Western Region Technical Attachment
NO. 04-07
July 14, 2004

The Rucker Canyon Flash Flood of July 21, 2002: Estimating Discharge for an Ungaged Site

Mike Schaffner, NOAA/NWS Weather Forecast Office, Tucson, AZ

Introduction

On July 21, 2002, a flash flood occurred in Rucker Canyon. Rucker Canyon is a 50 square mile basin and located in the southeastern corner of Arizona along the southwest flank of the Chiricahua Mountains or 80 miles east-southeast of Tucson (figure 1). This resulted in the overtopping of Rucker Bridge. The site is not gauged and has no hydrologic record. Just after the event, indirect discharge measurements were not conducted. As a result, there was no record of the magnitude of the event. Rainfall return frequencies indicated an impressive event. The goal of this project was to obtain a discharge estimate for an event which occurred one and a half years ago. It will be demonstrated that valuable information can still be obtained several years after a significant event. The estimated discharge required to reach bridge bottom (low steel) was calculated using a step-backwater model. This will represent the minimum discharge for the flash flood event in question.

Event Overview

The southeast Arizona Hazardous Weather Outlook, issued at noon on July 21st, called for a probability of precipitation in excess of one inch and severe thunderstorms to be near climatology south and east of Tucson. Even though a stable capping inversion was noted aloft, a few storms eventually broke through resulting in stronger thunder storms (Pytlak, 2004).

Radar indicated that precipitation began as early as 11:20 AM MST. A storm centered over Rucker Canyon intensified and remained stationary over the middle and lower portions of the canyon (downstream from Rucker Lake (figure 2)). By 12:20 PM, rainfall was quite heavy and continued till 1:50 PM. Fifteen-minute lightning detection network data recorded 20 to 40 positive/negative strikes during the most intense hour of the storm. Storm total radar precipitation estimates at 1:46 PM had one pixel of 5 to 6 inches and several of 4 to 5 and 3 to 4 surrounding it (figure 3). NWS COOP observer, from Rucker Canyon Ranch at mile marker 19 off of Rucker Canyon road, reported 4.7 inches over two hours. 4.0 inches were recorded the first hour followed by 0.7 inches the second hour. This confirmed hourly radar estimates. A RAWS site, called Rucker and located 2.9 miles downstream from Rucker Lake, reported minimal precipitation. As a result, the heavy rainfall was concentrated downstream and did not fall over the headwaters.

Watershed Characteristics

The majority of Rucker Canyon at Rucker Bridge (milepost 15.7 of the Rucker Canyon Road) is located in Coronado National Forest and the Chiricahua Mountains. Rugged terrain and canyons are common. Average channel slope from Rucker Bridge to Rucker Lake is 1.9 degrees. Average channel slope from Rucker Lake to headwaters near Painted Rock and Chiricahua Peak is even steeper. Elevations range from 5085 feet at Rucker Bridge to 6200 at Rucker Lake to 9600 feet between Painted Rock and Chiricahua Peak. The headwaters, above Rucker Lake, are composed of steep volcanic rocks. The upper portions of the creek have perennial water.

Discharge Estimation Methods

There are a variety of reasons to obtain discharge estimates for an ungaged site. These include documenting previous flood events and determining at what discharge a given feature (stream bank, levee, bridge low steel, or bridge deck) may be impacted. This information can be used in local studies (pre- or post-flood), help define key impacts for gauged sites without rating tables, or define bankfull and action flows.

Two primary methods exist for estimating post-event discharge. One is the slope area method commonly used by the USGS to estimate peak discharge of an event. Another is a step-backwater model which is done to develop a theoretical rating curve for a site. The former requires good highwater marks and a stable reach. Due to the general lack of highwater marks and the complicated nature of the reach near Rucker Bridge, a step backwater model was utilized.

Step-backwater Model

A step-backwater model is based on the idea of balancing the one-dimensional energy equation from one cross section to another. The model starts at the downstream cross section where channel geometry and boundary conditions are known. Velocity is computed for this cross section. This velocity is used to make an initial guess of the water surface elevation for the next upstream cross section. These steps are repeated (iteratively) until the energy equation is balanced to within the programs tolerance.

The US Army Corps of Engineers (USACE) HEC-RAS 3.1 step-backwater model was used. This model is used by government agencies, flood control districts, and consulting firms. It is available for free download from the USACE (http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html).

HEC-RAS can solve for both steady flow and unsteady flow. Steady flow solutions are selected in analysis for flood plain management and flood insurance studies. Steady flow solutions can evaluate flood plain encroachment and the impact of bridges and levees. HEC-RAS will substitute the momentum equation, for the energy equation, where water surface elevations vary rapidly. Such situations include around bridges as with Rucker Bridge.

Three types of information must be collected in order to define the initial conditions needed to run HEC-RAS. These include surveyed cross sections, estimated manning roughness values, and boundary conditions. Each of these will be discussed separately. Bridge structural details are needed as well.

Cross Sections

To define a bridge, four cross sections are generally needed. Cross sections 3 and 4 were placed downstream from the bridge and cross sections 5 and 6 were placed upstream from the bridge (figure 4). HEC-RAS will use these four cross sections to compute energy losses near the bridge. Flow generally constricts upstream from a bridge and expands downstream from a bridge. Cross section 3 (figure 5) must be located far enough downstream that flow is not impacted by the structure (i.e. flow has fully expanded). Cross section 6 (figure 6) must be located such that it is not impacted by flow constriction. It is best to determine the placement of cross sections 3 and 6 during a field visit which coincides with a high flow event. However on ephemeral streams in the semi-arid southwest, this is not practical due to the rapid rise and fall of most flash floods. Both the US Geological Survey (USGS) and USACE have established criteria to select cross sections when field investigation is not possible at the time of the flow event. In addition to cross sections 3 and 6, cross sections 4 and 5 were needed immediately downstream and upstream of the bridge (figure 7, 8). Cross sections 4 and 5 are commonly placed at the downstream and upstream toe of the bridge respectively. Their purpose is to define the bridge geometry. During the hydraulic computations, HEC-RAS automatically adds two cross sections inside of the bridge structure (figure 9). In order to define bridge structure, bridge structure must be measured. This includes pier and abutment geometry, bridge deck position, and weir type.

Besides cross sections 3 through 6 used to define the bridge, cross sections 1 and 2 were placed downstream. Cross section 1 was placed several feet upstream from a small side tributary (figure 10, 11, 12). Cross section 2 (figure 13, 14, 15) was placed upstream of cross section 1 and downstream of Rucker Bridge and its adjacent low water crossing. Cross section 2 coincides with the only well-defined high water mark (figure 16, 17).

Manning’s Roughness Coefficient (n)

Manning's roughness coefficient, n, is commonly used to depict flow resistance in open channels. The selection of n values involves judgment, skill, and subjectivity. Various publications and reference tables are available to aid in this process. The USGS has published a number of professional papers that verify n values in open channels. Such publications are rich in illustrative material. USGS Professional Paper 1584, "Verification of Roughness Coefficients for Selected Natural and Constructed Stream Channels in Arizona," by J. V. Phillips and T. L. Ingersoll (1998) proved quite helpful. Similar papers are available for other states and geographic regions including: California, Colorado, New York, and the southeastern US. USGS Water-Supply Paper 1849, "Roughness Characteristics of Natural Channels," by H. H. Barnes, Jr. (1967) displays color photographs and descriptive data for 50 stream channels where roughness coefficients have been determined. This can be found online at: http://www.engr.utk.edu/hydraulics/openchannels/Index.html. When dealing with channels that are densely vegetated, USGS Water Supply Paper 2339, "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains," by George J. Arcement, Jr., and Verne R. Schneider can be of help. Various analytical methods have been summarized by the USACE for those who prefer an analytical method (USACE Publication No. EM 1110-2-1601). Analytical methods still require field work and may not yield better n values than those deduced from traditional methods.

Since the channel banks, for many cross sections, were coarser than channel bottom, an average n value was selected for each cross section. Each cross section has average values labeled across the top. The table below displays n values for each cross section:

Cross Section	Roughness Value (n)
1	0.034
2	0.035
3	0.035
4	0.030
5	0.035
6	0.038

Table 1: Manning roughness values.

The n value at cross section 6 was estimated to be 0.038 excluding vegetation which was minimal (figure 18). At cross section 4 (figure 19) n values were slightly lower due to the presence of concrete bridge piers and concrete channel bottom directly below the bridge. The channel downstream of Rucker Bridge (cross sections 1 and 2) was composed of cobble banks and less coarse channel bed material. A reasonable n value for cross sections 1 and 2 is 0.034 or 0.035 respectively.

Boundary Conditions

Boundary conditions establish a starting water surface elevation. This is needed for the program to begin its calculations. There are four different boundary condition types. The type selected will depend largely upon the available data. These are: known water surface elevations, critical depth, normal depth, and rating curve. Normal depth has been selected. Normal depth requires the energy slope or when this is not available the slope of the channel bottom. The later was used. The slope of the channel bottom was obtained from the survey. This was 1.3 percent.

Steady Flow Simulation Results

Steady flow calculations were conducted using the subcritical flow option. In order to verify that the model solution was reasonable, known high water elevations were utilized. The elevation of the high water mark is known in cross section 2. It is known that water reached low steel on Rucker Bridge. One report had water flowing over Rucker Bridge while a second account had water splashing up and passively flowing over the bridge deck. Both accounts did report debris on the bridge deck which may have indicated at least brief overtopping of the bridge deck prior to eyewitness reports.

While it would be nice to assume that when water reached the high water mark in cross section 2 that water had also reached its highest point on Rucker Bridge, this may be incorrect. Inflow just downstream Rucker Bridge (from the low water crossing) may have impacted the quality of this high water mark. Channel modification downstream from Rucker Bridge was an issue as well. The simulation results are based on the assumption that channel geometry has not changed in any significant way since July 2002. Since the survey was not conducted till April 2004, this may be an incorrect assumption. Eyewitness reports stated that the right bank has not changed, but the left bank downstream of the bridge has been modified. Prior to the flood, the left bank was somewhat steeper and closer to the center of the channel. As a result, correlating the single high water mark with water elevation at the bridge should be handled with care.

