Local Applications of Fluvial Geomorphology

By

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Amy Dietz
Special Project
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Table of Contents

Amy Dietz
Special Project
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Abstract

This study proposed a method for developing regional curves based solely on hydraulic modeling. Regional curves relate bankfull channel geometry and discharge to drainage area and are typically used to design channel reaches in natural stream systems at locations where stream modifications are required. Such modifications may result from the following projects - highway improvement, bank stabilization, flood control, etc. There are simply situations where modifications must be made to reaches of natural streams in order to accommodate improved drainage structures or to address flooding, scour or erosion problems.

Tributaries of the Marais des Cygne River in Johnson County, KS were used for this study. The watershed for the region studied is predominantly rural and, thus, has many natural reaches. Moreover, detailed terrain data was available for the portion of the Marais des Cygne River considered in this study – with 1-ft contour interval data along the stream corridors.

HEC-RAS modeling was used at eight sites or stream reaches within the area studied. Each of the eight stream reaches were judged to be natural based of aerial photography. A HEC-RAS model was developed for each site at a riffle location. Each model used the downstream normal depth boundary condition and contained from 4 to 9 cross sections developed using HEC GeoRAS. The bankfull elevation was estimated for every cross section based on the elevation where the flow appeared from the cross section plot to spill out into one or both of the overbanks.

Trial and error was used for each model to determine the discharge (bankfull flow) that produced the minimum sum of squares of the differences between the computed water surface elevation and the assumed bankfull elevation for all modeled cross sections. The bankfull flow channel geometry parameters were then determined for each cross section and average values were related to drainage basin area via regional curves. The drainage basin areas used were from the recent Johnson County flood study of the Marais des Cygne River.

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Local Applications of Fluvial Geomorphology

1. Introduction

Geomorphology is the classification and study of the natural processes that occur in rivers and streams. Most stable streams meander slowly back and forth across the floodplain. Streams impacted by an urbanizing watershed change as rapidly as their watershed changes. Urbanization changes the rate and volume of runoff, the volume of sediment transported by the channel, and the water quality of runoff. Urbanization can create downstream flooding problems, and rapid changes in the stream location, cross-section and profile (Bledsoe, 2002).

In the past, engineers have addressed downstream flooding concerns created by increased peak runoff by storing excess runoff volume in detention ponds. Engineers have been less successful at addressing the other consequences of watershed urbanization. The use of concrete to “improve” the stream is an effective means of achieving stabilization, at least in a localized area. Such improvements are expensive to maintain, and improving the headwaters of a stream often mean eventually improving downstream areas as well. As improvements are carried downstream they become increasingly costly, requiring more materials and more design. More than $2 billion has been invested in stream restoration since 1980 (Kondolf, Anderson, Lave, Pagano, Merenlender, and Bernhardt, 2007). Once development in the watershed is complete and rapid changes to the stream’s location, cross-section, and profile are complete, stability may become less of a problem. Non point source pollution is the next major concern, since the urbanized stream typically loses riparian vegetation that would otherwise improve the water quality and ecological viability of the stream. Applying principals of fluvial geomorphology to a stream channel modification design is intended to stabilize the stream while bringing it closer to a pre-degradation condition.

Recently, local communities have taken steps to prevent degradation of urban streams. Stream setback ordinances are intended to eliminate floodplain development and prevent replacement of natural waterways with concrete. If the stream is to be left unpaved and the watershed urbanizes, even a channel restored to a stable but dynamic equilibrium may still pose a threat to infrastructure (Shields, Copeland, Klingeman, Doyle, and Simon, 2003).

This paper will provide a comparison of the literature of the science of stream geomorphology, a discussion of local attempts to apply this science, a discussion on the introduction of bias in geomorphic stream data collection, and conclusions.

2. The Science of Fluvial Geomorphology: An Overview

Intermittent headwater streams exhibit different geomorphologic characteristics than permanent flow riverine systems. Streams with limestone bedrock for a streambed and banks of silty clay exhibit different characteristics than streams with cobbled beds and sandy banks. This is why every study of a stream's geomorphology begins with a trip to the field. The most common method of documenting the stream geology is by conducting a Wolman Pebble Count (Wolman, 1954). Approximately one-hundred stream particles are measured in a random cross-section of the stream. Conducting pebble counts through both a pool and a riffle gives a more complete analysis of the stream geology.

The next step is to determine the bankfull elevation. The bankfull elevation is used to determine a number of stream characteristics, including bankfull depth, bankfull velocity, entrenchment ratio and bankfull discharge. The definition of bankfull discharge is the maximum discharge the channel can convey without overflowing into the floodplain (Copeland, McComas, Thorne, Soar, Jonas, and Fripp, 2001). In stable streams, bankfull is the discharge at which channel maintenance is the most effective at "moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels" (Dunne and Leopold 1978). Unless the stream is adjusting its morphology due to an urbanizing watershed, and then bankfull discharge and the effective discharge can be quite different (Shields, et al, 2003). The determination of bankfull elevation can be somewhat subjective, especially if field indicators are the sole basis of the determination (Williams, 1978). Regional curves developed to correlate drainage area to bankfull discharge can assist in bankfull determination in rapidly changing streams where field indicators are hard to find (Rosgen, 1998). Very few regional curves have been developed, and none have been published for local streams. The APWA standard suggests using the 50% storm as a rough upper estimate of bankfull. Although using a recurrence interval is useful as a preliminary estimate of bankfull, some studies have shown that this approach produces poor estimates of bankfull (Williams, 1978, and Kondolf, 2001) and of the effective discharge (Pickup, 1978, and Doyle, Miller, Harbor, 1999). One study found large discrepancies between the assumed relationship of bankfull discharge and effective discharge (Doyle, et. al, 1999). The sensitivity of bankfull elevation choice in determining bankfull flow is addressed in later chapters.

Further data typically gathered during an assessment of a stream's morphology include surveying the longitudinal profile, measuring the wavelength, sinuosity, and identification of features such as nickpoints, riffles, and pools.

3. Applying Principles of Geomorphology to Local Streams

The American Public Works Association, or APWA, has developed local standards for construction within natural streams. Section 5600 of the standard establishes buffer zones along natural streams with greater than 40 acres of contributing drainage area. If construction within the buffer zone can't be avoided, Section 5605.4 requires that a stream assessment be conducted. The stream assessment requires a plot of the bankfull flow profile, with one cross-section taken through each pool and riffle. The depth and width of bankfull flow is also required for each section. The bankfull flow and particle size is used to perform a critical shear stress analysis on the bed and bank materials. Unfortunately, the standard allows an average particle size to be used rather than requiring that the particle sizes in the bed and the banks be analyzed separately. The bed material was deposited under different conditions than the bank material, and mixing the two does not lend itself toward an accurate geomorphic analysis (Kondolf, Lisle, Wolman, 2003).

The intent of the standard is to apply the science of geomorphology to inform a design engineer on how best to maintain stream stability in areas where impacts to a natural stream can't be avoided. It is also intended to document pre-development conditions by noting features like active scour or depositional areas, point bars, islands, and areas of bed elevation change (or headcutting) that appear to be actively migrating upstream. The plan reviewer compares the proposed improvements with the natural or existing condition, and typically requires that changes to bankfull parameters be minimized to the greatest extent possible. Although the intent of the standard is good, it oversimplifies the science of geomorphology by relying on an observer's determination of bankfull elevations at just a few locations. This introduces the potential for bias, as discussed in later sections.

The standard suggests first field indicators and then return interval for determination of bankfull discharge. There is some consensus that using field indicators can introduce bias or uncertainty in bankfull determination (Williams, 1978, Johnson and Heil, 1996). Using a return interval to determine bankfull discharge is not recommended for channel restoration design, nor is the assumption that bankfull discharge and the channel forming (or effective) discharge are the same (Doyle, Shields, Boyd, Skidmore, Dominick, 2007). Difficulty in obtaining regional sediment discharge curves and calculating sediment discharge is one reason that the bankfull discharge is so often assumed to be equivalent to the effective discharge.

Design of stream restoration projects is beyond the scope of the standard; and yet stream restoration is precisely the goal following an impact that would require a stream assessment. What is the purpose of a stream assessment at one particular site, if it is not compared to a stream restoration design? If the purpose of a stream assessment is to establish the condition of the stream before construction, a few photographs and a topographical map would suffice.

Conducting a stream assessment on the headwaters of a stream (a little greater than 40 acres of drainage area) poses a challenge to designers trying to comply with the standard. Field indicators, already subject to observer bias, are even more difficult to find. Regulatory agencies like the Federal Emergency Management Agency or the Army Corps of Engineers seldom extend jurisdiction so far upstream. Headwaters are more likely to be impacted before construction begins, even in rural areas. For example, livestock can damage the banks and vegetation beyond all recognition. This is one reason why the APWA standard compares the bankfull determination to the 2 year return interval. Very large rivers are also difficult to find reference sites for (Palmer, et. al., 2005). Larger rivers, like the Missouri, are often channelized and/or dredged and 'maintained' for barge traffic.

4. Sensitivity or Bias in Bankfull Determination

Section 5605.4 of the APWA standard requires that the geomorphic bank-full width, depth, and discharge be estimated using field indicators as detailed in Chapter 7 of the USDA'S Stream Channel Reference Sites: An Illustrated Guide to Field Technique (Harrelson, Rawlins, Potyondy, 1994). Although the standard references Harrison, et al., as a guide to field techniques, the USDA's document is largely based on Rosgen's methods (Rosgen, 1994). Rosgen's name is omitted from the APWA standard because numerous recent critics have noted problems with using his methodology (Johnson, et al., 1996, Harmel, et al, 1999, Holt, et al., 2004, Ball, et al., 2007, Simon, et al., 2007, and Roper, et al., 2008, and others). Rogen's methods imply that once a stable stream is correctly classified, it remains within that classification. But stable streams can undergo cyclical changes in classification. For example, several years without a major flood can allow riparian vegetation to stabilize gravel banks and promote a single-thread meandering channel. A large flood can re-work that channel, stripping away vegetation and leaving a wide, braided gravel bed (Kondolf, 1998).

The failure of the Uvas Creek restoration project is thought to be due to a misapplication or oversimplification of Rosgen's methods. All of the rock weirs placed in Uvas Creek were washed out after about three months (Kondolf, Smeltzer, Railsback, 2001).

Figure 1: Rock Weirs Placed during the Restoration of Uvas Creek (Photo credit, Kondolf, et. al, 2001)

Figure 2: Restoration Efforts Washed Out of Uvas Creek (Photo credit, Kondolf, et. al, 2001).

Problems with in-stream structures, such as rock weirs, cross-vanes, and J-hooks have been noted in other studies. One study conducted in North Carolina found that 70% of the in-stream structures were significantly damaged or destroyed by the first significant flood event (Kochel, 2005). Kochel's study also noted accelerated bank erosion near the in-stream controls. Another study found that 60% of instream habitat structures surveyed in southwest Oregon and southwest Washington were either damaged or destroyed by 2-10 year storm events (Nawa, Frissell, 1992).

Like hydrology, geomorphology is not an exact science. However, hydrology results are comparable to years of hydrologic data recorded by weather stations and stream gauge sites nationwide. Regional curves and reference reach data for geomorphologic parameters are harder to find, the closest published results I could find were conducted by the USGS for Sugar Creek and its tributaries in Oklahoma. Regional curves for predicting sediment transport are even rarer.

The choice of bankfull elevation is a particularly sensitive parameter because it affects the results obtained for the entrenchment ratio, width-to-depth ratio, and sinuosity.

The Rosgen classification system is often used locally by designers to determine applicable reference reach data. The entrenchment ratio, bankfull width-to-depth ratio, and sinuosity are used to determine the primary stream type (Rosgen, 1994, 1996). The choice of bankfull elevation affects two of the three parameters, and was the principal discrepancy in determining stream classification amongst a study of several independent stream monitoring groups (Roper, Buffington, Archer, Moyer, Ward, 2008). The classifications were not determined by the teams themselves, but from the measurements they provided. It is possible that some of the individuals involved lacked training; but their data for other stream parameters was comparable. Another issue could have been the number of measurements taken, from four to eleven. Perhaps if more measurements were taken, it would be more clear when a mistake was made or a non-typical location chosen. A separate study conducted by the USGS for the state of New York did just that, plotting a profile of the bankfull elevations and then plotting a best fit line through multiple surveyed bankfull stage field indicators (Mulvihill, Ernst, and Baldigo, 2005). The study used HEC-RAS to determine bank-full discharge. Multiple estimated discharges were put in the model for each cross-section, and the discharge at the water surface elevation that most closely matched the surveyed bankfull indicators was chosen. Finally, the average discharge from all the cross-sections in the reach was calculated. When choosing between bankfull indicators, the study used the indicator closest to the expected result of a 1.5 year return interval.

The all of the studies discussed above either presume or create a single-thread meandering channel. Braided stream restoration is almost never discussed; multiple channels would almost certainly complicate bank-full elevation determination in the field. Since braided streams typically carry high sediment loads, bankfull elevation might change by a foot or more at the studied cross-section during evaluation. The failure of restoration efforts at Cuneo Creek, a braided stream is one example. It was ‘restored’ to a single-thread channel with symmetrical meanders, the amplitude and wavelength based on the consultants’ determination of bank-full elevation. Six years later, a flood event approximately equivalent to a 30-year return interval, washed the project out, leaving almost no evidence of restoration (Kondolf, 2006). Kondolf’s study points out that channels are almost always ‘restored’ to a single-thread meandering channel, even if there is no historical evidence to suggest that they ever had this configuration. He suggests that an unacknowledged cultural bias, and not science, may be the true driver for the choice of a stable single-thread, symmetrically meandering stream morphology. Culturally, we may simply find it more aesthetically pleasing (Kondolf, 2006).

5. Reducing Bias in Bankfull Determination

The following analysis was done to test an approximate method for determining regional curves for this watershed in regions that are close to natural. To reduce bias or sensitivity to choice of bank-full elevation, several cross-sections were cut at each location and an average bankfull height was used to determine the bankfull flow, bankfull width, bankfull width-to-depth ratio, bankfull depth, and average bankfull velocity. The following figure shows an aerial view of the watershed and the cross section locations.

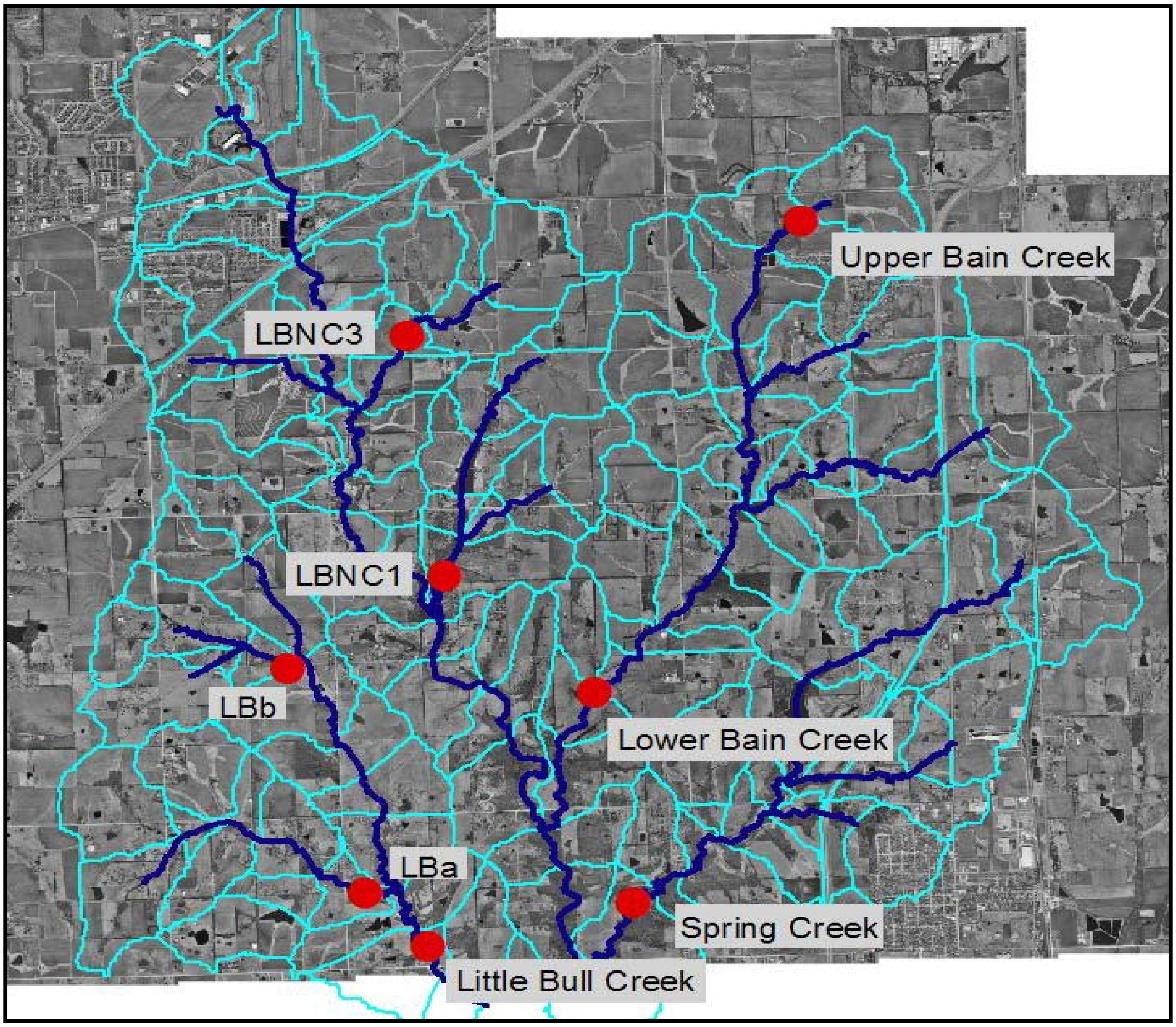

Figure 3: Cross Section Locations on the Tributary to the Marais Des Cygne River, Johnson County, Kansas (Not To Scale)

Tributaries of the Marais Des Cygne River within Johnson County, Kansas were chosen for analysis. The selected reaches were in rural watersheds, with very few road crossings. The drainage areas for each reach were based on sub-basin delineations created for a recent flood study conducted by Johnson County. Using HEC-GeoRAS 3.1, several cross-sections were cut for each reach from a TIN (triangular irregular network) generated from 1-foot contour information. These cross-sections were then imported into HEC-RAS 3.1.1 and a model was created. The cross-sections were chosen away from meanders, across riffles, and along representative stretches of each reach. Guidance on selecting cross-sections was taken from the USDA's Stream Channel Reference Sites: an Illustrated Guide to Field Technique, 1994. An aerial view of cross-sections taken for Lower Bain Creek appears in the figure below.

Figure 4: Cross Section Locations for Bankfull Discharge on Lower Bain Creek

Bank stations were placed at the bankfull location for each cross-section. The bank station should be placed at the highest elevation the water surface can reach before spilling out in to the floodplain (Copeland, et al, 2001). For the purpose of this exercise, it was necessary that the bankfull locations be at the same elevation on both stream banks. This is another potential source of bias, if one bank is appreciably higher than the other (Gordon, McMahon, and Finlayson, 2002). To answer this question, we have to refer back to the definition of bankfull flow and ask which bank is closest to the point of releasing water into the entire floodplain. In the figure below, the right bank was chosen as the location of the bankfull elevation.

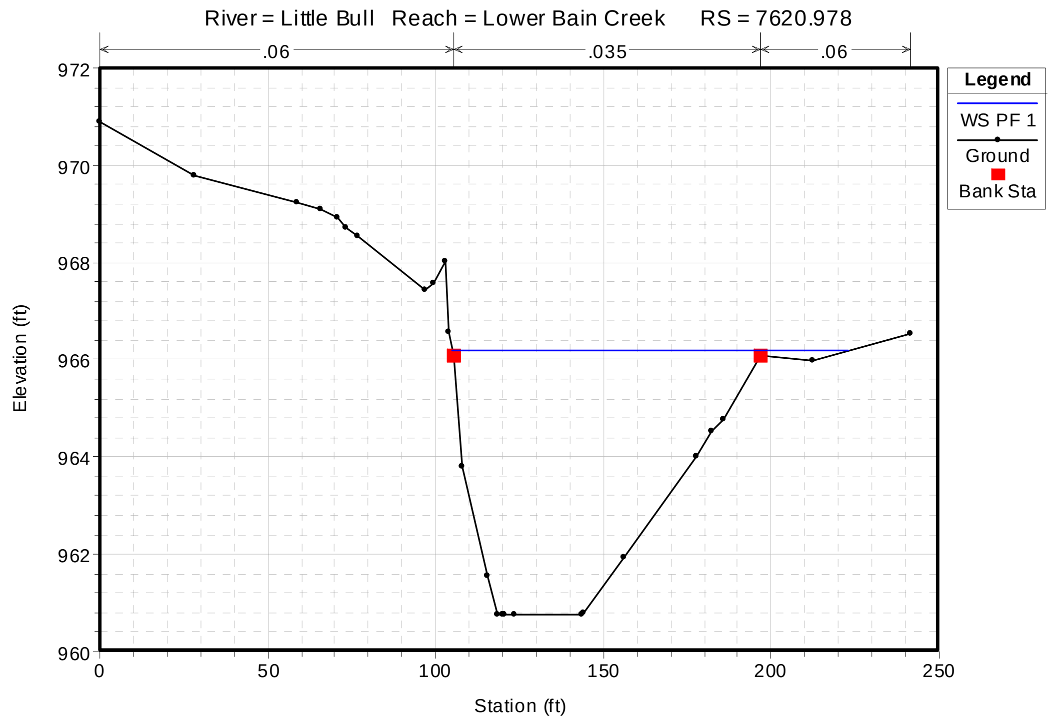

Figure 5: Determination of Bankfull Elevation at River Station 7620.978 on Lower Bain Creek.

The Manning's 'n' values that appear in Figures 6-10 were based on values used in a recent flood study conducted by Johnson County and verified using aerial photography.

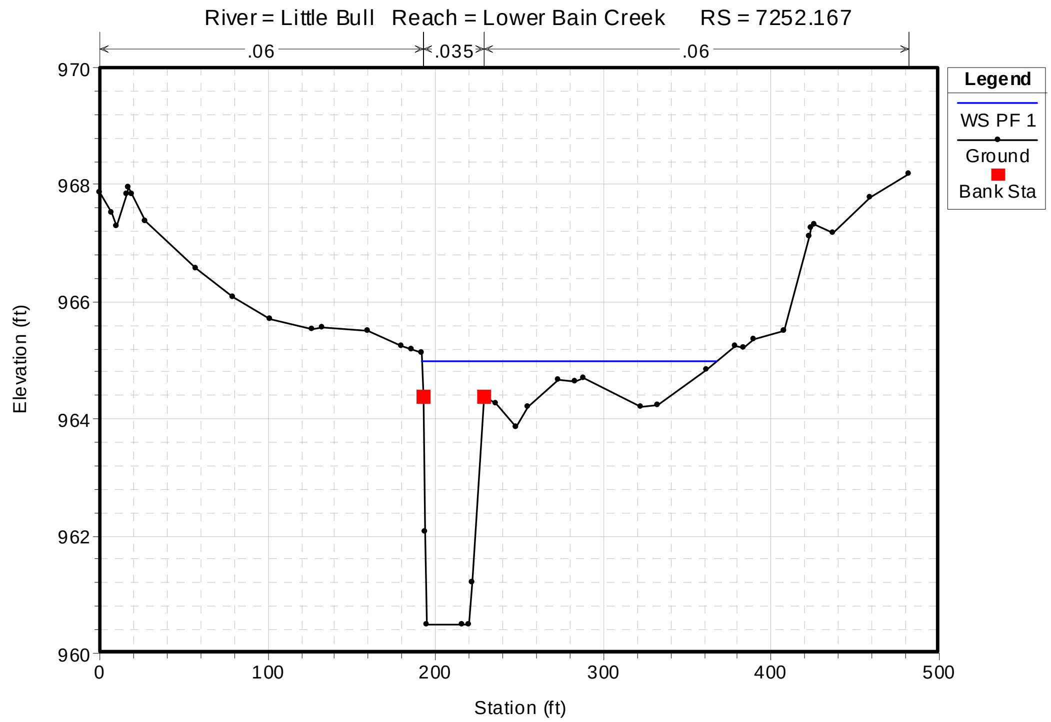

Figure 6: Determination of Bankfull Elevation at River Station 7252.167 on Lower Bain Creek.

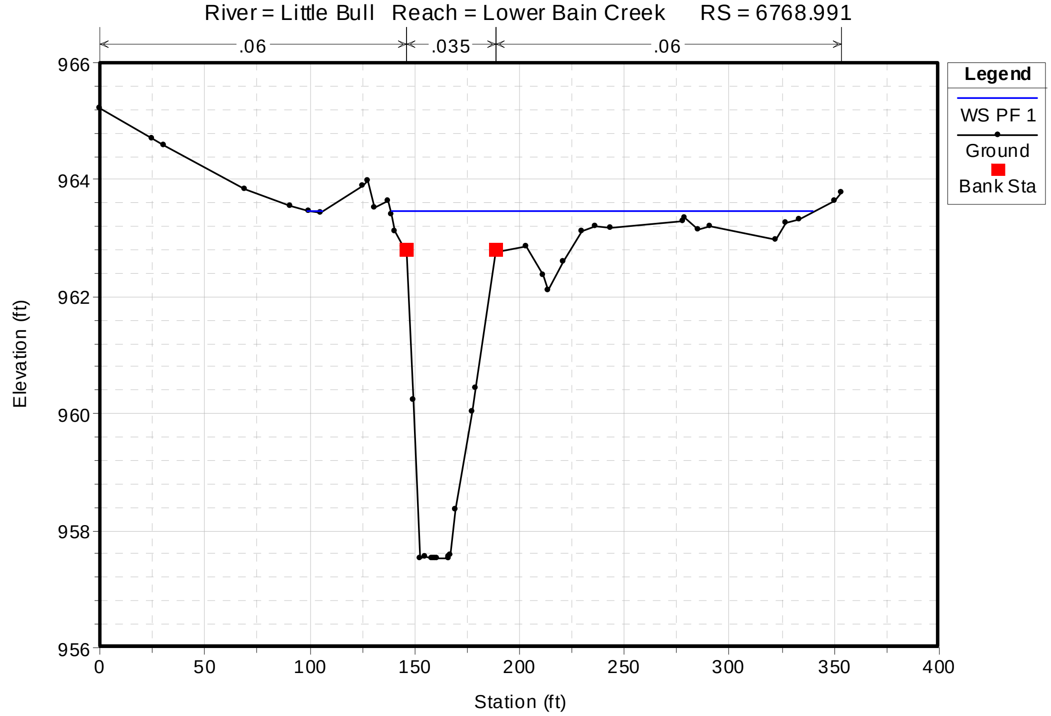

Figure 7: Determination of Bankfull Elevation at River Station 6768.991 on Lower Bain Creek.

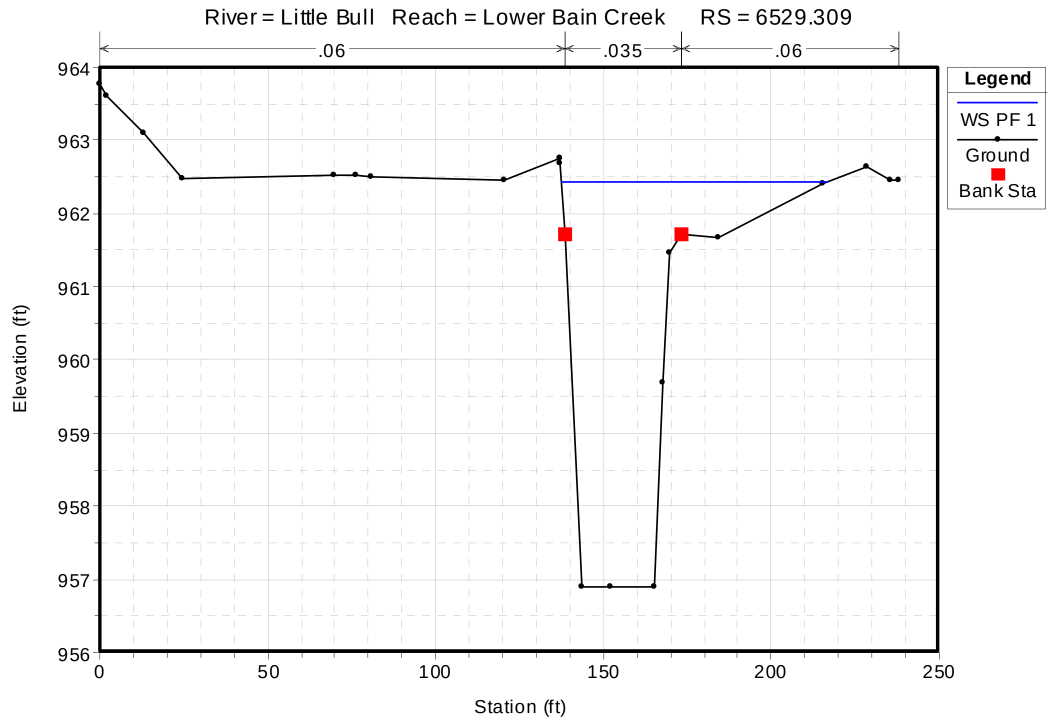

Figure 8: Determination of Bankfull Elevation at River Station 6529.309 on Lower Bain Creek.

