Title
Post-Project Performance Assessment of a Multi-Phase Urban Stream Restoration Project on Lower Codornices Creek

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Abstract

In Fall 2010, a partnership between the University of California-Berkeley and the cities of Albany and Berkeley completed the third of four restoration phases planned for a 0.6-mile stretch of Codornices Creek in Alameda County, California, between the San Pablo Avenue and UPRR crossings. Originally initiated in the mid-1990s to improve a straightened and channelized ditch, the project objectives were to convey the 100-year flood, improve user access to the creek, and establish an ecologically valuable riparian corridor dominated by native species (reducing invasive non-natives). We assessed the performance of the third phase of the project during a high flow of 136 cfs on October 5, 2011. We obtained relevant data and information from project designers, and on October 22, 2011, while evidence of the high flow was still fresh, we conducted a detailed topographic survey of the channel, surveyed high water marks, documented conditions with photographs, and mapped site conditions. In addition, we surveyed cross sections and high water marks in the downstream reaches (Phases 1 and 2 of the overall restoration project). High water marks show floodplain inundation was inconsistent throughout the three reaches, with the October 5 storm flow largely staying within the constructed banks in Phase 3, and overbank flow occurring in Phases 1 and 2. Our longitudinal profile shows Phase 3 incised up to 2 ft below the design grade in the upstream portions of the reach, and aggraded up to 2 ft at the downstream end. Survey results also confirm that additional vertical channel adjustment occurred during the October 5 flow. This, along with the presence of an active headcut, suggests that the channel is still in the process of finding geomorphic equilibrium. Cross-section monitoring in Phase 3 should proceed into the future to determine whether channel adjustments continue, and as a basis to assess whether more complexity should be introduced to promote aggradation, channel complexity, floodplain inundation, and more ecologically valuable habitat.

Introduction

The Codornices Creek Master Plan (Master Plan) prepared by Restoration Design Group (RDG) is a strategic agenda for a series of restoration projects along lower Codornices Creek in Alameda County, California. First initiated in the mid-1990s by the University of California at Berkeley, the City of Albany, and the City of Berkeley, these stakeholders implemented the project in conjunction with the adjacent University Village development. Introduced to improve a straightened and channelized ditch, the project objectives were to convey the 100-year flood, improve user access to the creek, and establish an ecologically valuable riparian corridor dominated by native species (reducing invasive non-natives) (UCC, 2005). The restoration project has been a subject of strong, long-term community interest, with significant financial investment and citizen involvement (Fullmer, 2008).

Codornices Creek originates in the hills of Berkeley, California, and flows west for 2.9 miles through a series of open channels and culverts, before emptying into the San Francisco Bay (Figure 1). Elevations of the basin range from sea level at the outlet near the Golden Gate Fields race track, to approximately 1,340 ft at the summit of Grizzly Peak. The watershed drains approximately 1.1 square miles of primarily urbanized portions of the cities of Berkeley and Albany. Downstream of Monterey Avenue, the creek serves as the border between Berkeley to the south and Albany to the north. Although the watershed is nearly 85% developed (Kier, 2004), the Codornices Creek channel is the only creek in the city of Berkeley that is predominantly an open earthen channel (Kent, 1993). This, along with the fact that the creek sustains a small population of steelhead *(Onchorynchus mykiss)*, makes it a high-value restoration target (UCC, 2005).

Problem Statement and Research Questions

This report evaluates the short-term hydraulic and geomorphic performance of Phase 3 of Codornices Creek restoration projects, and provides comparison to the performance of Phases 1 and 2. We decided to focus our efforts on this reach because of its recent construction, availability of design drawings, and our ability to isolate effects of a high flow of 136 cfs that occurred on October 5, 2011.

Our primary research questions are:

1. *Has the channel morphology of the reach restored in Phase 3 deviated from its original design?*
2. *Did it change significantly with the recent discharge event of October 5?*
3. *Is the channel morphology adjusting or in equilibrium?*
4. *How do inundation patterns in Phase 3 compare to those in Phases 1 and 2?*
5. *What are recommendations for the future monitoring and maintenance of the restored reach?*

Conducting such an assessment at this point is important, as further restoration on Codornices Creek is planned for a fourth phase, stretching from 8th St to San Pablo Avenue. Assessments from this report can be used to inform future restoration efforts, as well as to guide maintenance in the existing reaches.

Restoration Background

The Master Plan includes four restoration phases, spanning from the Union Pacific Railroad (UPRR) crossing at the downstream end to the San Pablo Ave crossing 0.6 miles upstream (Figure 2). Phases 1 and 2 were constructed in the summers of 2004 and 2006, respectively, while Phase 3, the focus of this study, was completed in the fall of 2010. Work on Phase 4 has yet to begin.

The design of Phase 1, which runs 989 ft with an average gradient of 0.4% from the UPRR crossing upstream to the 5th St. pedestrian bridge, included setting back fences to adjacent soccer fields, regrading the floodplain, constructing a highly sinuous meander pattern (sinuosity = 1.64) (Table 1), and installing willow *(Salix* sp.) plantings along the creek banks. By setting back nearby fencing, the meander belt width in this reach was increased by approximately 50% percent (RDG 2011, pers. comm., 14 Nov).

Table 1. Channel length, slope, and sinuosity, by phase.

Phase	Channel Length (ft)	Sinuosity	Slope (%)
1	989	1.64	0.4%
2	332	1.07	0.6%
3	643	1.13	1.2%

Phase 2 runs 332 ft with an average gradient of 0.6% from the 5th St pedestrian bridge to the 6th St crossing. This reach is significantly more confined by housing, commercial buildings, stormwater infrastructure, and a pedestrian path. Here, a less sinuous channel (s = 1.07) was constructed, with willows and alders planted along the entirety of the banks.

Phase 3 is characterized by a distinctly different design approach than Phases 1 and 2. Restoration planners expanded the riparian corridor and flood-prone area by relocating or removing buildings and infrastructure, creating a sinuous channel pattern (s = 1.13) with willows and rock slope protection on the outside of meander bends. This reach, characterized by a significantly higher slope (1.2%), required a series of boulder-weir grade control structures to reduce the channel gradient from the 8th St culvert (Figure 3). The design also required riprap along the outside of meander bends to protect adjacent property. The reach was planted with a more diverse mix of vegetation, including ash, toyon, coffee berry, rose, and a native seed mix to the planting palette. This new approach, in terms of the planting palette, is largely a response to community disapproval of the dense willow and alder thicket that has formed along the downstream reaches (RDG 2011, pers. comm., 14 Nov).

Research Methods

Existing Data Analysis

We gathered existing construction plans, design memos, photographs, and monitoring data from RDG and FarWest Restoration Engineering (FRE) to determine the baseline conditions against which to compare our data. This included longitudinal profile and cross-section data completed by RDG on September 14, 2011, prior to the October 5 flow, and a longitudinal profile of Phases 1 and 2 completed by FRE in 2010. We also conducted interviews, both in-person and via email, with RDG designers and Susan Schwartz of Friends of Five Creeks. From our interview with RDG we gathered data on the overall project's design process, timeline, and the social and environmental factors that influenced the latest phase's design.

Hydrology

We obtained precipitation, stream stage and discharge calculations at 15-minute intervals from the Balance Hydrologics rainfall and stream gages, located on Codornices Creek approximately 2,000 feet upstream of the Phase 3 project site (Figure 1). Stream gage data dating back to October 1, 2009 were provided by Balance Hydrologics. To better understand the relative magnitude of the October 5 flow, we investigated flood frequency data through multiple means. The gage data, which dates back to 2005, is an insufficient period of record for calculating flood frequency statistics. As an alternative, we reviewed a hydrology study completed for the project area during the planning of University Village (PWA, 1997). We also calculated flood frequency using the USGS StreamStats web application, which uses a combination of regional regression equations and a Geographical Information System (GIS) to output estimated 2, 5, 10, 25, 50, and 100 year discharges at the gage location. Additionally, we surveyed high water marks from the October 5 peak stage in Phases 1, 2, and 3 using a Real Time Kinematic Geographical Positioning System (RTK GPS).

Reconnaissance-Level Assessment

We initiated our field research with the LA 227 class field trip on October 8th, followed by a reconnaissance-level site visit on October 22nd to determine the data required to answer our research questions. During this site visit, we flagged high water marks (HWM) from the October 5th event for future surveying. We created a reach scale site conditions map of Reach 3 (Figure 4) to demonstrate geomorphic features, areas of instability, design elements such as grade control and bank protection, and non-native vegetation locations. We also completed photo-documentation of points of interest.

Topographic Survey

We collected topographic data in Phase 3 utilizing a RTK GPS survey of the longitudinal profile and six cross-sections (Figure 5a). Four of these cross sections (3A, 3C, 3D, and 3F) were also completed by our research team in conjunction with the LA 227 class field trip to the site on October 8th. We established rebar monuments at the cross-section endpoints during the October 8th field trip, capping each with plastic survey markers. On October 29th, our second and final day of field work, we resurveyed the cross-sections using an auto-level, rod, and tape, in order to compare the results to the RTK GPS results. We surveyed six additional cross sections on October 29th in Phases 1 and 2 using an auto-level, rod and tape (Figure 5b). We were unable to locate all the monuments associated with the Phase 1 and 2 Monitoring Report (FRE, 2010), so we estimated the locations based on the figures from the report. Upon receiving locations of two Phase 3 cross-sections surveyed by RDG on September 14, 2011, we returned to the site on November 19th to resurvey these locations (XS 3B, 3E). It should be noted that additional flows (all less than 136 cfs) occurred between the October 5th discharge and this survey date. Therefore, these two cross-sections do not isolate effects of the October 5th discharge, but are the only reference cross-sections we were able to reoccupy.

We tied all elevations into the North American Vertical Datum of 1988 using benchmarks located on the walking path near 6th and 8th streets (Figure 5a). Cross section plots for all three phases are presented in Appendix A.