Solution results for 3300 cfs show water reaching low steel on the upstream side of the bridge (figure 20). Solution results for 4000 cfs show water reaching just above low steel on the upstream side of the bridge, low steel at the downstream side of the bridge, and just below the high water mark along the right bank of cross section 2 (figure 21). Solution results for 4500 cfs show water almost overtopping the bridge on the upstream side, just above low steel on the downstream side, and at the elevation of the high water mark in cross section 2 (figure 22).

Cross Section	Q Total (cfs)	Minimum Channel Elevation (ft)	Water Surface Elevation (ft)	Velocity (ft/s)	Flow Area (sq ft)	Top Width (ft)	Froude #
6	2000	4.92	8.01	8.94	223.76	91.43	1.01
6	2500	4.92	8.41	9.57	261.31	93.36	1.01
6	3300	4.92	9.02	10.35	318.77	95.84	1
6	3500	4.92	9.42	9.81	356.95	97.46	0.9
6	4000	4.92	10.7	8.23	485.81	105.76	0.68
6	4500	4.92	11.93	7.21	624.26	118.32	0.55
5	2000	3.72	7.95	6.18	323.51	99.91	0.61
5	2500	3.72	8.44	6.71	372.75	100.11	0.61
5	3300	3.72	9.15	7.44	443.84	100.26	0.62
5	3500	3.72	9.79	6.9	507.57	100.39	0.54
5	4000	3.72	10.89	6.4	625.09	108	0.47
5	4500	3.72	12.04	6.01	749.14	108	0.4
4.5	Bridge						
4	2000	4.01	7.07	8.69	230.12	99.8	1.01
4	2500	4.01	7.44	9.35	267.41	99.85	1.01
4	3300	4.01	8.38	9.13	361.29	99.95	0.85
4	3500	4.01	8.64	9.04	387.31	99.98	0.81
4	4000	4.01	9.26	8.89	450.01	103.51	0.75
4	4500	4.01	9.84	8.8	511.62	108.29	0.71
3	2000	1.83	7.01	4.75	421.05	130.63	0.47
3	2500	1.83	7.76	4.77	524.31	144.85	0.44
3	3300	1.83	8.81	4.82	684.29	159.98	0.41
3	3500	1.83	9.06	4.83	724.42	163.5	0.4
3	4000	1.83	9.66	4.85	824.98	171.99	0.39
3	4500	1.83	10.23	4.86	925.56	180.09	0.38

Table 2: Solution results for 2000 cfs to 4500 cfs for cross sections near Rucker Bridge.

During the survey, it would have been nice to have an additional cross section between cross section 2 and 3 to better define the reach. Between these two cross sections, a low water crossing comes in that alters that natural channel geometry. HEC-RAS can interpolate additional cross sections. Four cross sections were interpolated (figure 23). Solution results were comparable to those discussed above.

In order to evaluate the effect of scour just downstream from the bridge, as reported by an eyewitness, a scour hole several feet deep was placed in the simulation (figure 24). Solution results were comparable to those without the scour hole.

A local property owner and eyewitness to part of the flash flood event reported that the left bank downstream from Rucker Bridge had been rebuilt after the event. The right bank was untouched. An attempt was made to approximate this in the model (figure 25). Solution results differed by 500 cfs from the above solutions. This yielded a discharge of 3500 cfs compared to 4000 cfs to reach low steel at both the upstream and downstream side of the bridge and a discharge of 4000 cfs compared to 4500 cfs to reach the high water mark in cross section 2.

Theoretical Rating Curve

HEC-RAS can generate a theoretical rating curve for each cross section. A theoretical rating curve is only as good as to how well the channel geometry is defined. Channels with shifting sand, as is quite common in southern Arizona, make poor sites to develop theoretical rating curves. Every time a flow event occurs, channel geometry is modified thus making the previous theoretical rating less accurate if not obsolete. Theoretical rating curves in stable channels (such as those lined with clay or course bed material) tend to have a longer life span. Those in concrete channels tend to be as good as those defined through human collected flow measurements and require little if any modification through time. The USGS, in Arizona, use HEC-RAS to create a theoretical rating curve for their new stream gauging sites. This is used a starting point. Flow measurements are then used to verify and if needed modify the original theoretical rating curve (Saeid Tadayon, USGS AZ, Personal Communication). The USGS has recently reported that their theoretical rating curve for Gila River at Duncan Arizona was excellent when compared to their flow measurements from the winter of 2003-2004 (Dan Evans, USGS AZ, Personal Communication). With any hydraulic model, output is only as good as the input parameters. If good channel geometry, manning n values, and channel slope are used as input, the model should output a fairly good theoretical rating curve that is representative of the site (Bill Reed, CBRFC Senior Hydrologist, Personal Communication).

The theoretical rating curve developed in this study can be helpful to estimate flows for future flow events at the site. It can be useful if the site is ever to be modeled using a site specific or distributed model that has shown skill in forecasting for ungaged basins. A rating curve was produced for the upstream and downstream sides of Rucker bridge (figure 26). Since the bridge is underlain with concrete, the rating curve should provide a relatively accurate depiction of the stage-discharge relationship at the site.

Precipitation Frequency and Return Flow Analysis

NOAA Atlas 14 was used to obtain precipitation frequency for the coordinates near Rucker Bridge. Spotter report of 4.0 inches in an hour or 4.7 inches in two hours amounts to in excess of a 1000 year return period. Since a point precipitation report is of limited value for hydrologic analysis, the aerial average precipitation over that portion of the basin receiving rainfall of one inch or greater was determined. In this case, the downstream half of the basin. This was estimated using the 2046 Z (1:46 PM) storm total precipitation. 2.8 inches over two hours was calculated which amounts to a 50 year precipitation return period.

Return flows for Rucker Canyon were calculated using methods discussed in USGS Water-Supply Paper 2433, “Methods of Estimating Magnitude and Frequency of Floods in the Southwestern United States,” by Thomas, Hjalmarson, and Waltemeyer (1994). This and other USGS publications like it (for other parts of the country) derive regression techniques that can be used to estimate return flows in ungaged basins. A 100-year return flow of 3,600 cfs was calculated for the 50 square mile Rucker Canyon basin.

Eyewitness reports stated that Bruno Creek had contributed to the flow. Bruno Creek is a 12 square mile watershed that normally enters Rucker Creek four to five hundred feet downstream of cross section 1 (figure 27). This added drainage area increases the calculated 100-year return flow to 4650 cfs for the combined Rucker Canyon-Bruno Canyon watershed.

Conclusions and Discussion

The July 21, 2002 storm was short-lived, relatively stationary, and an effective precipitation producer. Portions of Rucker Canyon received upwards of 4 inches within an hour. This resulted in a flash flood which overtopped Rucker Bridge and had a minimum discharge between 4000 and 4500 cfs based on current channel geometry and between 3500 and 4000 cfs based on estimated pre-2002 flood channel geometry. This amounts approximately a 100-year flood using USGS regression techniques to calculate return flows for ungaged basins.

While it is ideal to study a flash flood as soon as possible after an event, this technical attachment demonstrates that valuable information can be obtained sometime later for significant events. For a step-by-step plan of action on how to collect data and conduct a post flash flood analysis, see Appendix A.

Acknowledgements

Special thanks to the USGS Tucson water resources division for their input on the project. Cochise County flood control for providing information on the event. WFO Tucson WCM Tom Evans for assisting with the field survey.

References

Arcement, G., Jr., Schneider, V., 1990: Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains, *USGS Water Supply Paper 2339*.

Barnes, H., Jr., 1967: Roughness Characteristics of Natural Channels. *USGS Water-Supply Paper 1849*.

Dalrymple, T. and Benson, M.A., 1967: Measurement of peak discharge by the slope-area method. *USGS Techniques of Water-Resources Investigations, Chap. A2, Book 3.*

Phillips, J., Ingersoll, T., 1998: Verification of Roughness Coefficients for Selected Natural and Constructed Stream Channels in Arizona. *USGS Professional Paper 1584*.

Pytlak, E., 2004: Rucker Canyon Flash Flood WES Case. *NWS WR TA-Lite 04-27.*

Thomas B., Hjalmarson, H., Waltemeyer, S., 1994: Methods of Estimating Magnitude and Frequency of Floods in the Southwestern United States, *USGS Water-Supply Paper 2433*.

US Army Corps of Engineers, November 2002: HEC-RAS, River Analysis System User’s Manual, Version 3.1 *USACE CPD-68*.

US Army Corps of Engineers, November 2002: HEC-RAS, River Analysis System Hydraulic Reference Manual, Version 3.1 *USACE CPD-69*.

US Army Corps of Engineers, November 2002: HEC-RAS, River Analysis System Applications Guide, Version 3.1 *USACE CPD-70*.

US Army Corps of Engineers, 1991: Hydraulic Design of Flood Control Channels, *USACE EM 1110-2-1601*.

Appendix A: Basic Steps for Estimating Discharge at an Ungaged Site

Mike Schaffner, WFO Tucson

While it is difficult to simplify a procedure that will vary from situation to situation, below is an attempt at a step-by-step plan for collecting data and conducting post flash flood analysis at an ungaged site:

1.) After a flash flood event, archive the event using the Weather Event Simulator and collect any pertinent information such as spotter reports.

2.) Contact the county to obtain any information on the event or the hydrology in the area of the flash flood (such as flood studies). Also review the discontinued USGS streamflow gaging stations in the area to determine if the stream has ever been gaged. If there is a discontinued station, you can go to the rating curve and us the observed stage to determine the discharge. If a discontinued gaging station is not available, proceed to the next step.

3.) Visit the site of the flash flood as soon as possible. Locate a suitable reach. A suitable reach is one which:

A.) Has consistent cross sectional area, channel slope, and roughness values throughout.
B.) Is straight.
C.) Length is at least four times the width of the channel.
D.) Three cross sections (at a minimum) can be placed.
E.) Does not have any tributaries entering within the reach.
F.) High water marks are clearly evident on both left and right banks
G.) Channel disruptions, such as bridges, are not present.

If a suitable reach can be found, use the USGS slope-area method to compute the maximum discharge for the flash flood event. Refer to USGS Techniques of Water-Resources Investigations, Book 3, “Measurement of peak discharge by the slope-area method,” by Dalrymple and Benson (1967) if conducting a slope-area calculation. To download the USGS Slope-Area computation program, go to: http://water.usgs.gov/software/sac.html

If the reach is not suitable, you desire to evaluate the flash flood at a channel disruption, or want to develop a rating curve for the site, consider using a step-backwater model such as HEC-RAS. Continue to step 4 if using a step-backwater model. It should be noted that high water marks are surveyed to define the water surface slope or profile. Step-backwater models use channel slope whereas slope-area method uses the water surface slope.

