

Indirect discharge measurement of August 21, 2011 flood on the Rito de los Frijoles in Bandelier National Monument, New Mexico.

A rainfall event in the upper Rito de los Frijoles watershed during the afternoon of August 21, 2011 produced a large flood in the mid and lower portions of Frijoles Canyon in Bandelier National Monument (BAND). On August 24-27 the National Park Service Southern Colorado Plateau Network (SCPN) and the United State Geologic Survey (USGS) completed a total station survey of the Rito de los Frijoles stream channel near the Bandelier National Monument Visitor Center. Total station survey data were used in combination with high accuracy 2010 LiDAR data obtained from the Jemez River Basin Critical Zone Observatory to determine flood discharge and extent of flooding. SCPN used these data to construct a HEC-RAS model (USACE version 4.1.0) determining a maximum discharge of 7,270 cubic feet per second (cfs) for the August 21 flood. As a quality control measure SCPN provided the survey data to the USGS, who used the agency's Slope-Area Computation program to calculate a peak discharge of 6,775 cfs for the event. An average of the two calculated discharges gives a peak value of 7,000 cfs for the flood. Accuracy of indirect measurements of discharge using these methods is generally considered to be +or- 25% or greater (Jarrett 1987). The objective of this effort was to obtain sufficient stream channel and high water mark data to support hydraulic modeling capable of producing accurate estimates of discharge for the recent flood. These data are also being used to support development of updated floodplain delineation for the Rito de los Frijoles, with particular emphasis on guiding measures to protect visitors to the monument and the important sites administrative and cultural sites located in the Frijoles Canyon bottom.

Reach and Transect Selection

An overall strategy for the total station survey was developed through review of the site and discussions with BAND and SCPN staff. The upstream end of the reach was near the monument's visitor parking lot and the lower end was just downstream from the streamflow gaging station (Figure 1). This reach was selected because it is relatively straight and unobstructed and because of its close proximity to the streamflow gaging station. Approaching the surveyed reach from upstream the channel bends distinctly to the right. The channel downstream of the reach is relatively straight. Nine transects were distributed through the survey reach, numbered from 20 to 12 in downstream order. Transects were spaced at approximately even intervals and specific transect locations were selected based on lack of major obstructions that would inhibit ground survey and on the availability of visible high water marks. This reach is bounded on stream left by the monument entrance road and on stream right by a minor access road and overflow parking area. Sections of both of these roads were encroached by the August 21, 2011 flood and were included in the total station survey.

The channel through the survey reach was moderately incised pre-flood and has not changed significantly. Channel substrate is primarily sand, gravel, and scattered cobbles. The floodplain overstory vegetation is predominantly sparse mature Ponderosa Pine (*Pinus ponderosa*) and Rio Grande Cottonwood (*Populus wislizeni*), and the understory is dominated by dense New Mexico olive (*Forestiera neomexicana*). Herbaceous vegetation is sparse to nonexistent in the reach. Prior to the flood sediments on the floodplain were almost exclusively fine-grained and in most places were covered by organic litter

composed of pine needles and leaves. The flood deposited fine-grained sediments and ash over much of the floodplain at depths of up to one foot.