Results

Hydrology

Gage data show a peak discharge of 136 cfs on October 5, 2011 (Figure 6), in response to a 1.78 inch 24-hour rainfall total. The hydrograph shows a pre-storm baseflow of 0.7 cfs which peaked at 136 cfs then receded to 1.7 cfs, all within 8 hours. The flashiness exhibited here is typical of urbanized watersheds (Seaburn, 1969), and can likely be attributed to the long narrow shape, high gradient (15.8% mean basin slope), and high impervious surface cover (ISC) (28%) of the basin (NLCD 2001). Based on this ISC, the peak discharge is likely elevated between two and three-fold of what would occur in an unaltered watershed (Arnold & Gibbons 1996).

Results of the 1997 PWA and StreamStats flood frequency analyses are presented in Table 2. The differences are drastic, with the PWA calculations showing a 2-year flow discharge five-fold larger than the StreamStats analysis. When plotted against a regression of these points, the October 5, 2011 peak flow of 136 cfs is less than a 1-year flow according the PWA calculations and approximately a 3-year event according to the StreamStats calculations (Figure 7).

Table 2. Flood frequency analysis results from the USGS StreamStats web application (2011).

Recurrence Interval (years)	StreamStats Discharge (cfs)	PWA (1997) Discharge (cfs)
2	77.4	393
5	171	592
10	248	692
25	353	790
50	438	888
100	530	1085

Gage data from the previous two water years (2010, 2011) demonstrate that the 136 cfs flow was exceeded multiple times both years, including at least 6 distinct events since Phase 3 construction was completed in the summer of 2010 (Figure 8). Therefore the StreamStats calculation is likely a significant underestimation of the recurrence intervals of the flows specified. Although difficult to conclude without a longer period of record, the 1997 PWA calculations appear to be a more realistic, if not conservative, estimate of flood frequency in the existing watershed condition. The annual peak flows of the previous two water years were 373 cfs on January 20, 2010, and 352 cfs on March 24, 2011.

Reconnaissance-Level Assessment

We observed high water marks from the October 5 flow, which included debris deposits and scour lines, at or near the top of bank throughout the majority of Phase 3. Overbank flow did occur in the downstream portion of the reach, near RS 16+00 and downstream to the 6th St culvert at RS 14+00, where flow high water marks were noted on the floodplain along the toe of the side slope. In Phases 1 and 2, overbank flow was widespread, with evidence of flow inundating the soccer fields to the north near RS 7+00. Figure 9 shows the approximate flooding extents, created using high water mark elevations surface topography.

A visual assessment of Phase 3 suggests the channel has incised in the upper segment (RS 17+00 to 19+95), as evidenced by the exposed clay hardpan composing the channel bed and lack of mobile bed substrate (Figure 10). These areas are mapped in Figure 4. Other evidence is the exposed undersides of riprap along outer meander bends (Figure 11) and an active headcut at RS 17+25 (Figure 12). Evidence of minor lateral erosion is evident along the outer edges of meander bends, primarily at the upstream and downstream ends of riprap. It is also apparent that a plug of coarse sediment has accumulated at the 6th St culvert at the downstream end of Phase 3 (Figure 13). The non-native invasive emergent vegetation species watercress (*Nusturtium aquaticum*) along with sedge species has established a dense mat over the deposited sediment. The pioneer species watercress is prevalent throughout the reach, forming dense mats over fine sediment deposits and point bars (Figure 4).

Despite being highly sinuous, the channel lacks in-stream complexity features, such as large woody debris, that are capable of trapping sediment, creating scour pools, and providing habitat (Gurnell et al, 2002). The lone wood structure, a rootwad embedded in the left bank at RS 16+40, has induced a scour pool and provides some habitat (Figure 14). As described above, the majority of the channel is composed of clay-hardpan, which provides little habitat for macroinvertebrates or salmonid spawning.

Topographic Survey

The Phase 3 longitudinal profile and high water marks surveyed subsequent to the October 5 storm are plotted against the September 2011 RDG longitudinal profile, as-built profile, and RDG top of bank in Figure 15. This comparison shows up to 2 ft of aggradation near the 6th St culvert (RS 14+90) since construction, and up to 1 ft due to the October 5th storm. Upstream of RS 15+90 the thalweg profile shows incision from the design profile, with a maximum amount of 2 ft of incision since construction. The scour pool caused by the rootwad is evident at station 17+09, as well as the headcut at RS 17+40. Incision was most severe from the grade control structure at RS 18+30 to the grade control structure at RS 19+90. Comparison of cross-sections 3B and 3E with the September 14th, 2011 RDG cross-sections shows approximately 6 inches of incision at 3B and minimal change at 3E (Figure 16). There was no evidence of significant lateral change.

Comparison of the top of low bank profile surveyed to water surface elevation calculated from our high water marks confirms that the October 5 storm event caused widespread inundation in Phases 1 and 2. In Phase 1, the high water marks extend to the soccer fields to the north of low flow channel. In Phase 2, the high water marks extend to the toe of the adjacent footpath. In contrast, flows did not escape channel banks for the majority of Phase 3, save for in the lower portion of the reach (Figure 9).

Discussion

Although we were unable to obtain the design bankfull discharge, it is apparent that the existing channel banks overtop at recurrence interval greater than 1-2 years, a discharge often used as a benchmark for stream restoration projects (Dunne & Leopold 1978). At a flow that was exceeded six times in the 2011 water year, the project was at or above bankfull stage in Phase 3, including locations where the channel experienced significant incision. Additionally, overbank flow was widespread in Phases 1 and 2. It has been documented that, unlike rural streams, discharges identified as bankfull, effective, channel forming, and 1.5-year discharges often diverge greatly (Moyle et al., 2007). In this case, the two main factors in shaping channel geometry, bankfull discharge and sediment supply (Dunne & Leopold 1978), are significantly altered from their natural state. This, along with the disparity in flood frequency analysis results, reinforces the need for detailed hydrological, hydraulic and sediment studies for stream projects in urbanized watersheds. The severe underestimate of flood frequency by the StreamStats application is a significant finding. Although the application integrates factors of urbanization, such as impervious surfaces, into its calculation of recurrence intervals, it is far from being a reliable design tool.

Incision in Phase 3 is likely a response to translation of lateral hydraulic energy to vertical hydraulic energy, as is typical in many urban streams (Booth, 1990). Although the channel corridor was expanded, adjacent land uses still required a confined corridor and armoring of the outside of meander bends. The reach has a high gradient, which increases energy and shear stress. With the channel unable expand laterally, it responded in turn by exerting hydraulic forces vertically. Active incision is evident at the 6-inch headcut at RS 17+40. The headcut is likely to migrate upstream to the next grade control structure at RS 18+25. Upstream of the RS 18+25 grade control structure, the gradient has nearly flattened and is unlikely to incise more, unless upstream grade control structures fail.

Aggradation at the 6th St culvert is likely due to a backwater effect created at high flows by the undersized 6th St culvert. This causes the velocity of turbid water to slow and the suspended and bedload sediment to settle and accumulate. The 6th St culvert was not replaced during the restoration phase due to the complications with addressing downstream constrictions and flood risks (RDG 2011, pers. comm., 14 Nov). It is possible that the sediment deposited here is the same sediment scoured from the upstream segment of Phase 3. Regardless, the sediment scoured from the channel bed in the upper reach has not been replenished by upstream sources.

While the sediment plug at the 6th St. culvert is likely to pass through over time, the aforementioned plug of sediment is being stabilized by the dense mat of grass and watercress. The mats may be problematic as they occupy potential habitat for native species and can decrease baseflow channel capacity which could potentially accelerate incision (Tabacchi et. al, 2000). There was no watercress found in Phases 1 and 2, likely due to the lack of available light from dense willow/alder thickets. It is likely the watercress will be shaded-out if a riparian canopy is allowed to develop; however preferences for visual aesthetics and accessibility calls for maintenance of woody riparian vegetation in Phase 3.

Conclusion

Judging from our site surveys and analysis, the channel morphology of Phase 3 has deviated from its original design, with incision in the upper portion of the restored phase, and aggradation downstream at the 6th St culvert. Following the October 5 storm, channel morphology changed further, indicating that the channel has yet to reach geomorphic equilibrium. Further indication that the channel is adjusting is the active headcut. These adjustments are likely due to a combination of factors, including: adjacent land use constraints that required bank protection; a high gradient, high energy reach; a wetter than average El Niño winter that immediately followed construction; and a lack of in-stream features to trap sediment and induce scour. While some adjustment of the thalweg profile is expected, the effects of the previous winter and the October 5 storm on Phase 3 are evident.

In some locations of Phase 3, ecologically valuable substrate has been scoured from the channel bed and is not being sufficiently replaced. Little channel complexity or roughness exist to encourage deposition and creation of further channel complexity. Such incision has also resulted in less frequent inundation of the floodplain. Inundation patterns in Phase 3 differ from those in Phases 1 and 2. A moderate discharge that inundated a majority of the floodplain in Phases 1 and 2 only escaped Phase 3 banks in areas where the aforementioned culvert caused backwater build-up in lower reaches. Significant woody debris is unlikely to recruit naturally at the site due to the many road crossings and culverts upstream of the study area. Further monitoring should be completed to determine the potential need to add additional roughness to the channel to increase complexity, aggradation, and potentially more frequent floodplain inundation.

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Interviews and Meetings

Susan Schwartz phone interview. October 28, 2011.

RDG interview. November 14, 2011.