4.) Locate a suitable reach for a step-backwater model simulation. This reach should meet as many of the requirements for a slope-area reach as possible. A step backwater model was used in this case primarily due to the lack of high water marks and the need to evaluate flow at a channel disruption in the form of a bridge.

5.) Select cross sections. Cross sections should be perpendicular to the channel. A minimum of four cross sections are needed to define a bridge. Additional cross sections can be placed downstream from the bridge if desired. If you are not defining a bridge, up to a dozen cross sections can be surveyed in. Generally the greater the number of cross sections, the greater the chances that the model will converge. A minimum of 50 feet should separate cross sections that have slopes equal to or exceeding one degree. Allow more separation for gentler slopes or at least one width of the channel apart.

6.) Flag high water marks present at selected cross sections.

7.) Note roughness values at each cross section.

8.) Take pictures upstream and downstream, at each cross section, looking in the direction of flow.

9.) Obtain survey equipment. This should include tripod and survey level, telescoping measuring rod, and two or three 300 foot tape measures. Tape measure can be used to define the cross sections and measure distance between cross sections.

10.) Survey in each cross section.

11.) If surveying a bridge, place a minimum of one cross section upstream and one downstream from the bridge. These should be free from contraction and expansion forces respectively. Then place one cross section upstream and one downstream of the bridge to define bridge geometry. These should be in close proximity to the bridge. Bridge data, including position of bridge piers, deck, abutments, and weir type, should be recorded.

12.) Input data into HEC-RAS. If using HEC-RAS for the first time, it is advisable to obtain training and/or have your results reviewed by someone proficient with the program. For more information refer to HEC-RAS user manuals. Download HEC-RAS and user manuals at: http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html

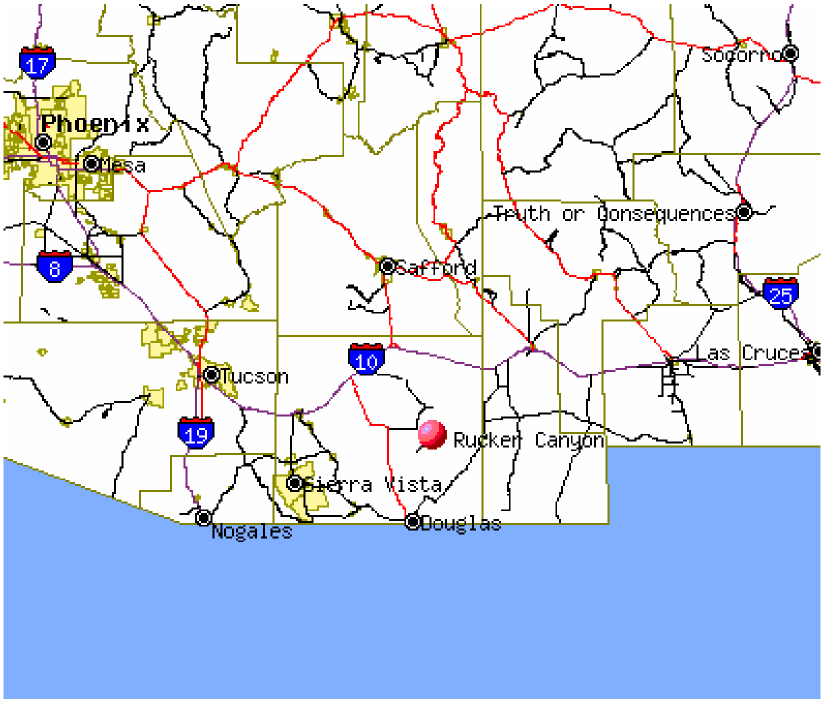


Figure 1: Map of southern Arizona and New Mexico showing location of Rucker Canyon in southeast corner of Arizona. Image courtesy of US Census Bureau TIGGER maps.

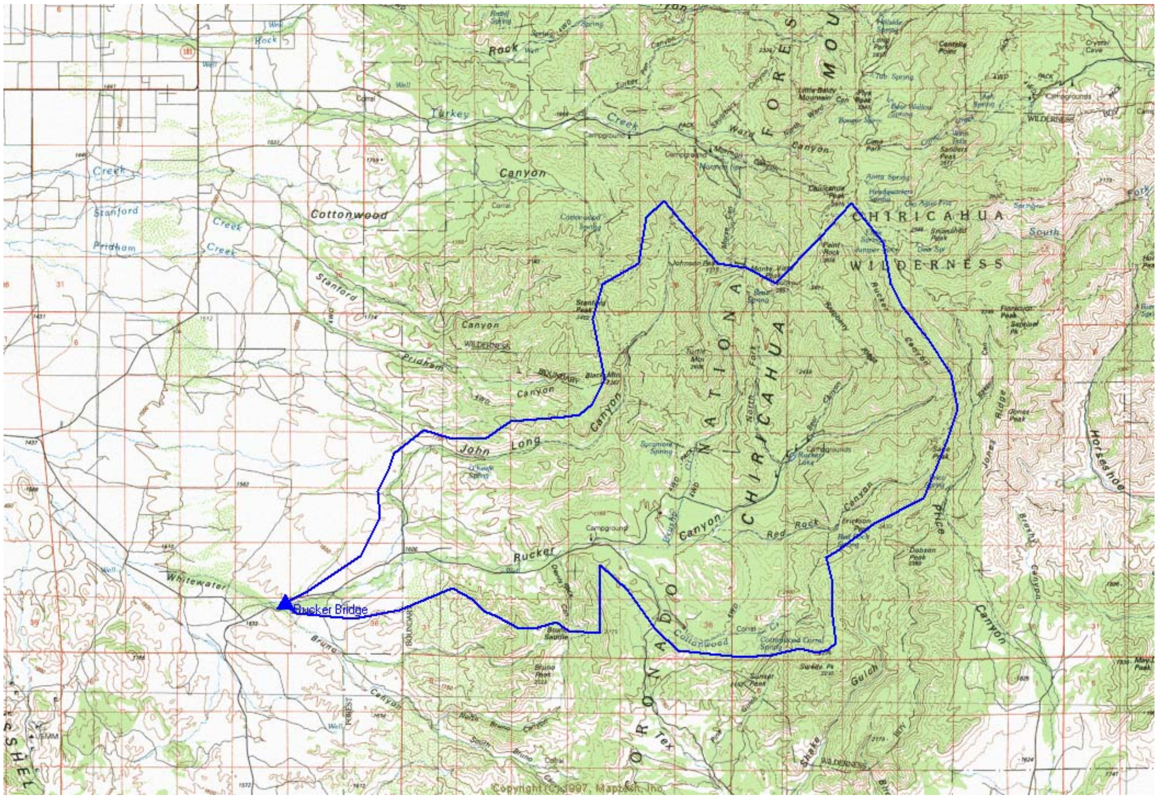


Figure 2: Watershed boundary for Rucker Canyon at Rucker Bridge overlaid over USGS 1:100000 topographic map. Bridge location showed by blue triangle. Rucker Lake is located just to the east of the "R" in Chiricahua.

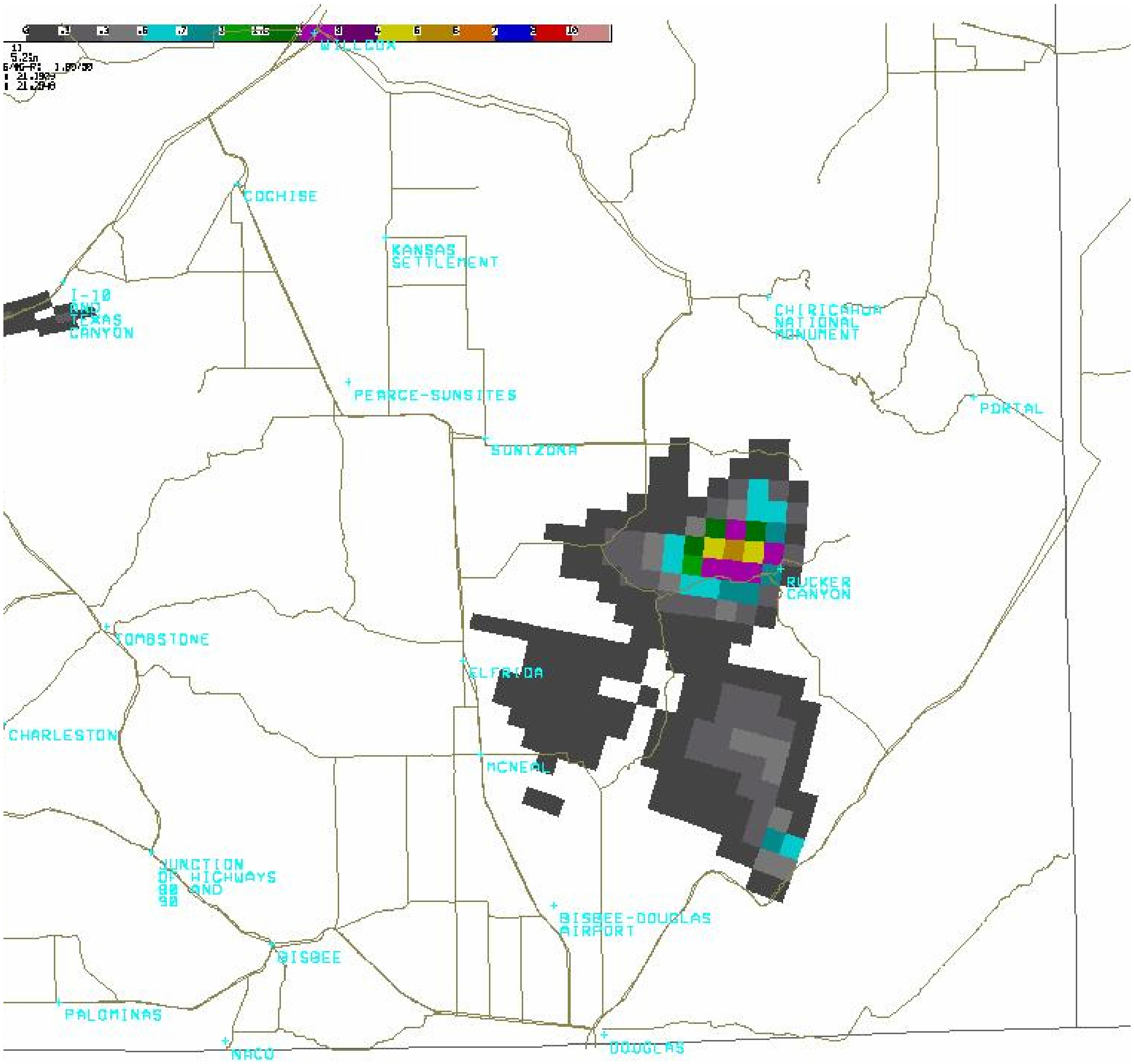


Figure 3: Storm total precipitation image from 20:46Z (1:46 PM) on July 21, 2002. Rucker Lake is located at the end of the road heading in a northeast direction from Rucker Canyon label. Rucker RAWS is located just to the east of the Rucker Canyon label.