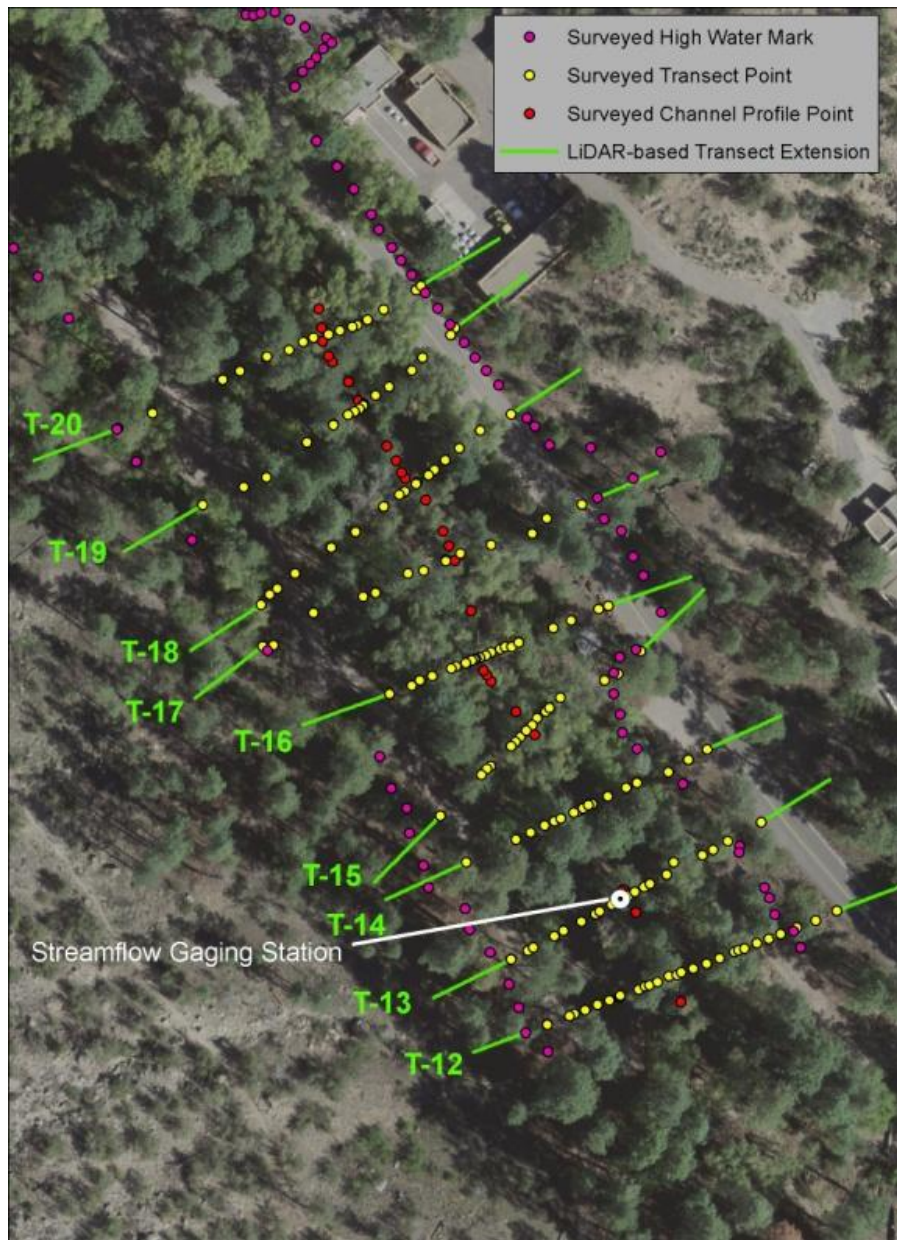


Figure 1. Aerial view of the Rito de los Frijoles near the Bandelier National Monument Visitor Center. Showing locations surveyed with a total station after the August 21, 2011 flood including transects, high water marks, channel thalweg, and transect extensions constructed from 2010 LiDAR data.

Site Conditions at Time of Total Station Survey

Site specific challenges included a substantial amount of heavy equipment operating within the surveyed area, limited number of trained staff, time constraints, visibility obscured by the large number of riparian tree trunks (and high piles of flood debris) in the area to be surveyed, and forced rapid evacuations following rainfall in the upper watershed.

GPS Survey

SCPN set up two Promark-3 L1-GPS GPS units at multiple sites on flat or gently sloping surfaces with excellent sky views in the Visitor Center area. These GPS units ideally collect data for about 6 hours to establish +/- 3 cm horizontal control.

UTM coordinates using high-resolution control points that were established with Promark-3 L1-GPS units.

Total Station Survey

Equipment used for the total station survey of Rito de los Frijoles included the SCPN Topcon GTS239 total station, Recon datalogger with SurveyPro software, and standard metric fiberglass survey rods and prisms. Whenever possible, backsights were established with a tripod and tribrach-mounted prism to ensure precision.

The total station data were collected in metric units and a combined scale factor calculated for this location and elevation was used. The calculated combined scale factor was 0.999476; the earth curvature adjustment was set to "off"; and the applied atmospheric correction (AC) was 60 ppm (based on local elevation and ambient temperature). An arbitrary survey grid was established with its origin set to X= 50,000; Y=50,000; Z=1,000.

The survey crew consisted of Ellen Soles (NPS-NAU), Mike Matush (NMED), Stephen Monroe (NPS-SCPN), Collin Haffey (NPS-BAND), Anne Tillery (USGS), and Stephen Brown (USGS).