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FIGURES

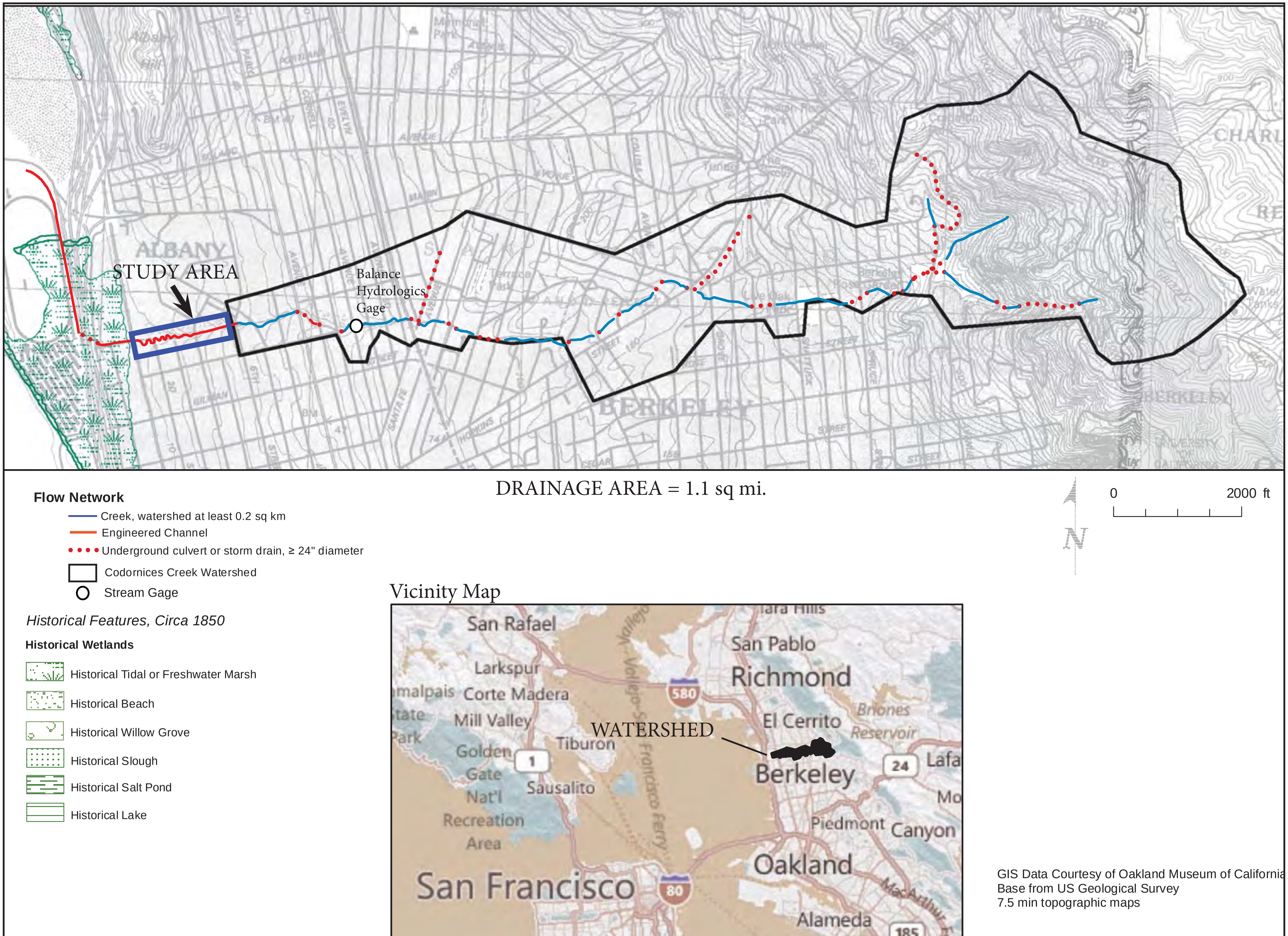

FIGURE 1. VICINITY AND WATERSHED MAP

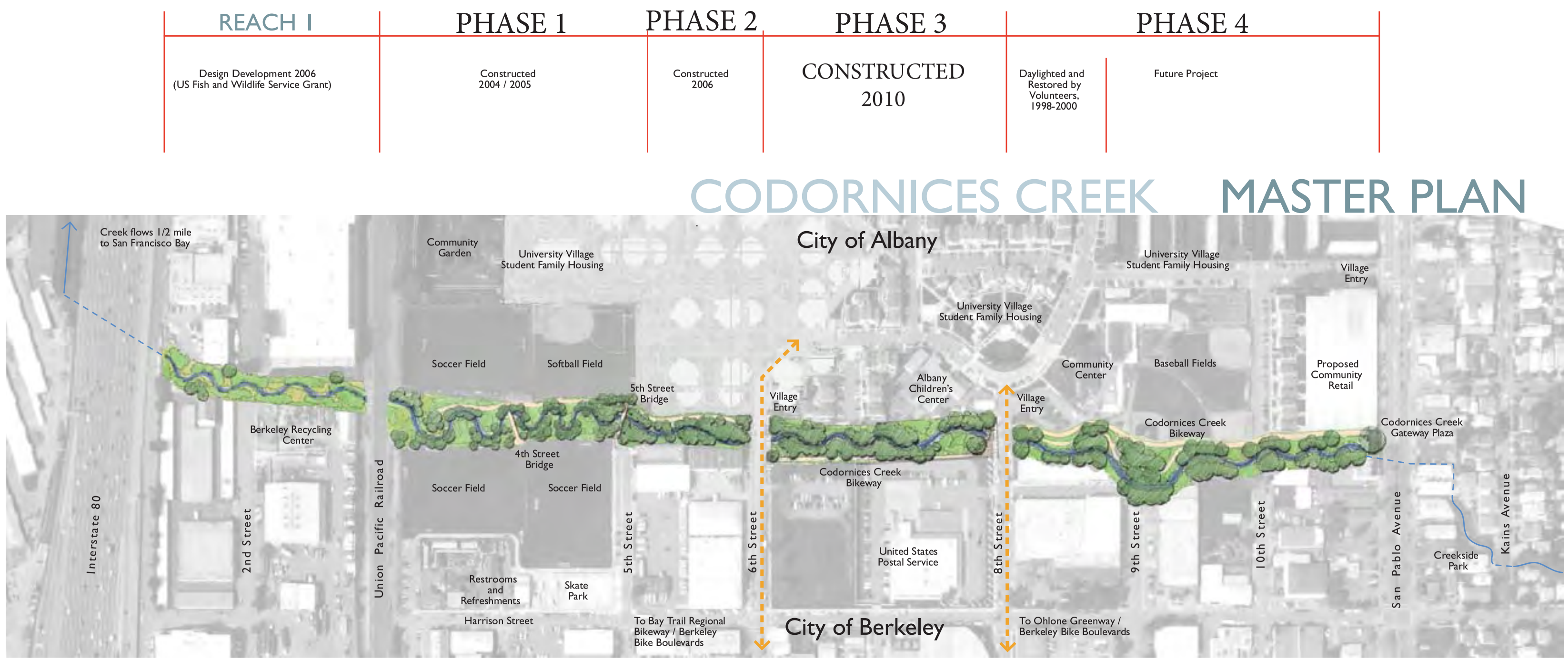

FIGURE 2. SITE AND PHASING MAP (FROM RDG)