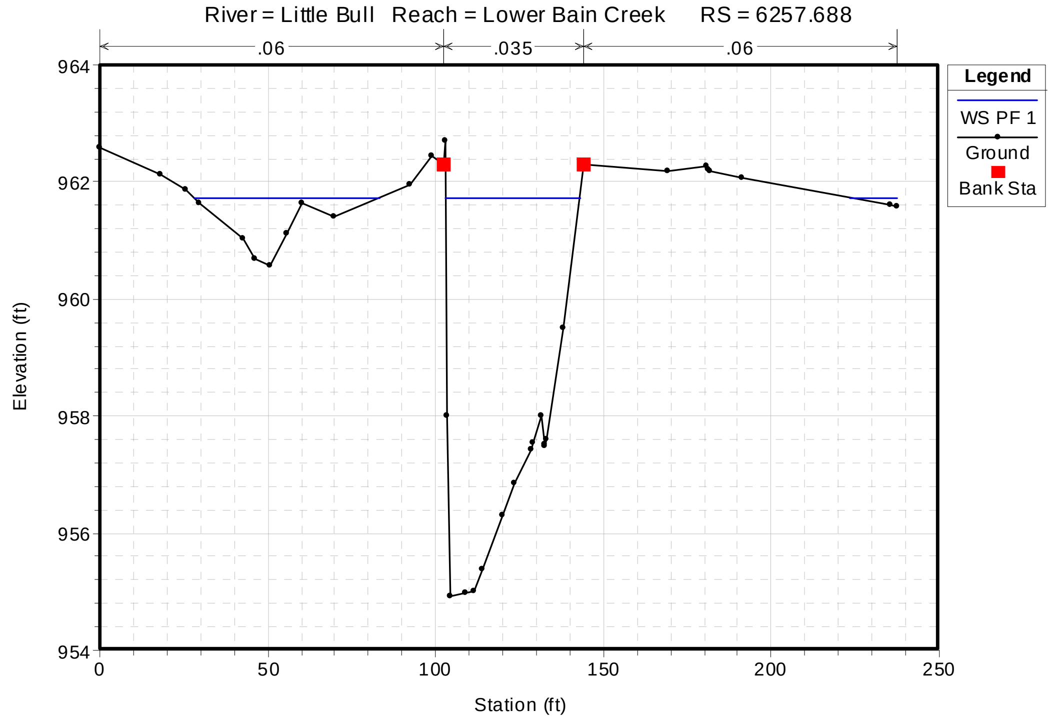

Figure 9: Determination of Bankfull Elevation at River Station 6257.688 on Lower Bain Creek.

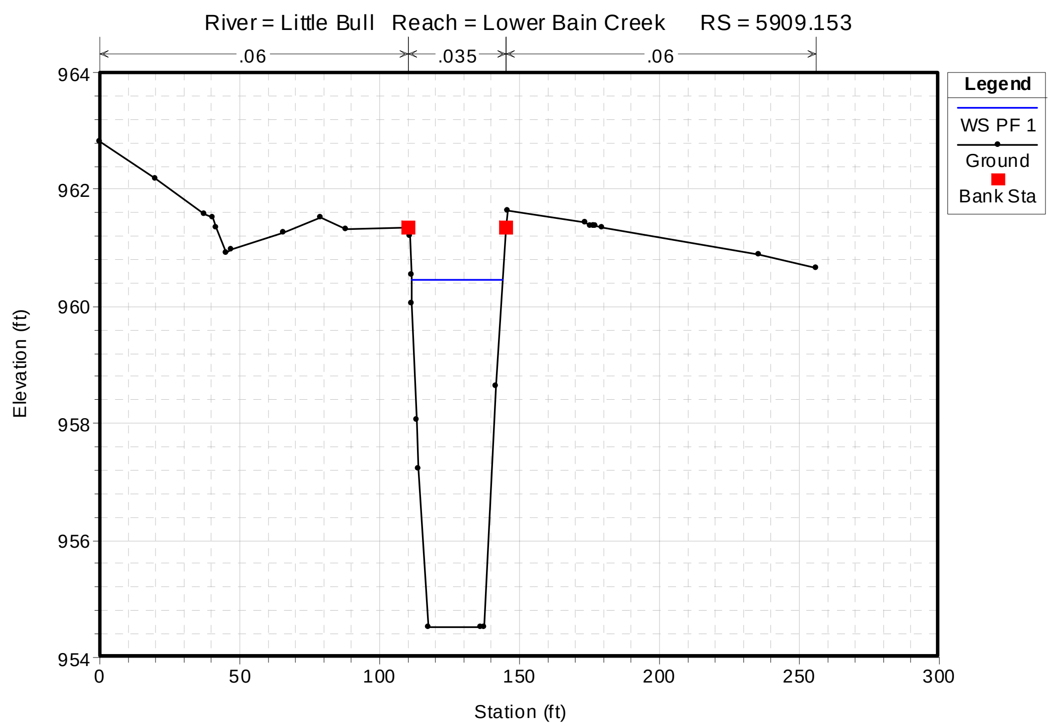

Figure 10: Determination of Bankfull Elevation at River Station 5909.153 on Lower Bain Creek.

The downstream reach boundary conditions were assumed to be normal depth using the channel slope as the slope input. The analysis was conducted assuming a constant discharge for five to eight cross-sections at each location.

In this analysis, several bankfull discharges were calculated simultaneously using a trial and error procedure that minimized the sum of the squares of the differences between the water surface elevation, shown in Column 3, and the bankfull elevations, shown in Column 2, for Lower Bain Creek. See Table 1, on the following page.

Table 1: Bankfull Discharge Determination for Lower Bain Creek

		Column 1	Column 2	Column 3	Column 4	Column 5
Reach	Station	Bankfull Discharge	Bankfull El.	W.S.	Delta	Delta SQ
	(ft)	(cfs)	(ft)	(ft)		
Lower Bain Cr	7620.978	1030	966.08	966.18	0.10	0.01
Lower Bain Cr	7252.167	1030	964.38	964.98	0.60	0.36
Lower Bain Cr	6768.991	1030	962.80	963.45	0.65	0.42
Lower Bain Cr	6529.309	1030	961.72	962.44	0.72	0.52
Lower Bain Cr	6257.688	1030	962.30	961.73	-0.57	0.32
Lower Bain Cr	5909.153	1030	961.36	960.45	-0.91	0.83

The bankfull discharge shown in Column 1 in the table above minimizes the difference between the elevations shown in Column 2 and Column 3, and the difference is shown in Column 4. In Column 5, the values from Column 4 are squared. The sum of Column 5 was then compared to the sum of Column 5 for other bankfull discharges to determine which bankfull discharge most nearly matched the physical bankfull elevations shown on the cross-sections. The resulting bankfull discharge for each reach is the discharge that produced the best fit of the computed water surface elevations and the bankfull elevations. The water surface elevations shown in Column 3 were computed with HEC-RAS. The Manning's 'n' values used were consistent with the channel and bank values determined during Johnson County's floodplain modeling of each reach, and verified using aerial photographs.

It's clear that choosing just one of these cross-sections over another can change the resulting bankfull depth by as much as a foot. If the cross-section chosen was taken through a particularly wide pool, then the resulting bankfull discharge will be significantly affected. A return interval was calculated for the discharges at each location, varying from 1 to 2 years. A recent flood study by Johnson County supplied 500, 100, 50, 25, 10, 5, and 2 year discharges for each reach. These discharges were plotted versus return interval on a semi-log chart and an exponential equation was fit to the data. The equation was then used to estimate the return interval given the bankfull discharge. Figure 11 shows such a plot for Little Bull Creek. The bankfull discharge for Little Bull Creek was 890 cfs thus $Tr = 0.982e^{0.000668(890)} = 1.78$ years.

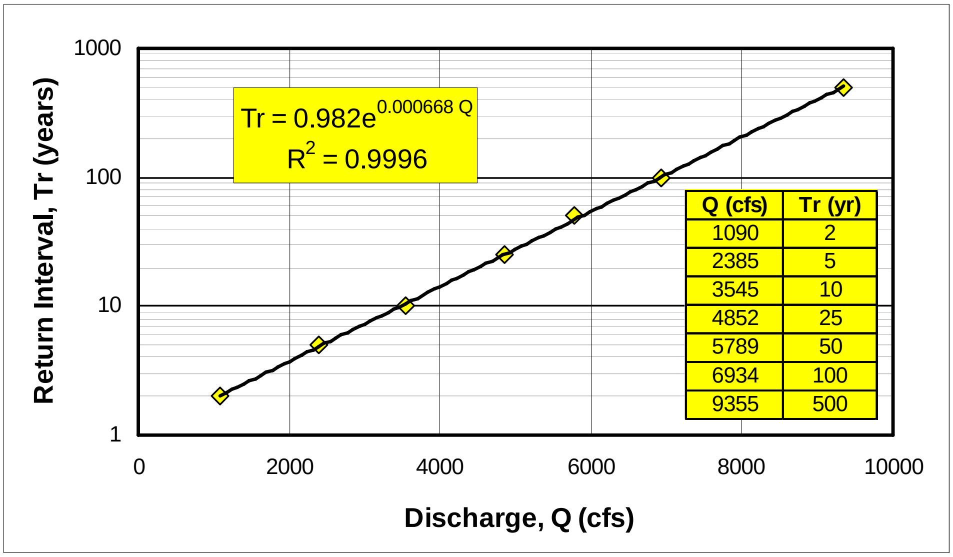

Figure 11: Discharge versus Return Interval from Johnson County Study for Little Bull Creek.

In general, for smaller streams the return interval was closer to the 1 year event and for larger streams; the return interval was closer to the 2 year event. A stream assessment per the APWA standard requires just one cross-section through each pool and riffle, and without reference reach information it's difficult to know how representative these sections are. Table 2 summarizes the estimated bankfull discharge data for all the project locations.

Table 2: Bankfull Discharge and Return Interval for all Project Locations.

Reach	Approx. Station	Bankfull Discharge (cfs)	Drainage Area (ac)	Return Interval (yrs)
Upper Bain Cr	30657.9	45	218	1.01
LBb	854.776	570	550	1.44
LBNC3	4820.411	310	703	1.21
LBNC1	1849.463	310	1101	1.21
LBa	2536.393	360	1307	1.25
Spring Creek	4879.852	575	2957	1.44
Little Bull	5262.479	890	3379	1.78
Lower Bain Cr	7620.978	1030	4096	1.95

The resulting discharge, width, depth, velocity, and flow area were plotted verses contributing drainage area for each location, below. The width, depth, velocity, and flow area, were obtained from the HEC-RAS output tables; and an average was calculated from all the cross-sections in each reach.

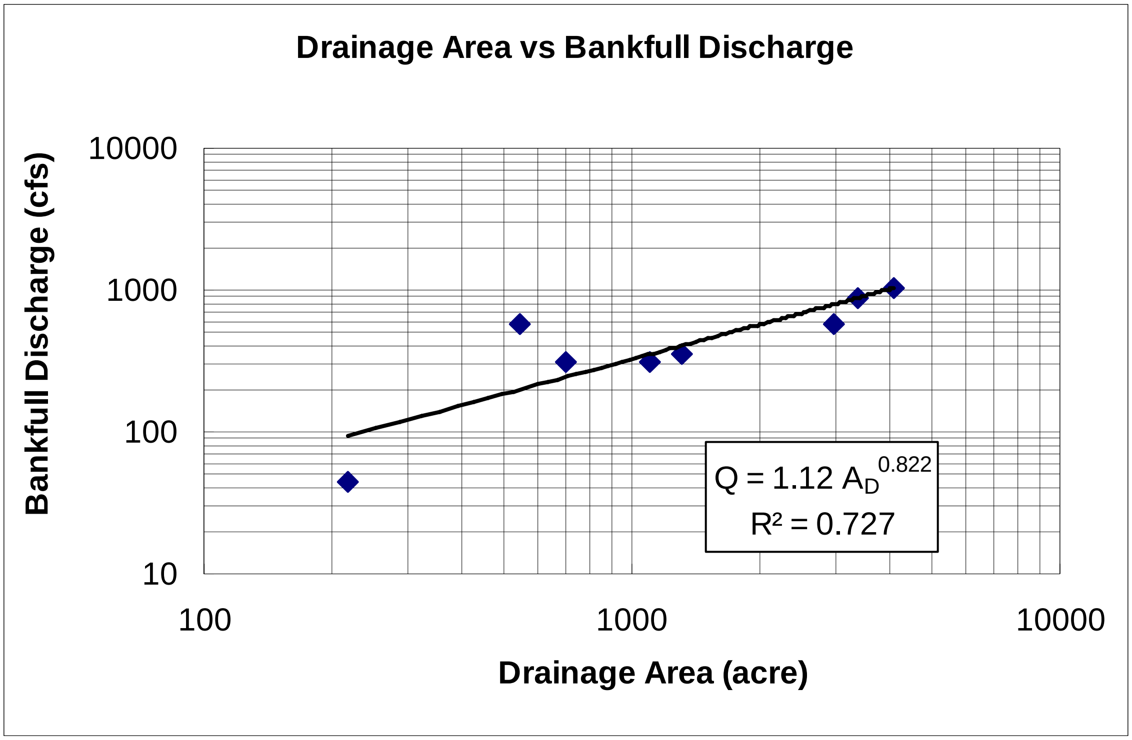

Figure 12: Drainage Area vs. Bankfull Discharge

Figure 12 is sometimes referred to as a 'regional curve,' or 'reference reach data.' The idea is that the drainage area vs. bankfull discharge is comparable to other stable rural streams in the region with similar bed and bank geology. If provided with detailed regional curves for a particular watershed, a plan reviewer could determine whether a stream assessment per APWA Section 5605.4 provided to him by an applicant was comparable to a larger data set. It would be an oversimplification to assume that a stream in an urbanizing watershed would fit this data. For example, in an incised channel, the bankfull discharge is far greater than the effective discharge (Doyle, et al, 2007).

Similarly, we cannot assume that if the post-project and pre-project bankfull parameters remain unchanged, the stream itself will not change post-construction or post-watershed development. Wildcat Creek in Richmond, California is one example of a failed restoration project based on applied fluvial geomorphology. The project fell victim to the watershed-wide effects of urbanization, sedimentation, and changes in hydrology (Holt, Battaglia, 2004). Likely, these variables would have undermined a more traditional stabilization design as well. It's an oversimplification to assume that a river can be restored or stabilized by creating a desired physical form (Kondolf, 2006). In contrast, the Carmel River at Schulte Road had suffered the loss of riparian vegetation due to the pumping of groundwater and subsequent drawdown of the water table. The riparian vegetation was restored, and the channel was allowed to migrate across a narrowly defined historic floodplain (Kondolf, et al, 2007). Once the processes of water and sediment supply were restored to the Carmel River, those processes created the stable fluvial forms (Kondolf 2000, Wohl et al. 2005, Kondolf et al. 2006).

A detention basin can be used to reduce post-construction bankfull discharge to pre-construction peak levels. However, if a stream flows at bankfull discharge for a longer period of time due to a greater runoff volume, then more sediment may be eroded from the stream banks during a channel forming event (MacRae, 1997). Furthermore, streams with sandy beds and banks are likely to become less stable if there is a significant long-term reduction in bed load due to the presence of a detention basin (Bledsoe, 2002).

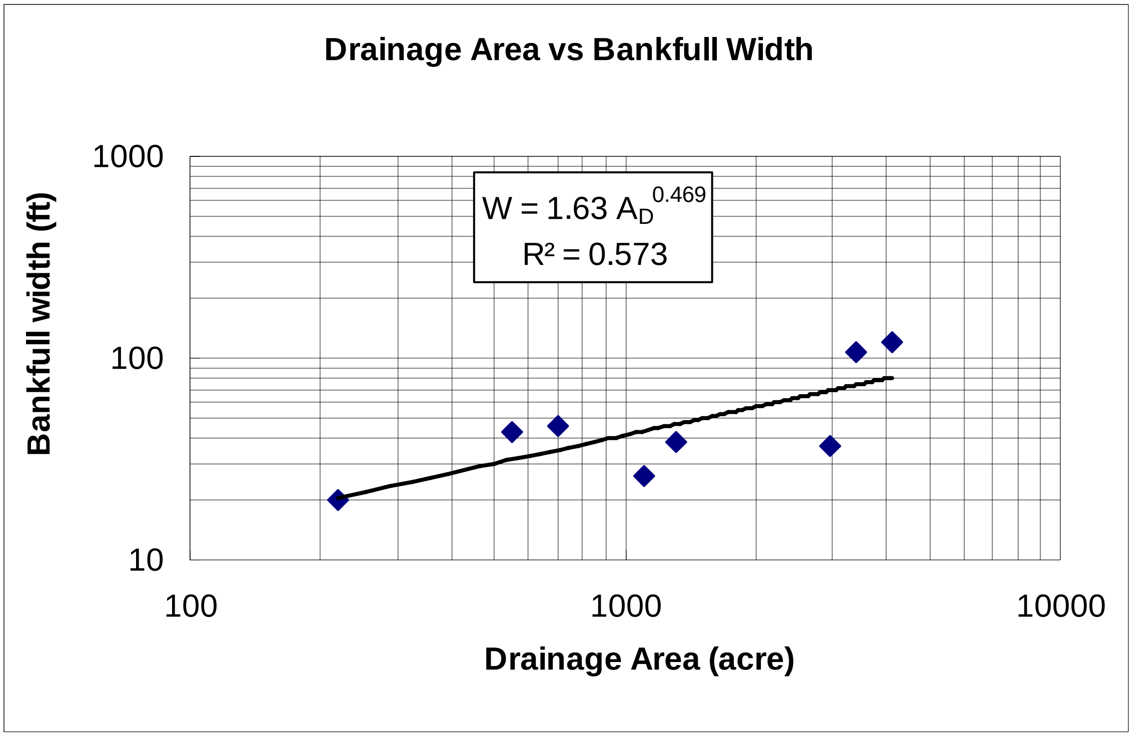

Figure 13: Drainage Area vs. Bankfull Width

As indicated in Figure 13, the bankfull width varies considerably as the stream gets larger. This brings into question the utility of plan form ratios as required for stream analysis in APWA 5600. The standard acknowledges that streams are variable, and ratios outside of the typical range do not necessarily indicate problems. The ratios are intended to qualitatively evaluate bank stability, and not for use as a target for stream 'rehabilitation.'

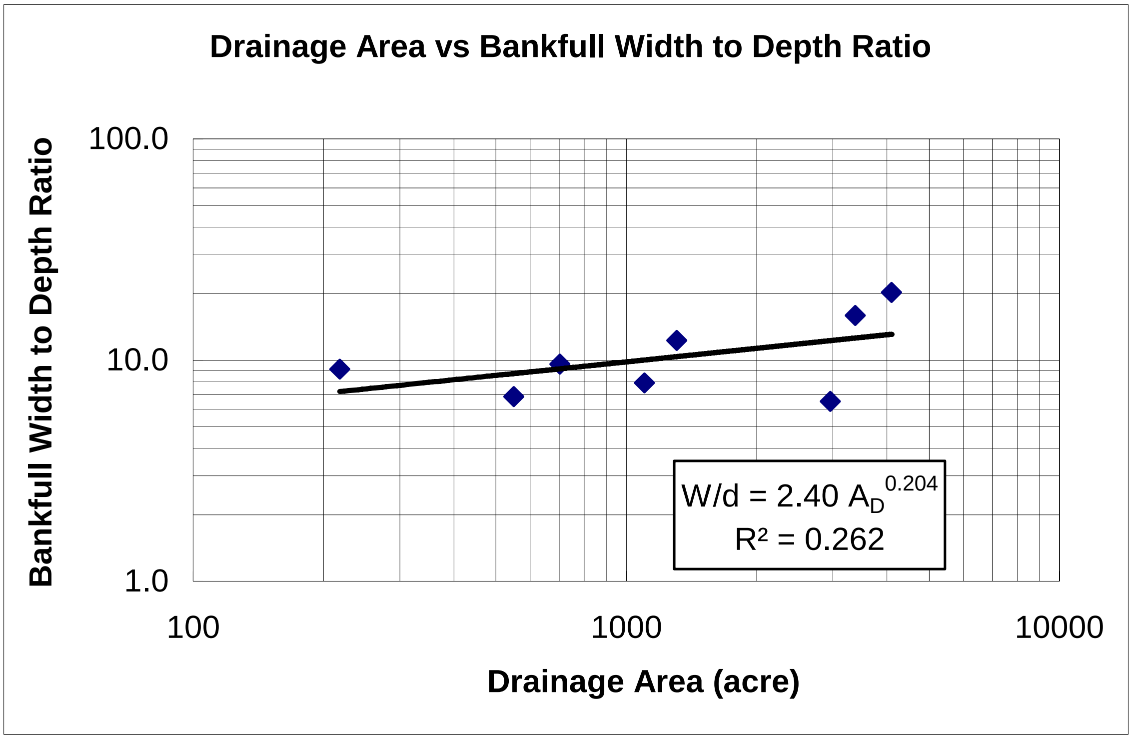

Figure 14: Drainage Area vs. Bankfull Width to Depth Ratio

The width-to-depth ratios shown above vary widely, considering that only one person was involved in determining bankfull elevation. Using a numerical model, Simon et al. found equilibrium width-to-depth ratios varying by as much as 200% (Simon, Doyle, Kondolf, Shields, Rhoads, McPhillips, 2007. Although changes in width are often treated as an indicator of bank and/or channel instability, if the width is considered continuously and compared to stream power, it can be correlated to the combination of slope and discharge (Doyle, et. al., 1999).

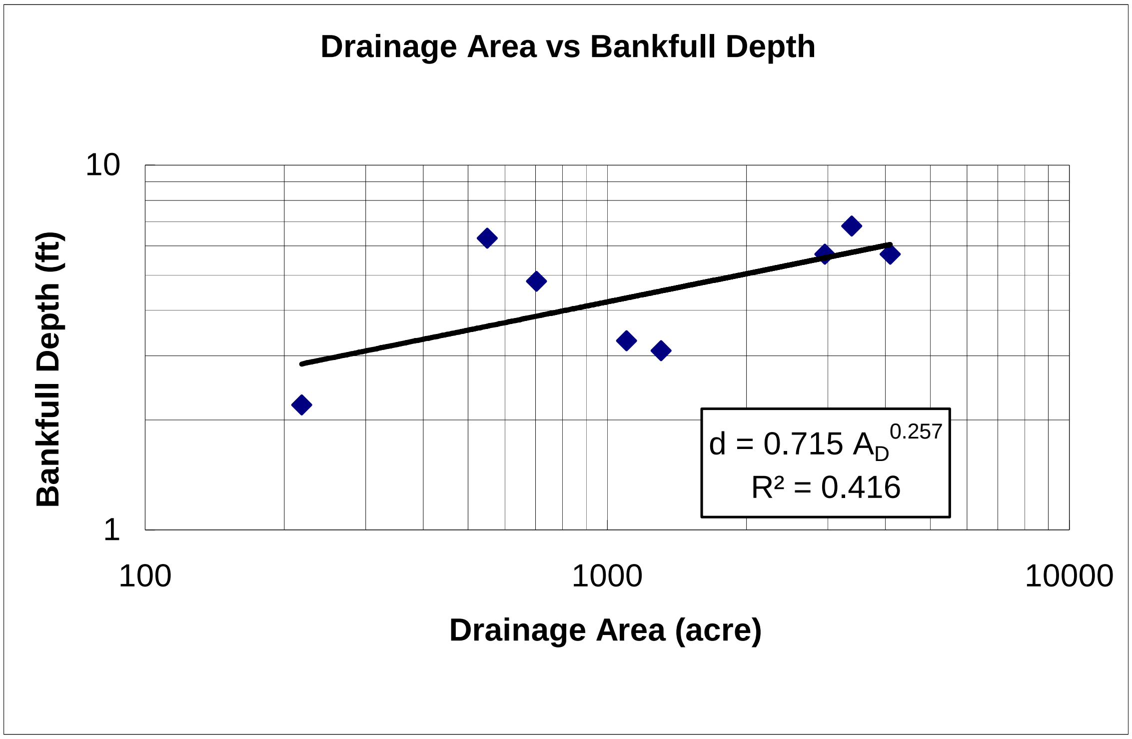

Figure 15: Drainage Area vs. Bankfull Depth

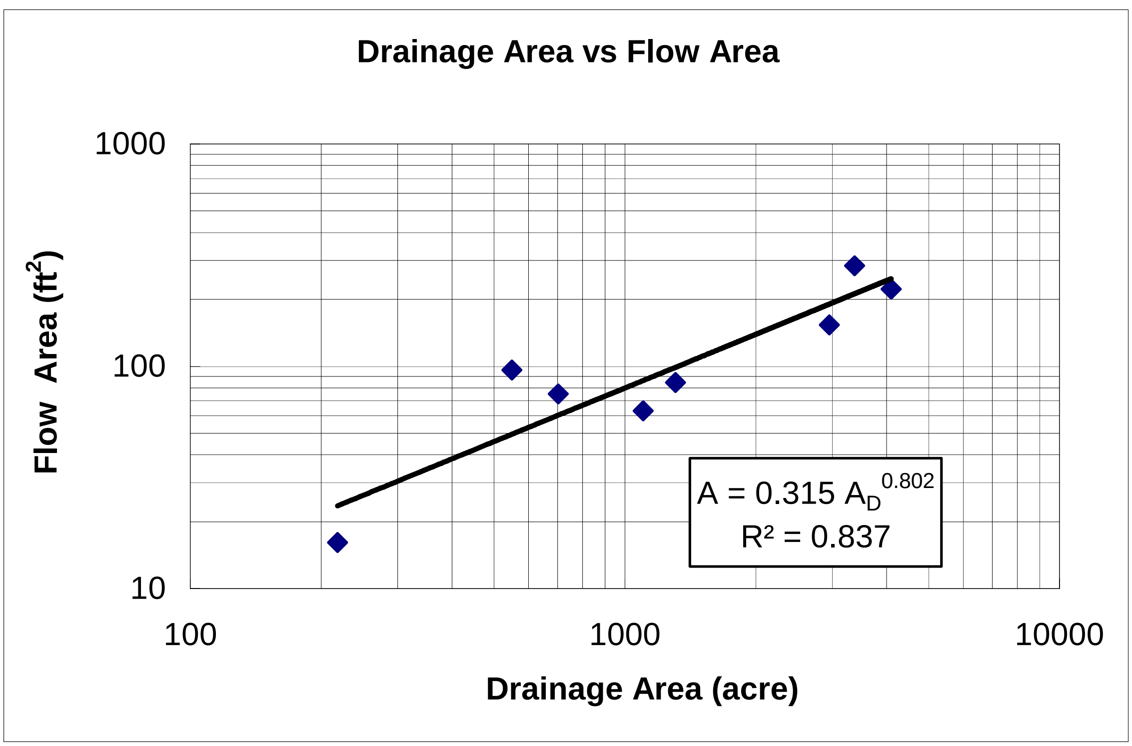

Figure 16: Drainage Area vs. Flow Area

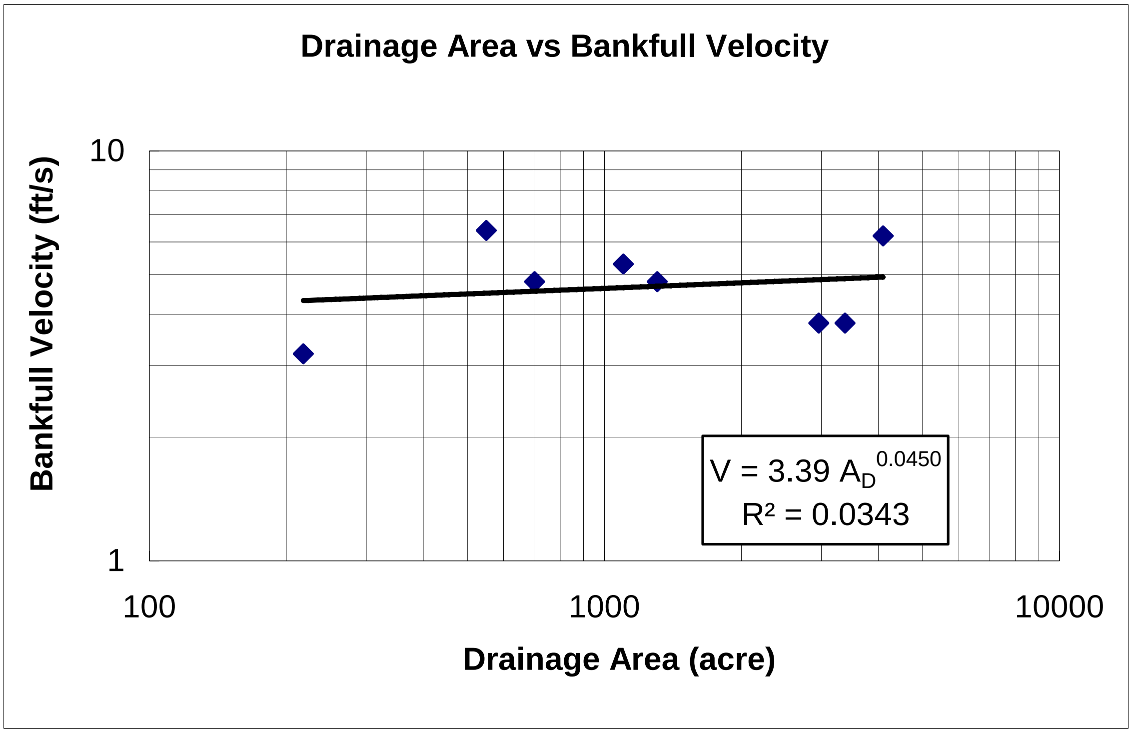

Figure 17: Drainage Area vs. Bankfull Velocity

6. Conclusions

Attempts at stream stabilization, either using ‘hard’ structural methods or ‘green’ geomophologically-based methods can be successful if a careful approach is chosen. Failures are usually due to an expectation of the ‘tail to wag the dog,” or for the desired and constructed physical stream form to achieve stream stability, rather than allowing the discharge and sediment of the stream to create a stable physical form. In an urban environment, there is often too little space to allow the stream to create a new natural and stable physical form. Additionally, stakeholders may want to construct lakes and ponds or turn the stream into more of a water feature for aesthetic reasons. In that case, there are few alternatives to simply creating a canal to address both stability and flooding concerns.