Survey Control

Initial local survey control (5/8" rebar driven about 1.5 ft. deep) was established at a location that would enable us to survey both points as soon as the units could be removed; the two other pre-determined locations for the next day's GPS occupations were well out of sight behind various buildings. A second control, the center of the top square bolt of an obvious fire hydrant in parking area, was established to provide the initial backsight and to serve as a second occupied point (OP) for the total station. We also selected a number of other controls visible on the LiDAR data (most of them obvious building corners) to be surveyed.

Available "LiDAR controls" (e.g., building corners) were surveyed first, followed by as much of the HWM on floodplain left (the parking area and entrance road) as could be seen from the initial OP. We selected two and placed more controls; both 5/8" rebar: on the left channel bank near the corner of the V.C. (the first OP for surveying the upstream channel transects and profile) and between the entrance road and channel about 140 m downstream (to be the initial OP for downstream work).

Backsight checks after each turn showed excellent accuracy; previously surveyed controls were also re-shot after each turn. Horizontal errors on backsight checks of existing controls or new controls, were between 3 and 7 cm; vertical errors were minimal (1 cm or less).

Transect Survey

A “stake-to-line” procedure was used to survey transects in order to avoid time lost in stringing taglines. Rod people established the virtual line perpendicular to the channel by standing on either side of the channel; “stake-to-line” used these points as the initial line that was then surveyed as far as possible either to the V.C. (on floodplain left) or to the extreme high water mark on floodplain right. The off-line tolerance was set at 0.05 meter. However, in order to speed up the work we increased the tolerance to as much as 3 m on the three upstream-most transects.

As much of each transect, stream profile, and HWMs on each side of the channel as possible were surveyed from each setup. Due to limited visibility we were unable to survey high water marks at the far right end of some transects. In addition, we surveyed points along the tops and at the ground surface of the long line of Jersey barriers extending about 100 m upstream of the V.C.; the last few to be installed to extend a short distance downstream of the V.C. were not yet in place and their positions and heights were estimated by the rod crew and these estimated points were also surveyed.

Profile Survey

In addition to transects, the channel thalweg was surveyed at approximately 1 meter intervals and all significant grade breaks.

Integrated Total Station – LiDAR Data Processing

Initial processing of total station survey data collected along the Rito de los Frijoles floodplain in Bandelier National Monument from 8/24/2011 to 8/26/2011 was completed using Terramodel (V. 10.4). Accuracy was “Roughly” within 1-2 cm horizontally in most cases, but only within 0.25 m for points collected near the end the survey. The discrepancy is due to limited detail in field notes, therefore large differences between the early and final shots on 8/27/11 cannot be explained (or corrected).

The total station survey was reported in a local arbitrary coordinate system and adjusted to UTM, NAD83 CORS 96 Geoid03 coordinates using high-resolution control points established with Promark-3 L1-GPS units. The total station data were transformed and rotated using three L1-GPS control points with Underhill Geomatics Copan Lite v11. The transformation RMS error was 0.057 m, and the angle of rotation was $-71^{\circ}37'19.62''$.

A correction factor of 847.345 m was added to the total station survey height data to convert it to orthometric height using Geoid03 datum (CorGeoid03). The correction factor was calculated by averaging the difference in height between two of the L1-GPS control points and the matching total station survey points. The height differences were less than 1cm between two of the control points. The third control point was excluded from the average height difference because the comparison of two-hour control blocks had inconsistent results, and the elevation of that point was inconsistent with the elevations of the two other control points.

The outer ends of each cross section were extended using a multipoint surface created from classified point-return (LAS) data from a 2010 LiDAR flight by the Jemez River Basin Critical Zone Observatory. As a quality control check, the LiDAR and total station data were compared for the overlapping portions of the cross sections and showed good agreement (Figure 2).