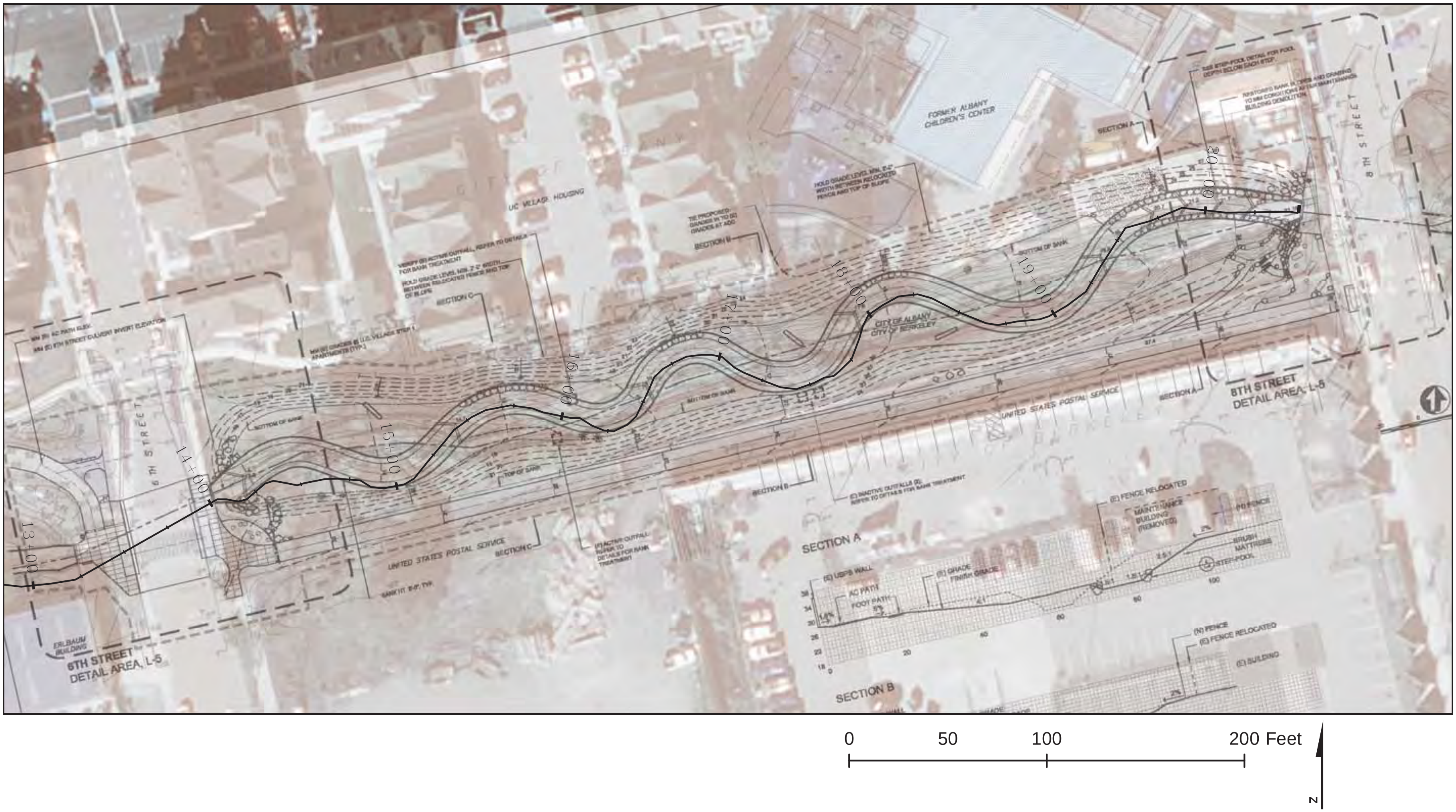

FIGURE 3. PHASE 3 CONSTRUCTION DRAWINGS OVERLAID ON PRE-PROJECT AERIAL

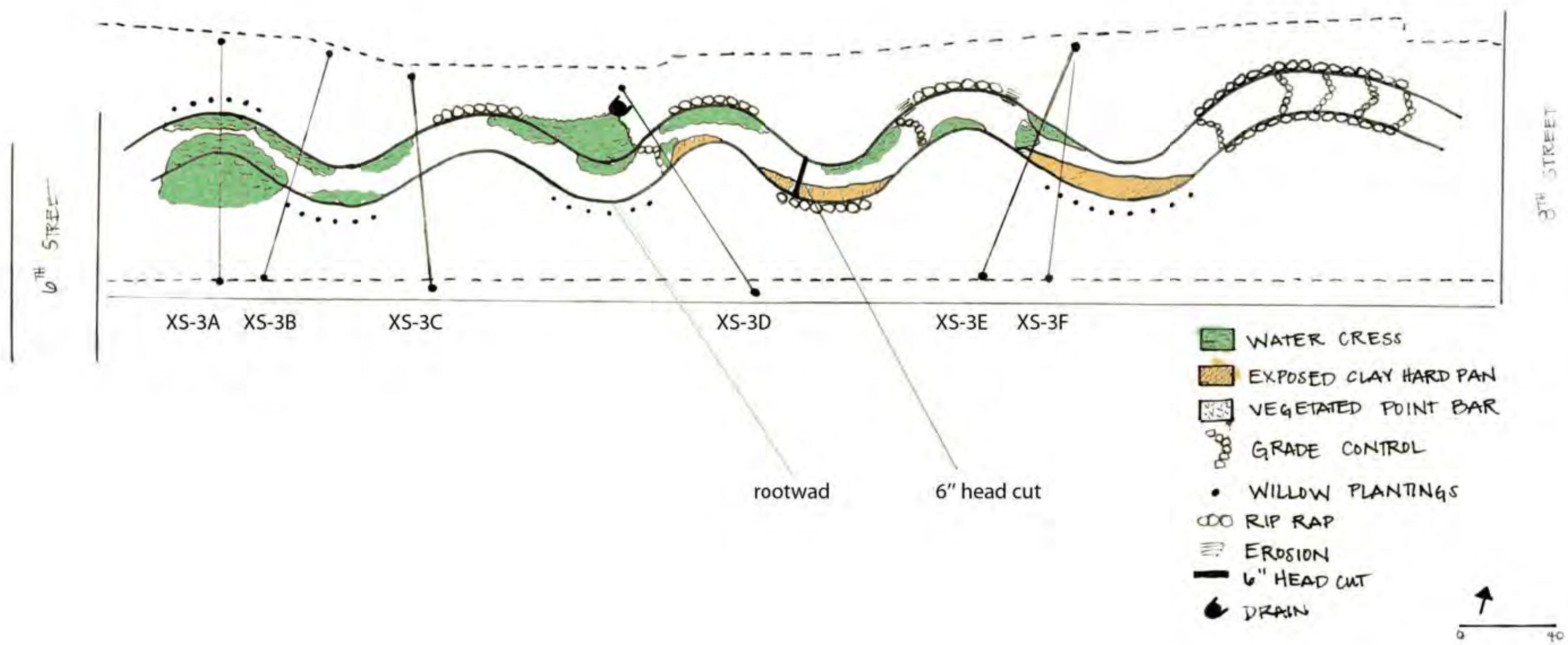

FIGURE 4. Highlighted features of phase 3

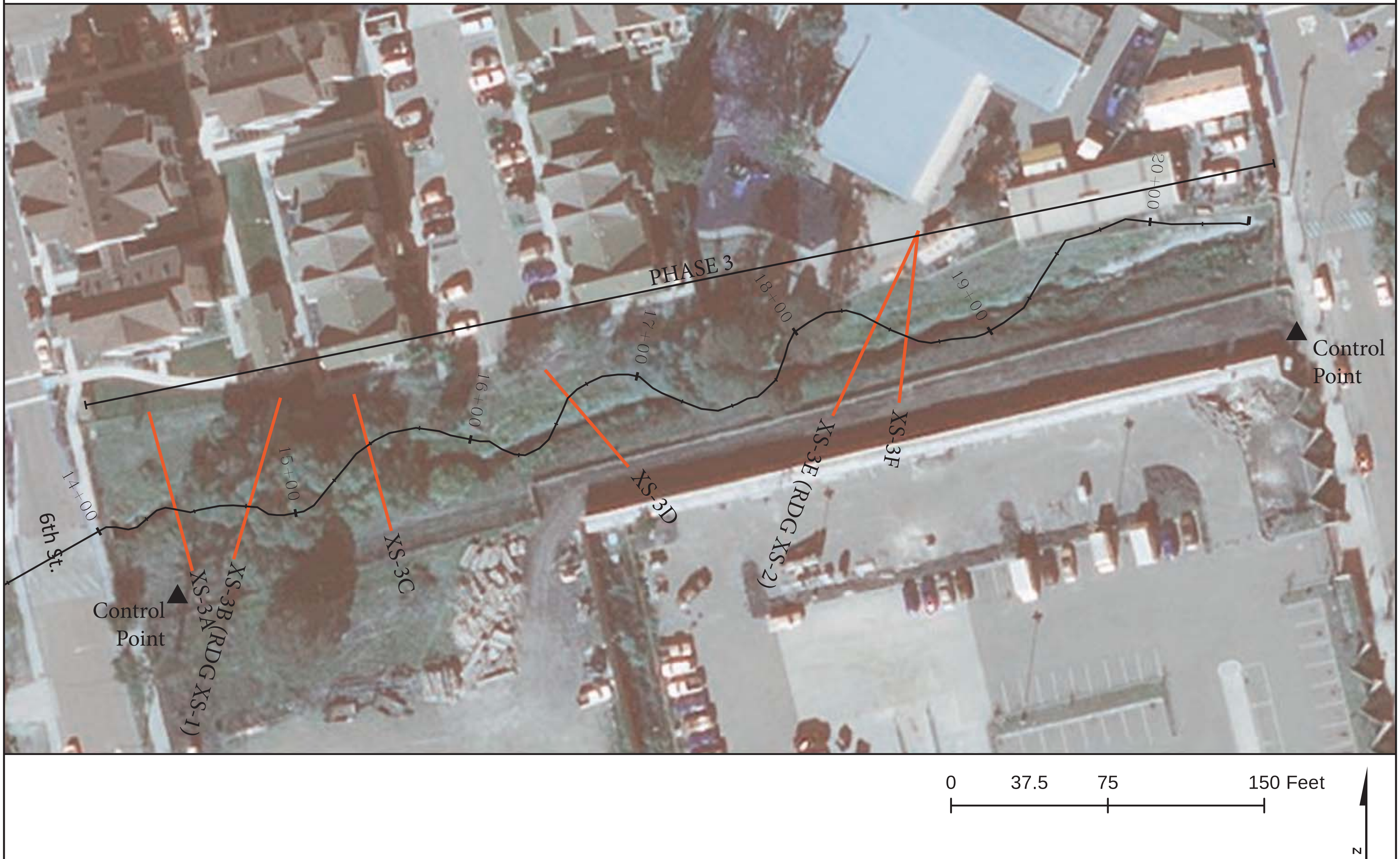

FIGURE 5a. River Stationing and Cross Section Locations (Phase 3)

FIGURE 5b. River Stationing and Cross Section Locations (Phases 1+2)