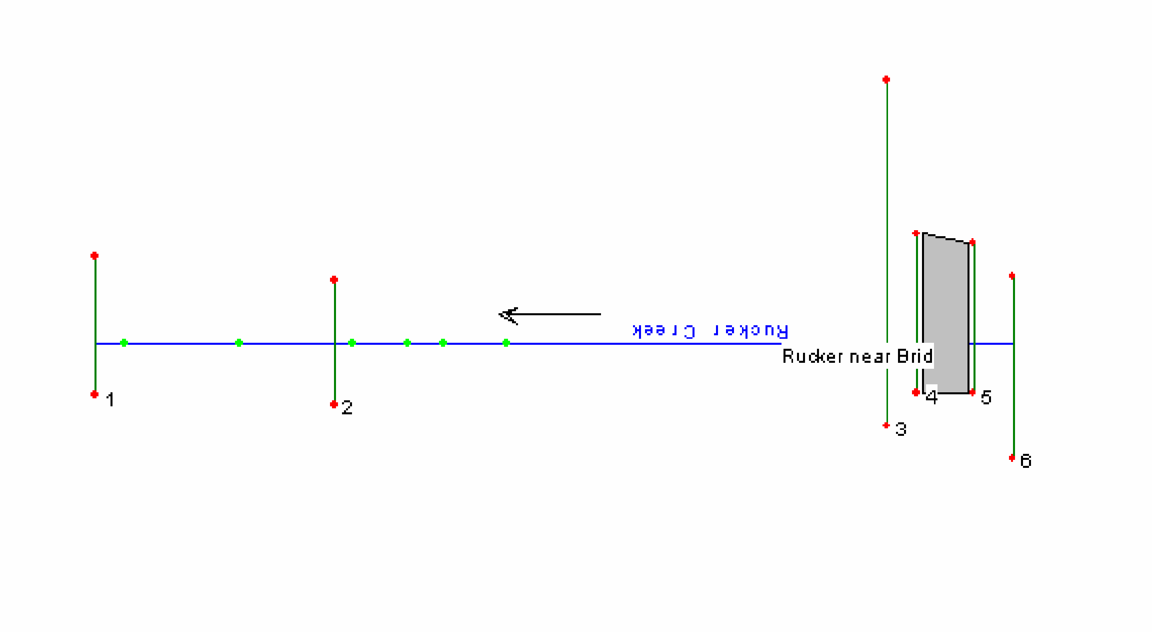


Figure 4: View of HEC-RAS geometric data. Cross section 1 is most downstream. Bridge represented by gray area between cross sections 4 and 5. Cross sections 3 - 6 needed to define bridge. High water mark surveyed in on right bank of cross section 2. Ground distance from cross section 1 to cross section 6 is equal to 324 feet. Stream reach is straight as shown above.

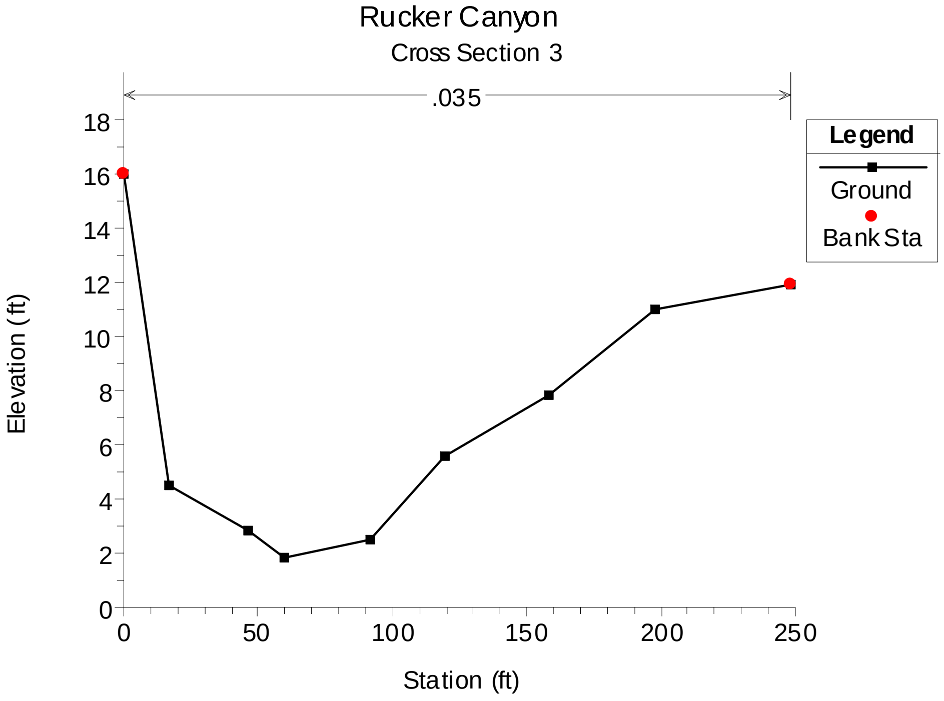


Figure 5: Cross section 3. Cross section is located 10.5 feet downstream from cross section 4 and 12.25 feet downstream from the bridge structure. Cross section view is from upstream looking downstream.

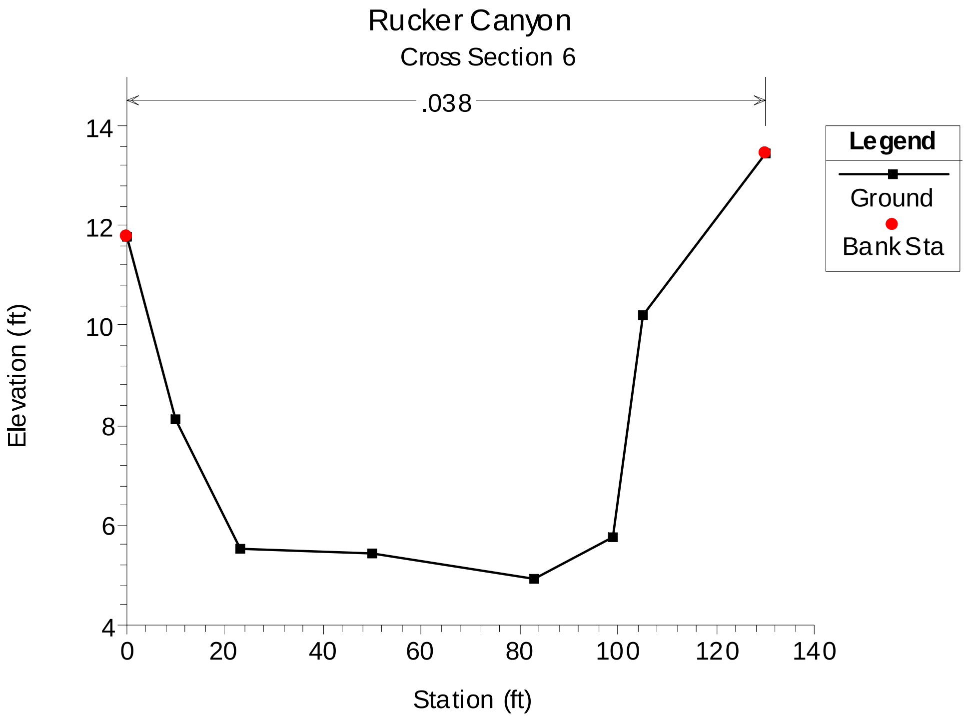


Figure 6: Cross section 6. Cross section is located 14.5 feet upstream from cross section 5 and 16.25 feet upstream from the bridge structure. Cross section view is from upstream looking downstream. The near-vertical slope on the right bank is an area of rip rap bank protection.

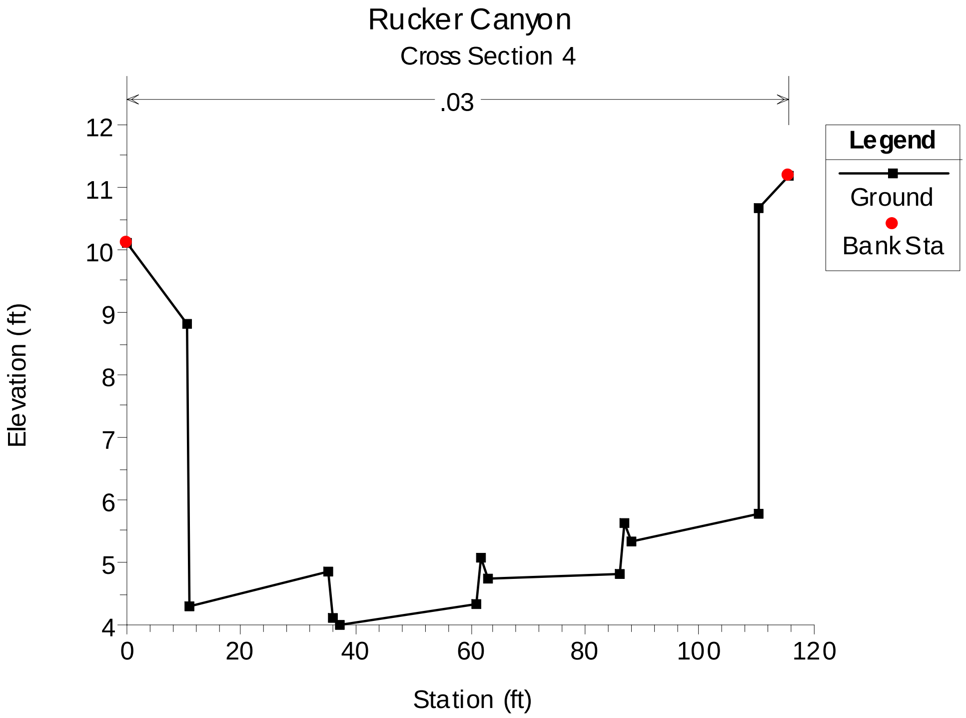


Figure 7: Cross section 4. Cross section is located 10.5 feet upstream from cross section 3 and 1.75 feet downstream from the bridge structure. Cross section view is from upstream looking downstream.

