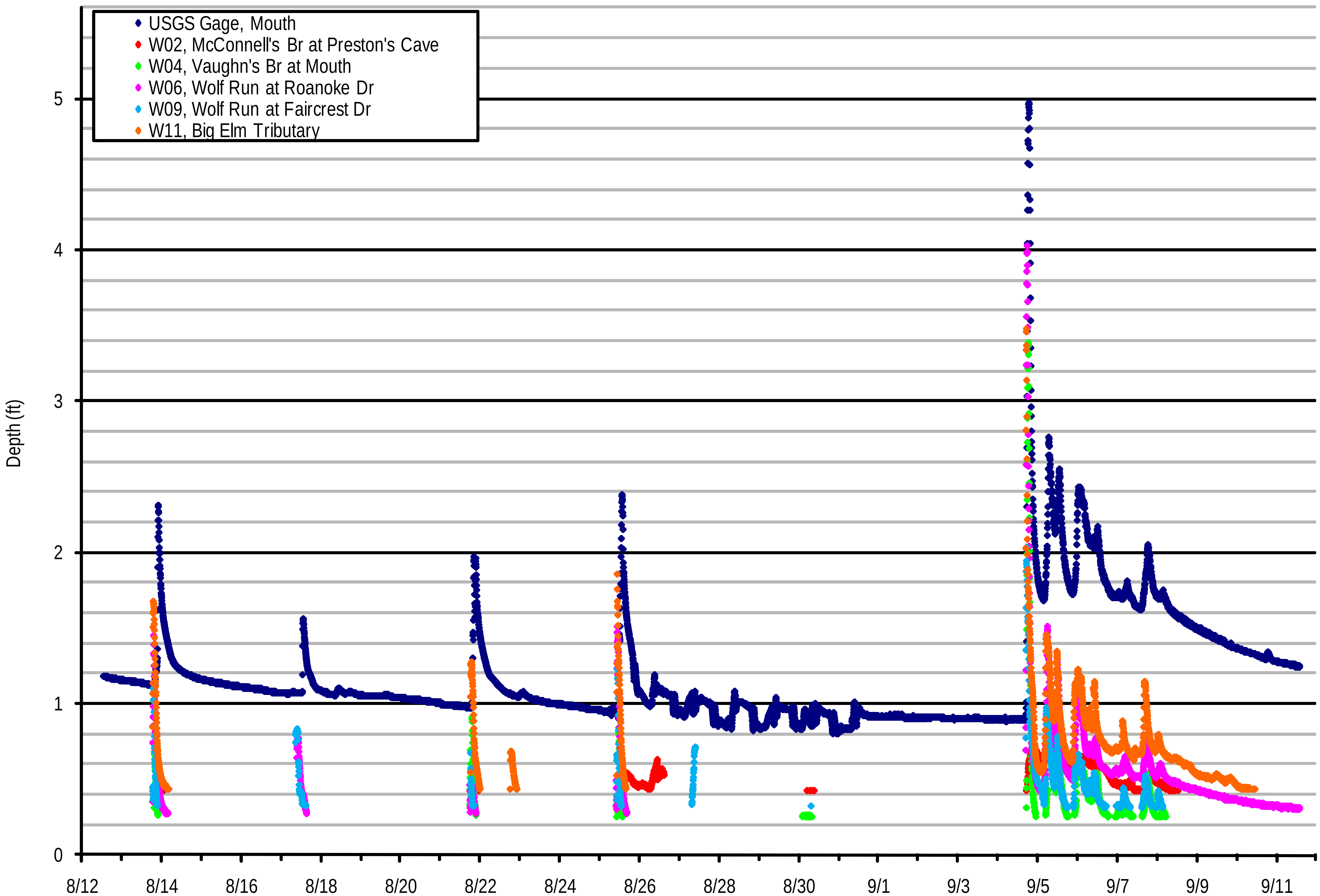
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W06, Wolf Run at Roanoke Dr