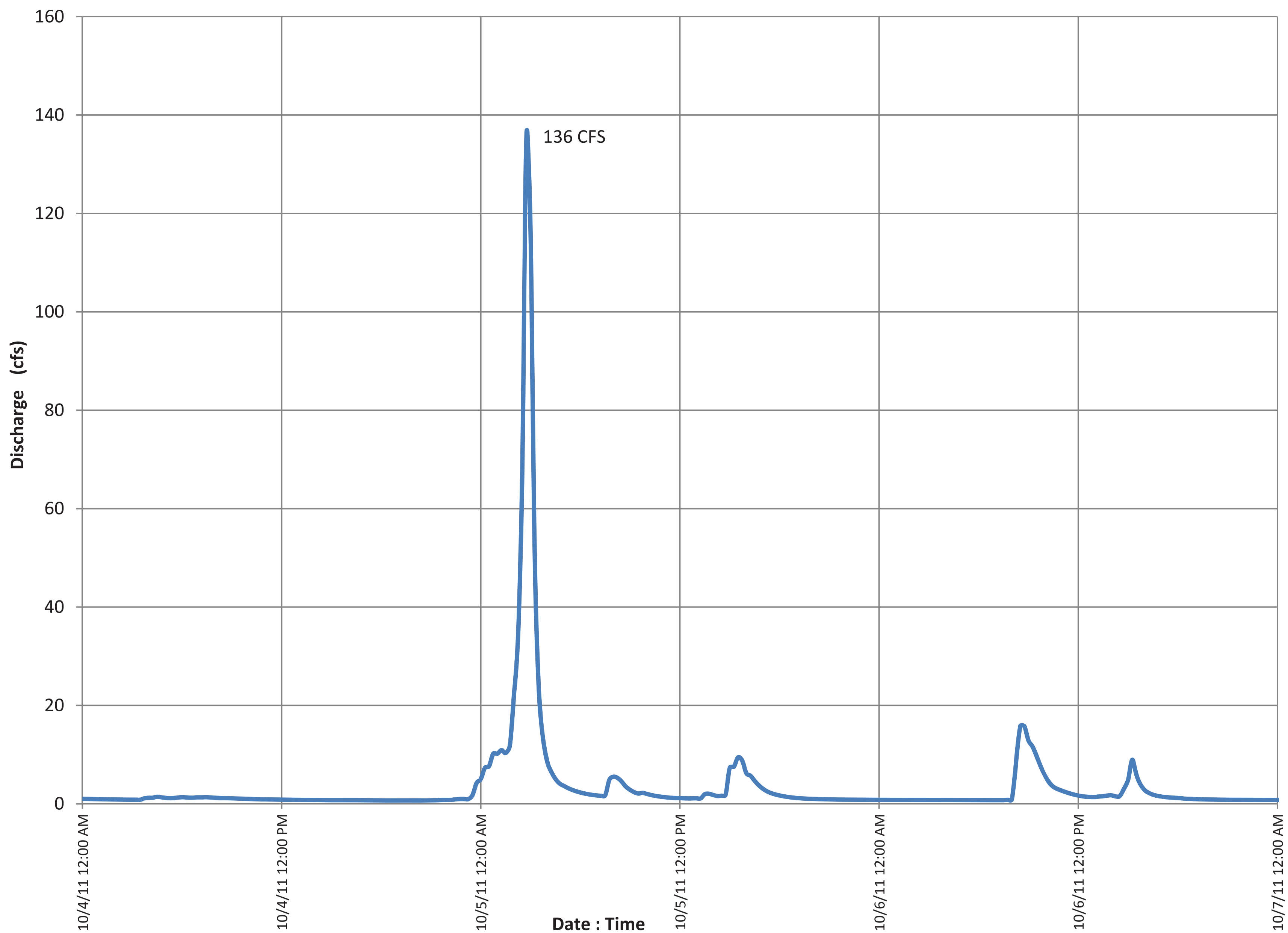

FIGURE 6. Hydrograph of October 5th flow (Balance Hydrologics, 2011)

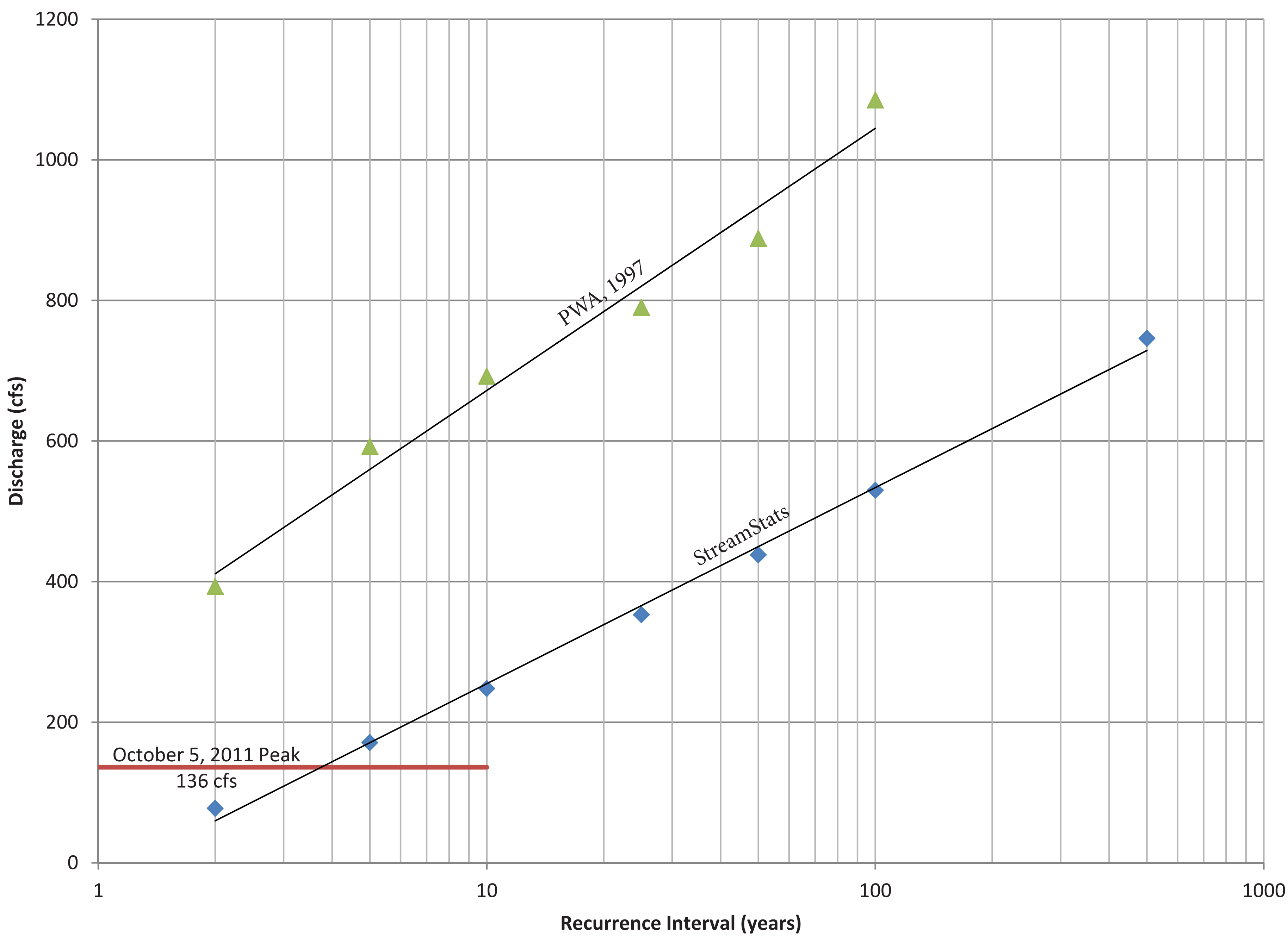

FIGURE 7. Results of Flood Frequency Analyses

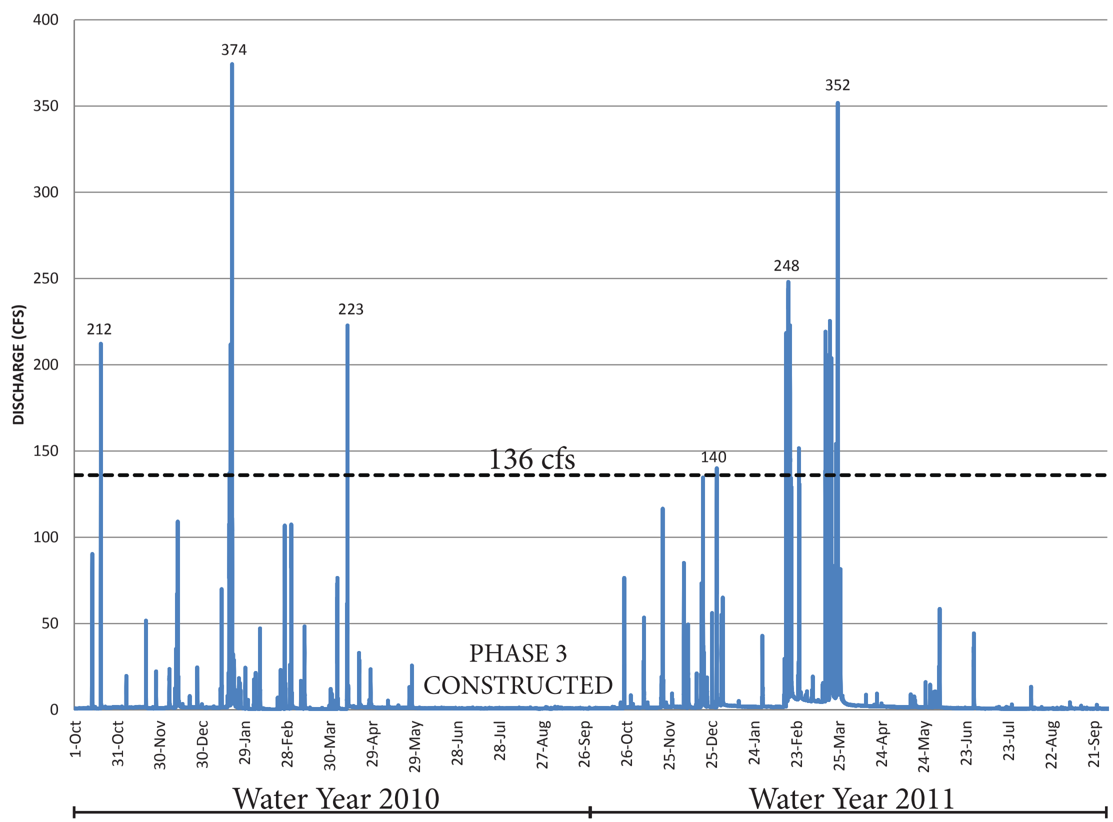

FIGURE 8. 2010-2011 WATER YEAR HYDROGRAPHS (Balance Hydrologics, 2011)