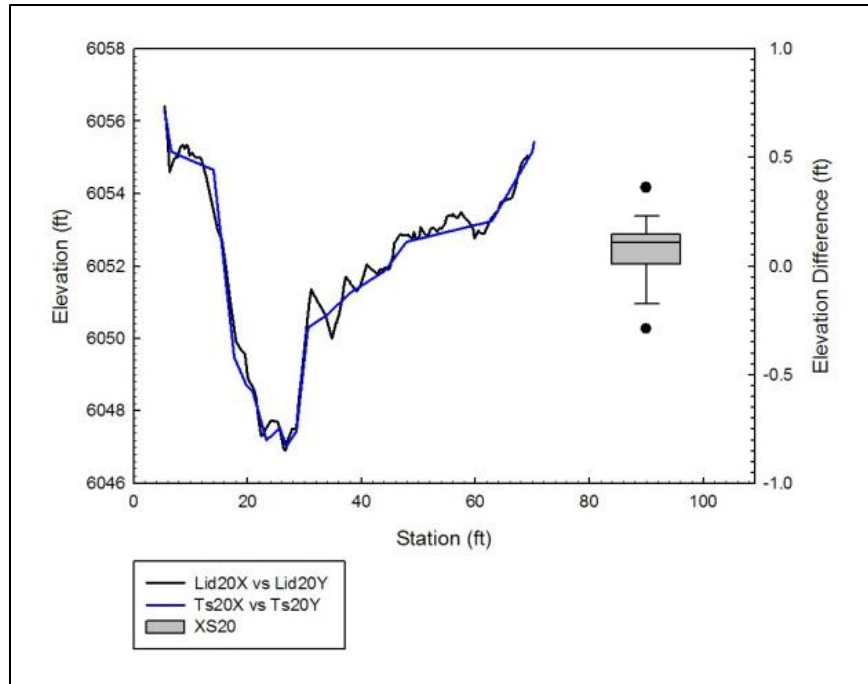


Figure 2. Example of comparison of stream channel cross sections from 2010 UA CZO LiDAR data and August 2011 total station survey of Rito de los Frijoles.

High Water Marks

High water marks (HWM) throughout the surveyed reach were clear, consisting of recently deposited litter and debris, minor scour in some places, and ash deposition on banks and standing trees. Evidence of surge and rapidly changing stage was obvious in some places. On channel left the stream overtopped the Entrance Road, forming a non-contributing backwater area, documented in videos of the flood taken by park rangers. HWMs were observed in the field and documented photographically. When possible HWMs at the end of each transect were surveyed in the field with a total station, however, in some cases we were unable to survey HWMs due to obstructions. To compensate for this we surveyed additional HWMs throughout the reach at stations not aligned with transects. To define HWMs for transects where these marks were not surveyed we chose to calculate a linear regression using appropriate surveyed HWMs (Figure 3).

A regression was chosen as a conservative approach because individual HWM elevations can be affected by local flow conditions, debris, and survey error. Ideally, these problems would be assessed using field notes describing the position and quality of the HWMs (USGS-TWRI3-A), but in this case time and survey conditions did not allow for thorough documentation of all HWMs throughout the surveyed reach. Several of the left bank high water marks were not used in the regression because surface water appeared to have pooled on the road along that bank, creating a false surface. A few additional high water marks were removed because they substantially differed from multiple adjacent marks. The station position of each high water mark on individual cross sections was calculated with a simple linear extrapolation using the two nearest bracketing survey points.

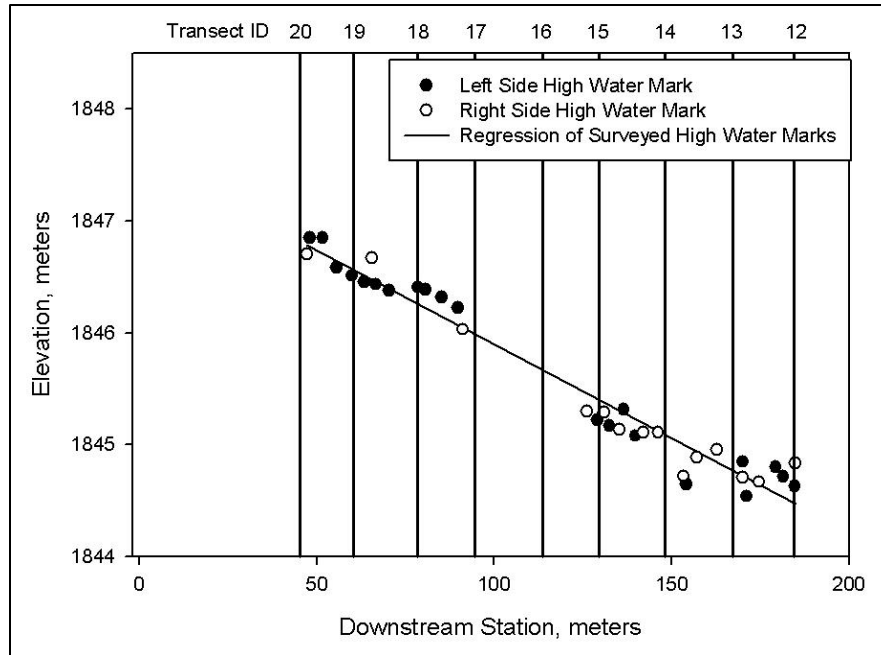


Figure 3. High water mark regression line for August 21, 2011 flood in the Rito de los Frijoles.