W09, Wolf Run at Faircrest Dr
W11, Big Elm Tributary
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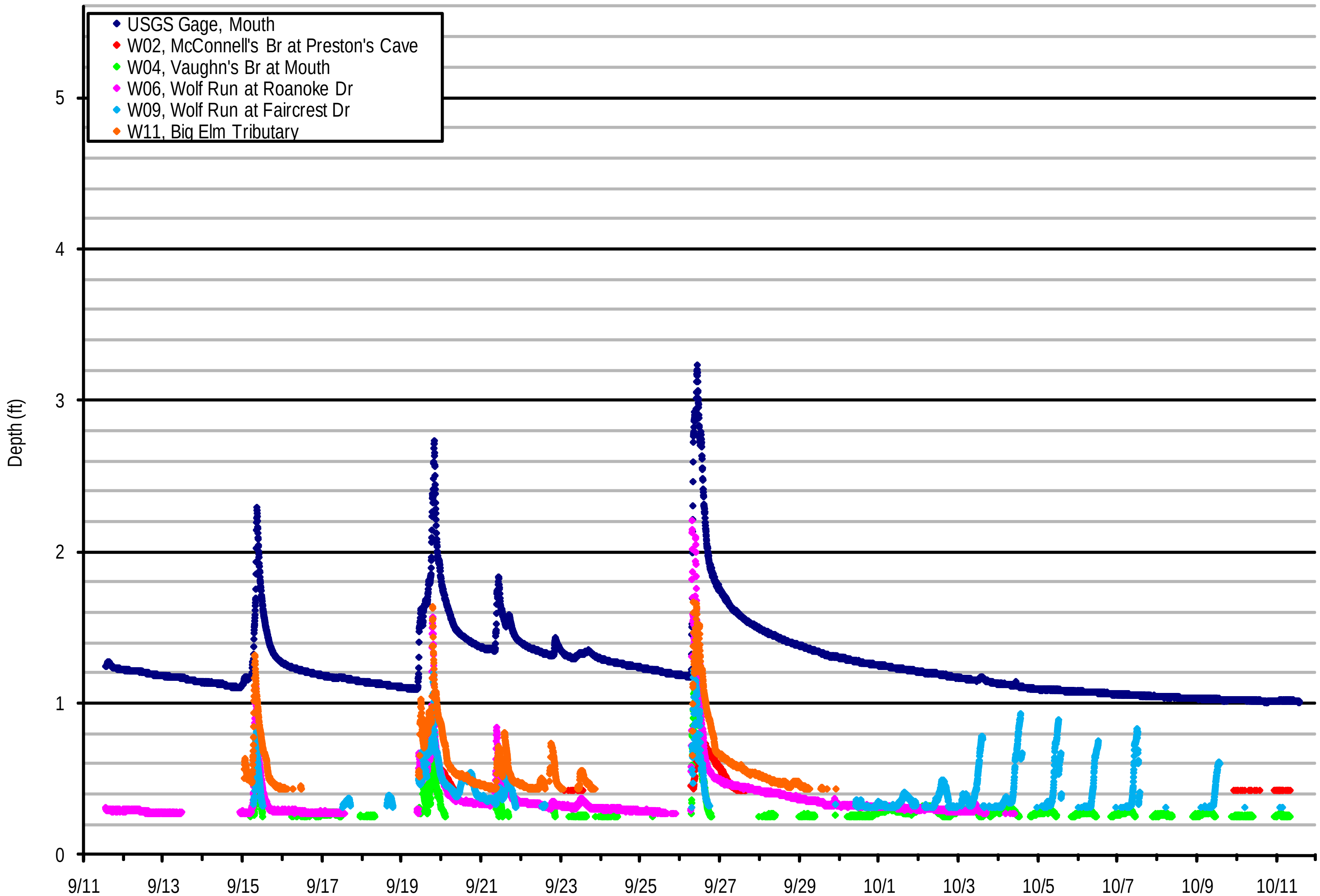