FIGURE 9. Approximate flooding extents of October 5, 136 cfs flow

FIGURE 10. Photograph of Phase 3 near RS 18+00

FIGURE 11. Photograph of Phase 3 near RS 17+50

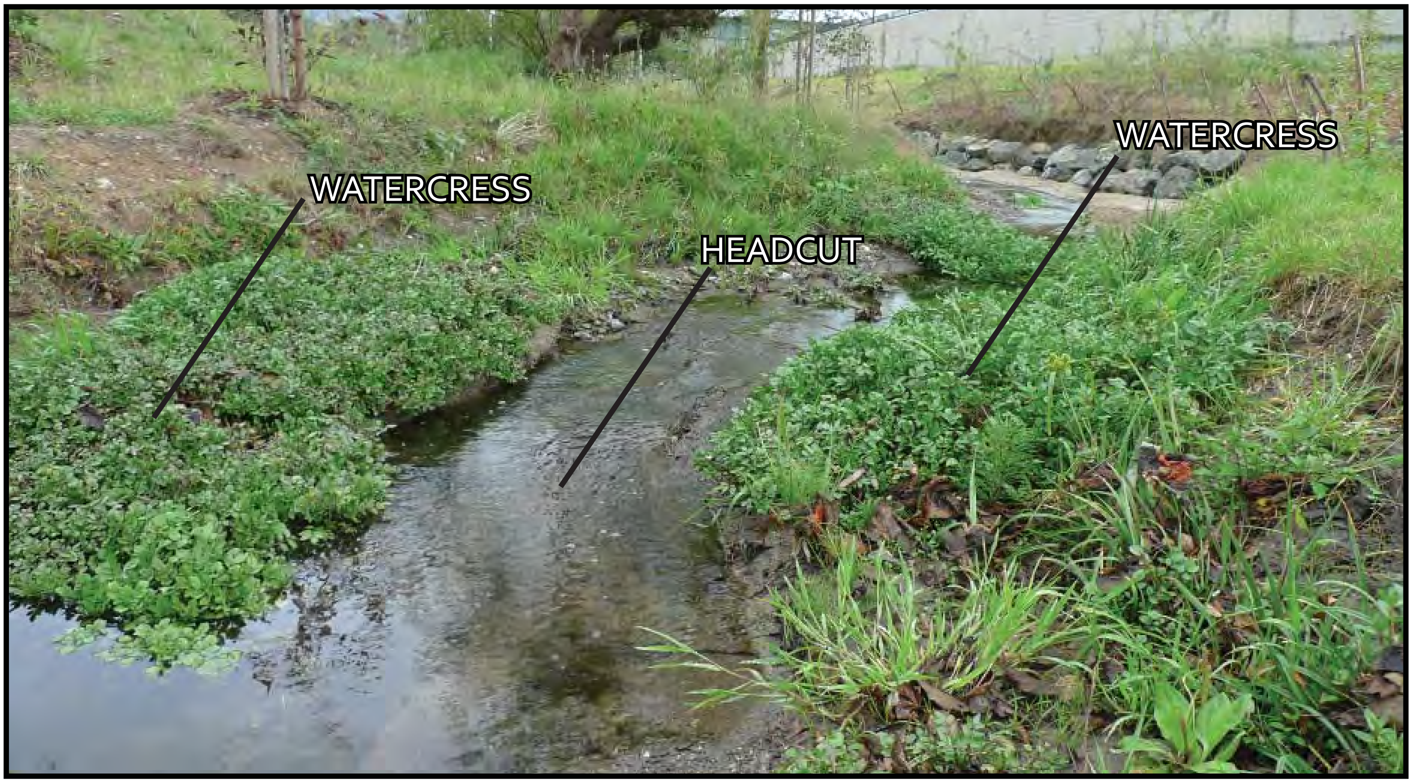

FIGURE 12. Photograph of Phase 3 near RS 17+50

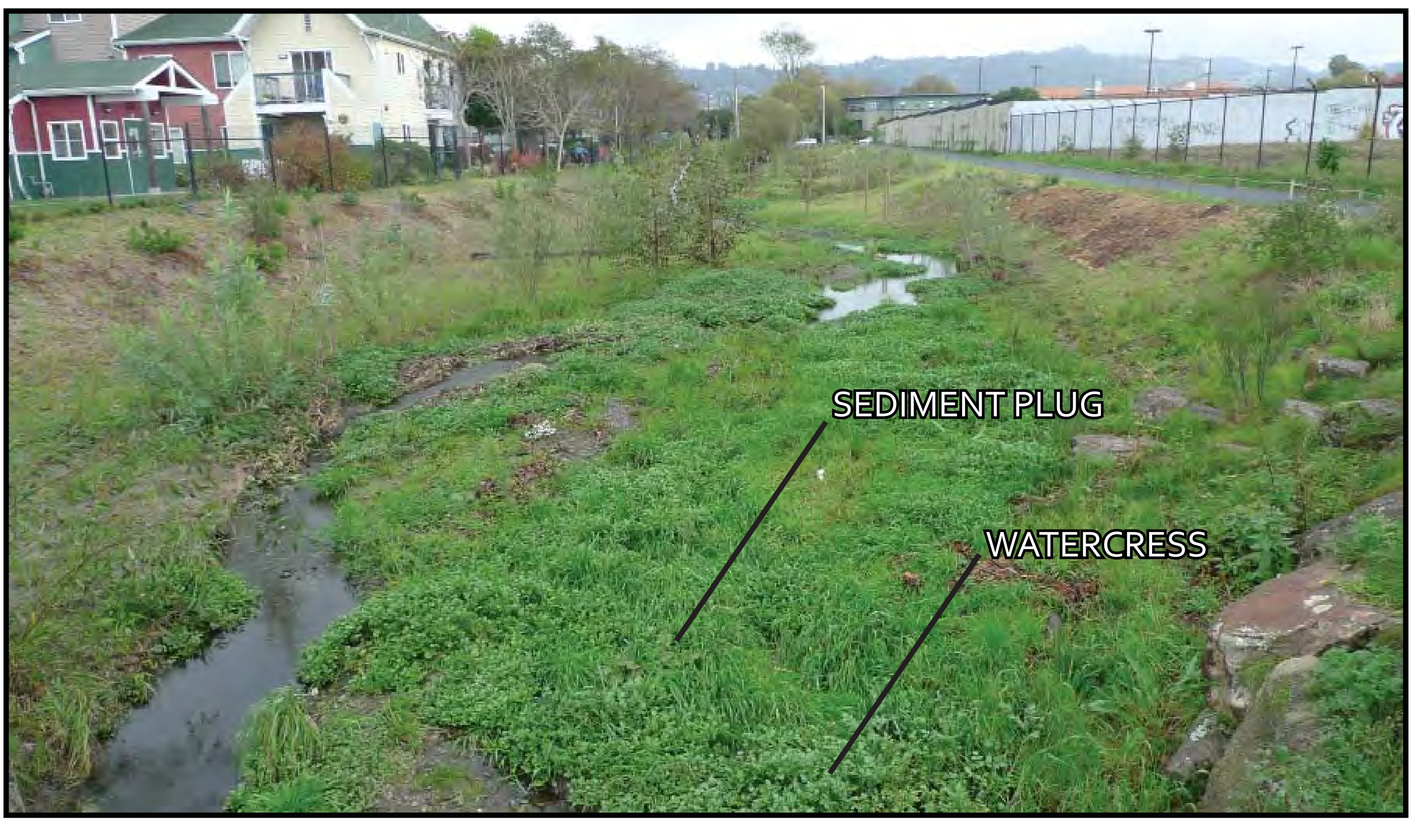

FIGURE 13. Photograph of Phase 3 near RS 14+00

FIGURE 14. Photograph of Phase 3 near RS 16+40.

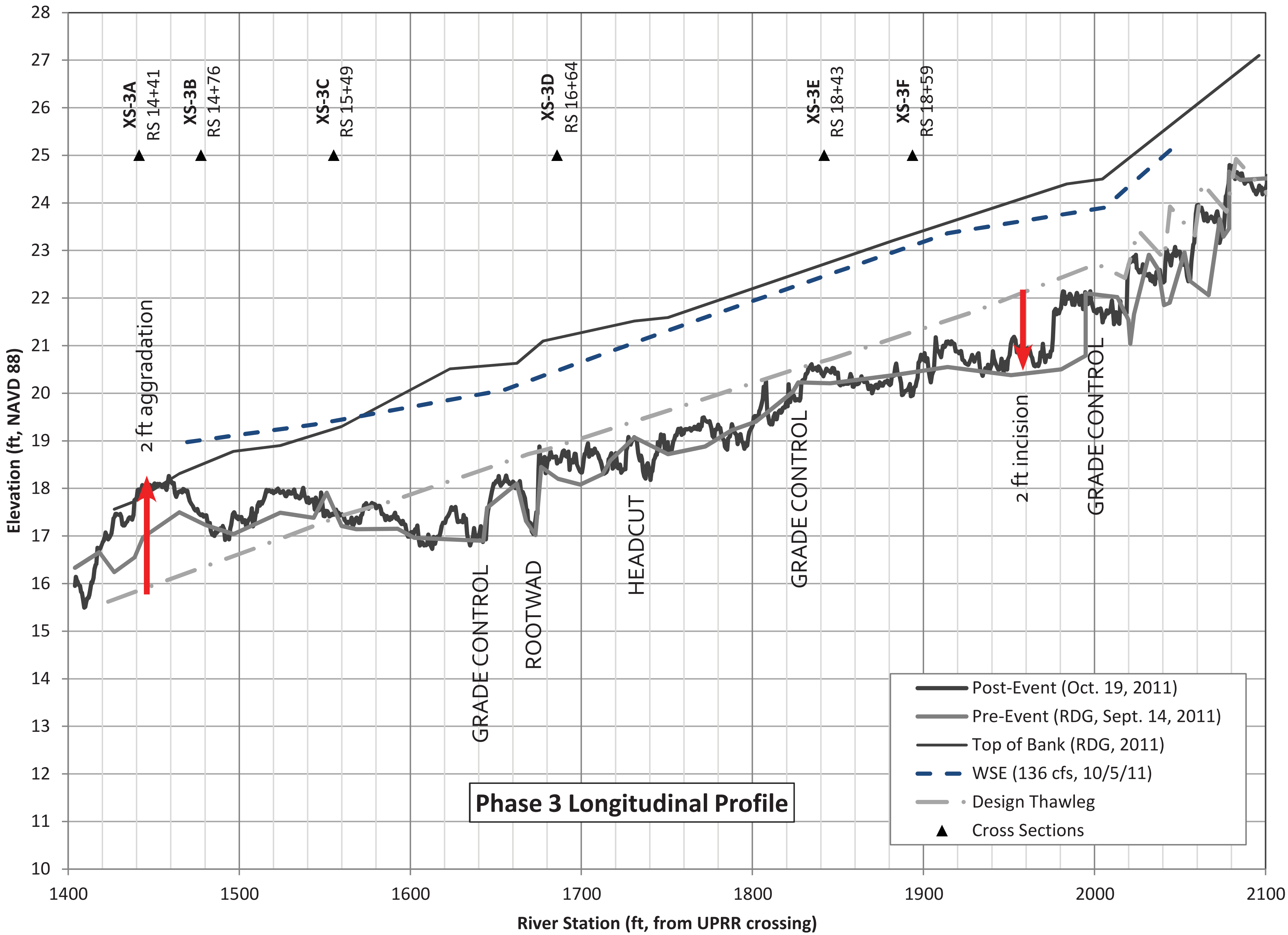

FIGURE 15a. Longitudinal Profile Comparison and High Water Surface Elevation of Phase 3