This study proposed an approximate method for developing regional curves for a watershed that has detailed terrain data. In this case, 1-ft contour interval data was available for all the streams in the watershed. Several undeveloped (natural) reaches were selected in the watershed. Not only were these reaches undeveloped, but their contributing watersheds were also undeveloped. Additionally, there were no upstream detention basins or other flood controls that would affect the hydrology of the streams. A HEC-RAS model with several cross sections was developed for each reach. The bankfull elevation was estimated at each cross section from the cross-section plots. The bankfull discharge was then computed for each reach using a trial and error procedure that minimized the sum of the differences squared between the bankfull elevation and the computed water surface elevation for all of the cross sections in the reach. In other words, the bankfull discharge for a reach is the discharge that produced the best fit of the computed water surface elevation and the bankfull elevation. The regional curves were then developed by plotting the bankfull discharges verses the drainage areas and fitting a trend line to the data. Curves were also developed for the width, with-to-depth ratio, depth, velocity, and flow area in the same manner. Hopefully, the rise of available regional data can inform designers and managers for more effective natural stream restoration practices.

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Appendix I – Cross-Sections

Upper Bain Creek

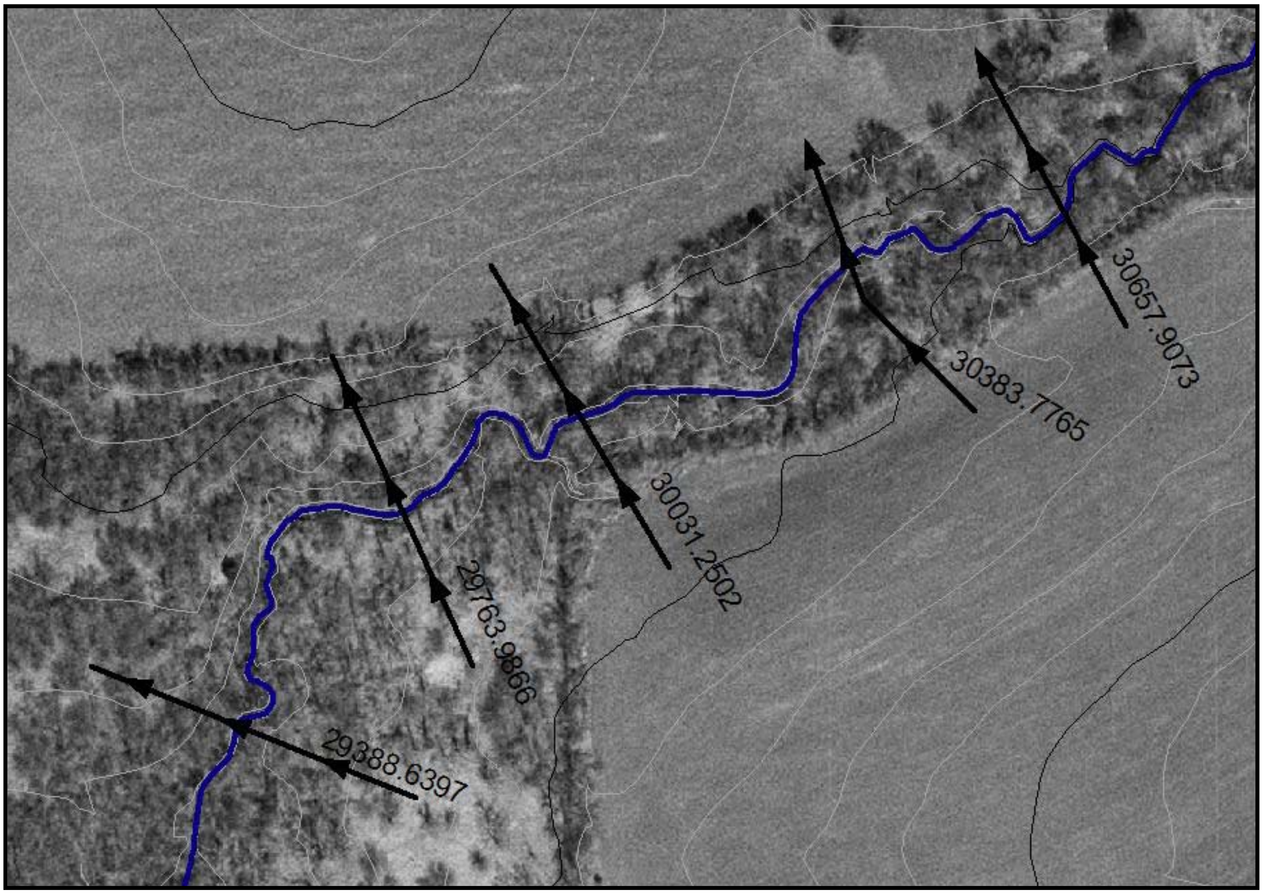

Exhibit 1: Aerial Photograph, Contours and Cross-section Locations for Upper Bain Creek.

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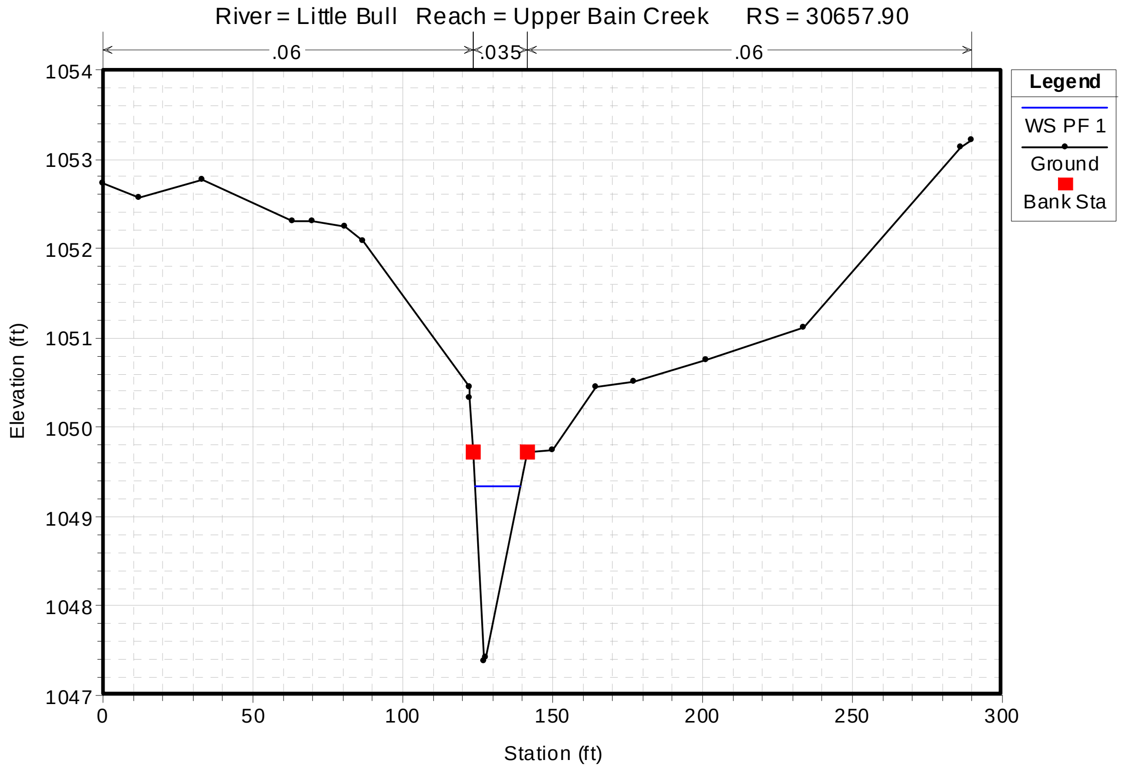

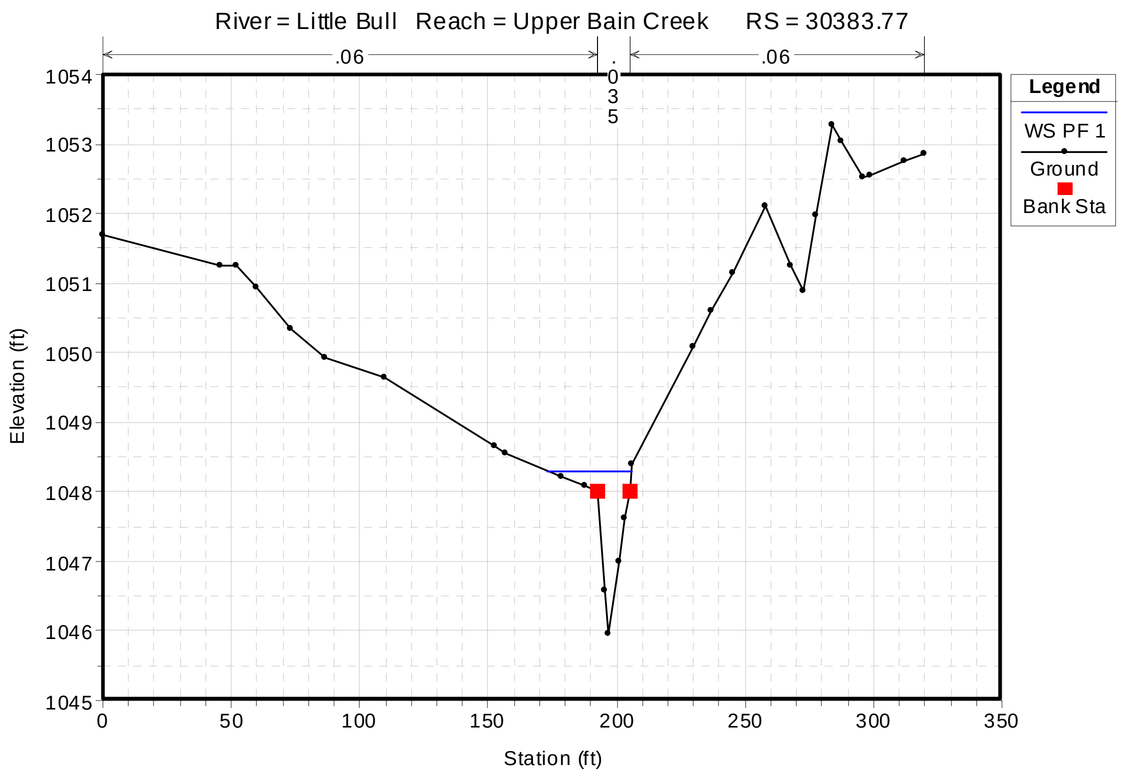

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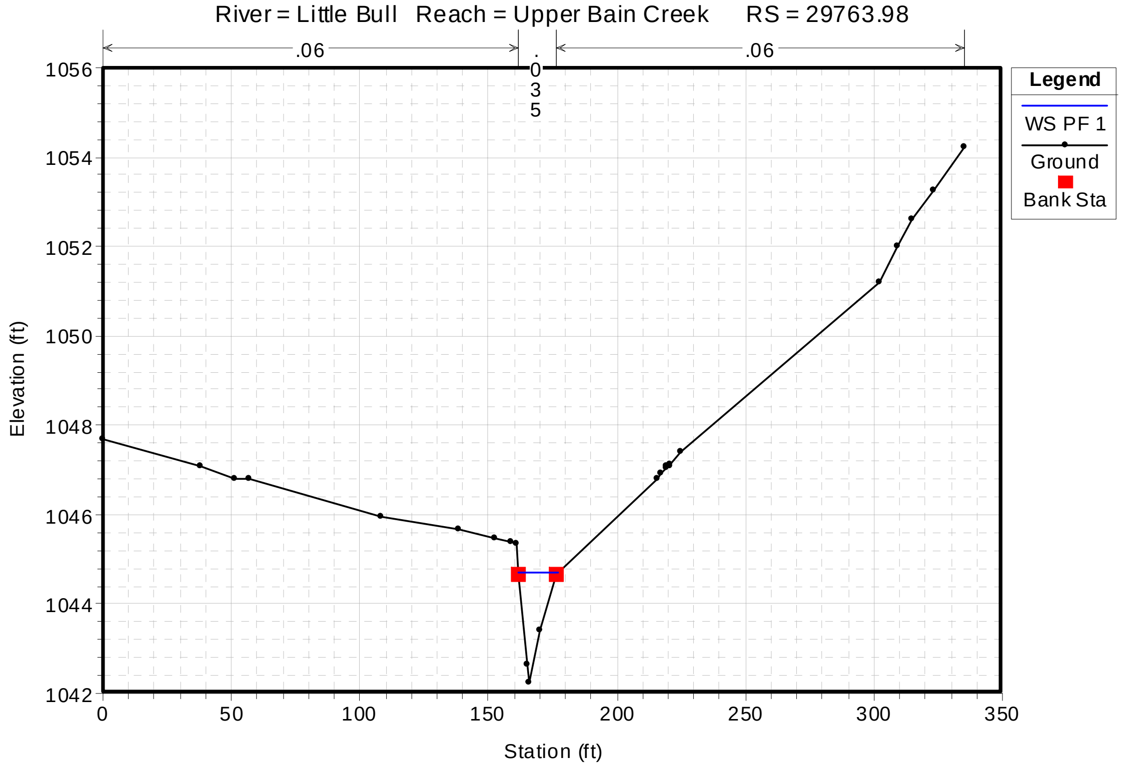

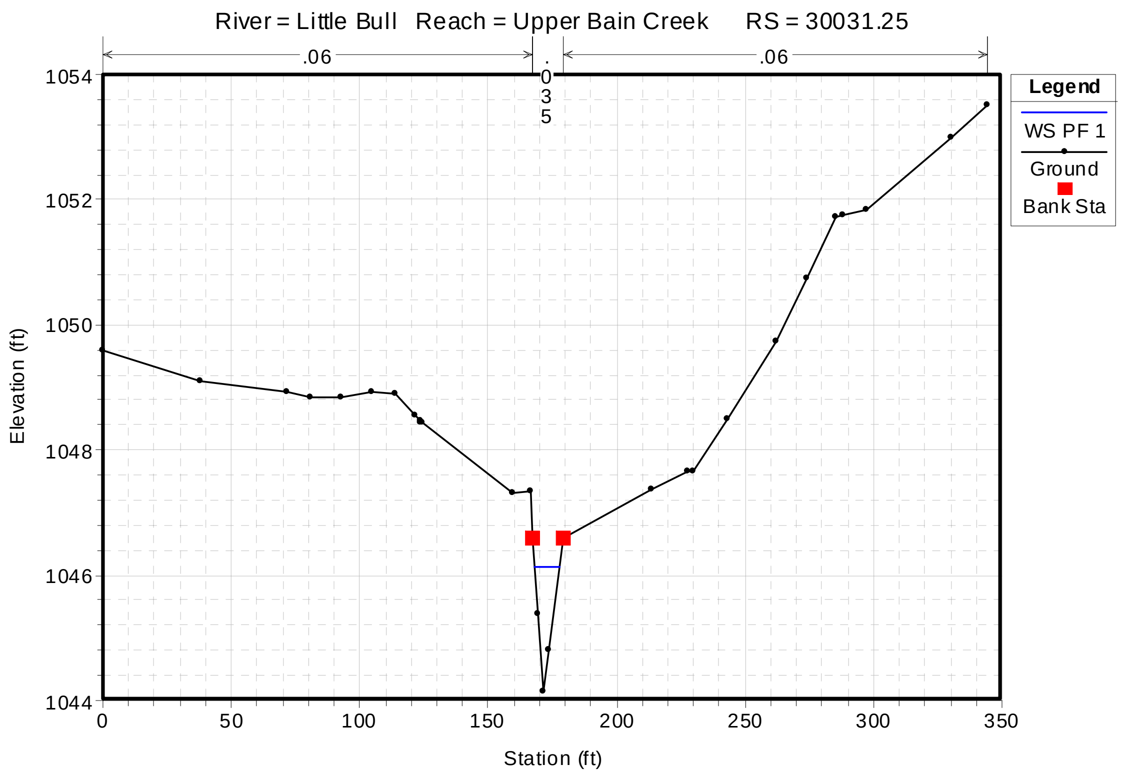

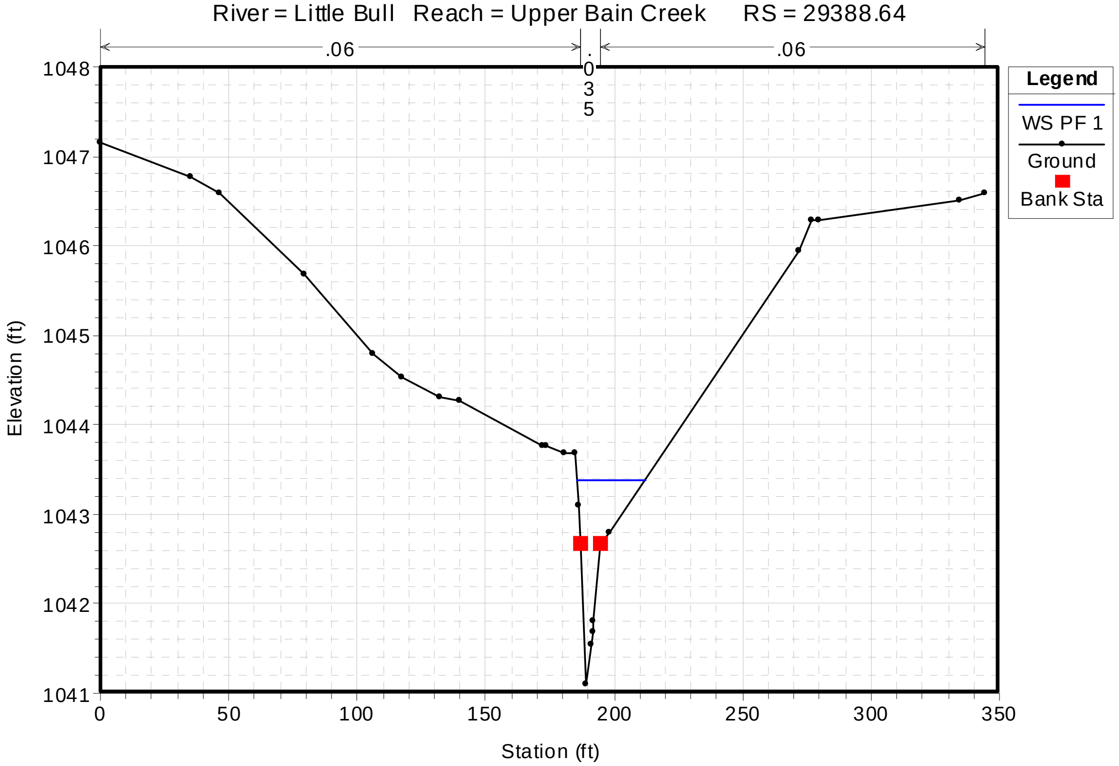
River = Little Bull Reach = Upper Bain Creek RS = 29388.64
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
1048
1047
1046
1045
1044
1043
1042
1041
Station (ft)
0
50
100
150
200
250
300
350

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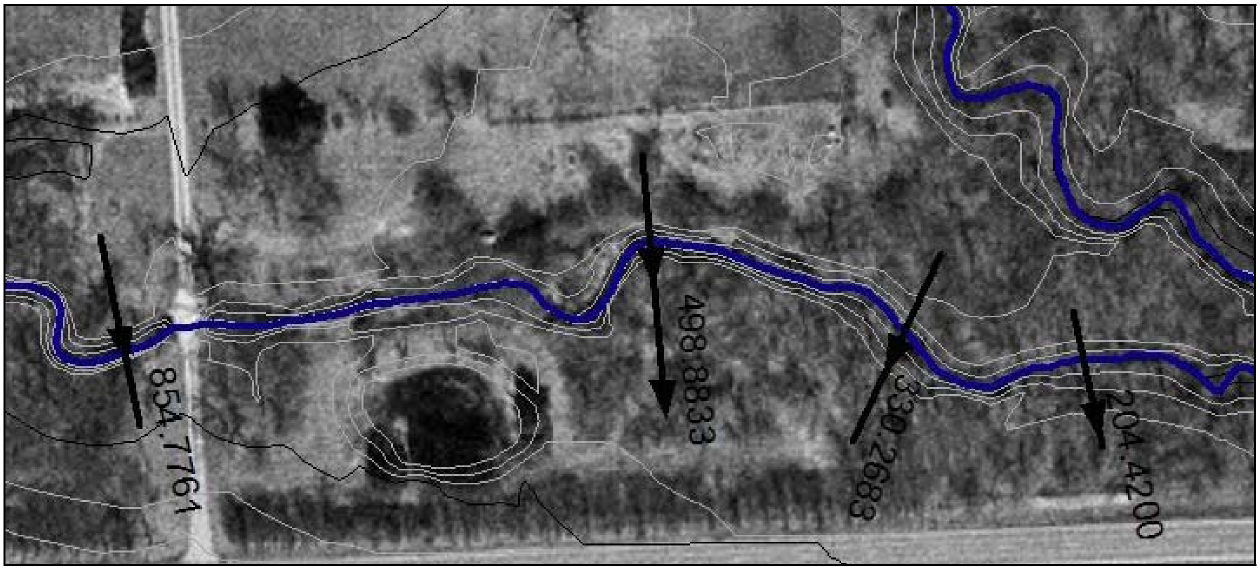
LBb



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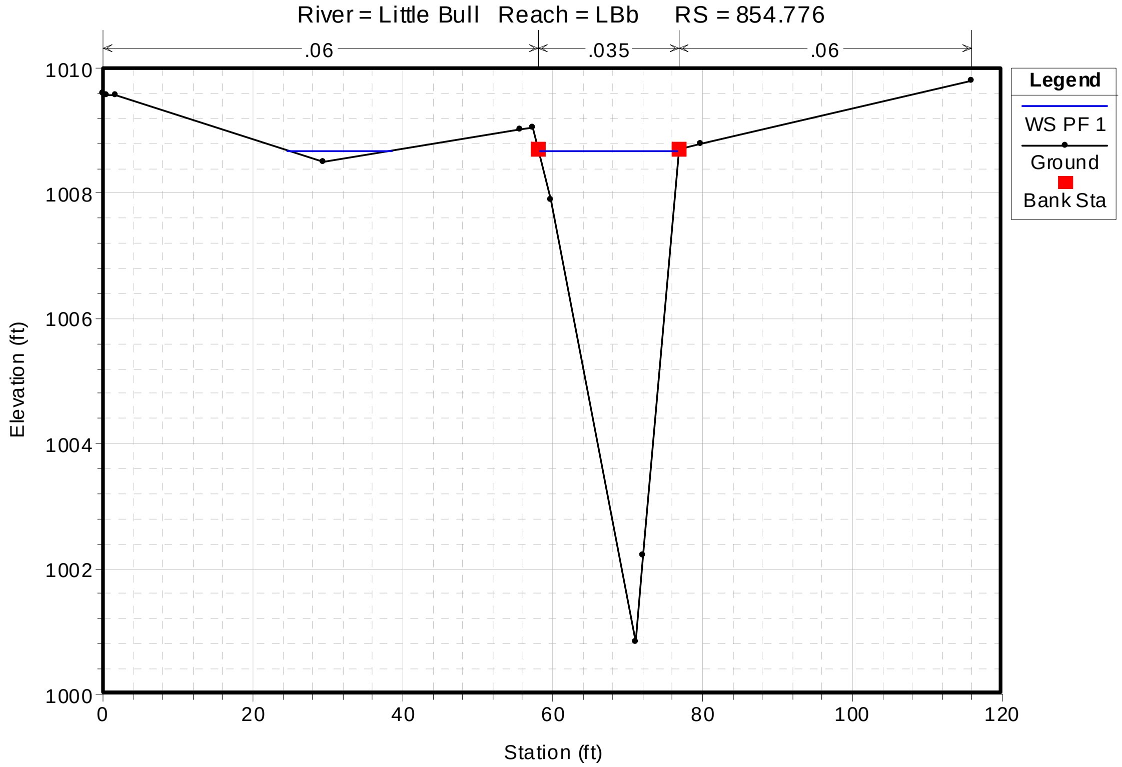
LBb.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.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
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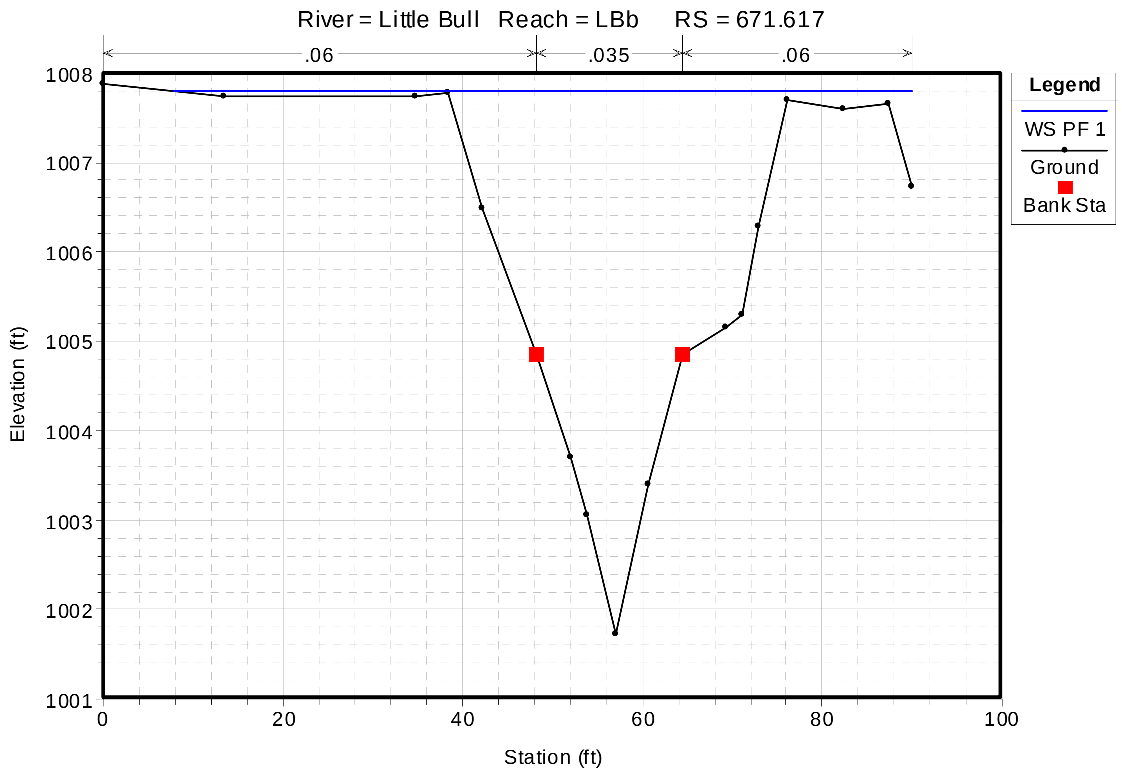
1008
1006
1004
1002
1000
0
20
40
60
80
100
120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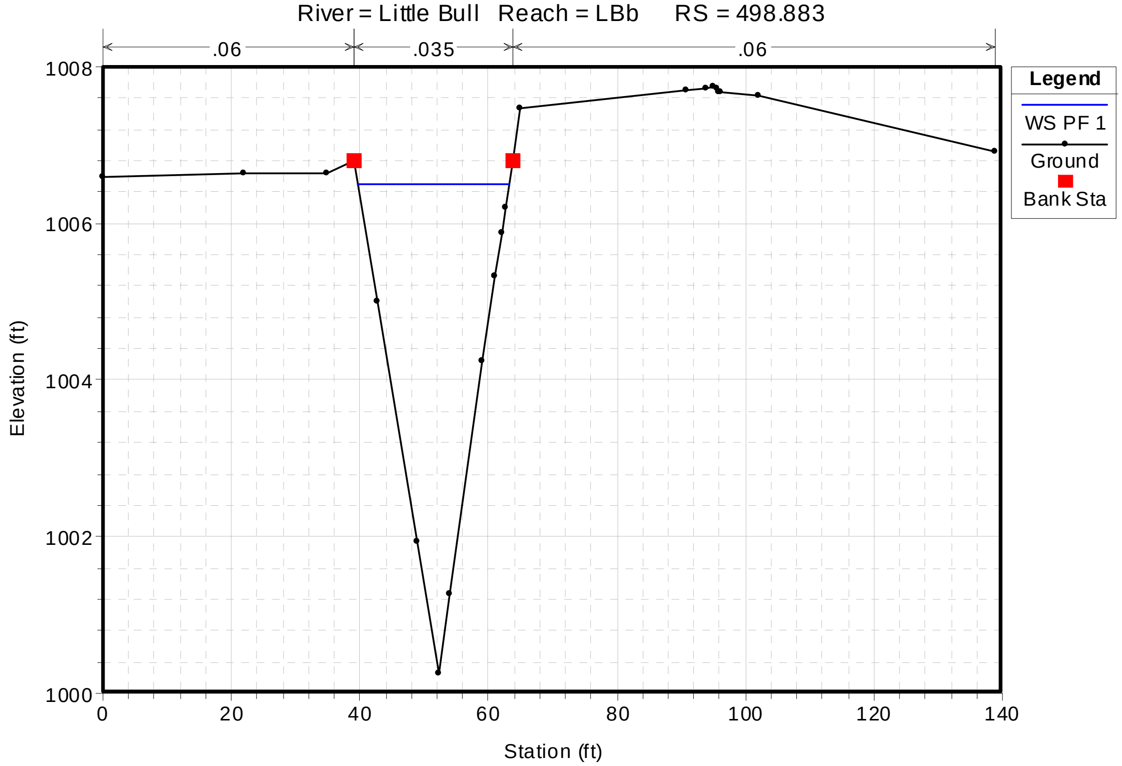
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
1008
1007
1006
1005
1004
1003
1002
1001
0
20
40
60
80
100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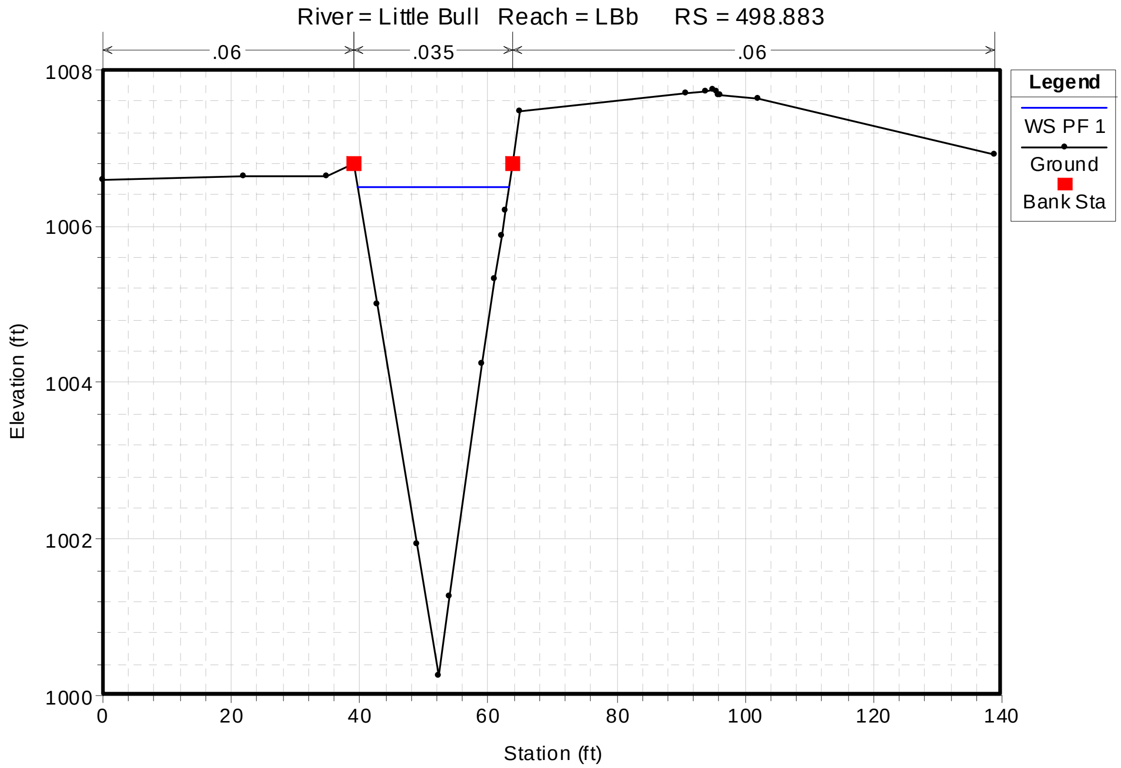
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
1008
1006
1004
1002
1000
Elevation (ft)
0
20
40
60
80
100
120
140
Station (ft)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.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
1008
1006
1004
1002
1000
Elevation (ft)
0
20
40
60
80
100
120
140
Station (ft)