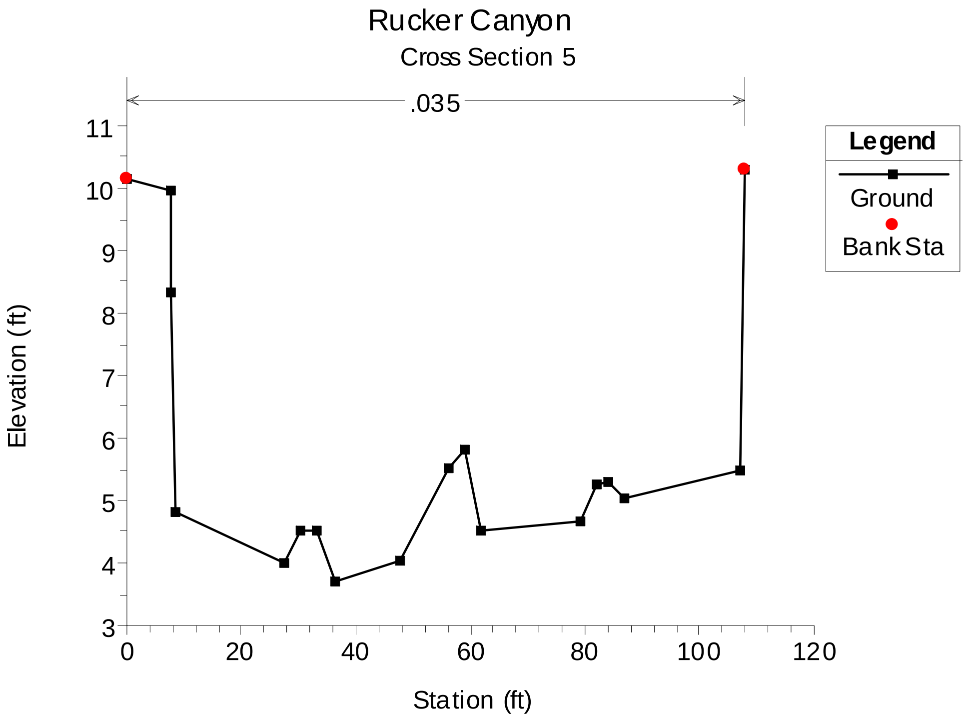


Figure 8: Cross section 5. Cross section is located 20 feet upstream from cross section 4 and 1.75 feet upstream from the bridge structure. Cross section view is from upstream looking downstream.

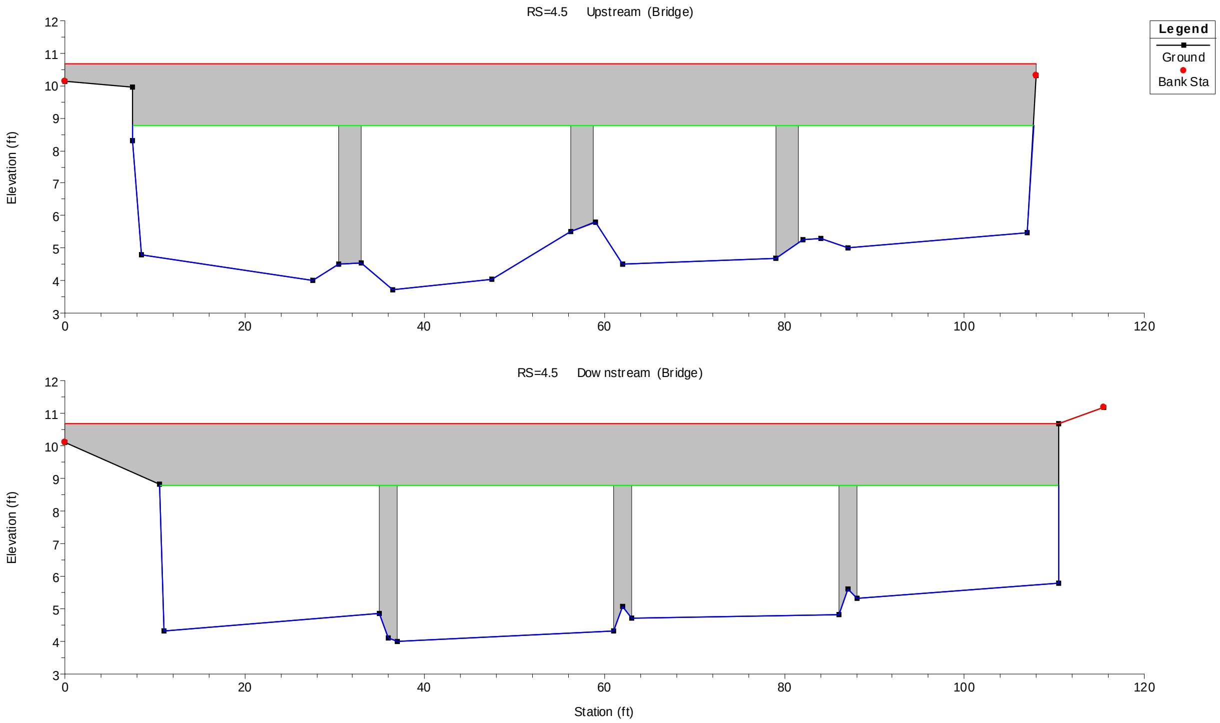


Figure 9: Bridge cross sections. Upstream cross section shown on top and downstream cross section shown on bottom. Blue line represents channel bottom, green line represents bridge low steel, and red line represents bridge deck. Cross section view is from upstream looking downstream.

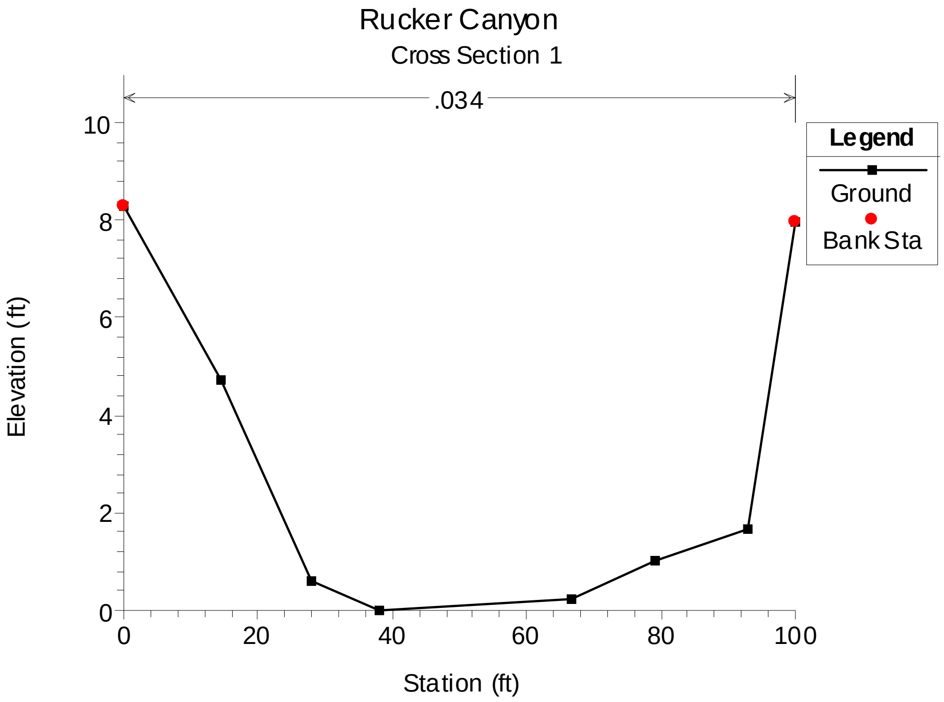


Figure 10: Cross section 1. Cross section is located 86 feet downstream from cross section 2. Cross section view is from upstream looking downstream.

Figure 11: Cross section 1 as viewed from top of left bank looking north. While not taught at the time, tape measure shows approximate position of cross section. Small tributary seen entering just downstream of cross section at right bank. Tucson WCM Tom Evans in foreground for scale.

Figure 12: Cross section 1 looking upstream. Tape measure shows approximate position of cross section. Cross section 2 was located upstream near tree along right bank. Rucker Bridge and adjacent low water crossing seen in distance.

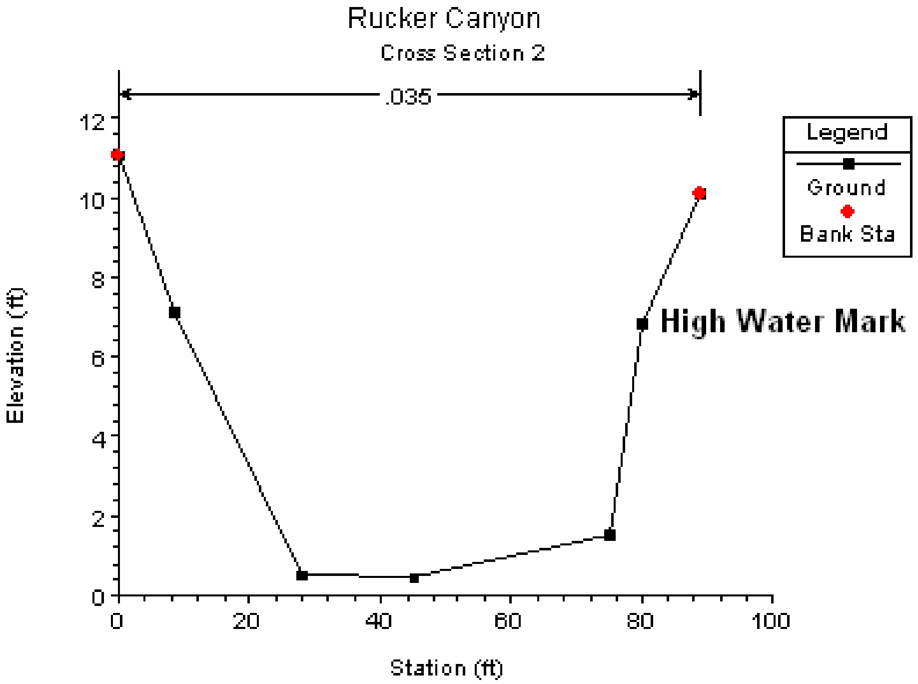


Figure 13: Cross section 2. Cross section is located 86 feet upstream from cross section 1 and 193 feet downstream from cross section 3. Cross section view is from upstream looking downstream.