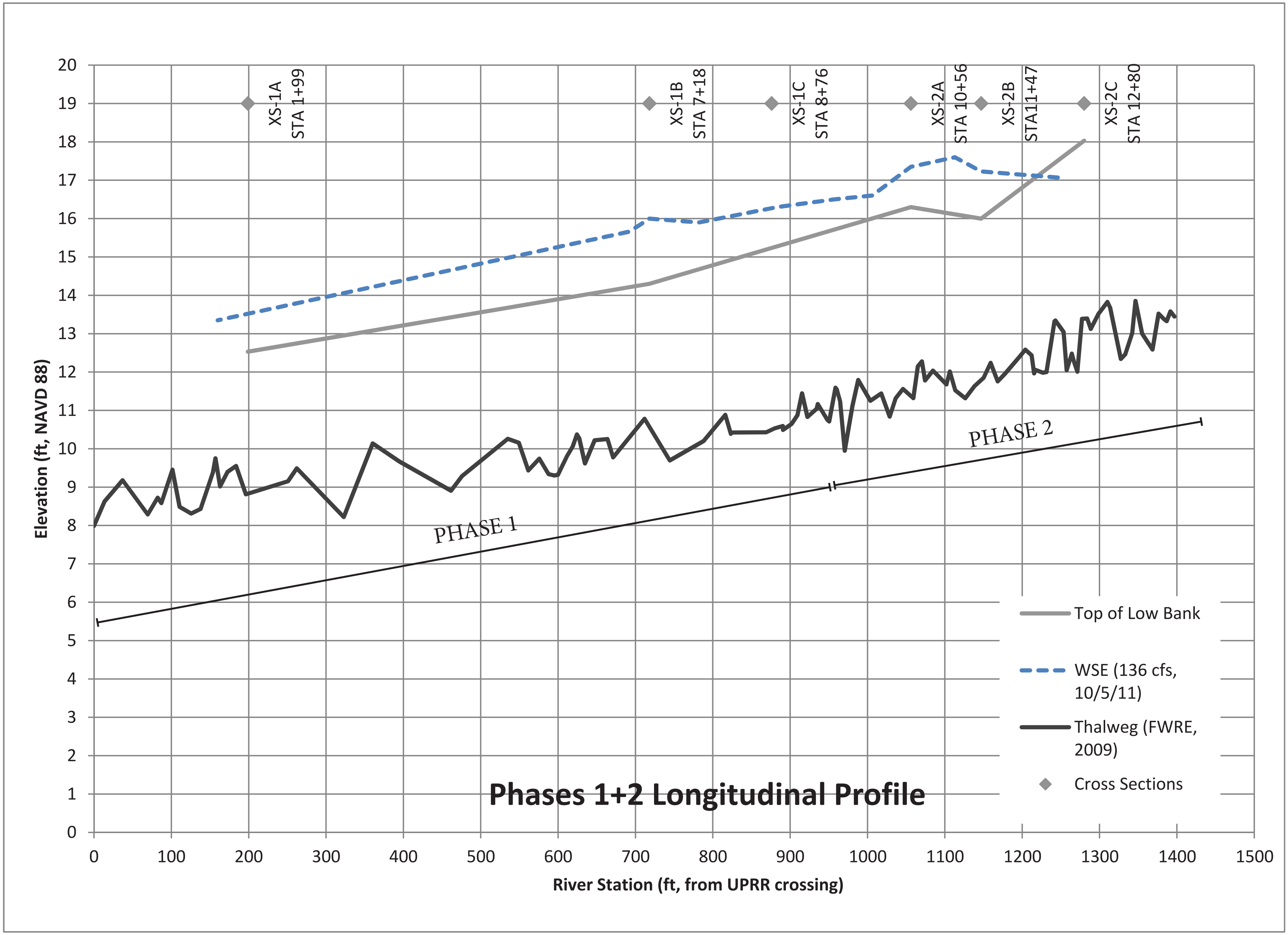

FIGURE 15b. Longitudinal Profile Comparison and high water surface elevation of Phases 1 and 2.