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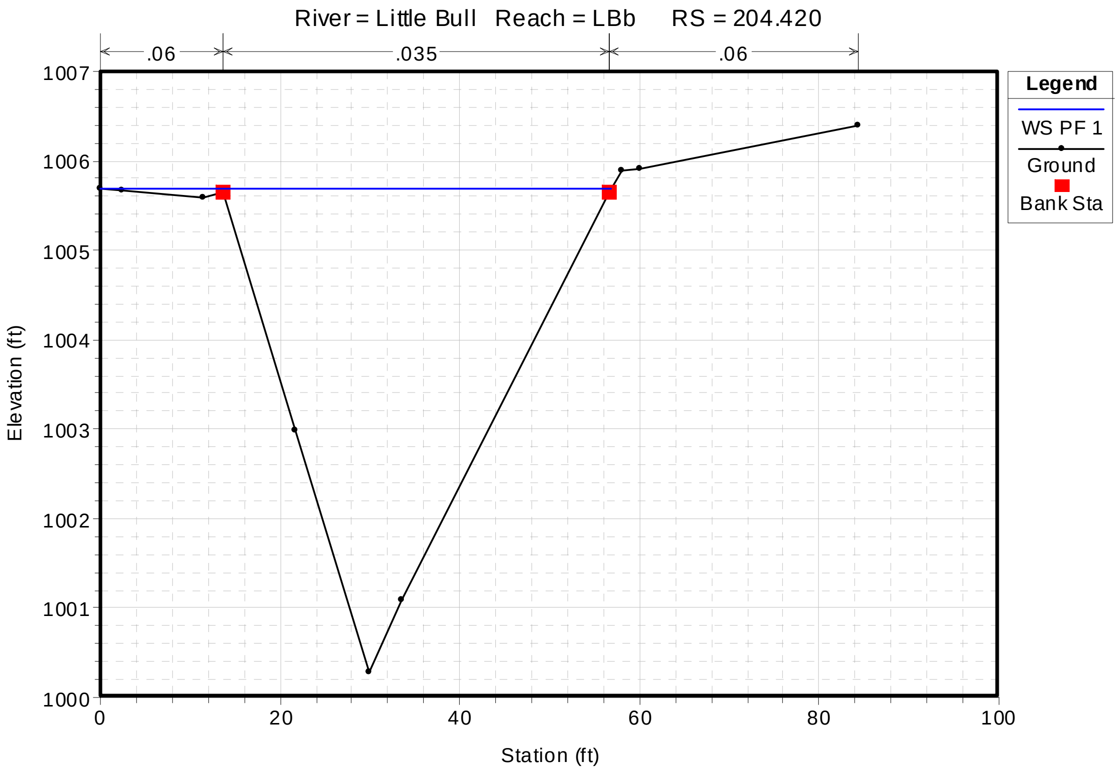

LBNC3

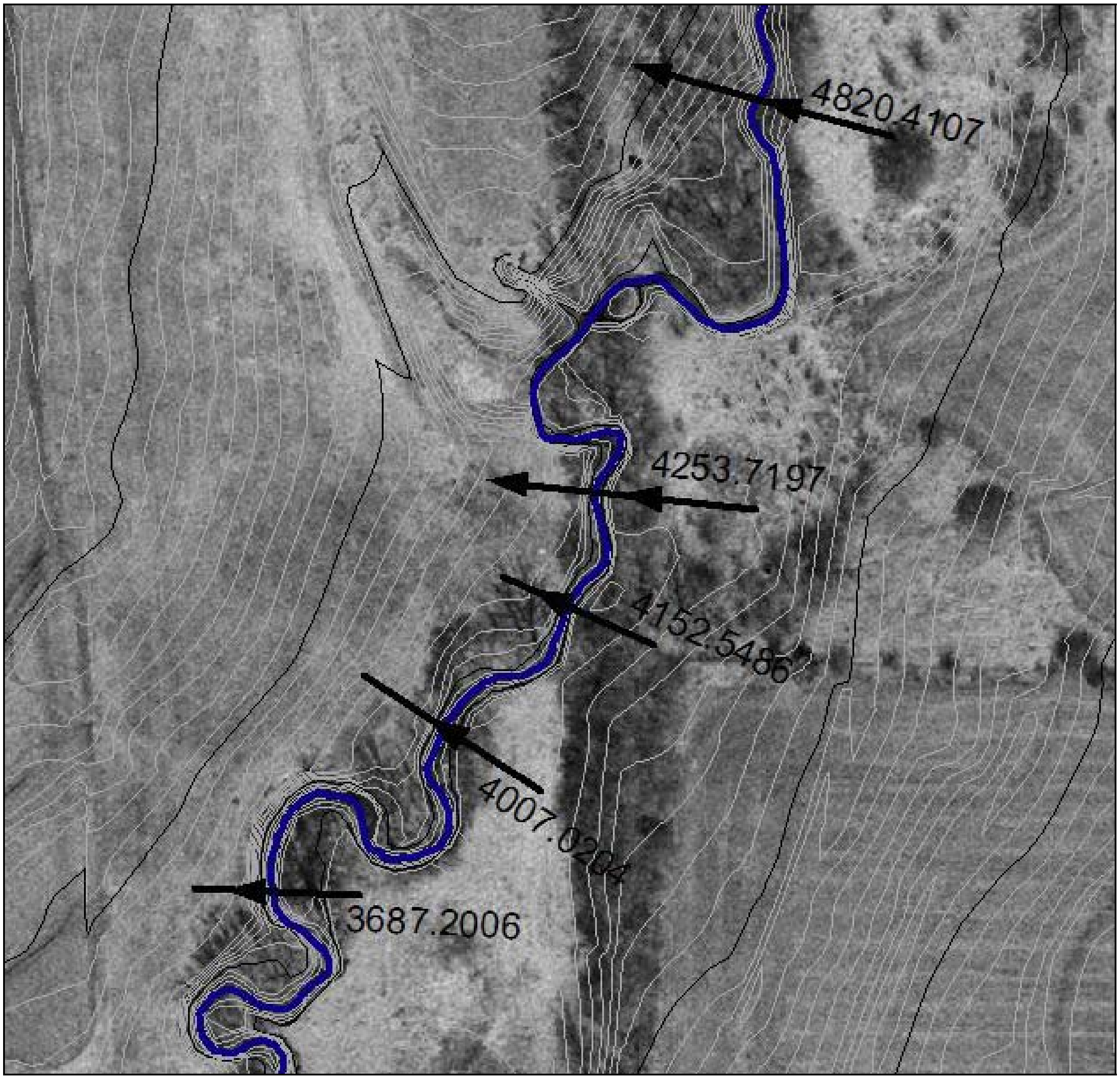

Exhibit 3: Aerial Photograph, Contours and Cross-section Locations for LBNC3.

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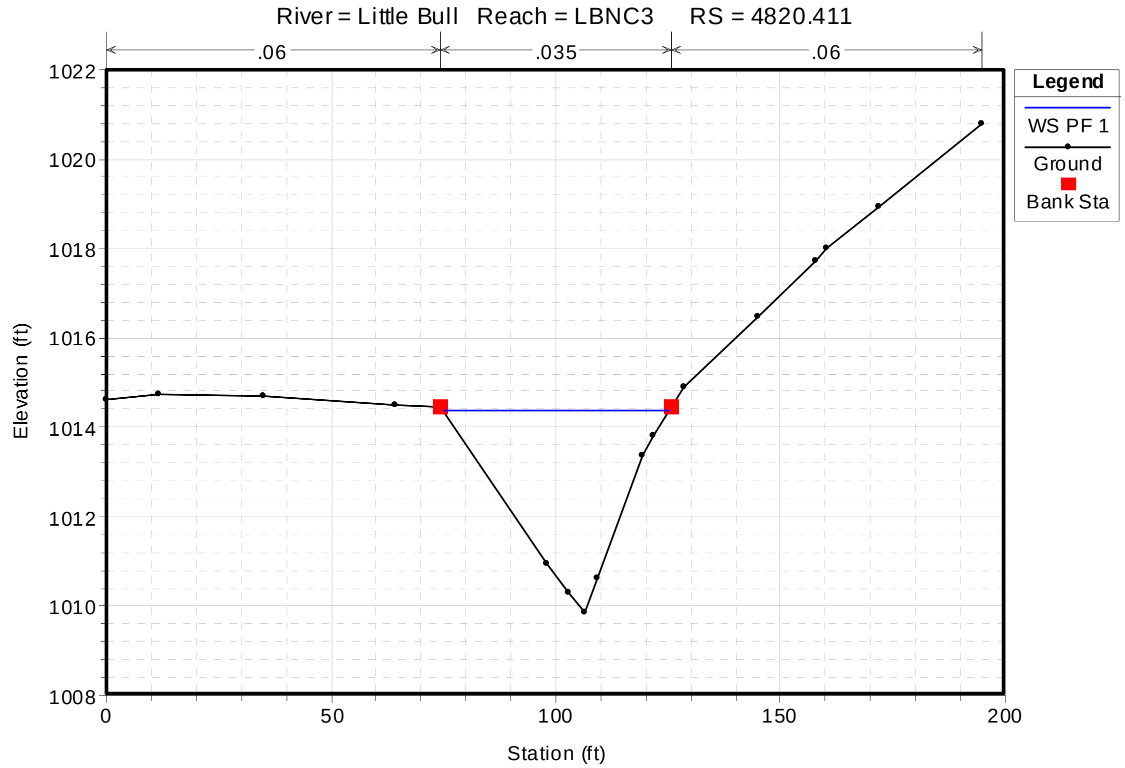

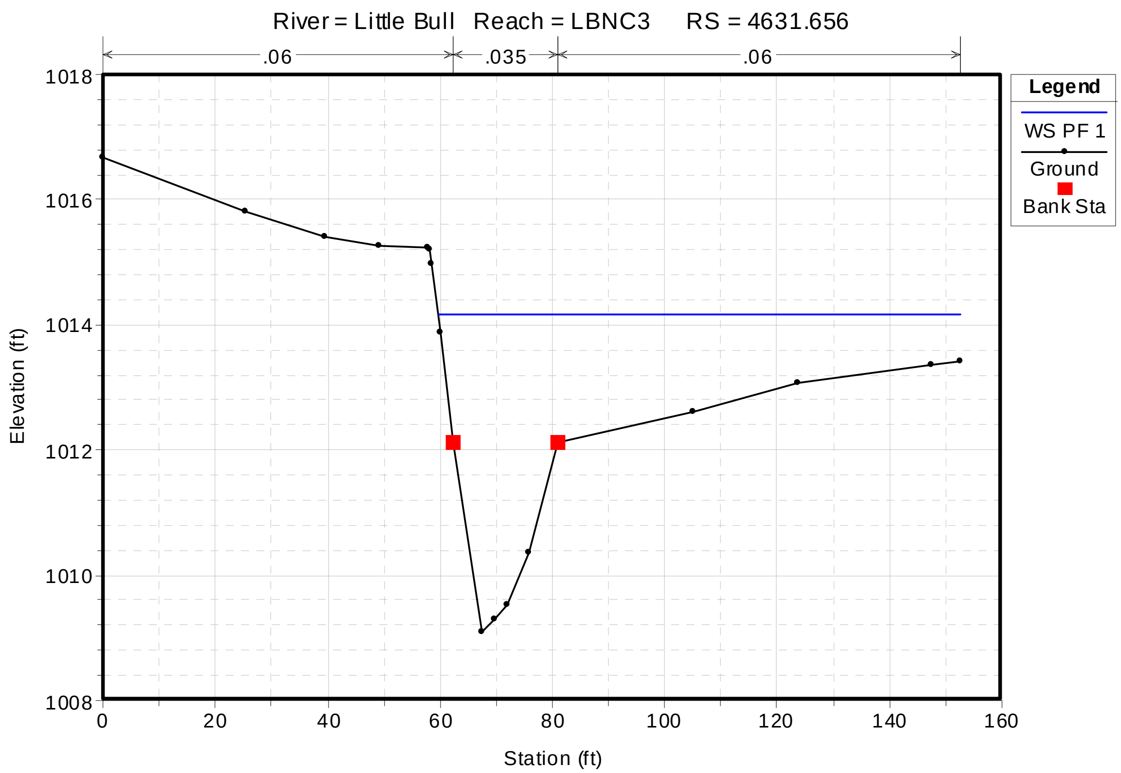

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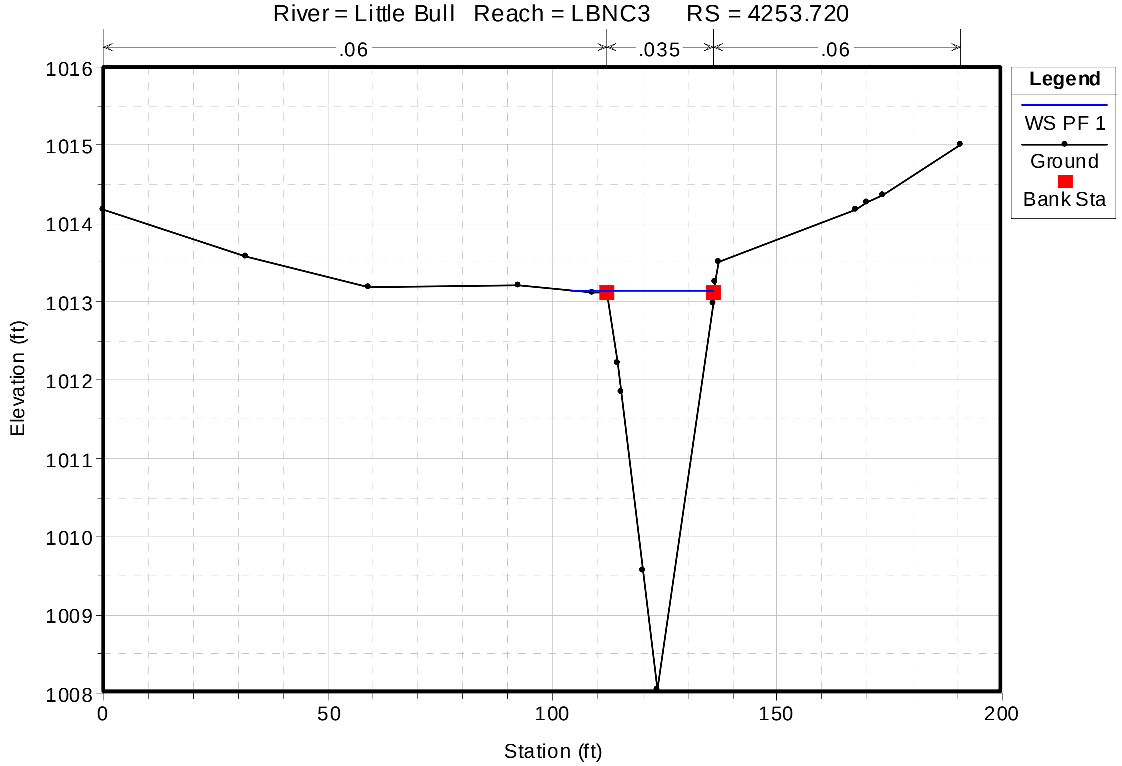
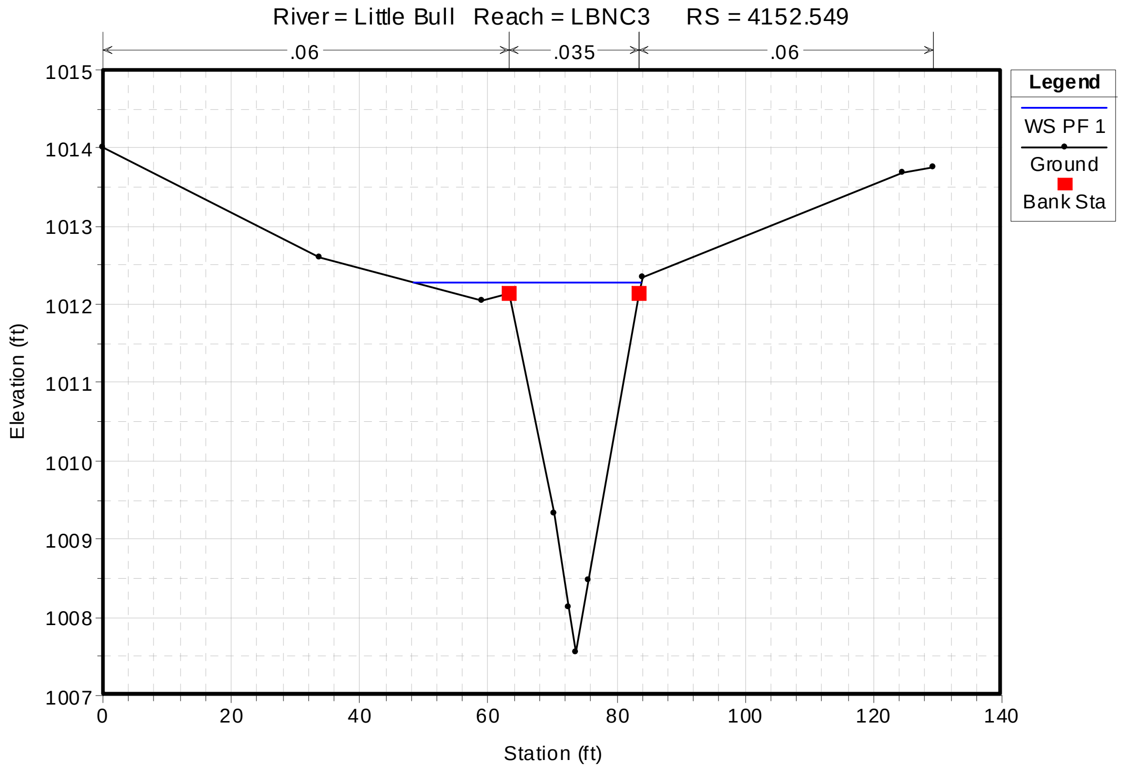
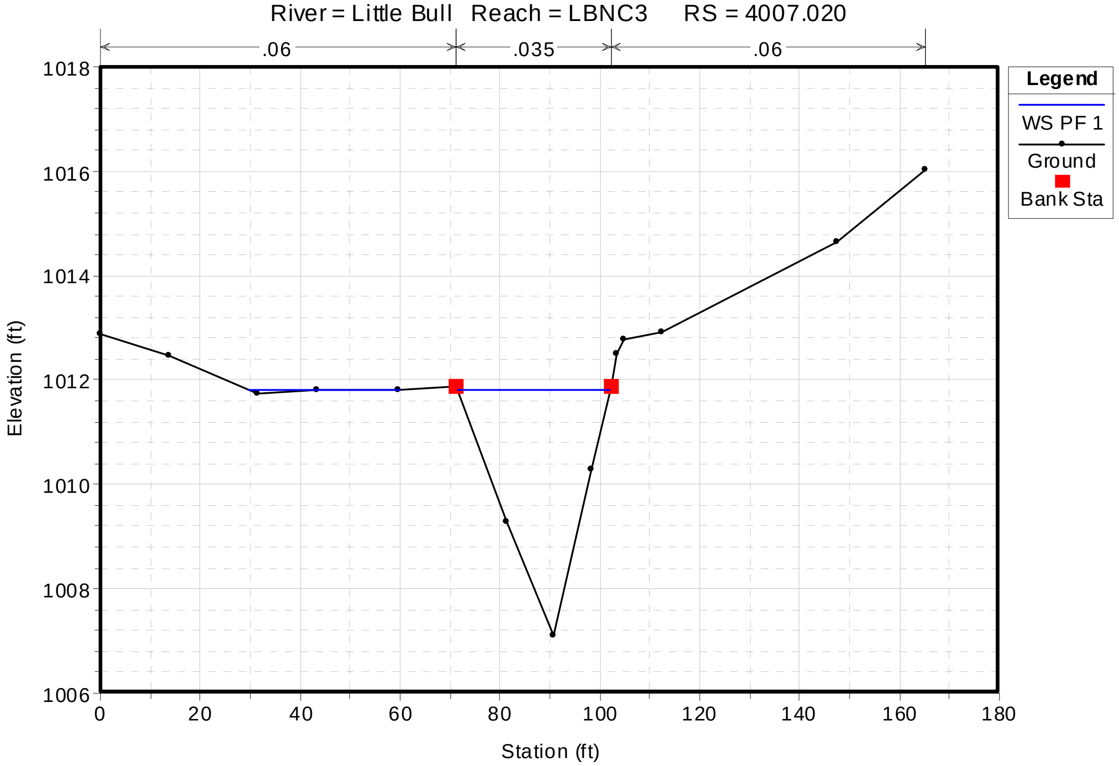
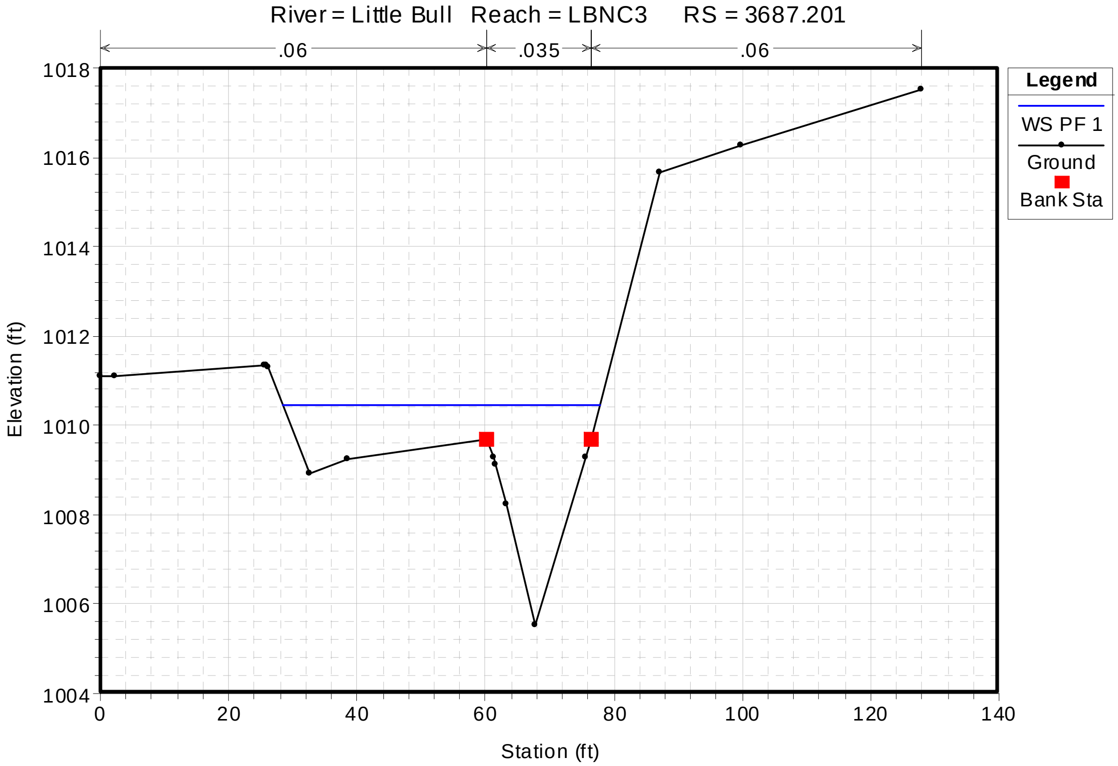


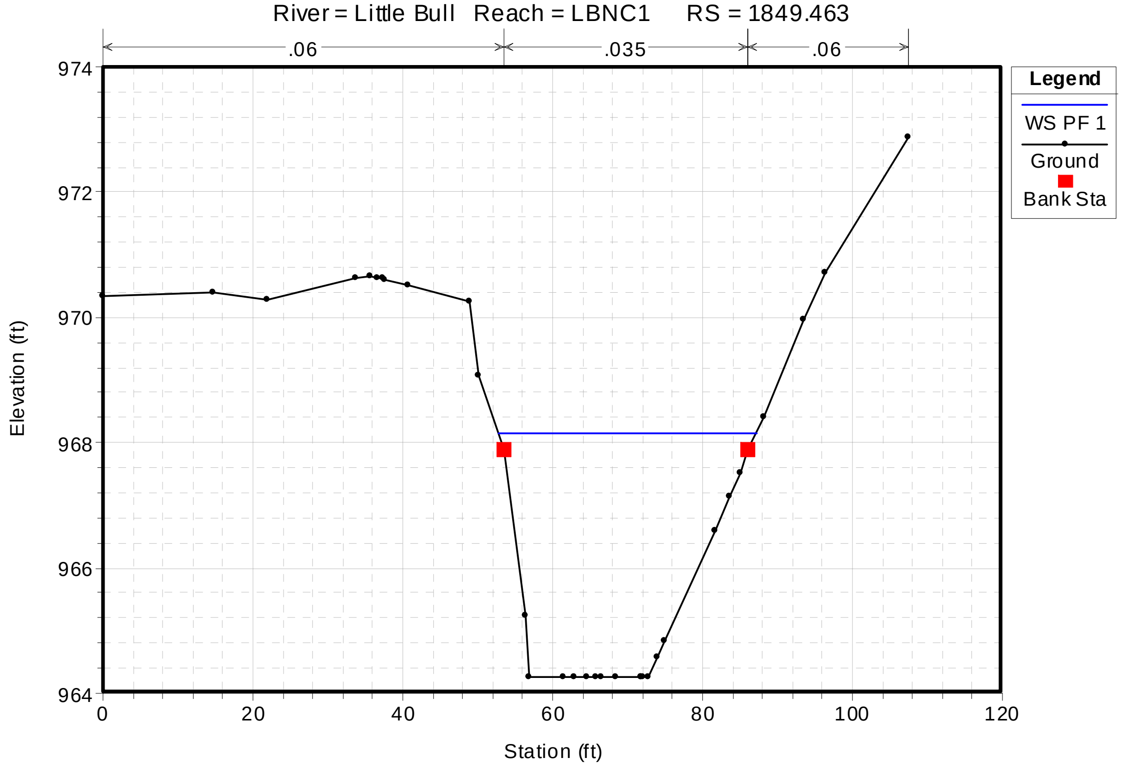



River = Little Bull Reach = LBNC3 RS = 4007.020
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)


River = Little Bull Reach = LBNC3 RS = 3687.201
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)