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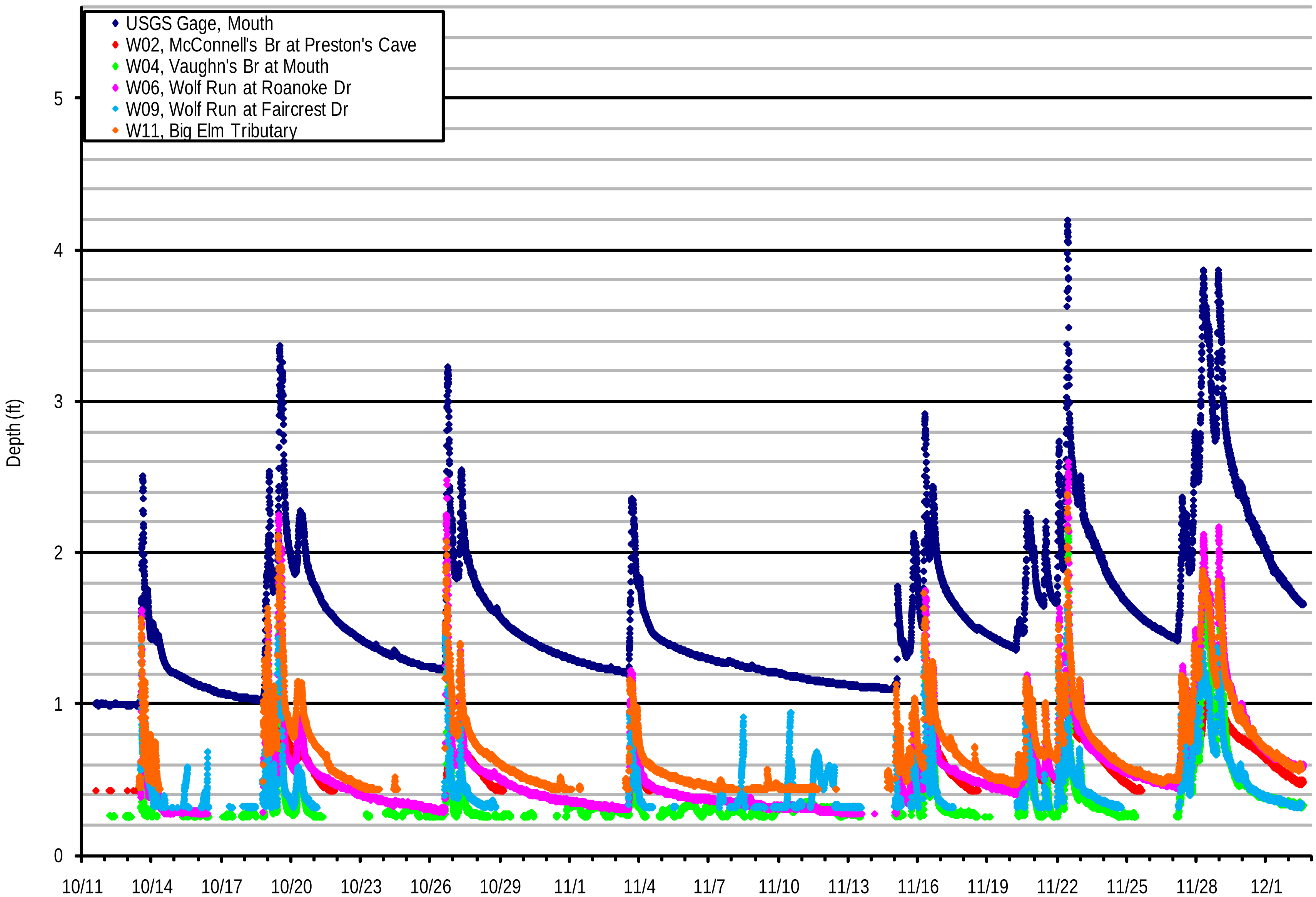
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