Figure 14: Cross section 2 looking upstream. Tape measure shows approximate position of cross section. Rucker Bridge and adjacent low water crossing seen in distance.

Figure 15: Cross section 2 looking downstream. Tape measure shows approximate position of cross section. Cross section 1 located in distance where in-channel vegetation ends.

Figure 16: Cross section 2 as viewed from top of left bank looking north. Tape measure shows approximate position of cross section. High water mark located just above top of survey rod leaning against tree on right bank.

Figure 17: High water mark located at right bank of cross section 2. Debris, including a metal arrow bent by the flow, was discovered within.

Figure 18: Cross section 6 looking downstream towards Rucker Bridge. Cobbles dominate channel bottom as well as banks.

Figure 19: Rucker Bridge as seen from low water crossing just downstream of bridge. Yellow survey tripod seen on downstream-north side of bridge.

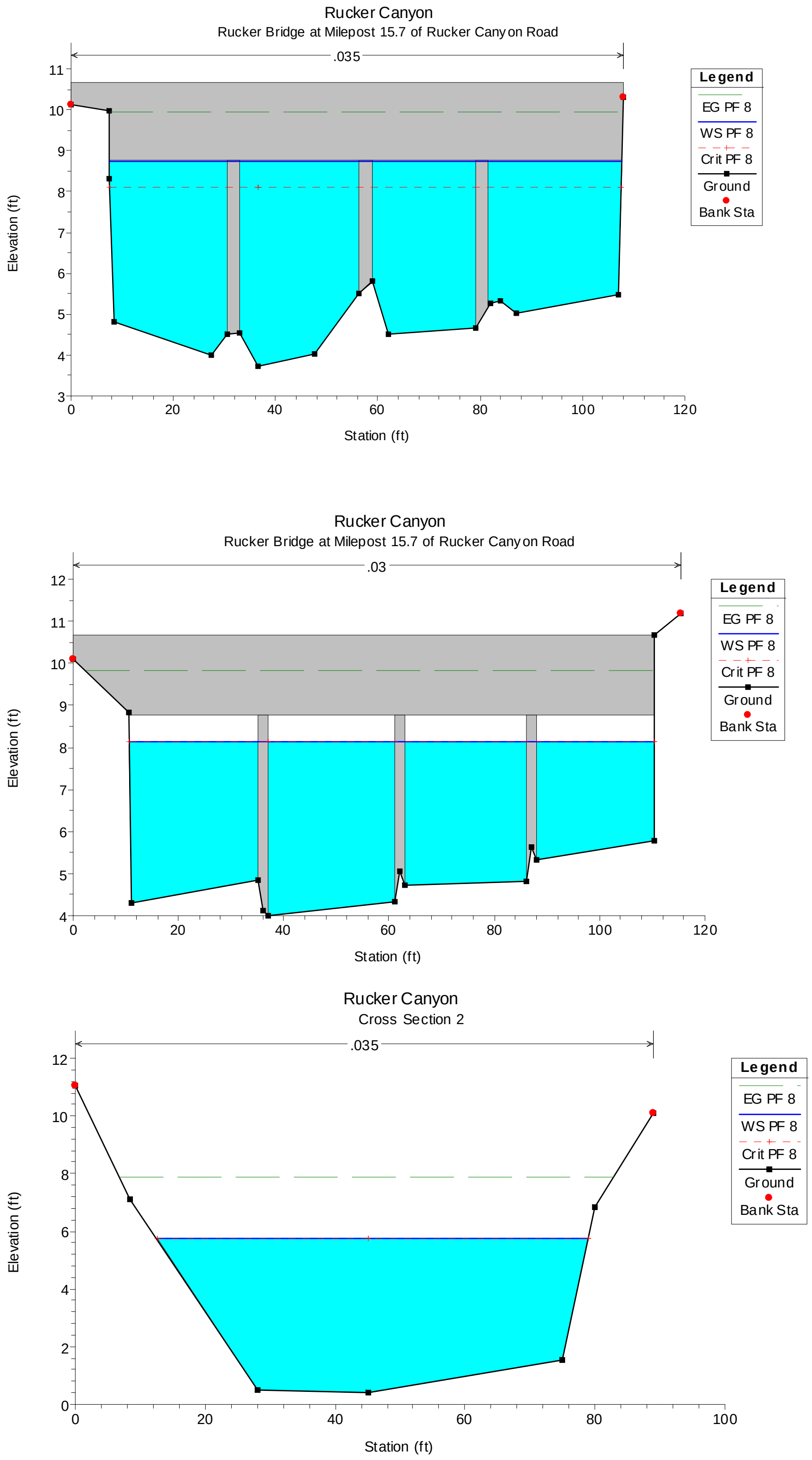


Figure 20: Water surface elevations at 3300 cfs for bridge cross section upstream, downstream, and 205 feet downstream from the bridge structure (cross section 2). Water surface elevation profile represented by solid blue line, water surface critical flow profile represented by dashed red line (coincides with water elevation profile for downstream bridge cross section and cross section 2), and energy profile represented by dashed green line. Cross section view is from upstream looking downstream.

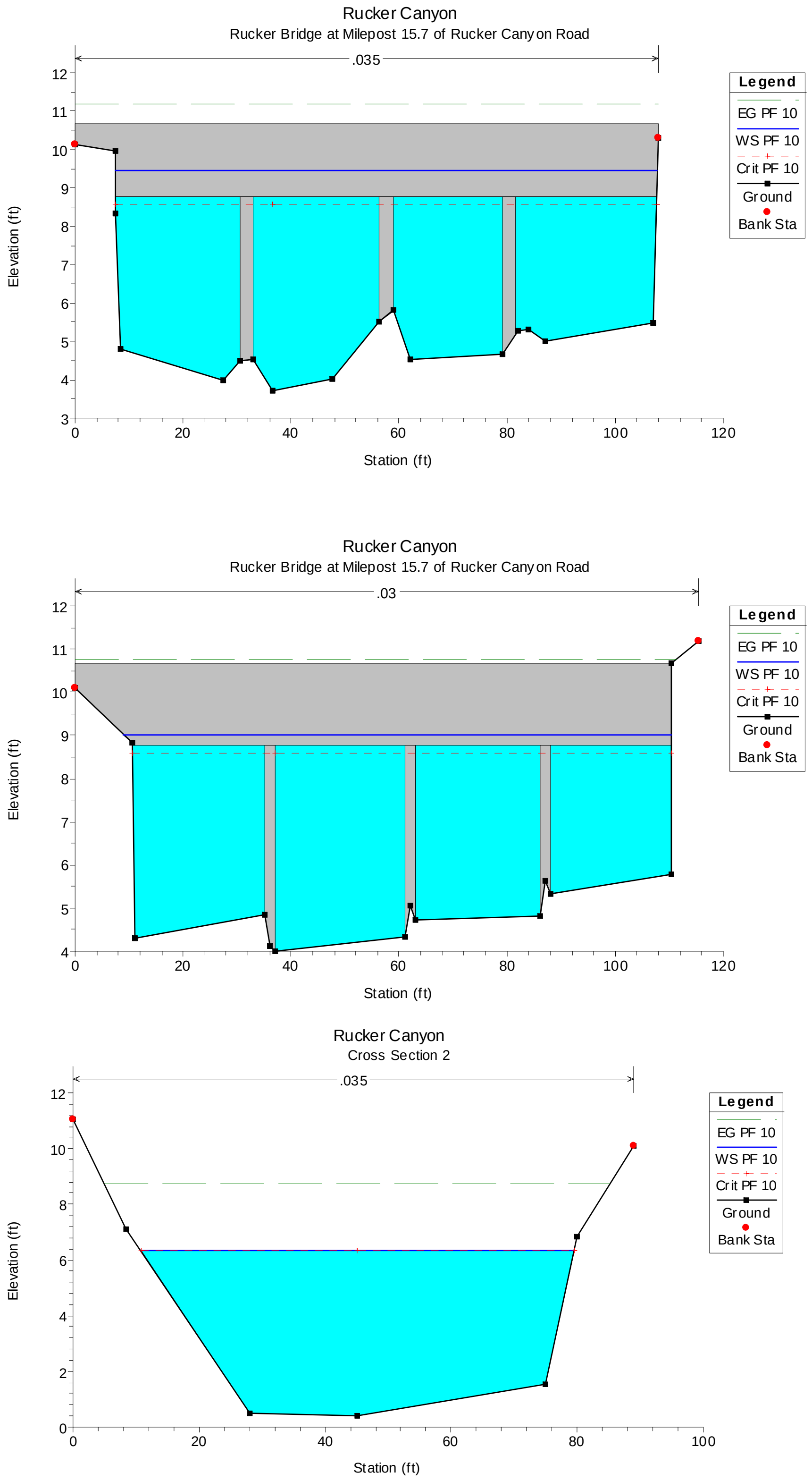


Figure 21: Water surface elevations at 4000 cfs for bridge cross section upstream, downstream, and 205 feet downstream from the bridge structure (cross section 2). Water surface elevation profile represented by solid blue line, water surface critical flow profile represented by dashed red line (coincides with water elevation profile for cross section 2), and energy profile represented by dashed green line. Cross section view is from upstream looking downstream.