LBNC1

Exhibit 4: Aerial Photograph, Contours and Cross-section Locations for LBNC1.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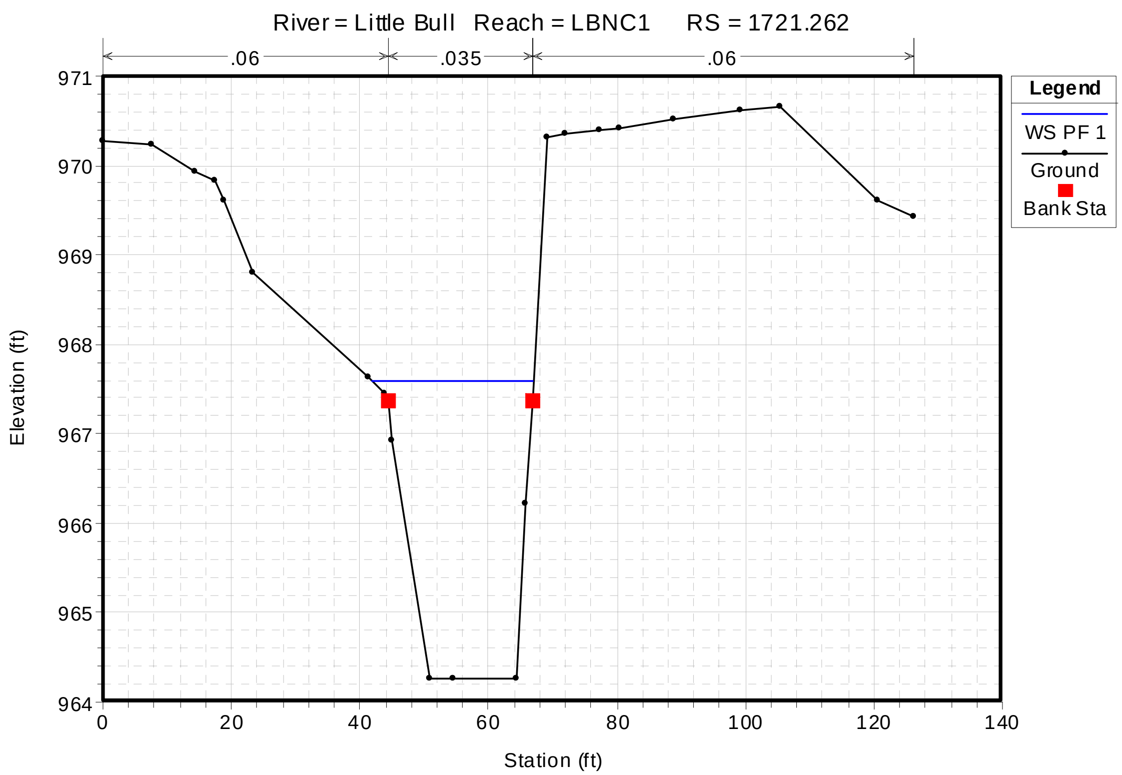
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
974
972
970
968
966
964
Elevation (ft)
0
20
40
60
80
100
120
Station (ft)


River = Little Bull Reach = LBNC1 RS = 1721.262
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
971
970
969
968
967
966
965
964
Elevation (ft)
0
20
40
60
80
100
120
140
Station (ft)

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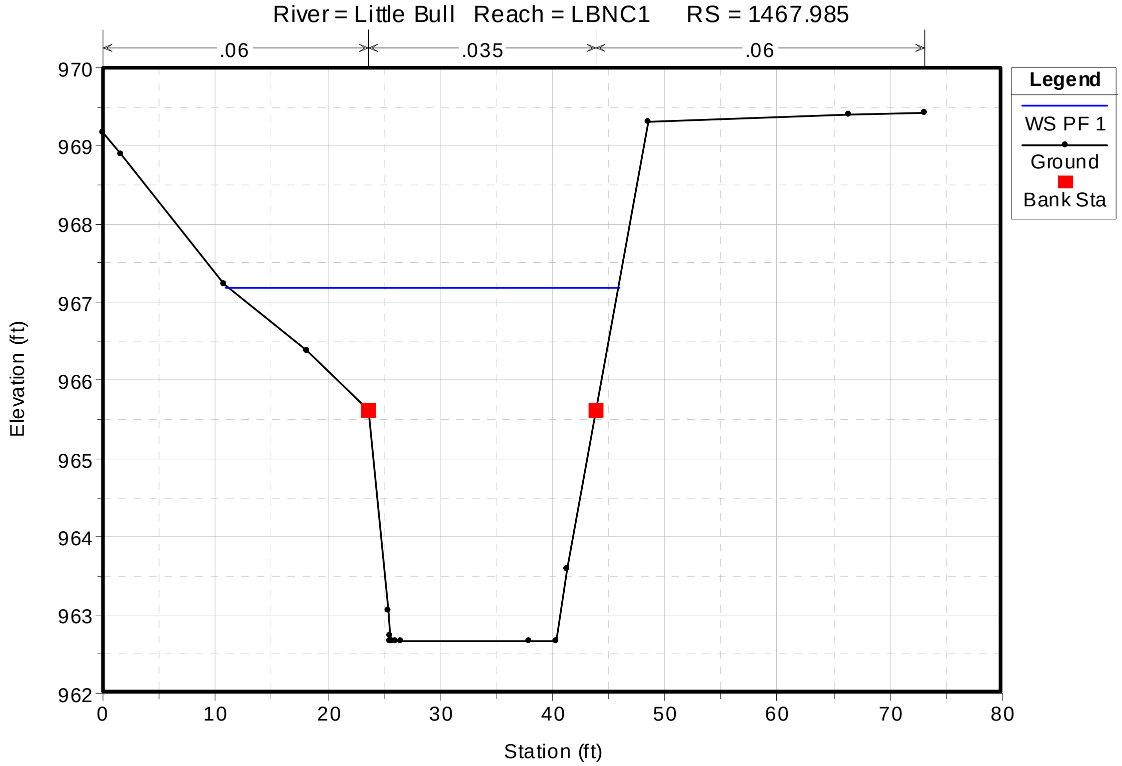
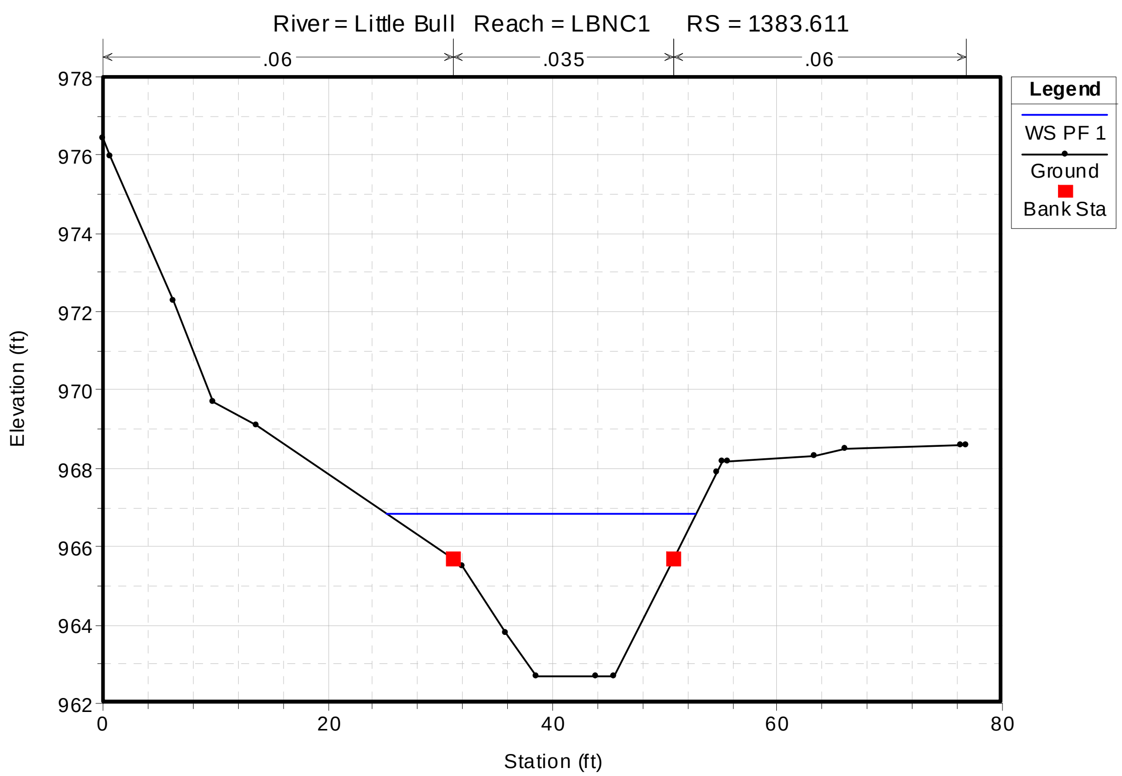
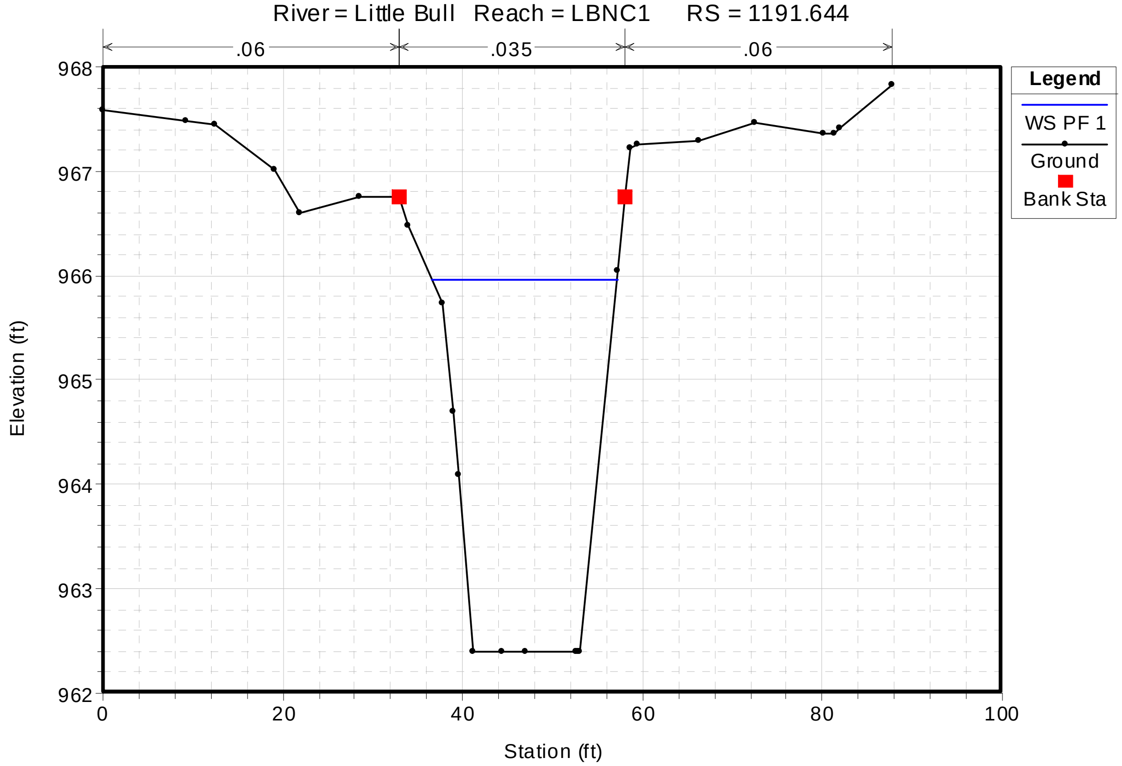
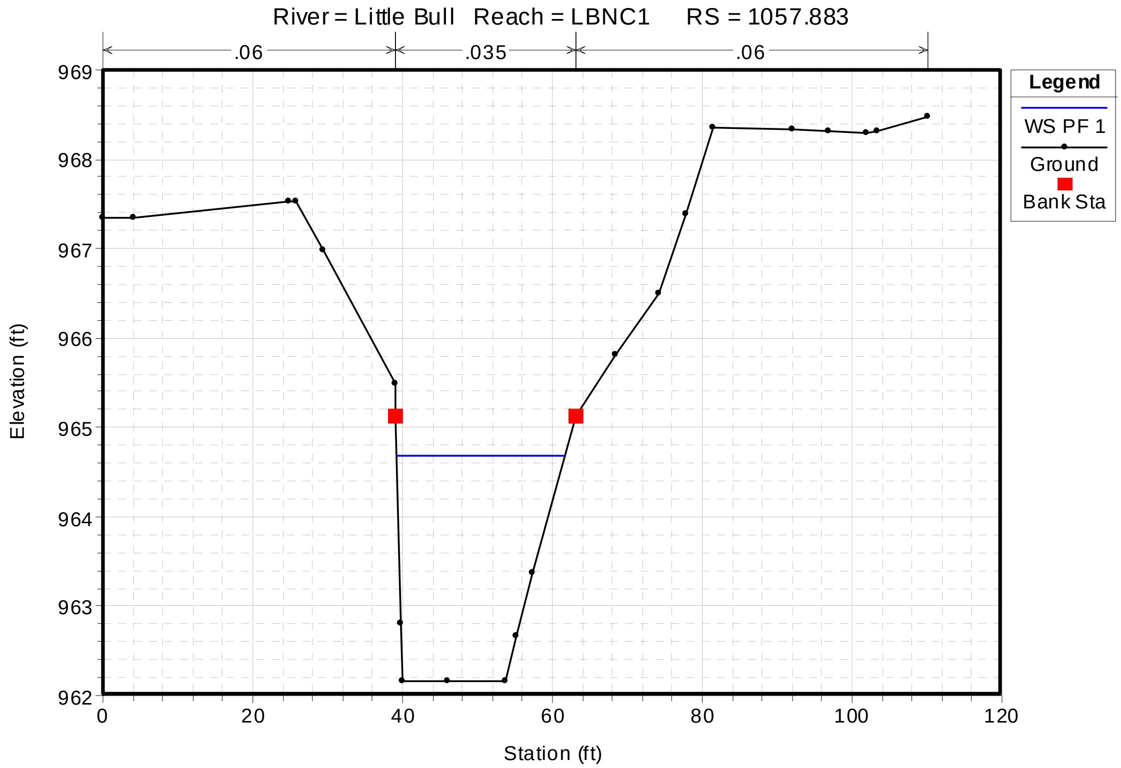





River = Little Bull Reach = LBNC1 RS = 1191.644
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
968
967
966
965
964
963
962
0
20
40
60
80
100
Station (ft)


River = Little Bull Reach = LBNC1 RS = 1057.883
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
969
968
967
966
965
964
963
962
0
20
40
60
80
100
120
Station (ft)

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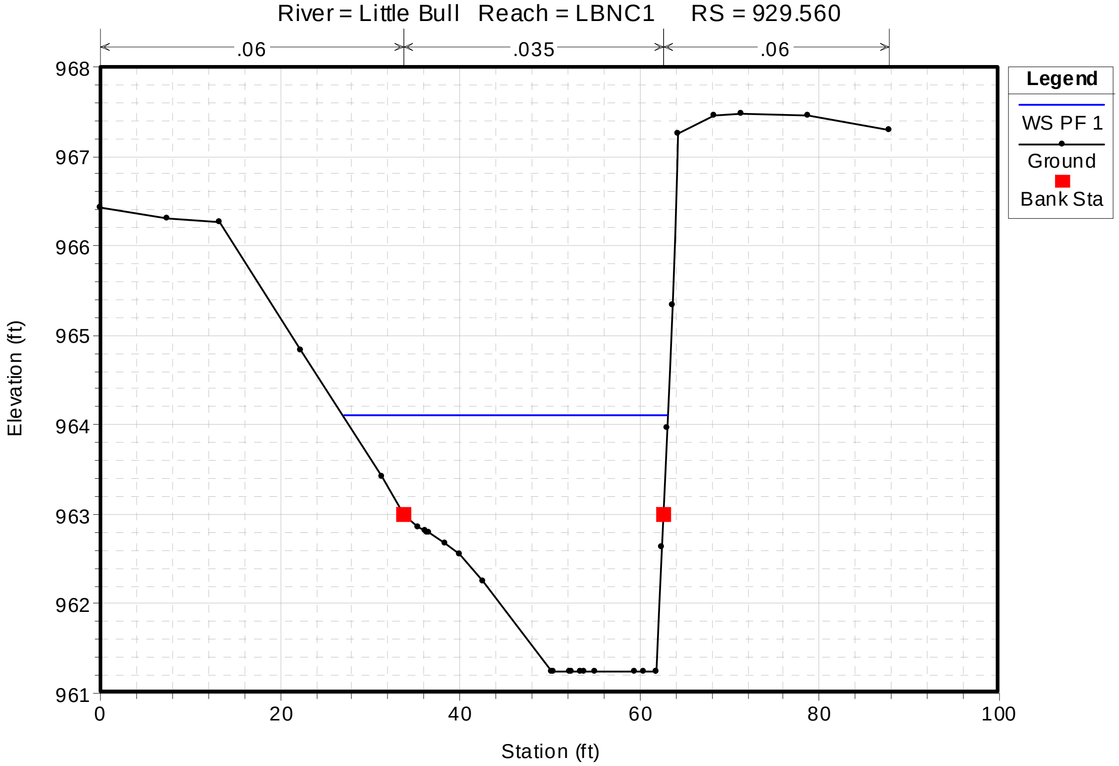
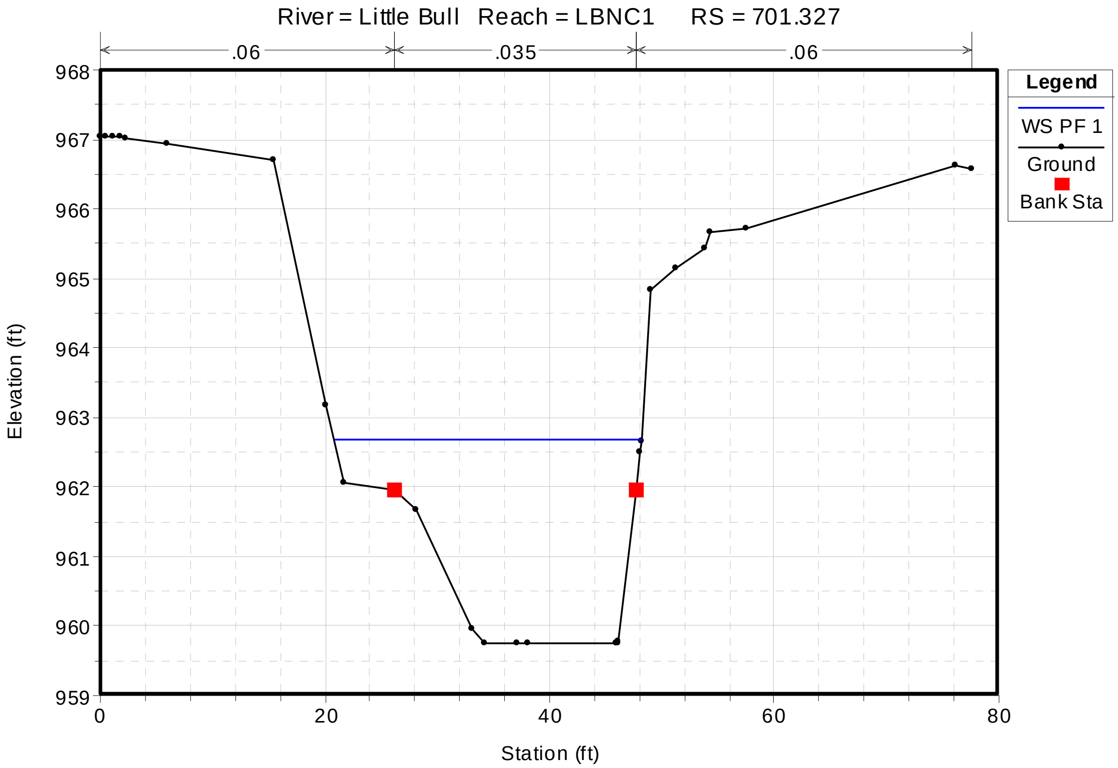




LBa

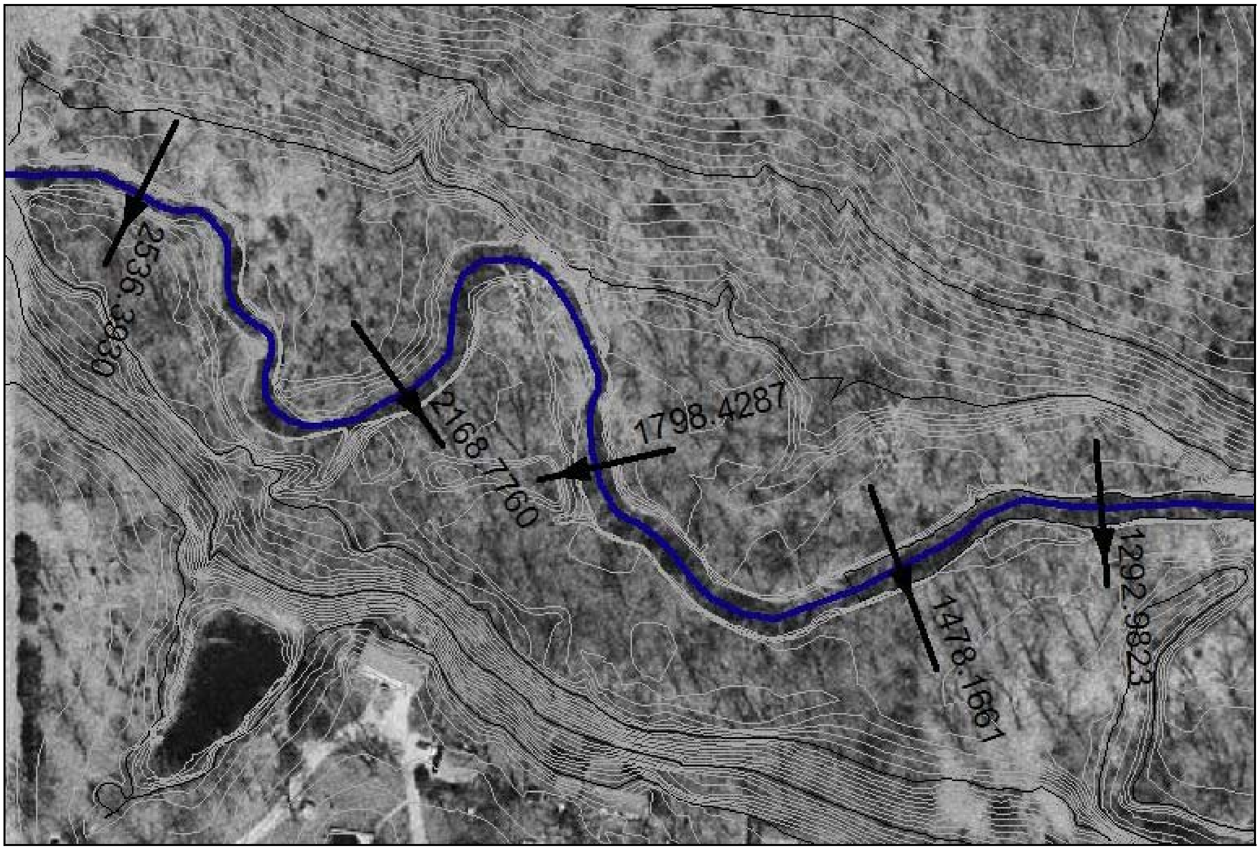
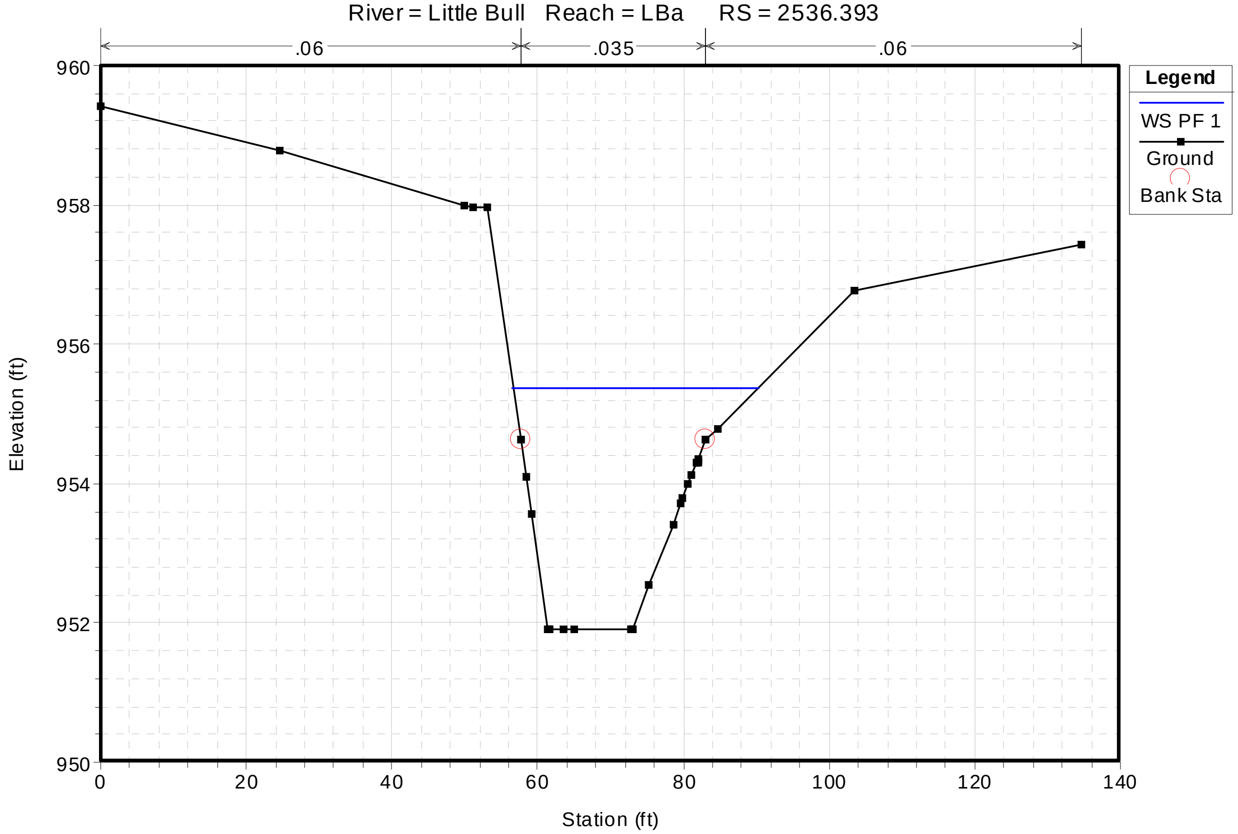


Exhibit 5: Aerial Photograph, Contours and Cross-section Locations for LBa.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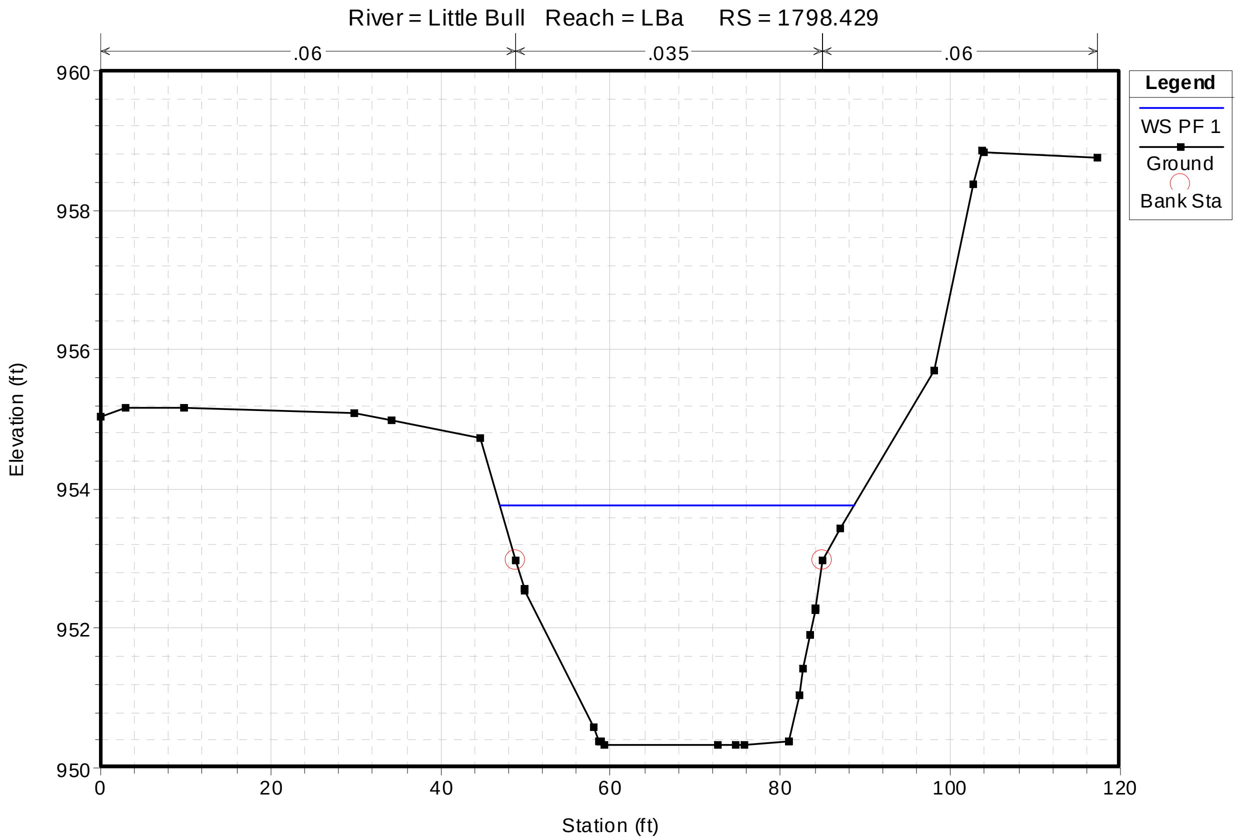
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
960
958
956
954
952
950
0
20
40
60
80
100
120
140


River = Little Bull Reach = LBa RS = 1798.429
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
960
958
956
954
952
950
0
20
40
60
80
100
120