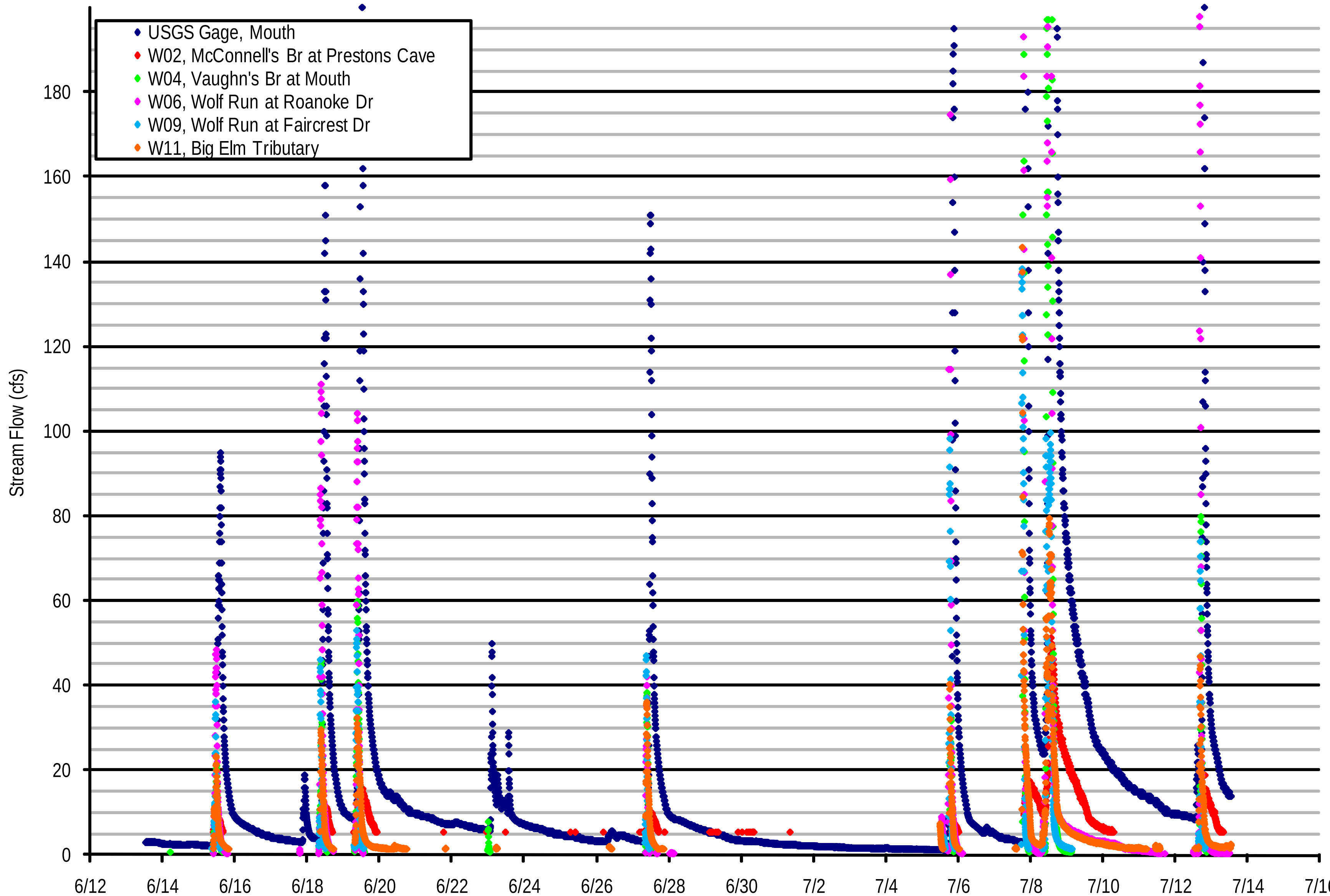
APPENDIX B – STREAM FLOW CHARTS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W06, Wolf