Channel Roughness

Approximate locations along each transect where Mannings' "n" values changed were flagged and surveyed. Photographs of each transect were taken documenting reach conditions including channel and floodplain roughness at the time of the survey. Initial "n" value estimates based on field observations were developed using the method recommended in Arcement and Schneider (1989) and are shown in Table 1. Each transect was subdivided based on field observations of roughness factors and channel morphology. Channel roughness values for the active channel at most transects are comparable to values used by USGS for a slope-conveyance computation of a flood occurring in the Rito de los Frijoles on August 29, 2007 (USGS 2007).

Table 1. Estimated n values for Rito de los Frijoles near Bandelier Visitor Center

Station	n1	n2	n3	n4	n5	n6	n7	n8
20	0.06	0.085	0.039	0.09	0.08	0.06	-	-
19	0.06	0.15	0.0402	0.15	0.09	0.02	0.04	-
18	0.06	0.1	0.0633	0.113	0.02	0.06	-	-
17	0.06	0.1	0.0423	0.095	0.02	0.07	0.06	-
16	0.06	0.085	0.042	0.095	0.02	0.06	-	-
13	0.06	0.125	0.036	0.125	0.02	0.081	0.02	0.06
12	0.06	0.112	0.034	0.113	0.02	0.09	0.02	0.06

Roughness on the floodplain throughout the surveyed reach was very high with n values ranging from 0.034 to 0.125. All stations above observed high water marks were assigned $n = 0.060$. Discharge estimate error increases as n values increase by a factor indicated by Aldridge and Garrett (1973) and shown in Table 2.

Table 2. Estimated discharge estimate error for various ranges of n values.

' n ' value	Probable maximum error
<0.050	+ or - 0.005
0.50 – 0.075	+ or - 0.010
>0.075	+ or - 0.015

HEC-RAS Model

The Hydrologic Engineering Center River Analysis System (HEC-RAS) is a software package designed by the United States Army Corps of Engineers to perform one-dimensional hydraulic calculations. HEC-RAS is a one dimensional step backwater model that computes water surface profiles from one cross-section to the next by solving an energy equation using a standard step iterative procedure. Model input parameters include a series of cross-sections, a friction parameter in the form of Manning's n values distributed across each cross-section, and flow data including flow rates, flow change locations, and boundary conditions. For steady state mixed-flow simulations the boundary conditions used are known upstream and downstream water surface elevations. HEC-RAS subdivides flow in the main channel from the over-banks and conveyance is calculated for each subdivision and the total conveyance and the velocity coefficient for each cross-section (USACE 2010).

Total station and LiDAR survey data for the Rito de los Frijoles in station/elevation coordinate form for all cross-sections were entered into HEC-RAS (USACE v. 4.1.0, 2010). Transect numbers 14 and 15 were not included in the model because they were non-perpendicular to flow or included large non-contributing areas at the left side of the reach. Each transect used in the model was divided into sub-sections based on field observations of roughness transitions and Manning's n values were assigned to each interval (see previous section). HEC-RAS computes and applies weighted n values for each sub-section. Reach length between transect center of flow and right and left overbank was determined from total station survey data. The established upstream and downstream boundary conditions were defined using 'observed water surface' determined from surveyed high water marks and linear regression. Main channel bank stations were set at estimated bankfull elevations. Expansion and contraction coefficients were set to zero. Modeled conditions included 35 streamflow values, steady flow through the reach and discharges ranging from 92 cfs to 7,410 cfs. Discharges in the lower range of these values were selected based on stage-discharge relationships obtained from USGS Rating 3.1. This rating was developed for streamflow gaging station number 08313350 Rito de los Frijoles in Bandelier National Monument, New Mexico, destroyed by the flood of August 21, 2011. This rating is defined up to a gage height of 5.20 feet arbitrary datum (1,240 cfs). Modeled discharges were chosen based on stage values determined for floods observed during August through September 2011. Modeling utilized a 'steady flow' analysis, as limited stage/discharge values are known for high flows in this reach of Rito de los Frijoles. The model was run using a 'mixed flow regime' based on hydraulic conditions possibly passing from subcritical to supercritical observed in videos of the flood taken by Tom Betts, Chief Ranger, Bandelier National

Monument. Modeled stage values for each transect, and the stream profile, were evaluated and appeared consistent and appropriate. HEC-RAS determines conveyance within each segment based on n , area, and hydraulic radius. Sensitivity analysis was conducted defining discharge where optimum correspondence between modeled and observed high water marks occurs at maximum number of transects (Figure 4).