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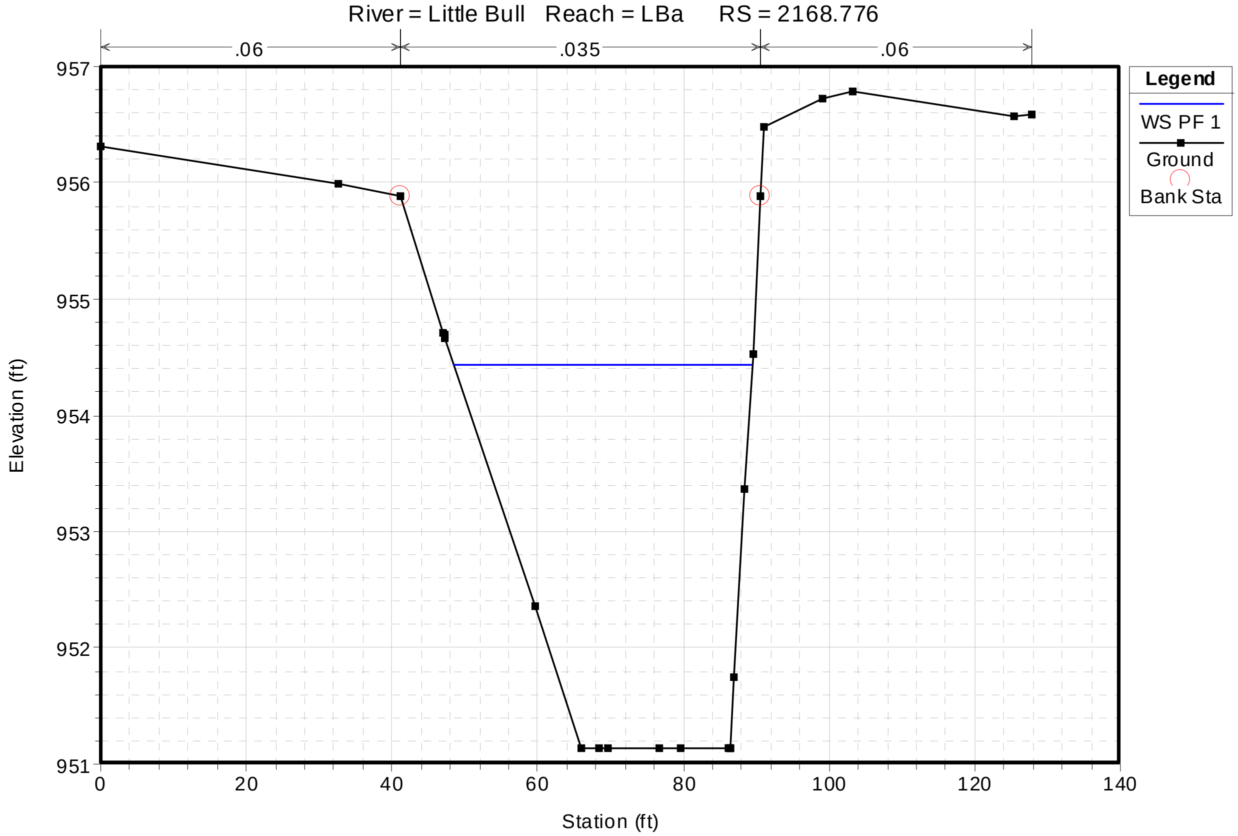

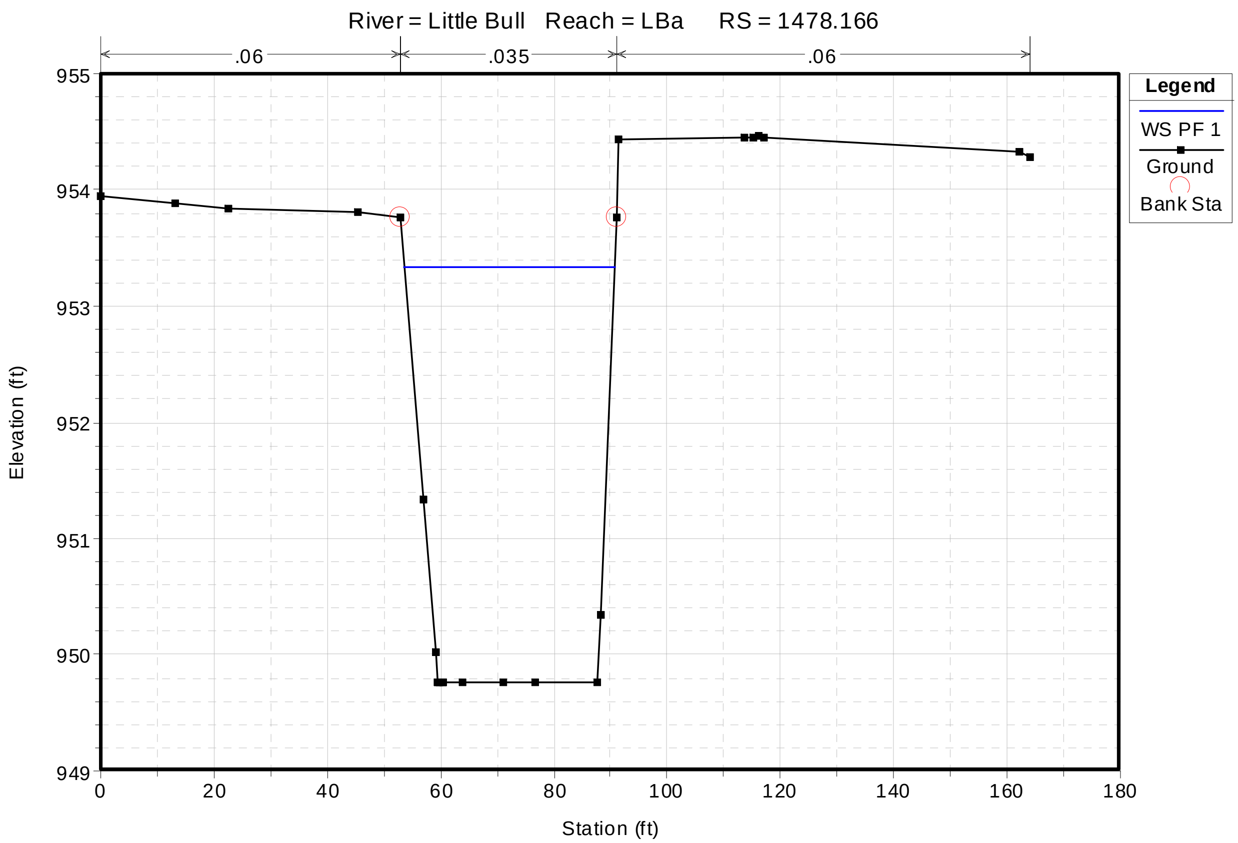

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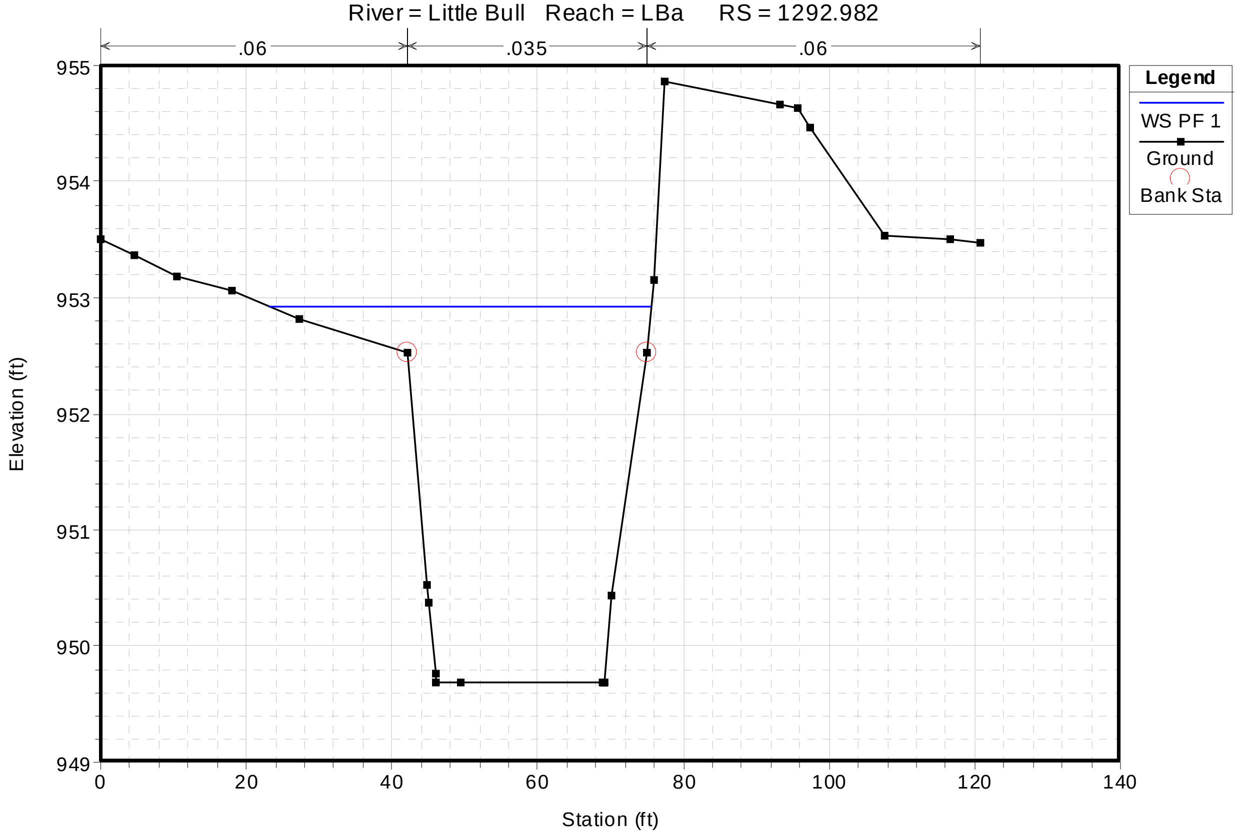

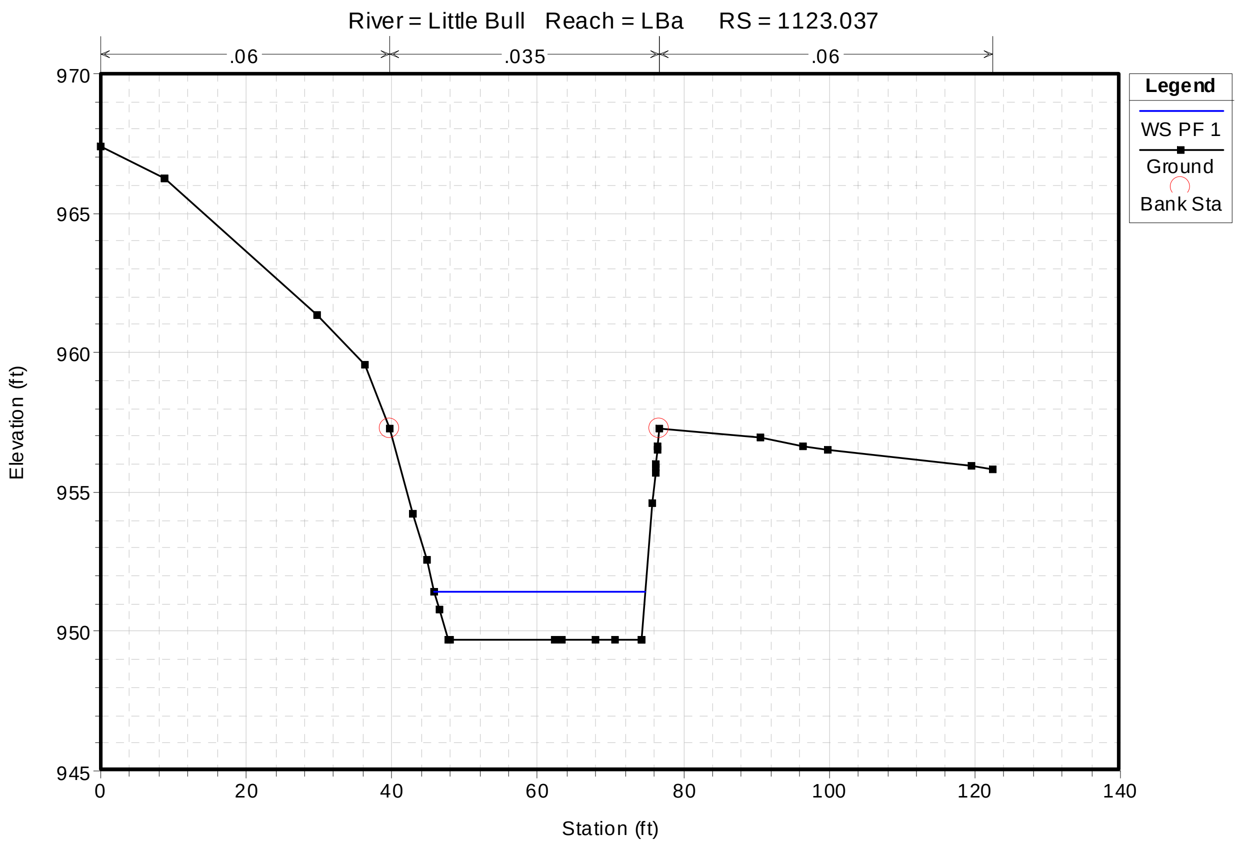

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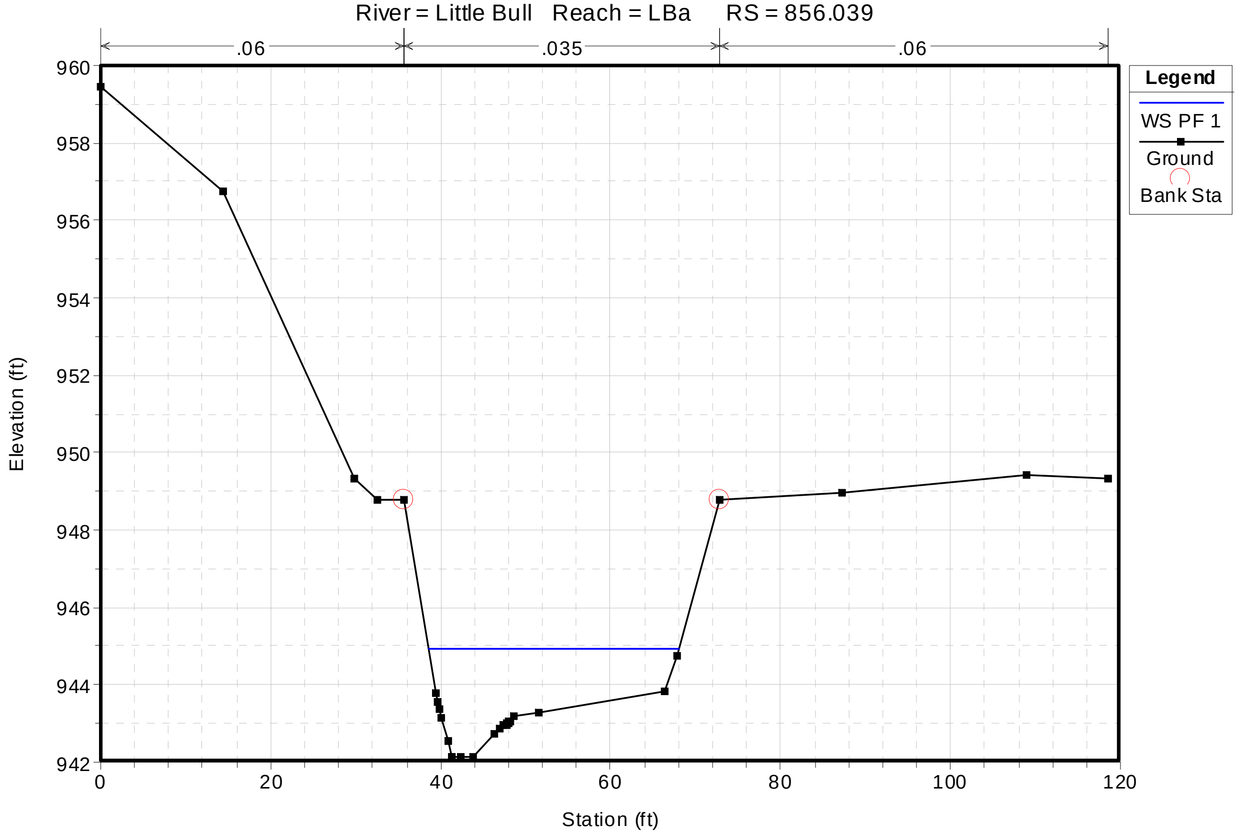

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Spring Creek

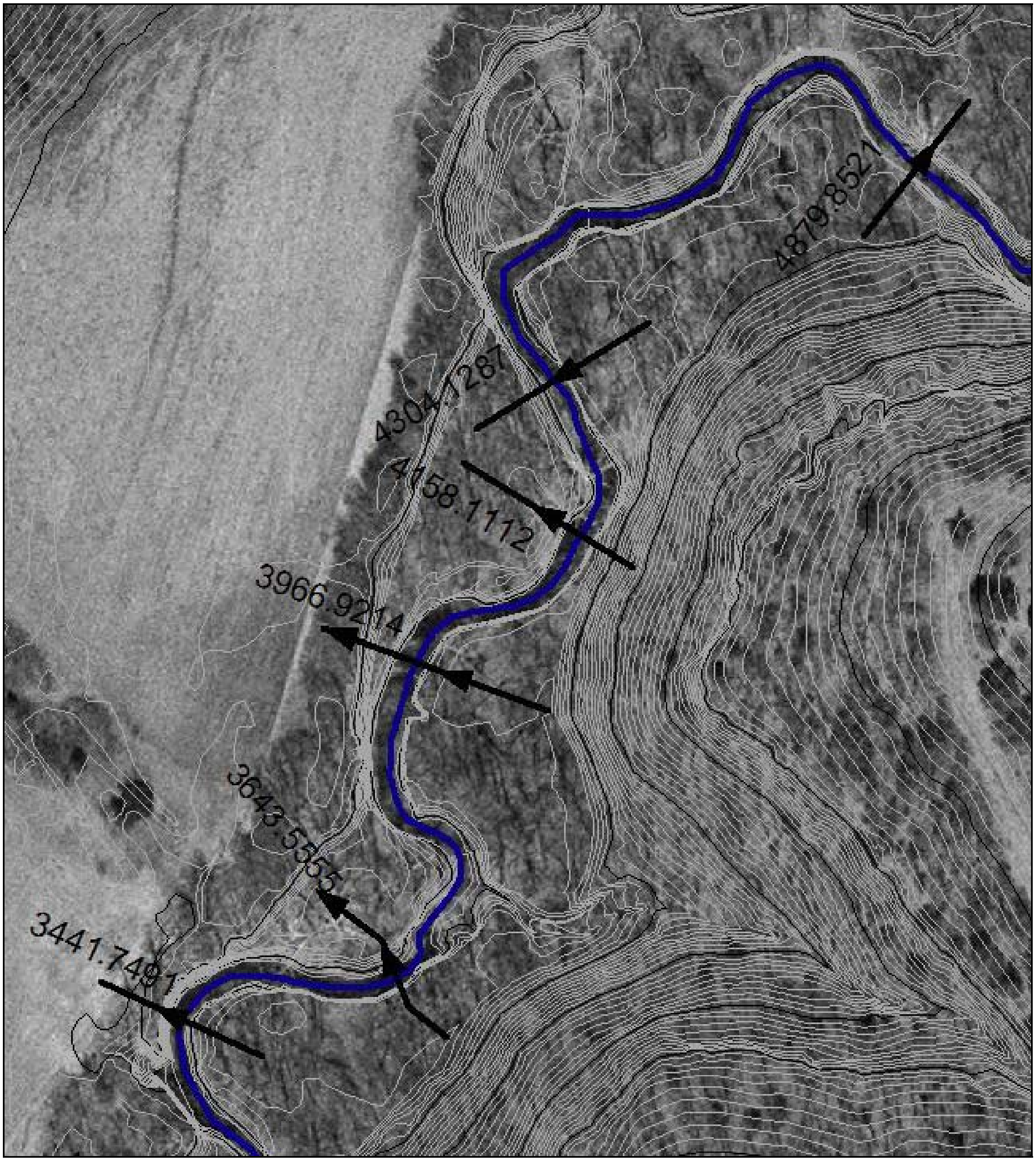

Exhibit 6: Aerial Photograph, Contours and Cross-section Locations for Spring Creek

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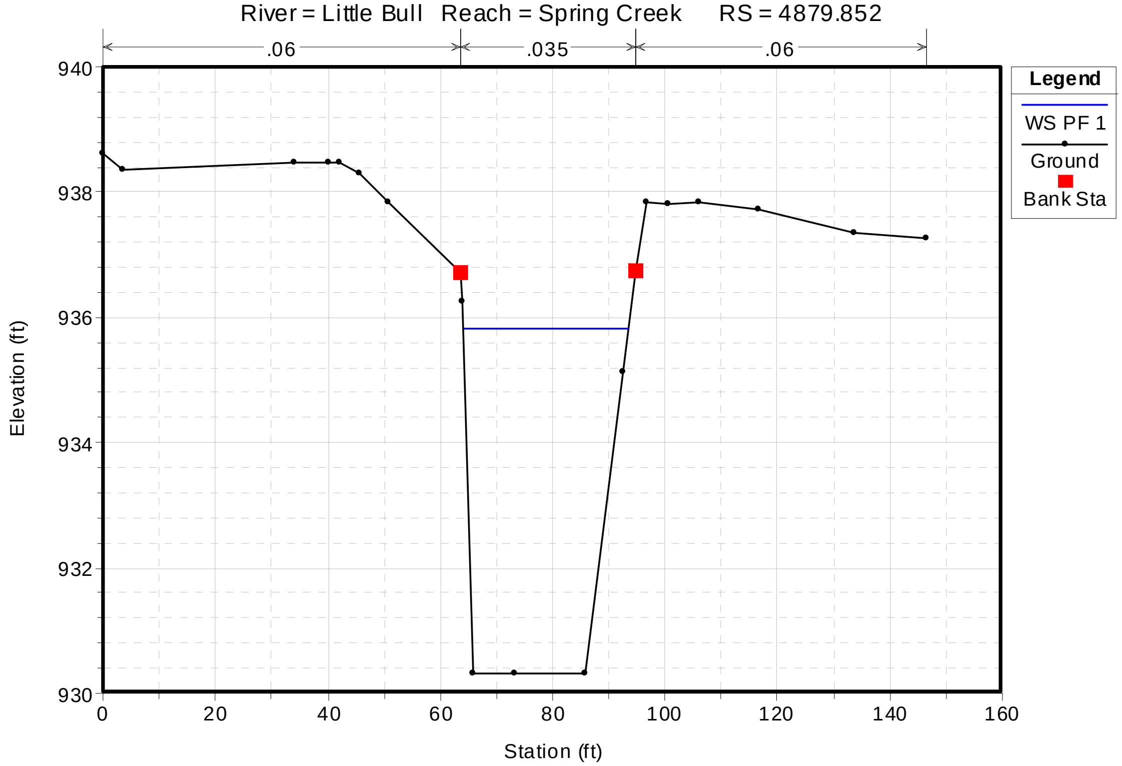
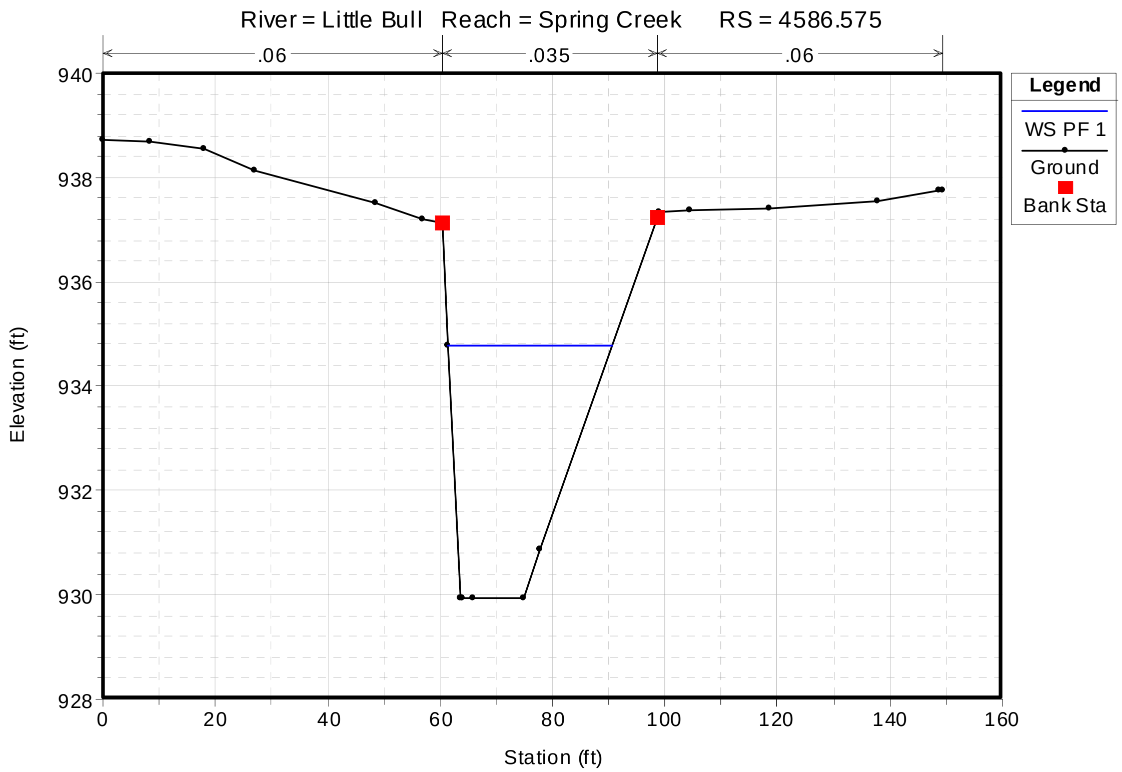
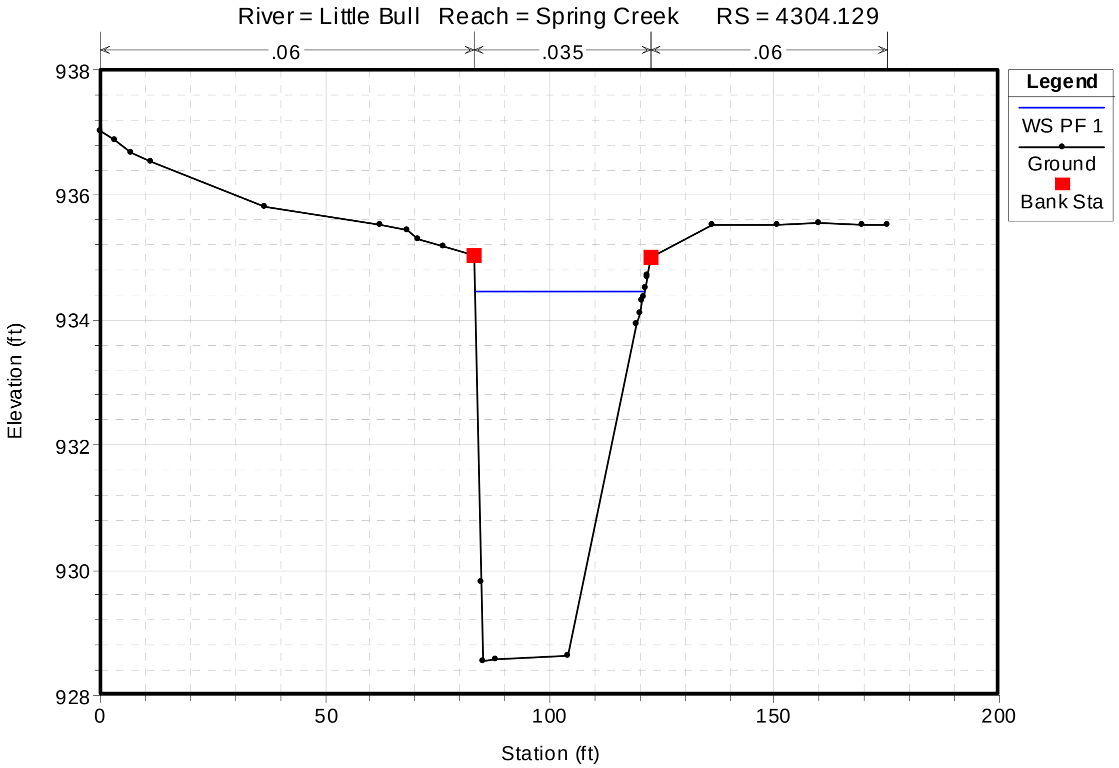
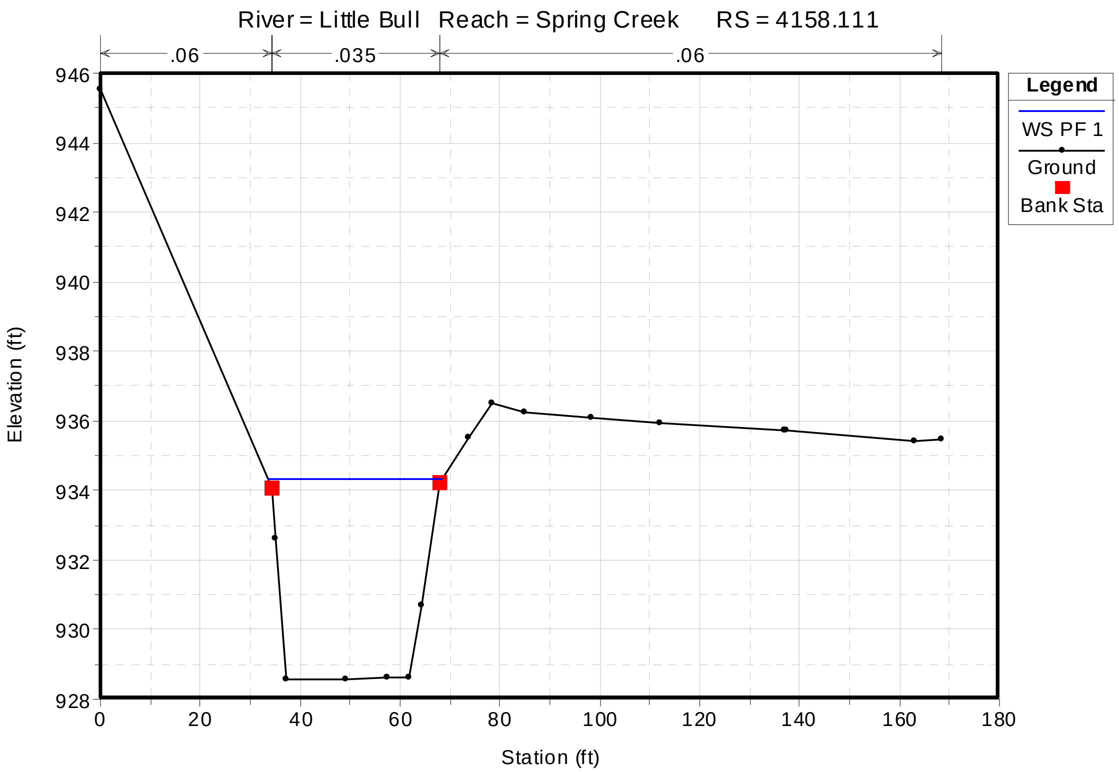
Fall 2009