Run at Roanoke Dr
W09, Wolf Run at Faircrest Dr
W11, Big Elm Tributary
Stream Flow (cfs)
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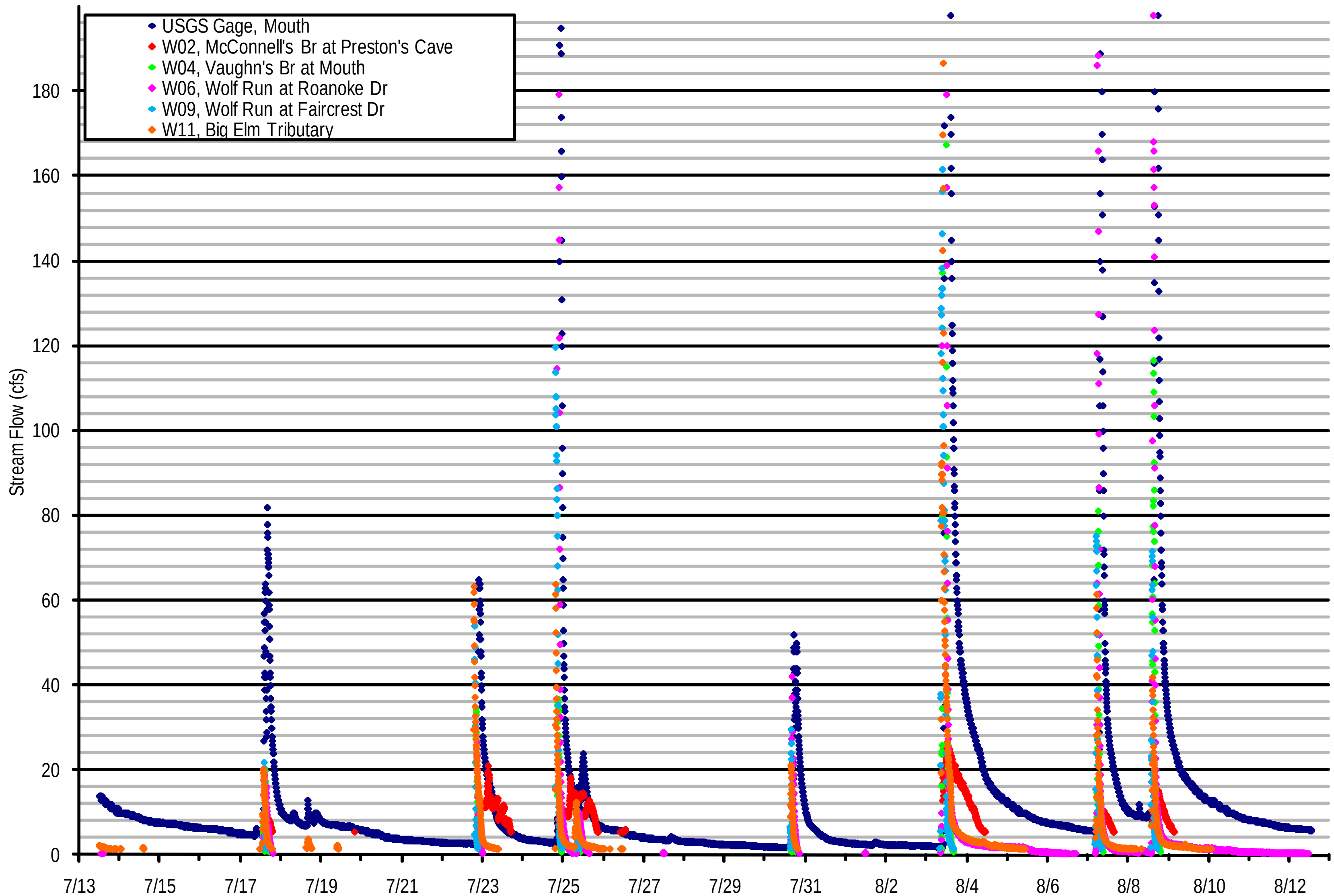

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