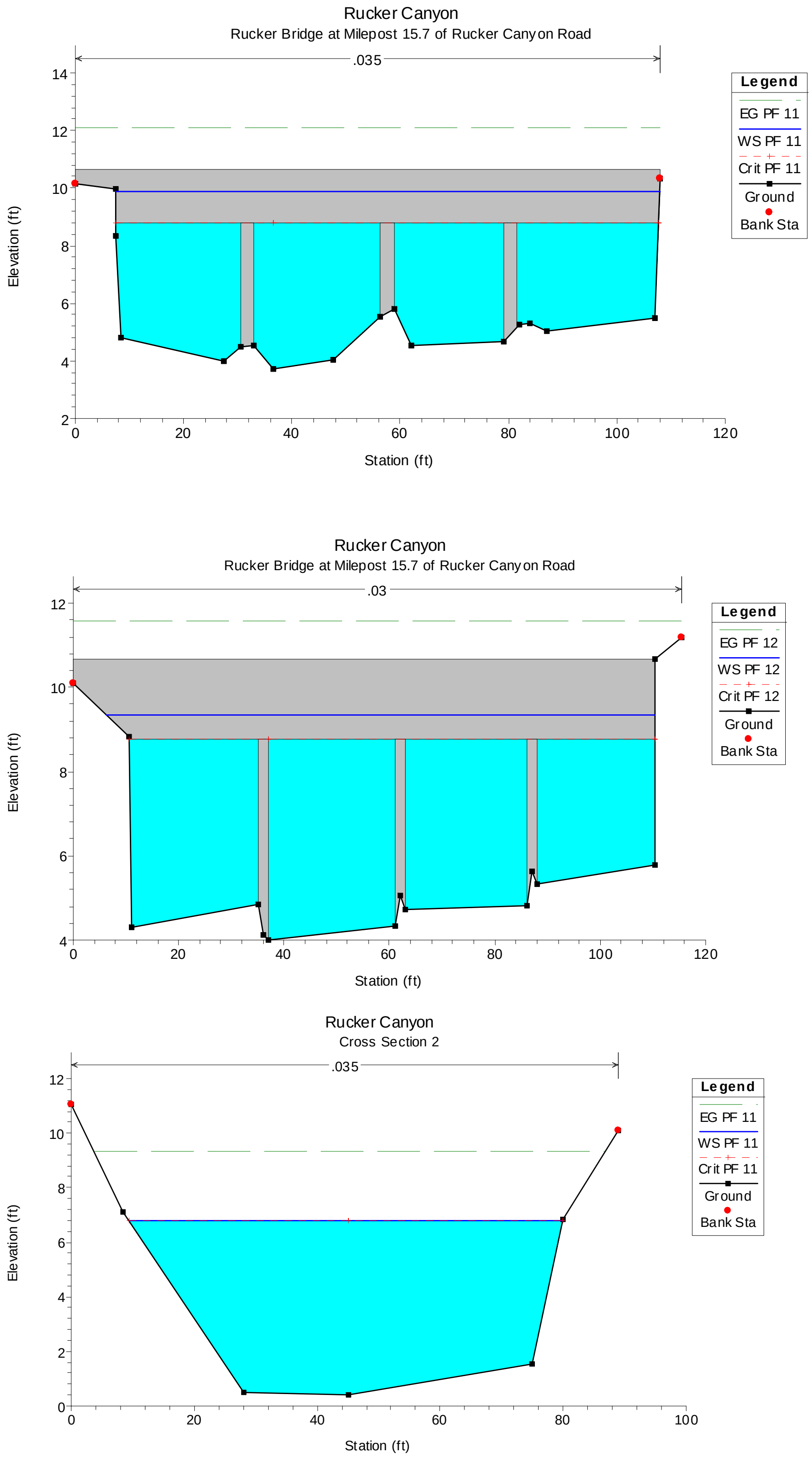


Figure 22: Water surface elevations at 4500 cfs for bridge cross section upstream, downstream, and cross section 2. Water surface elevation profile represented by solid blue line, water surface critical flow profile represented by dashed red line (coincides with bridge low steel for bridge cross sections and water elevation profile), and energy profile represented by dashed green line. Cross section view is from upstream looking downstream.

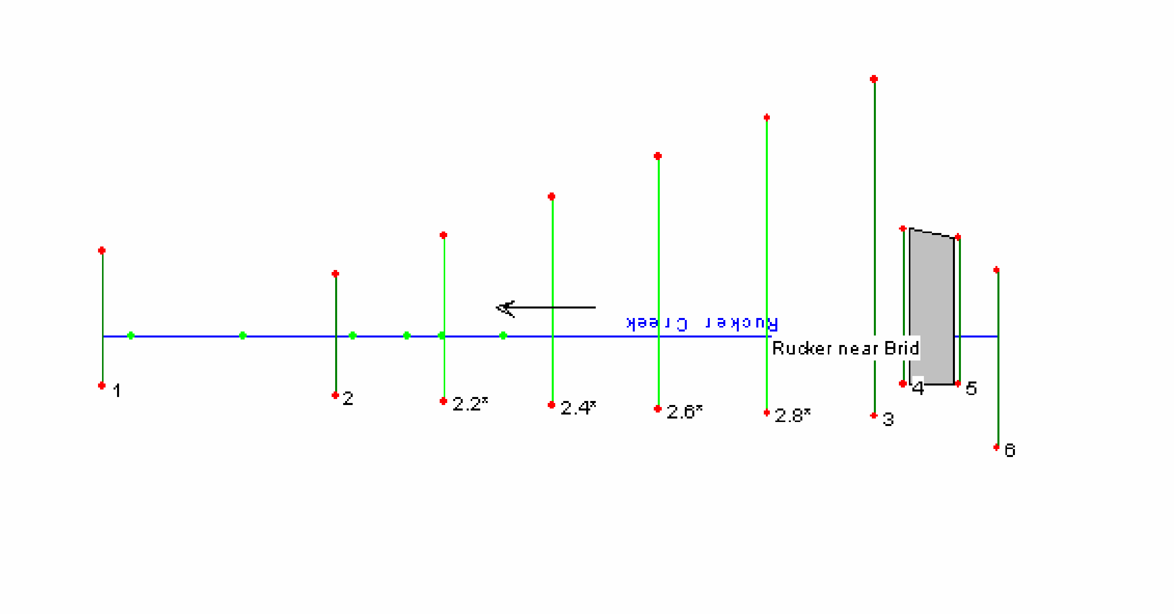


Figure 23: View of HEC-RAS geometric data with four cross sections interpolated between cross section 2 and 3.

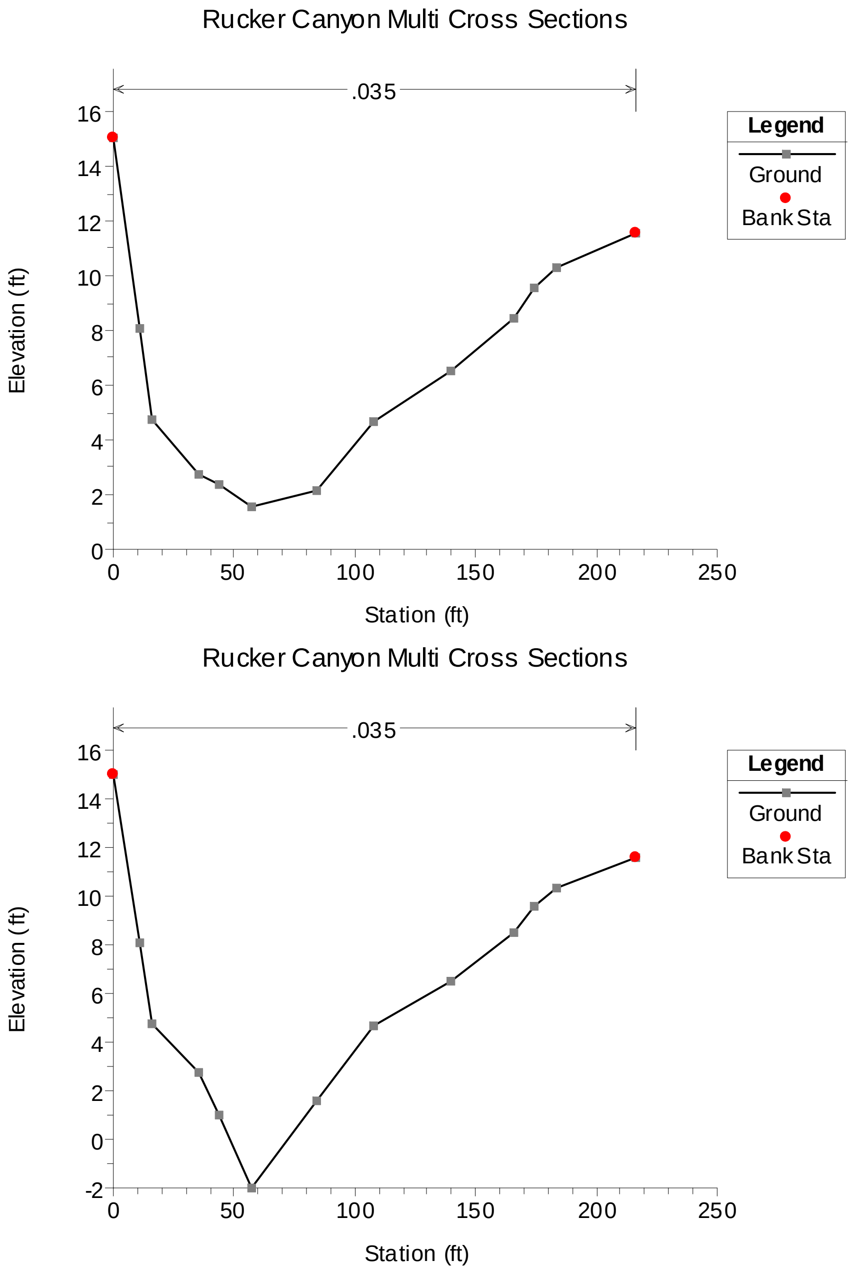
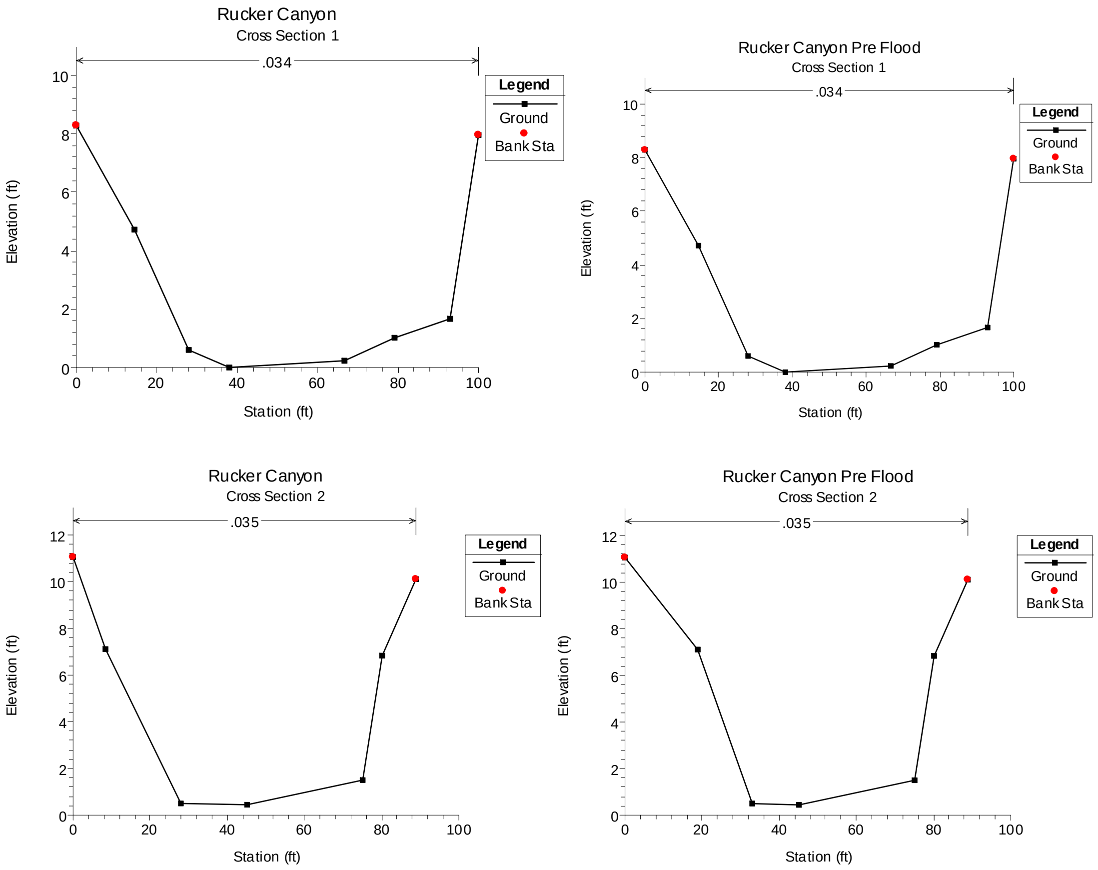