River = Little Bull Reach = Spring Creek RS = 4304.129
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
938
936
934
932
930
928
0
50
100
150
200
Station (ft)


River = Little Bull Reach = Spring Creek RS = 4158.111
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
946
944
942
940
938
936
934
932
930
928
0
20
40
60
80
100
120
140
160
180
Station (ft)

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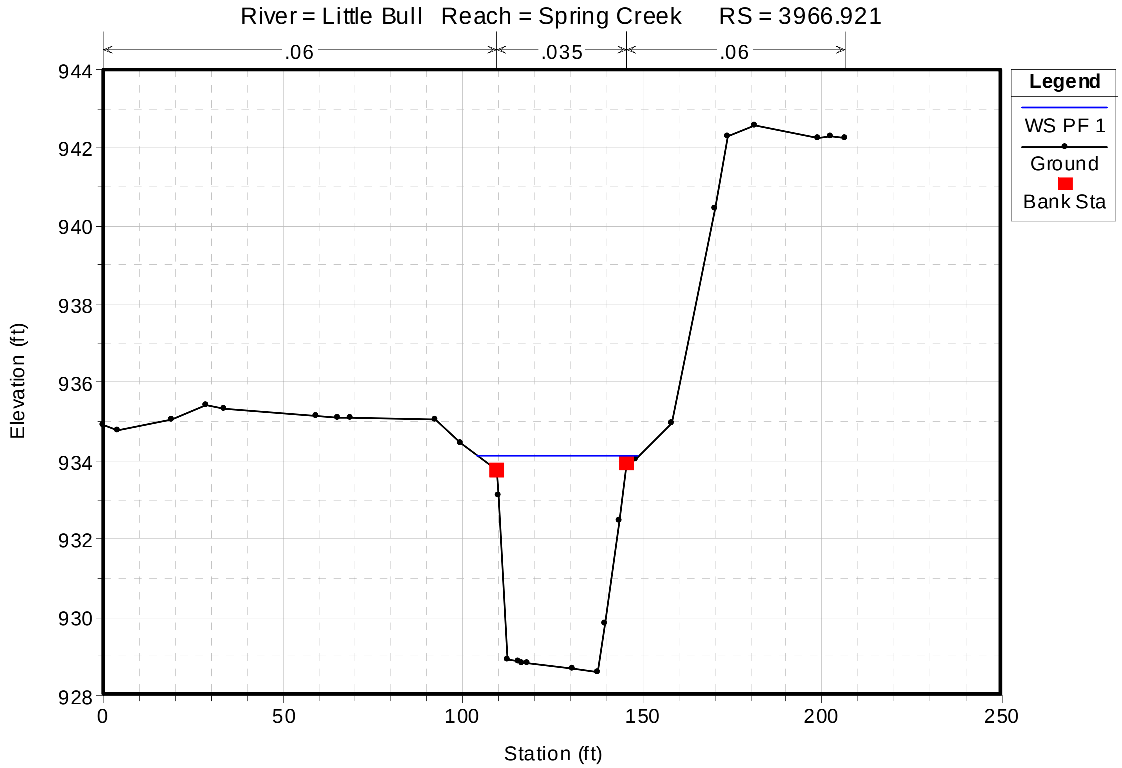

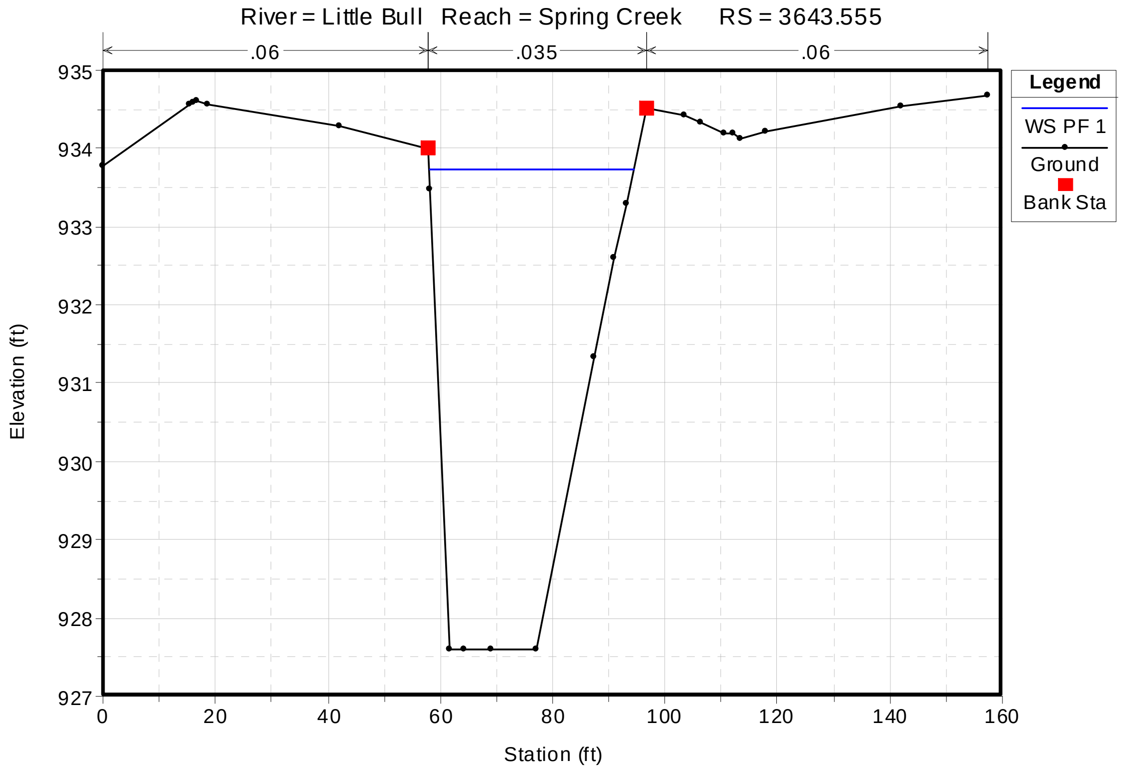

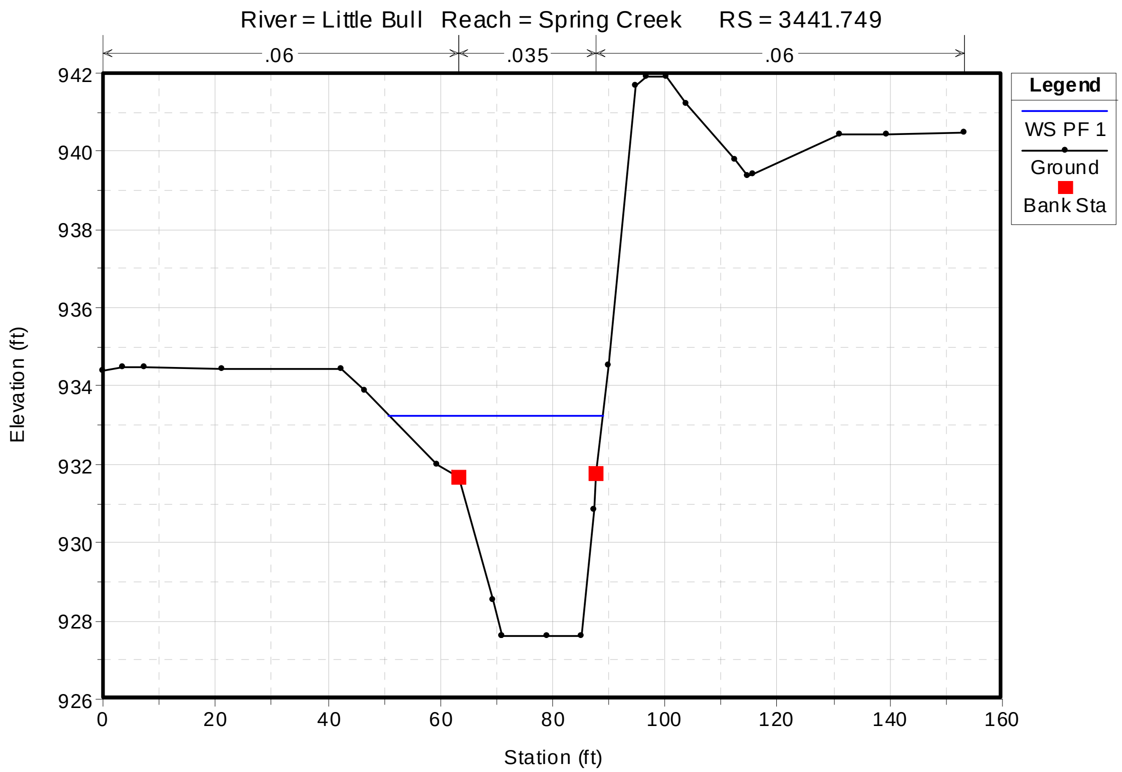
River = Little Bull Reach = Spring Creek RS = 3441.749
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
942
940
938
936
934
932
930
928
926
0
20
40
60
80
100
120
140
160
Station (ft)

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Little Bull Creek

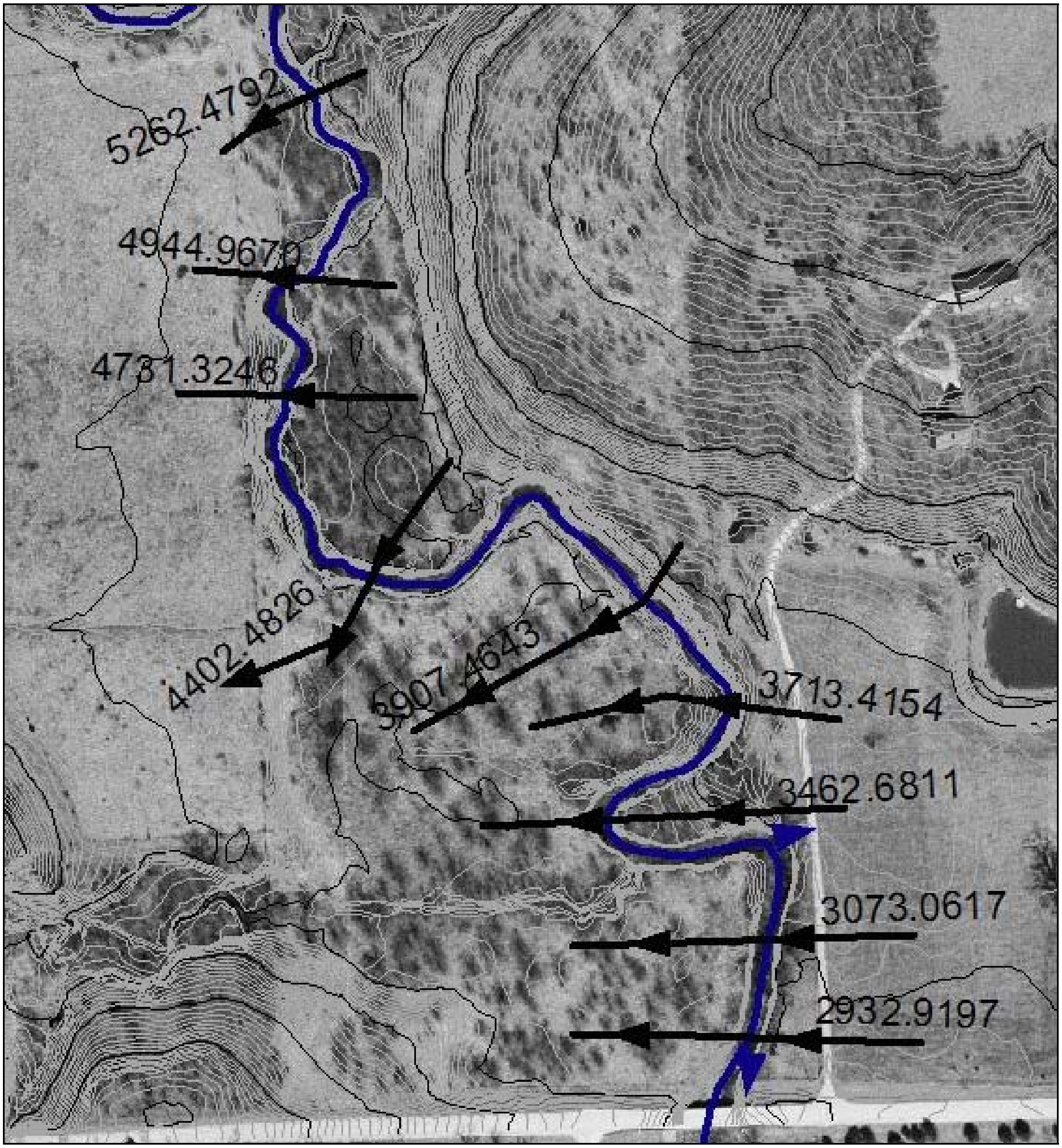
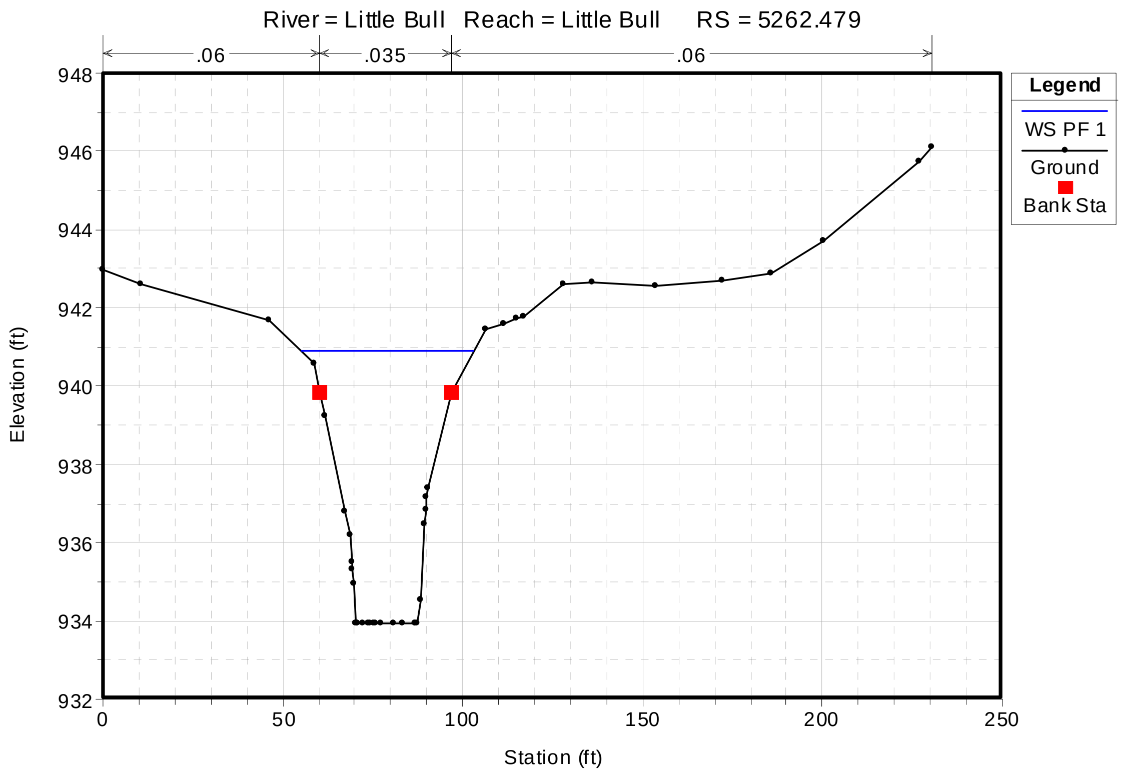
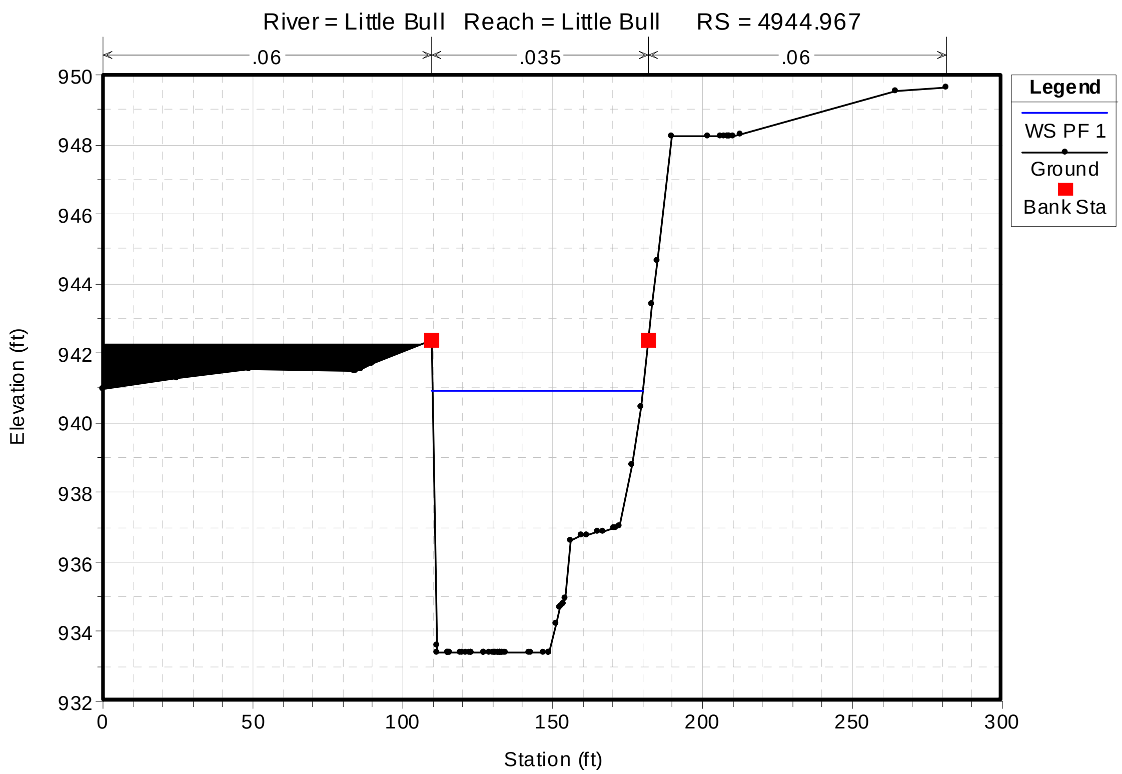
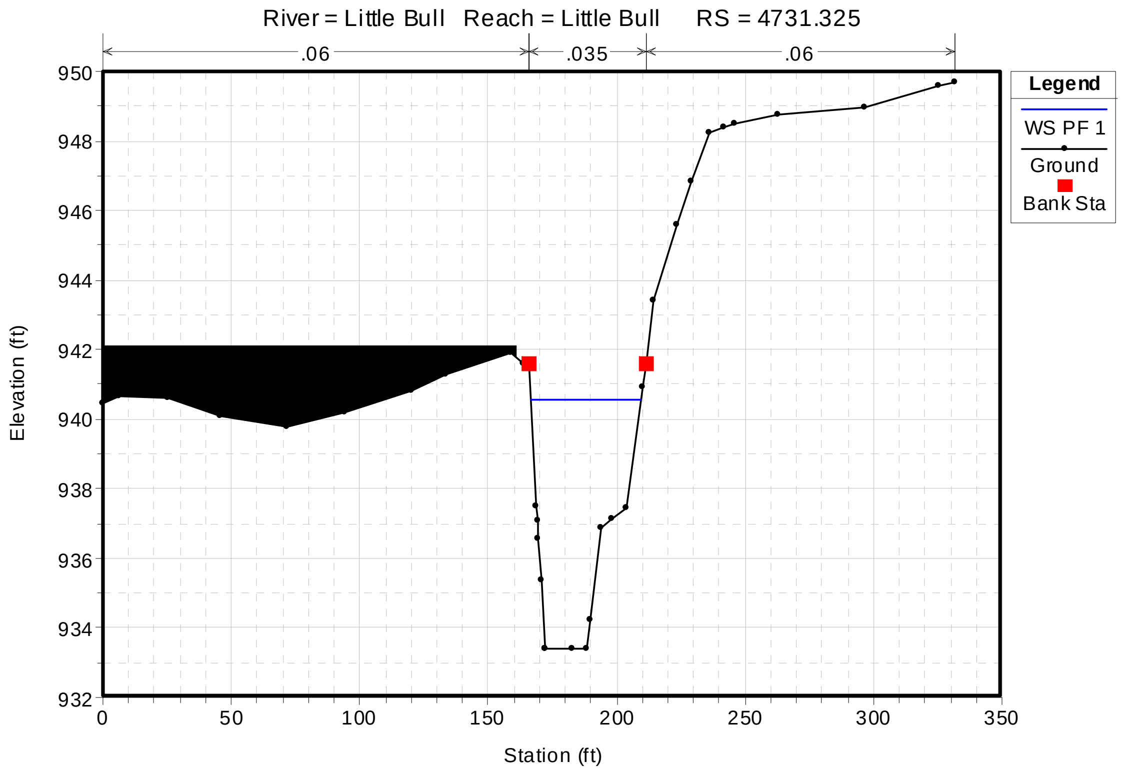
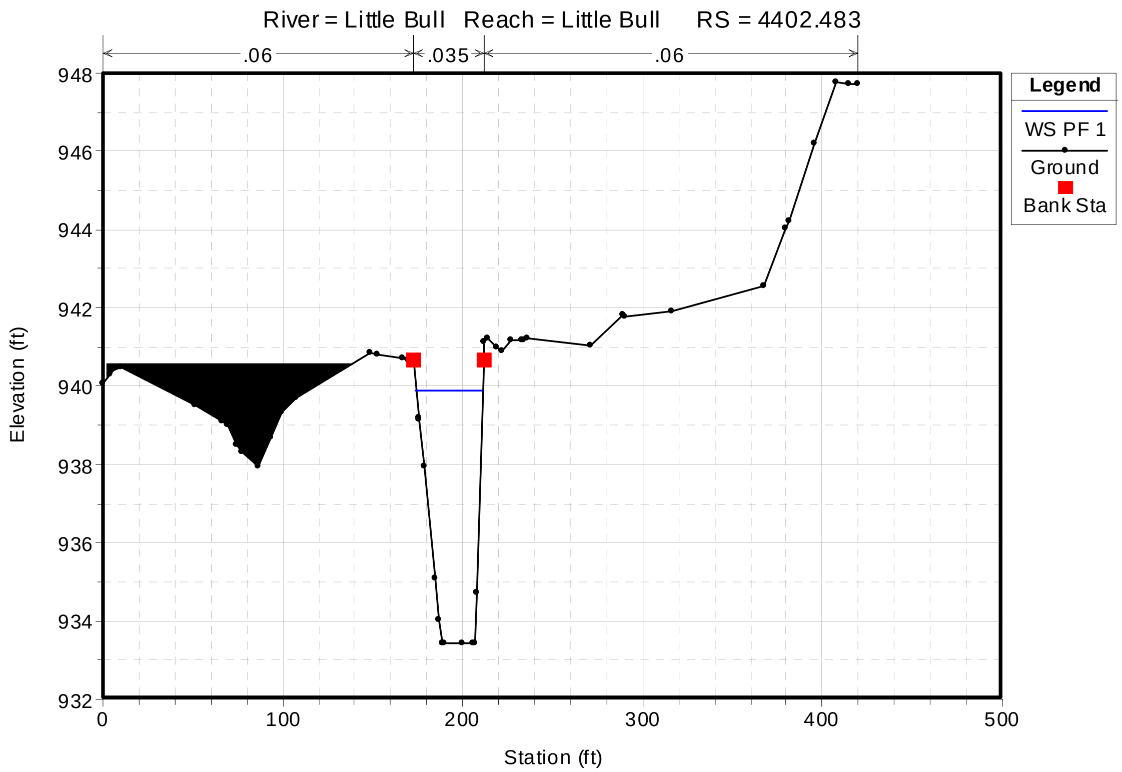


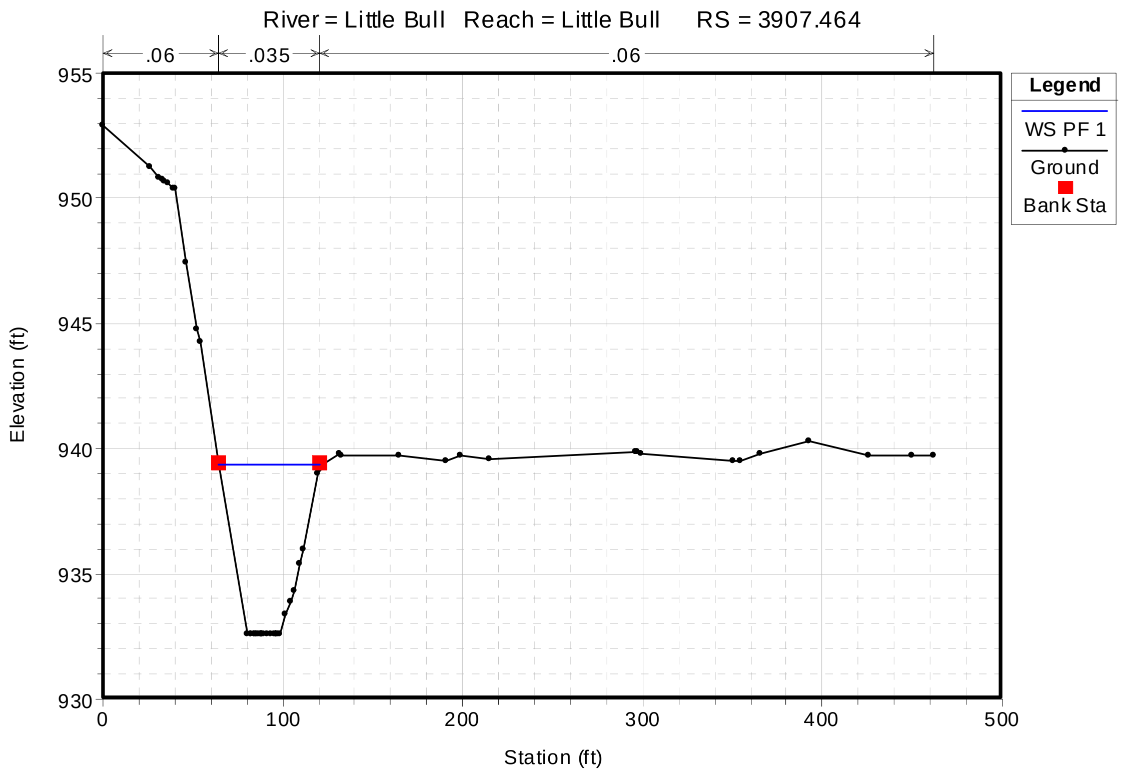
Exhibit 7: Aerial Photograph, Contours, and Cross-section Locations for Little Bull Creek.