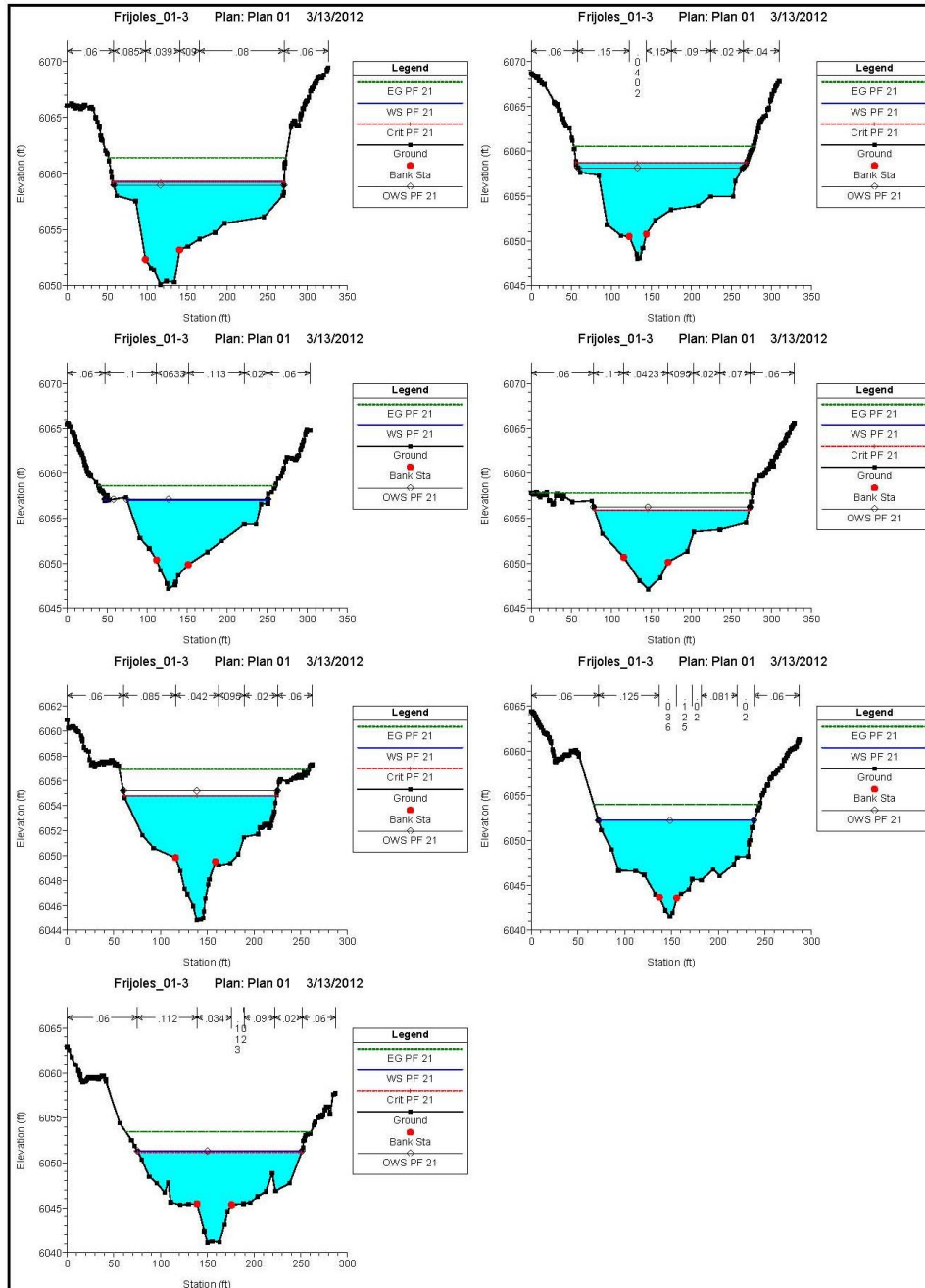


Figure 4. Transects from HEC-RAS model for Rito de los Frijoles showing relation of modeled and surveyed high water mark water elevations for flood on August 21, 2011.