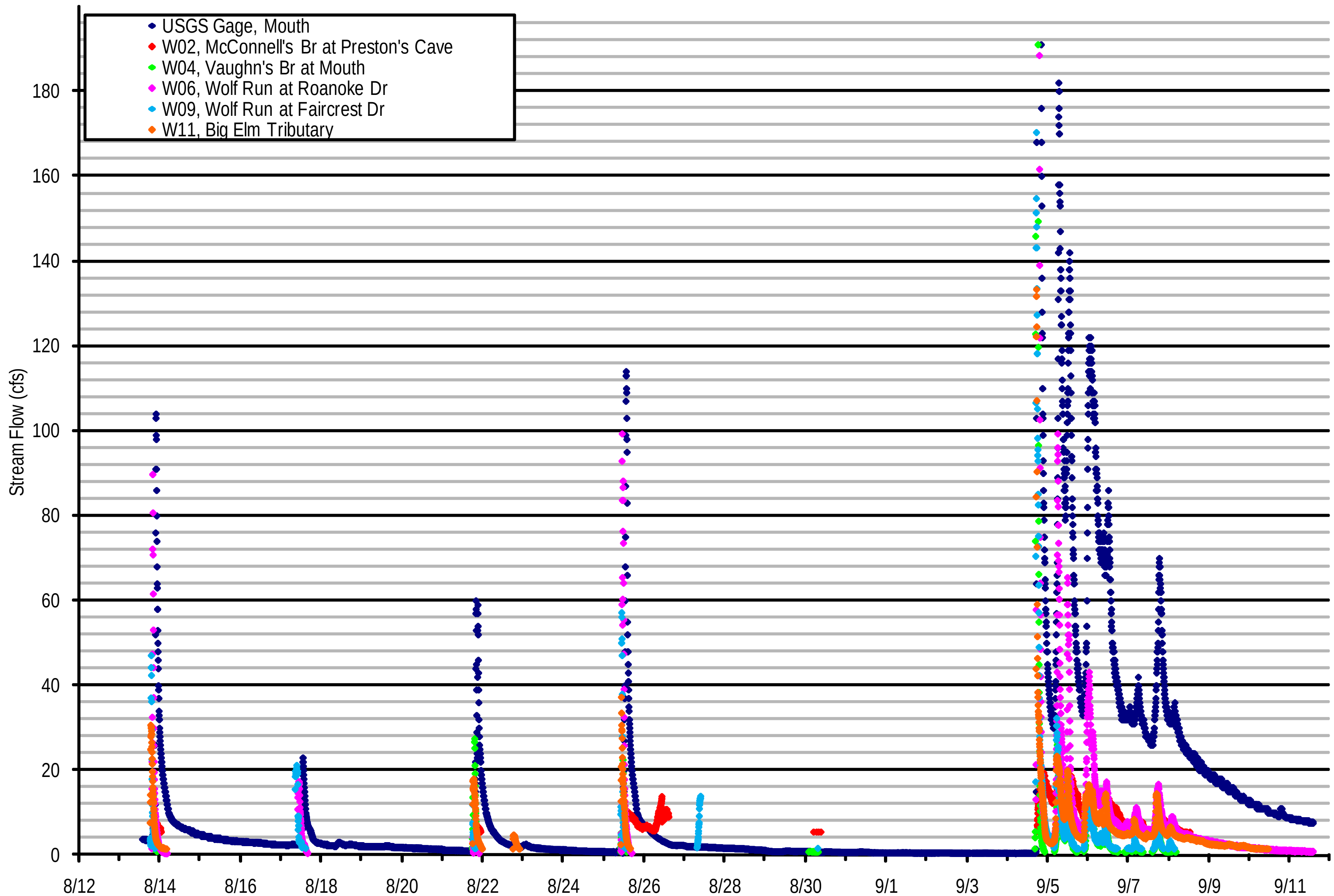
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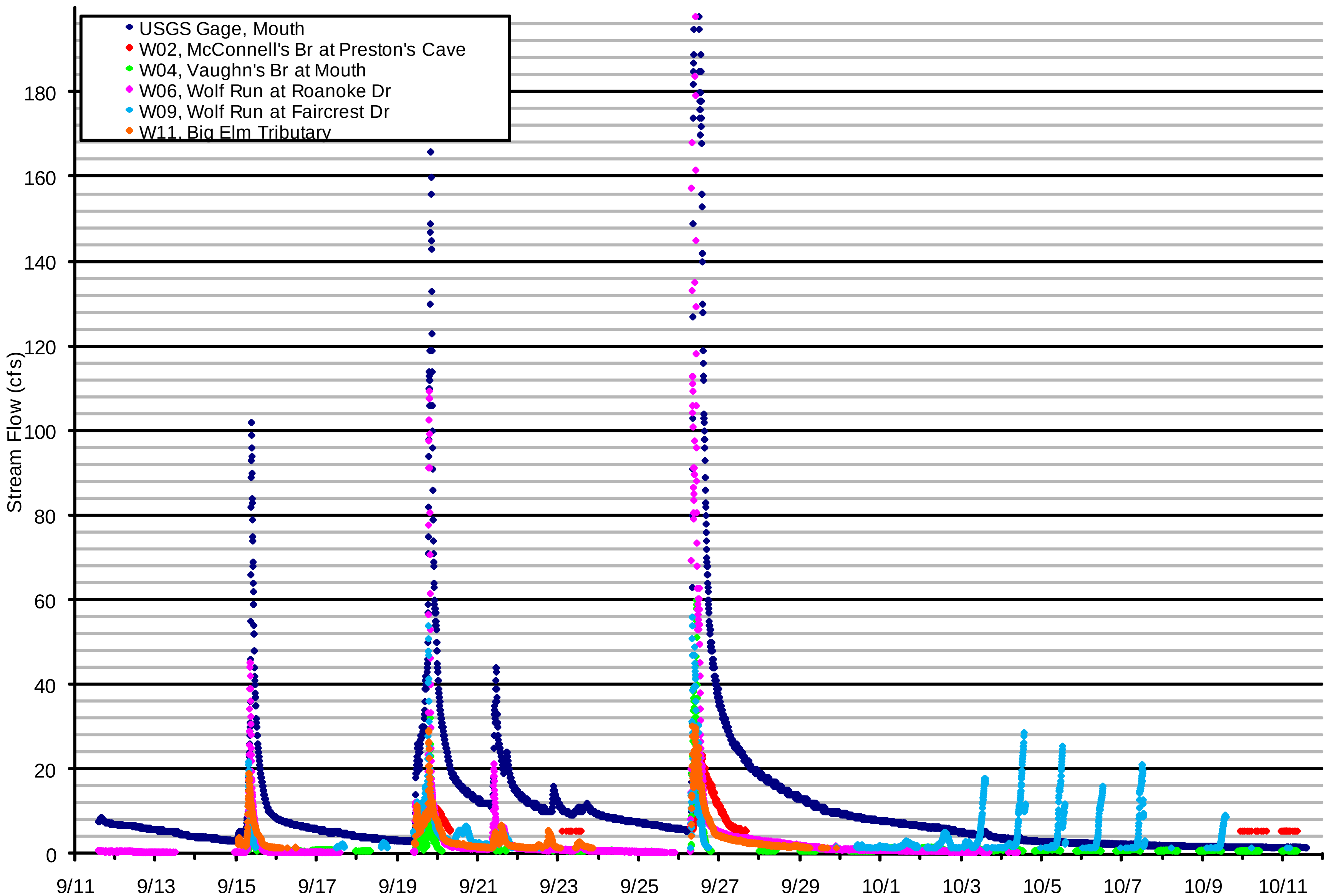