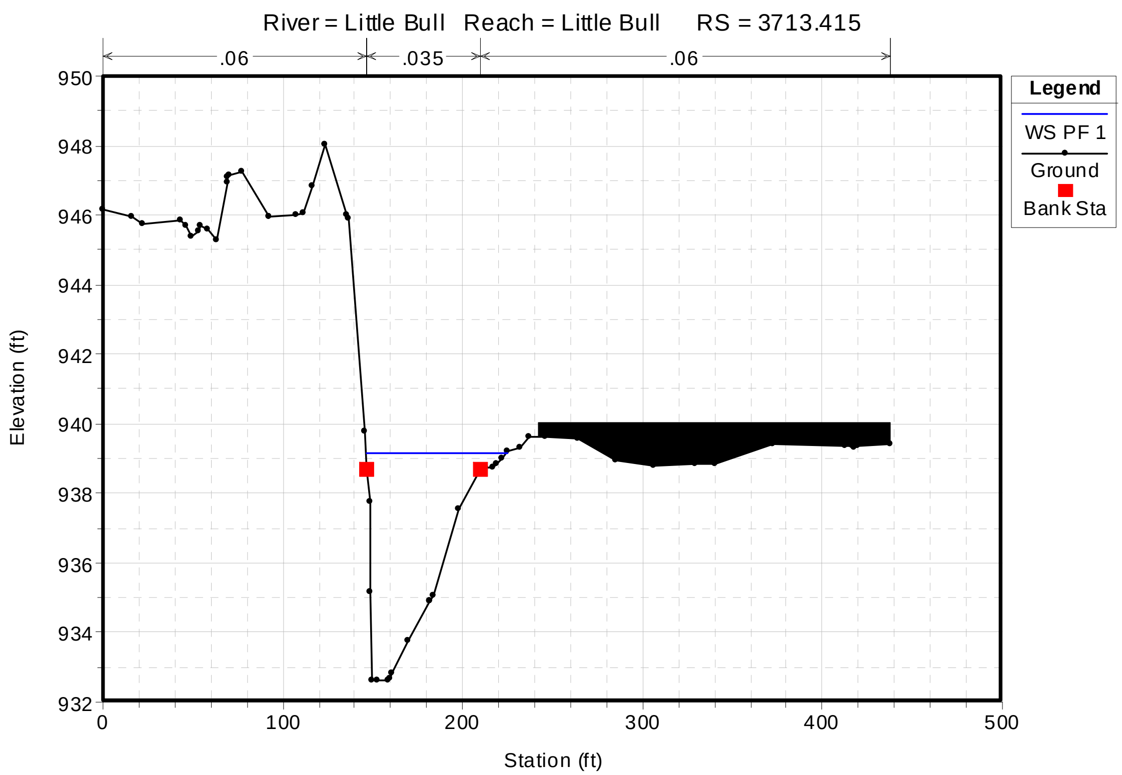

River = Little Bull Reach = Little Bull RS = 5262.479
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
948
946
944
942
940
938
936
934
932
0
50
100
150
200
250
Station (ft)

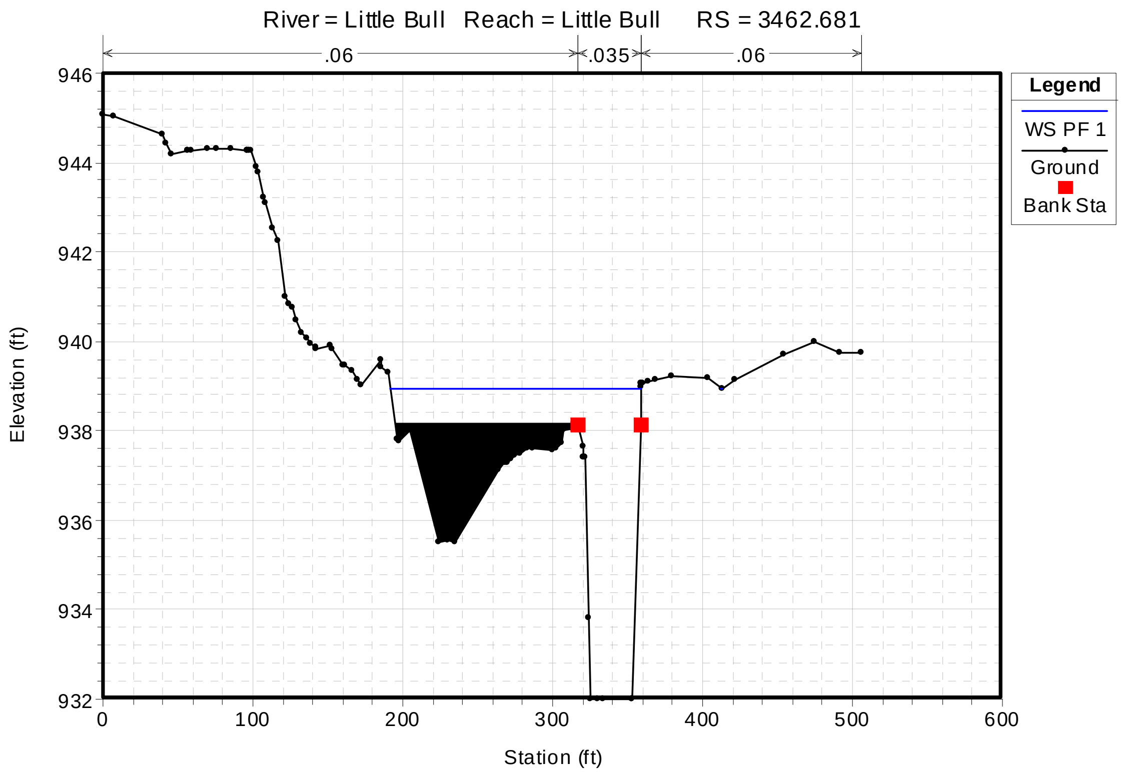

River = Little Bull Reach = Little Bull RS = 4944.967
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
950
948
946
944
942
940
938
936
934
932
0
50
100
150
200
250
300
Station (ft)

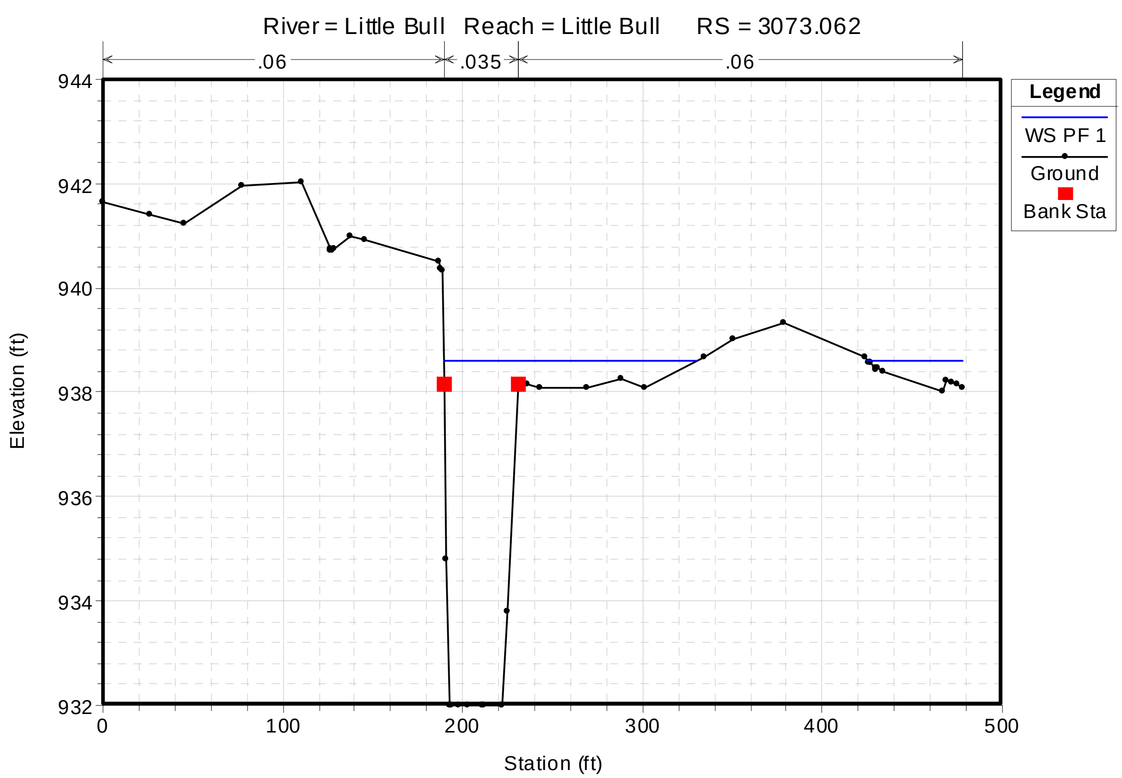

River = Little Bull Reach = Little Bull RS = 4731.325
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
950
948
946
944
942
940
938
936
934
932
0
50
100
150
200
250
300
350
Station (ft)


River = Little Bull Reach = Little Bull RS = 4402.483
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
948
946
944
942
940
938
936
934
932
0
100
200
300
400
500
Station (ft)


River = Little Bull Reach = Little Bull RS = 3907.464
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
955
950
945
940
935
930
0
100
200
300
400
500


River = Little Bull Reach = Little Bull RS = 3713.415
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
950
948
946
944
942
940
938
936
934
932
0
100
200
300
400
500


River = Little Bull Reach = Little Bull RS = 3462.681
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
946
944
942
940
938
936
934
932
0
100
200
300
400
500
600


River = Little Bull Reach = Little Bull RS = 3073.062
.06
.035
.06
Legend
WS PF 1
Ground
Bank Sta
Elevation (ft)
Station (ft)
944
942
940
938
936
934
932
0
100
200
300
400
500

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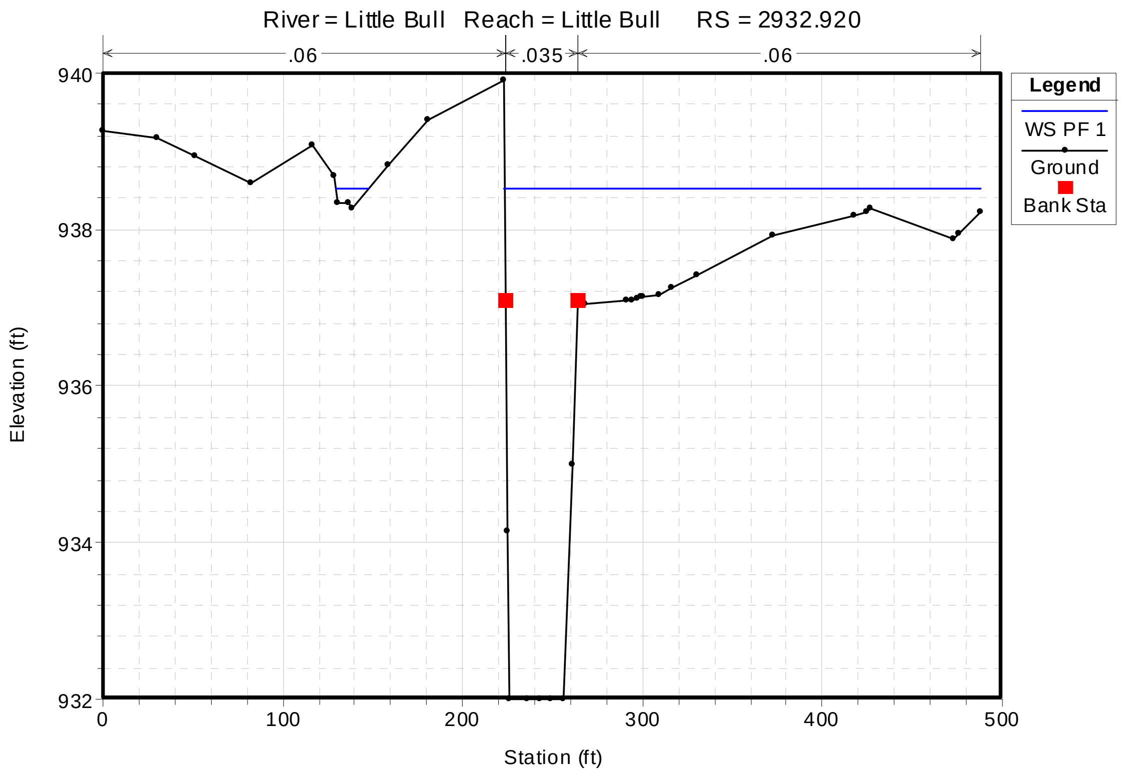

Lower Bain Creek

Exhibit 8: Aerial Photograph, Contours, and Cross-section Locations for Lower Bain Creek.

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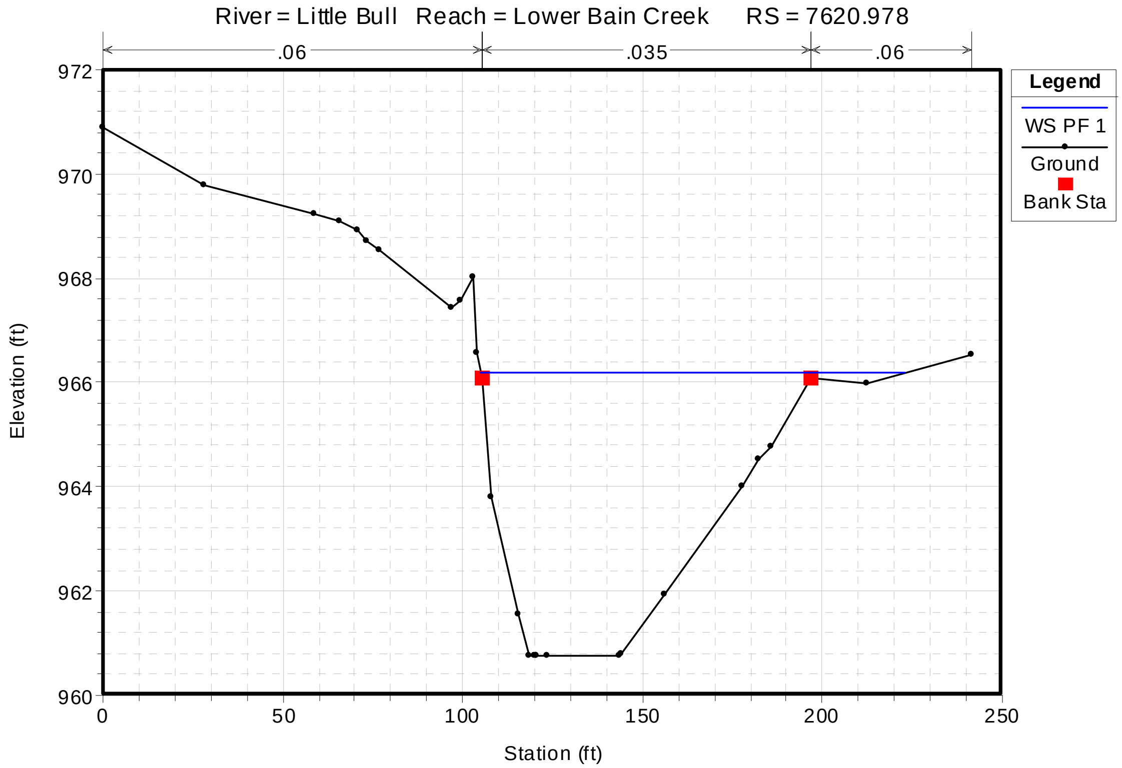

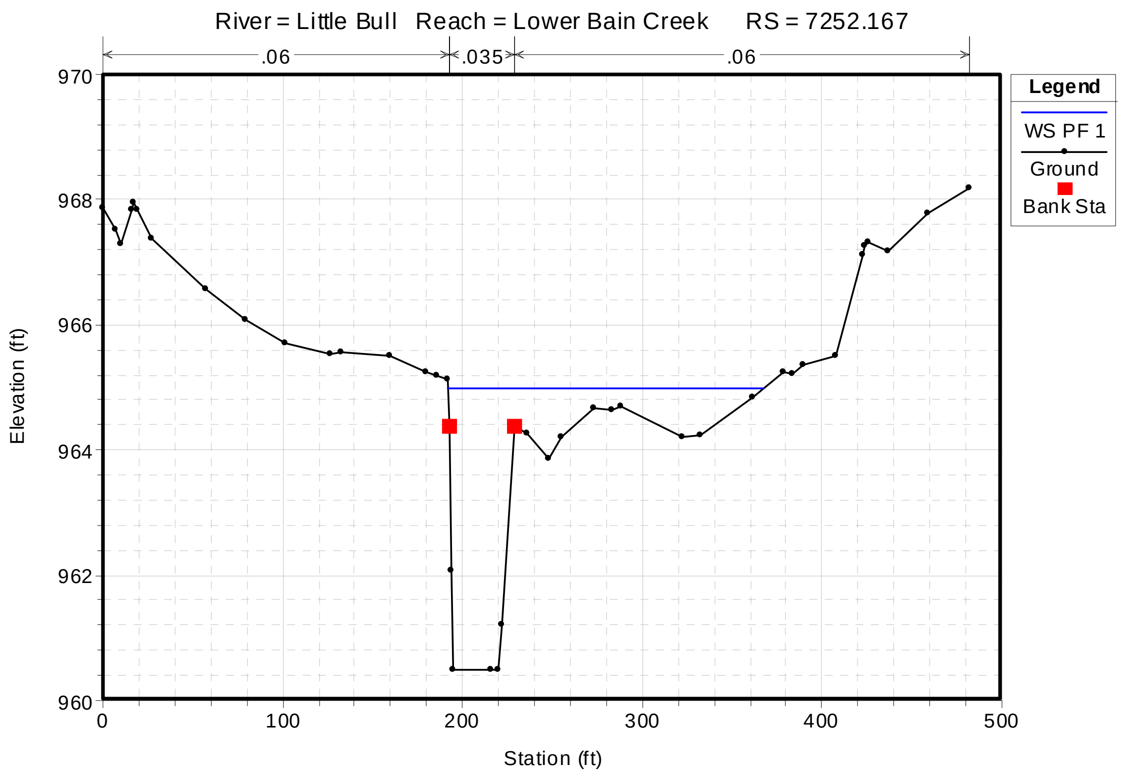

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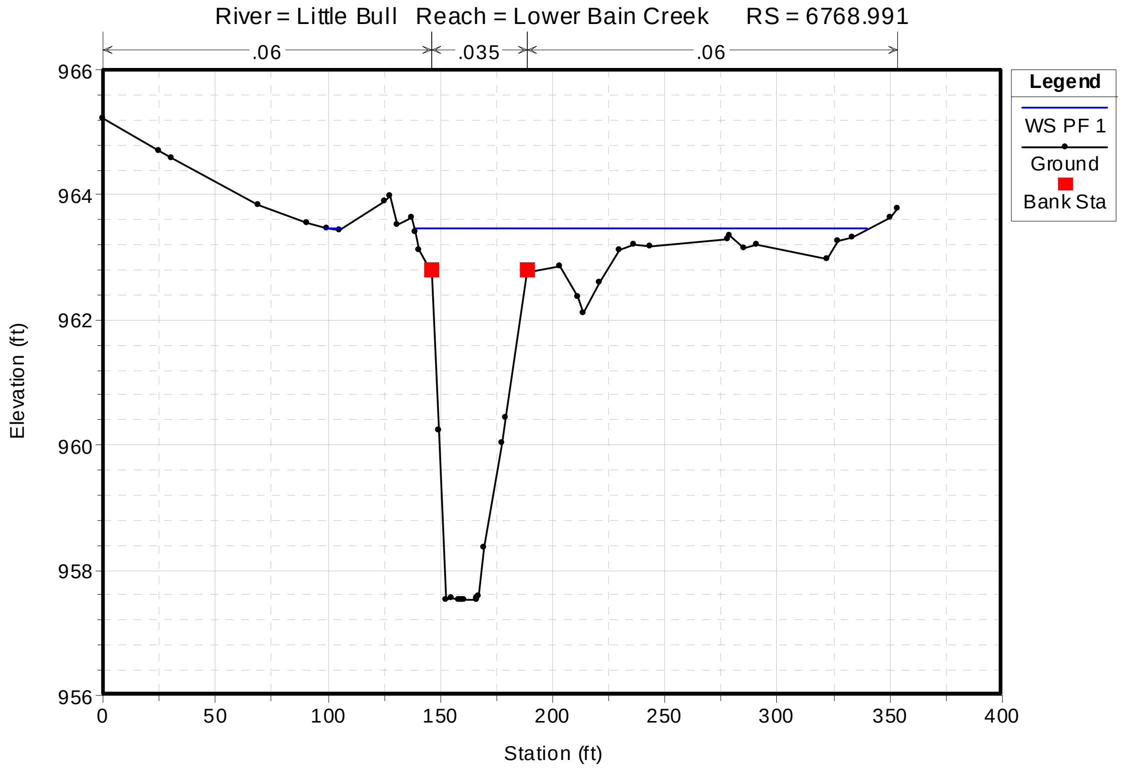

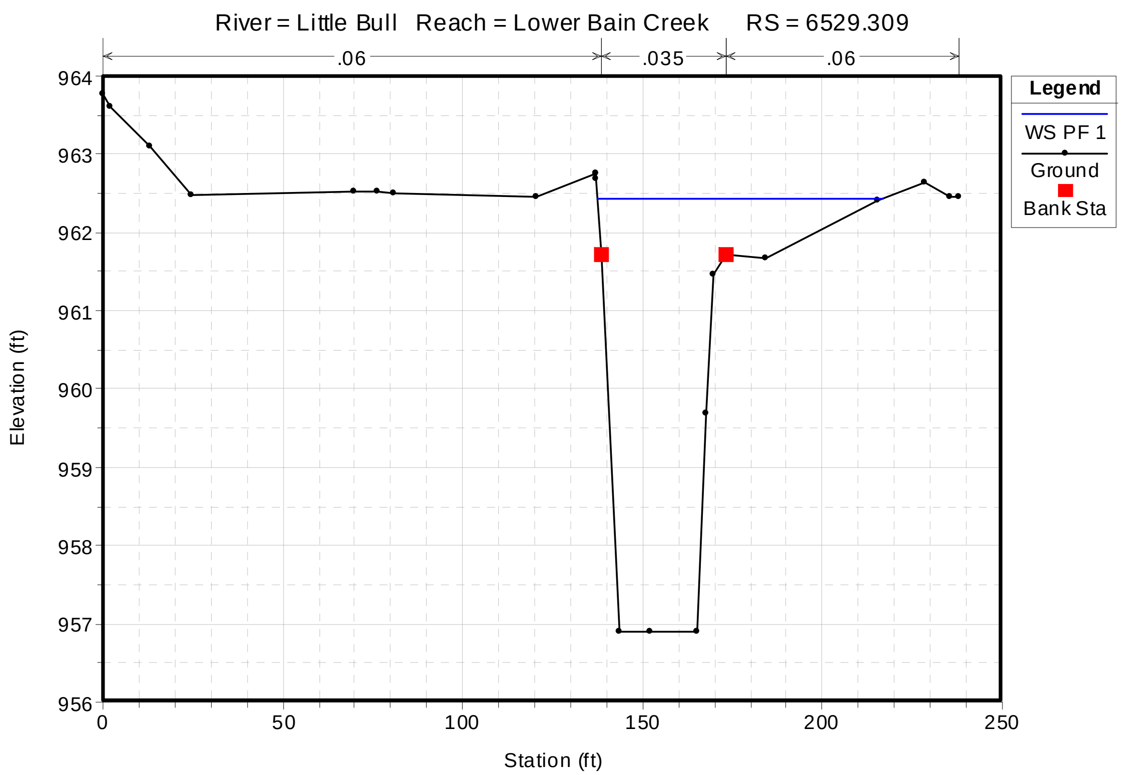

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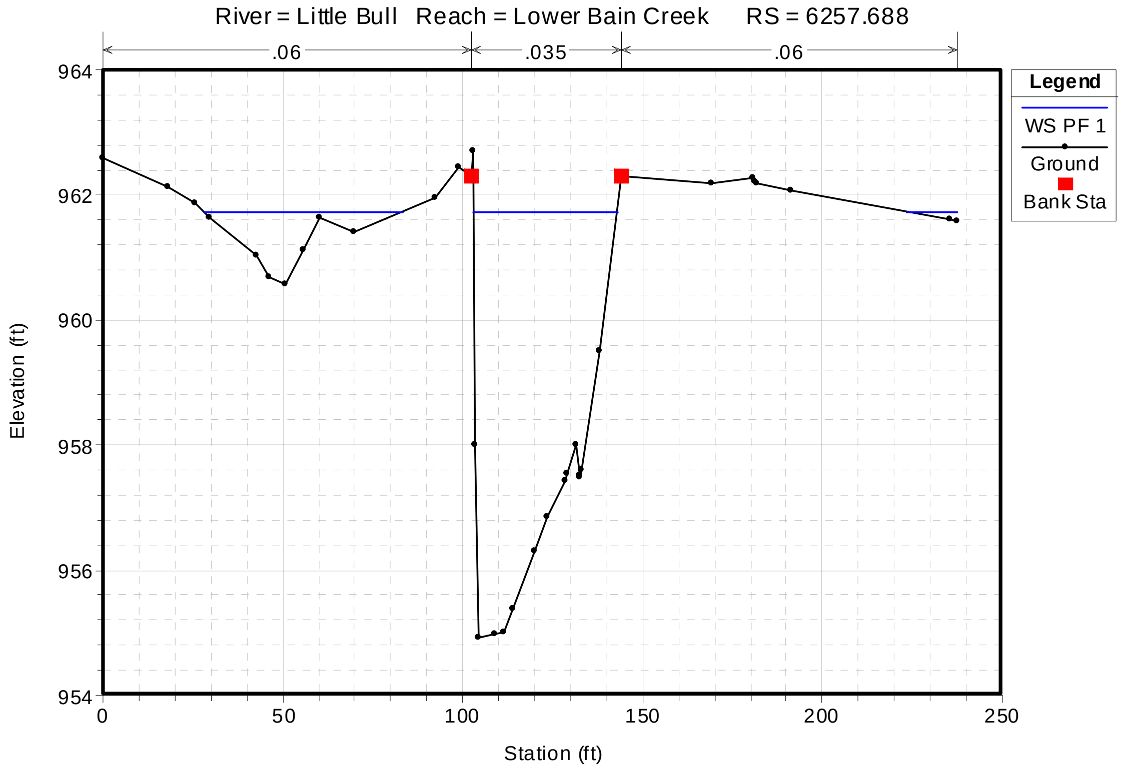

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Appendix II – HEC-RAS Output Tables

HEC-RAS V.3.1.1 Output Table

Reach	River Sta	Bankfull Discharge (cfs)	Minimum Channel Elevation (ft)	Water Surface Elevation (ft)	Velocity Channel (ft/s)	Flow Area (sq ft)	Top Width (ft)	Maximum Channel Depth (ft)
Spring Creek	4879.852	575	930.33	935.81	4.24	135.54	29.49	5.48
Spring Creek	4304.129	575	928.56	934.45	3.5	164.42	37.63	5.89
Spring Creek	4158.111	575	928.56	934.3	3.43	167.96	34.77	5.74
Spring Creek	3966.921	575	928.62	934.11	3.47	166.95	44.63	5.49
Spring Creek	3643.555	575	927.61	933.73	3.64	157.89	36.34	6.12
Spring Creek	3441.749	575	927.61	933.26	4.85	128.04	38	5.65
Upper Bain Creek	30657.9	45	1047.38	1049.34	2.95	15.24	15.53	1.96
Upper Bain Creek	30383.77	45	1045.96	1048.3	2.65	19.37	32.7	2.34
Upper Bain Creek	30031.25	45	1044.15	1046.13	4.6	9.77	9.69	1.98
Upper Bain Creek	29763.98	45	1042.24	1044.7	2.63	17.1	15.23	2.46
Upper Bain Creek	29388.64	45	1041.11	1043.38	3.18	19.15	26.47	2.27
LBNC1	1849.463	310	964.26	968.16	3.2	96.96	34.47	3.9
LBNC1	1721.262	310	964.26	967.6	5.06	61.49	25.19	3.34
LBNC1	1191.644	310	962.4	965.97	5.51	56.3	20.66	3.57
LBNC1	1057.883	310	962.16	964.68	6.87	45.15	22.37	2.52
LBNC1	701.327	310	959.75	962.68	5.91	55.06	27.26	2.93
LBNC3	4820.411	310	1009.84	1014.37	2.78	111.52	50.29	4.53
LBNC3	4253.72	310	1008.04	1013.14	5.14	60.41	31.79	5.1
LBNC3	4152.549	310	1007.55	1012.29	6.4	50.37	35.49	4.73
LBNC3	4007.02	310	1007.09	1011.81	4.24	73.62	60.81	4.72
LBNC3	3687.201	310	1005.52	1010.47	5.47	79.66	49.52	4.95
LBb	854.776	570	1000.84	1008.68	8.01	72.36	32.47	7.84
LBb	498.883	570	1000.25	1006.49	7.86	72.49	23.49	6.24
LBb	330.268	570	1000.28	1006.13	4.7	123.75	57.82	5.85
LBb	204.42	570	1000.29	1005.69	4.91	116.79	56.88	5.4
LBa	2536.393	360	951.91	955.38	5.15	72.6	33.72	3.47
LBa	2168.776	360	951.14	954.44	3.57	100.9	40.92	3.3
LBa	1798.429	360	950.33	953.77	3.37	108.64	41.77	3.44
LBa	1478.166	360	949.77	953.33	3.11	115.93	37.07	3.56
LBa	1292.982	360	949.68	952.93	3.89	96.3	52.47	3.25
LBa	1123.037	360	949.68	951.43	7.4	48.67	28.98	1.75
Little Bull	5262.479	890	933.93	940.88	4.86	187.13	47.52	6.95
Little Bull	4944.967	890	933.41	940.9	2.16	412.88	70.22	7.49
Little Bull	4731.325	890	933.41	940.56	4.25	209.59	42.91	7.15
Little Bull	4402.483	890	933.41	939.88	5.03	176.8	36.83	6.47
Little Bull	3907.464	890	932.62	939.39	3.43	259.16	55.91	6.77
Little Bull	3713.415	890	932.62	939.17	3.54	256.15	78.79	6.55
Little Bull	3462.681	890	932.01	938.94	3.52	333.59	167.59	6.93
Little Bull	3073.062	890	932.01	938.59	3.71	292.19	193.18	6.58
Little Bull	2932.92	890	932.01	938.52	3.33	418.06	282.82	6.51
Lower Bain Creek	7620.978	1030	960.76	966.18	3.09	336.03	117.75	5.42
Lower Bain Creek	7252.167	1030	960.49	964.98	6.68	217.5	175.29	4.49
Lower Bain Creek	6768.991	1030	957.53	963.45	5.52	241.75	208.4	5.92
Lower Bain Creek	6529.309	1030	956.9	962.44	6.61	173.63	79.54	5.54
Lower Bain Creek	6257.688	1030	954.91	961.73	5.46	209.91	109.38	6.82
Lower Bain Creek	5909.153	1030	954.51	960.45	6.54	157.46	32.96	5.94