Figure 24: Scour hole added to cross section 2.8. Cross section prior to scour and including scour whole shown on top and bottom of figure respectively. Cross section view is from upstream looking downstream.



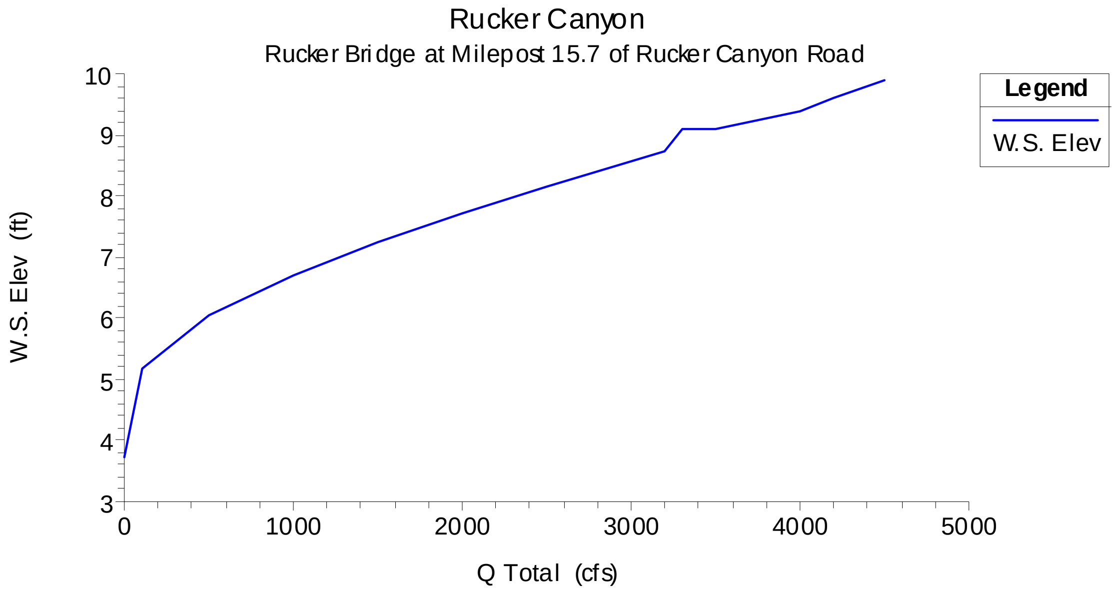
Rucker Canyon
Cross Section 1

Rucker Canyon Pre Flood
Cross Section 1

Rucker Canyon
Cross Section 2

Rucker Canyon Pre Flood
Cross Section 2

Figure 25: Cross sections 1 and 2 for current (left side of figure) and estimated pre-flood channel geometry (right side of figure). Cross section view is from upstream looking downstream.



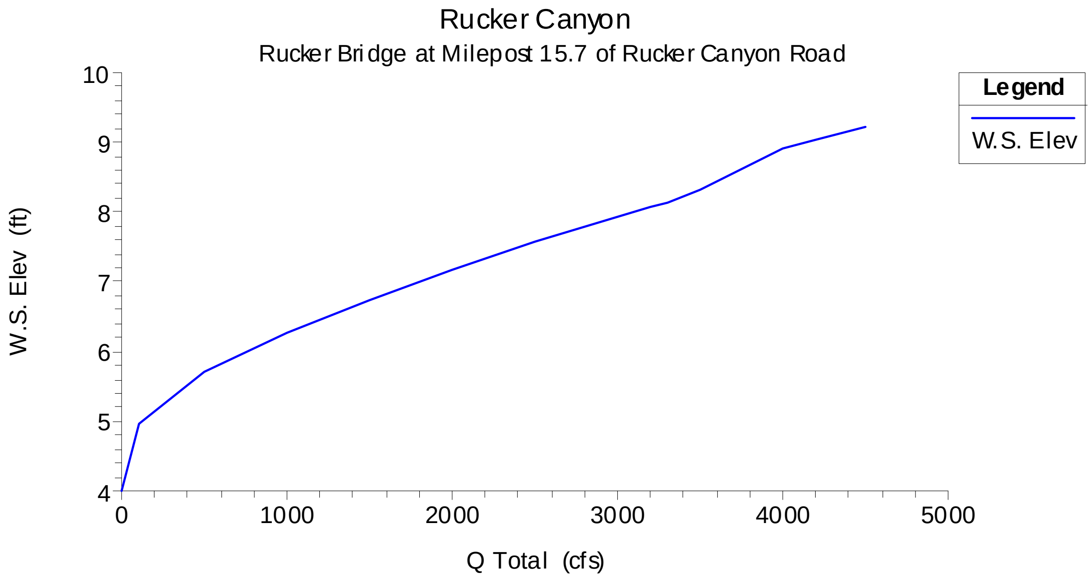


Figure 26: Theoretical rating curve for upstream (top) and downstream (bottom) side of Rucker Bridge at milepost 15.7 of Rucker Canyon Road. Bump in upstream rating curve appears to be a reaction to the water first coming into contact with bridge low steel.

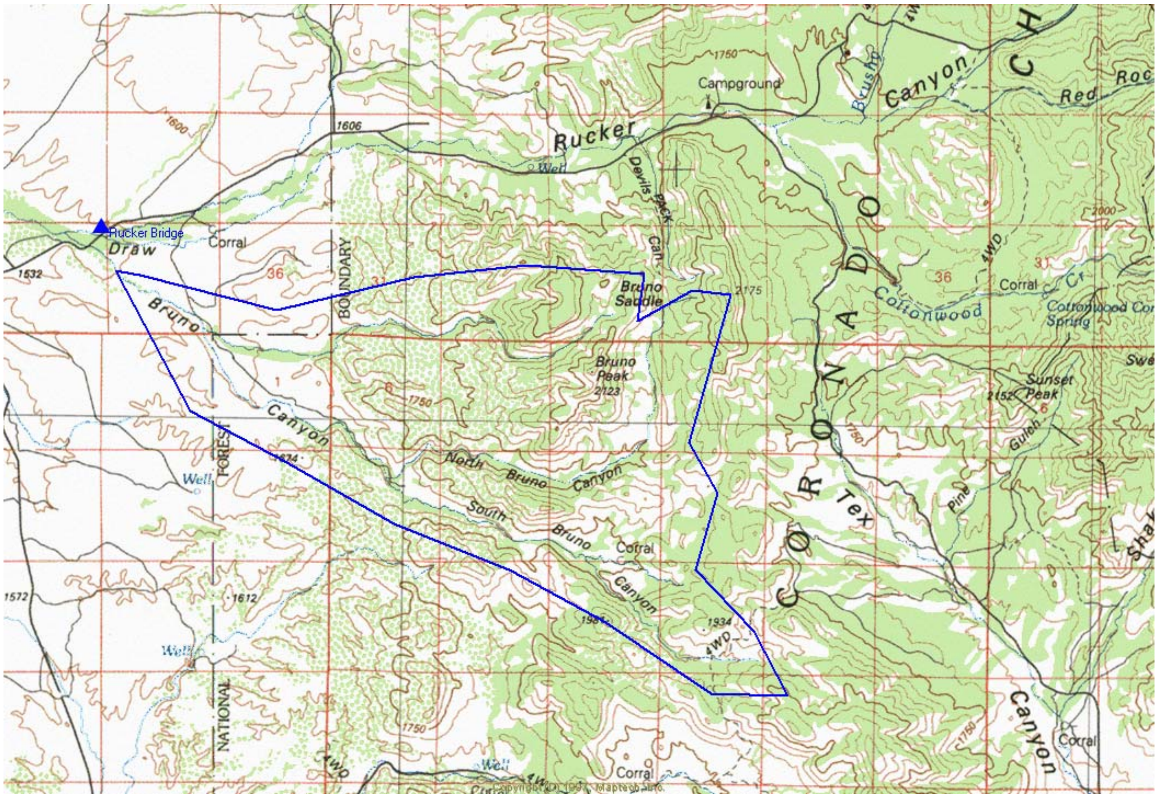


Figure 27: Watershed boundary for Bruno Canyon near Rucker Bridge overlaid over USGS 1:100000 topographic map. Bridge location showed by blue triangle.