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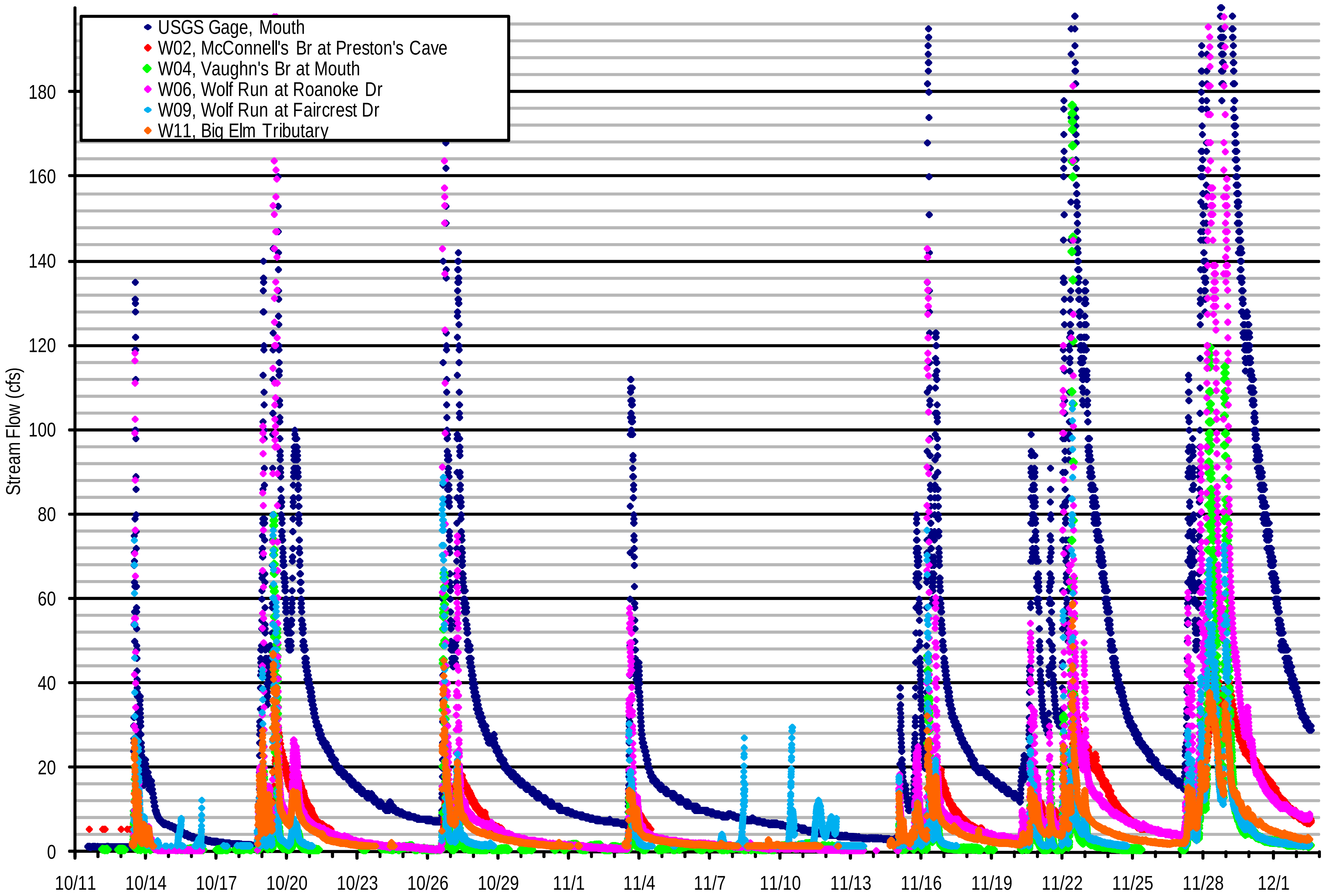

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