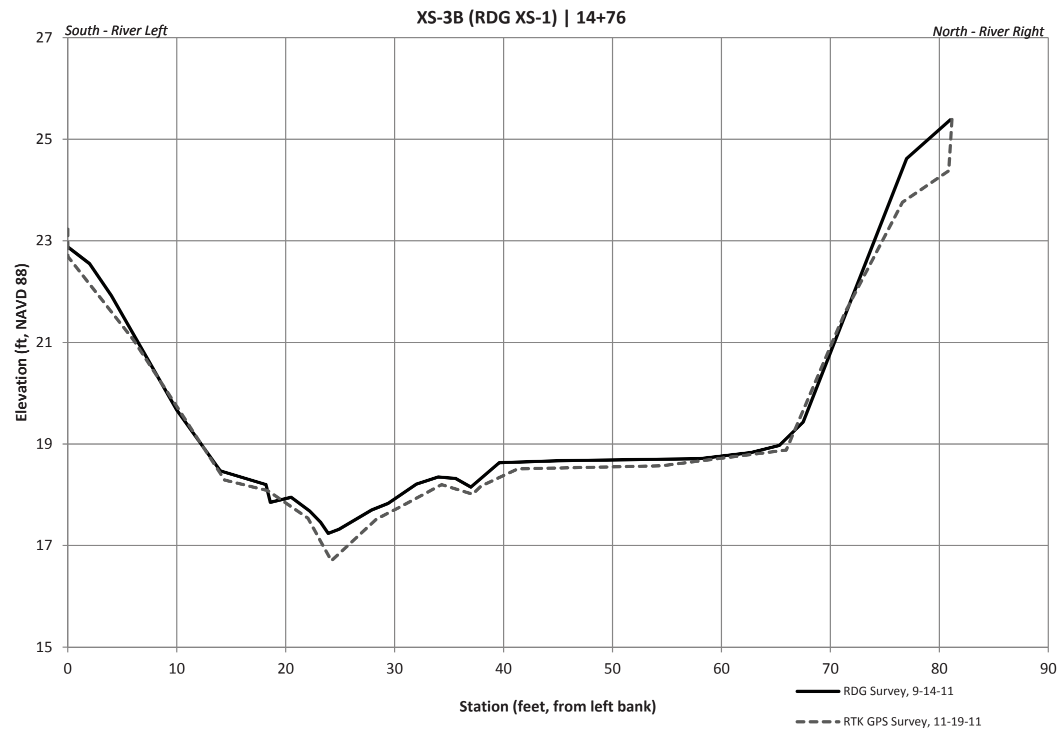

FIGURE 16a. Comparison of XS-3b with RDG Sept. 2011 Survey

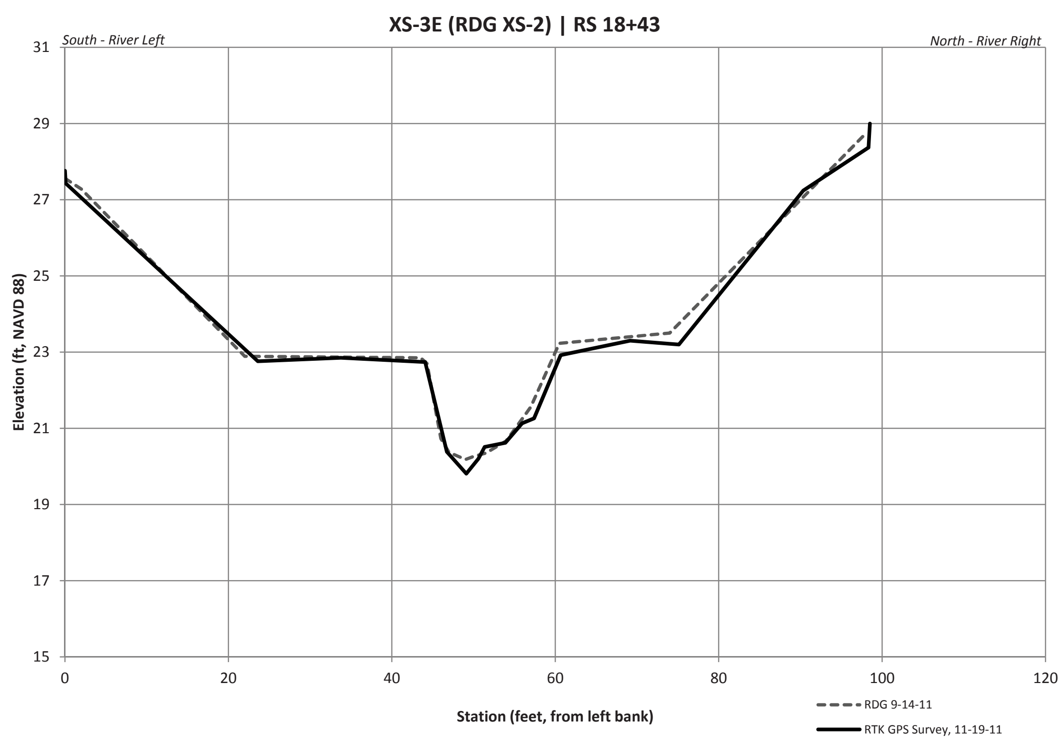

FIGURE 16b. Comparison of XS-3E with RDG Sept. 2011 Survey

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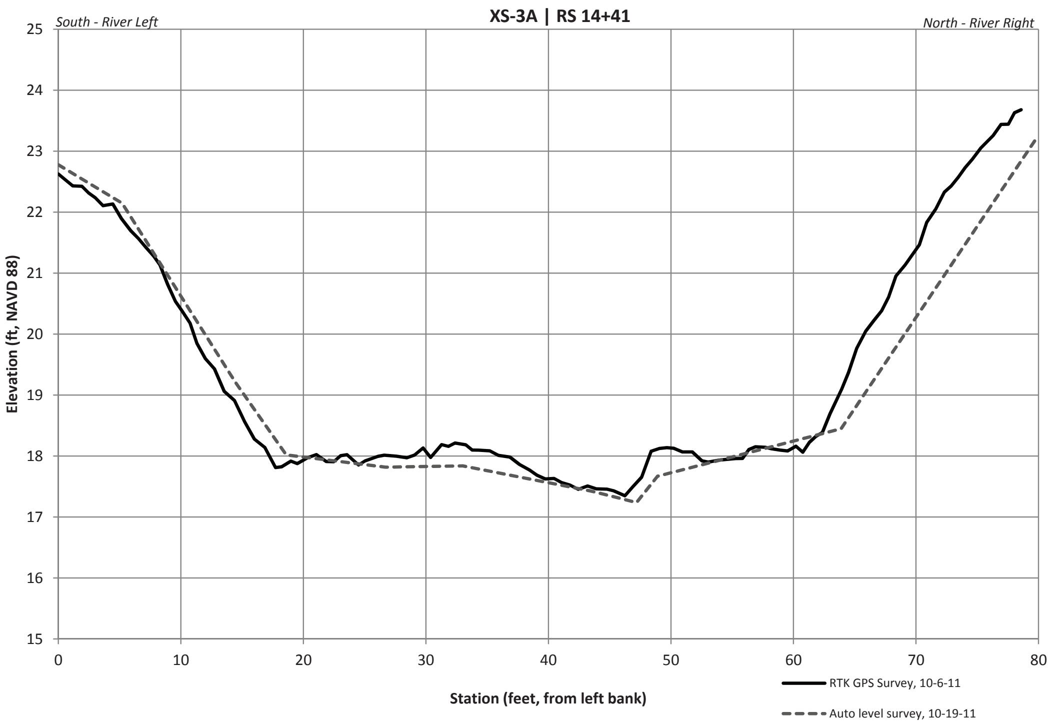
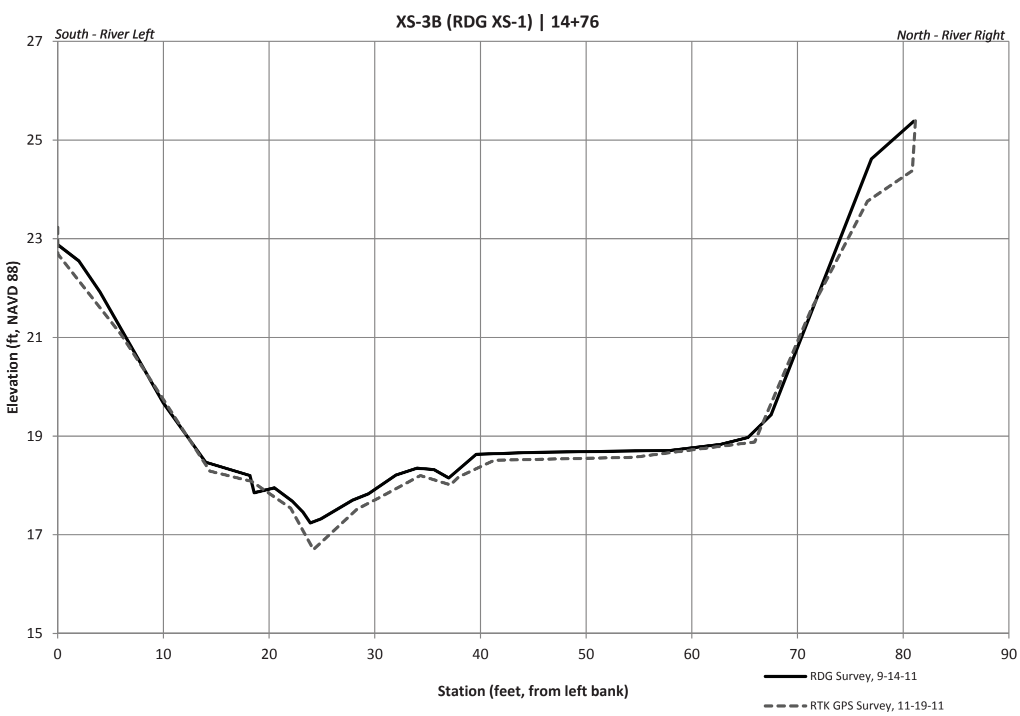
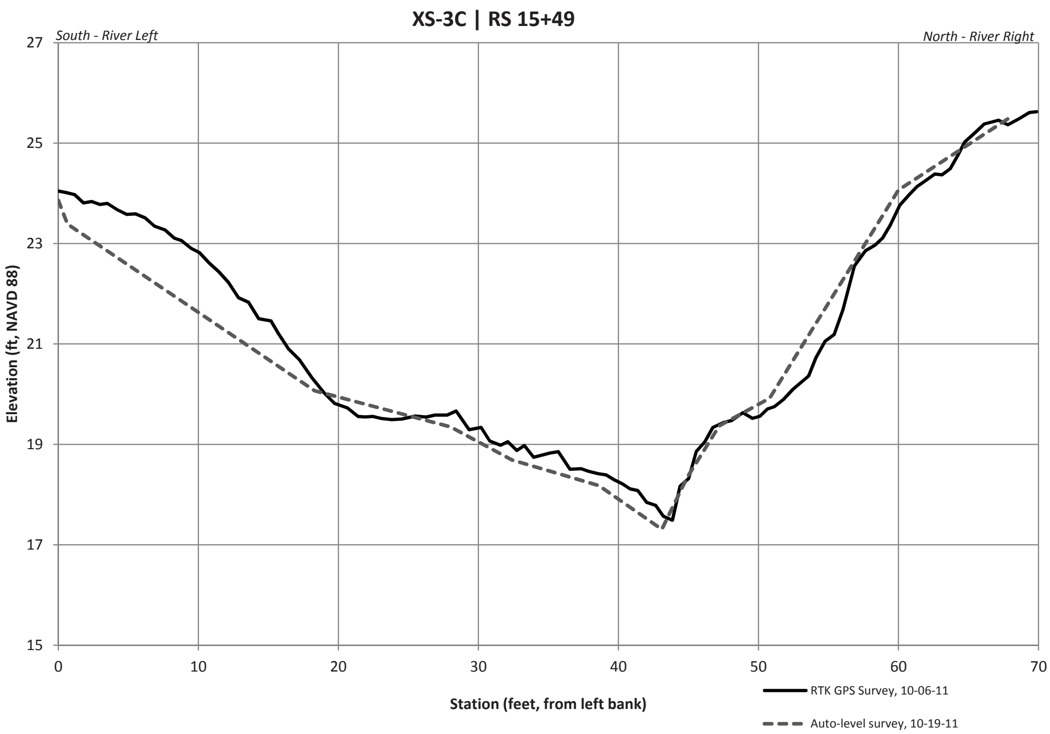
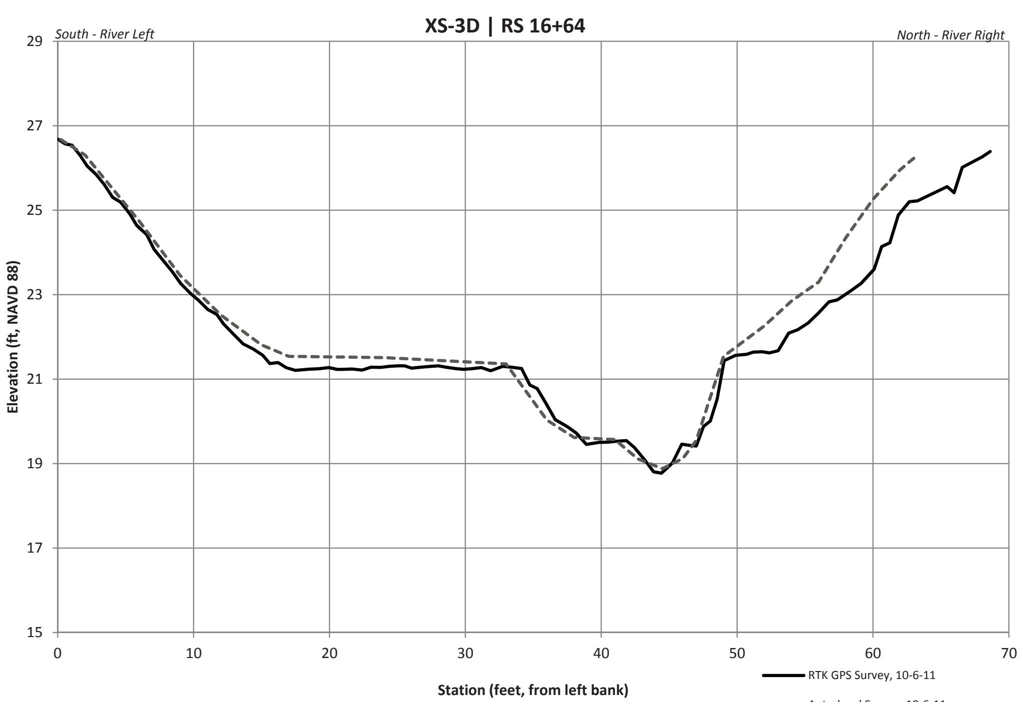
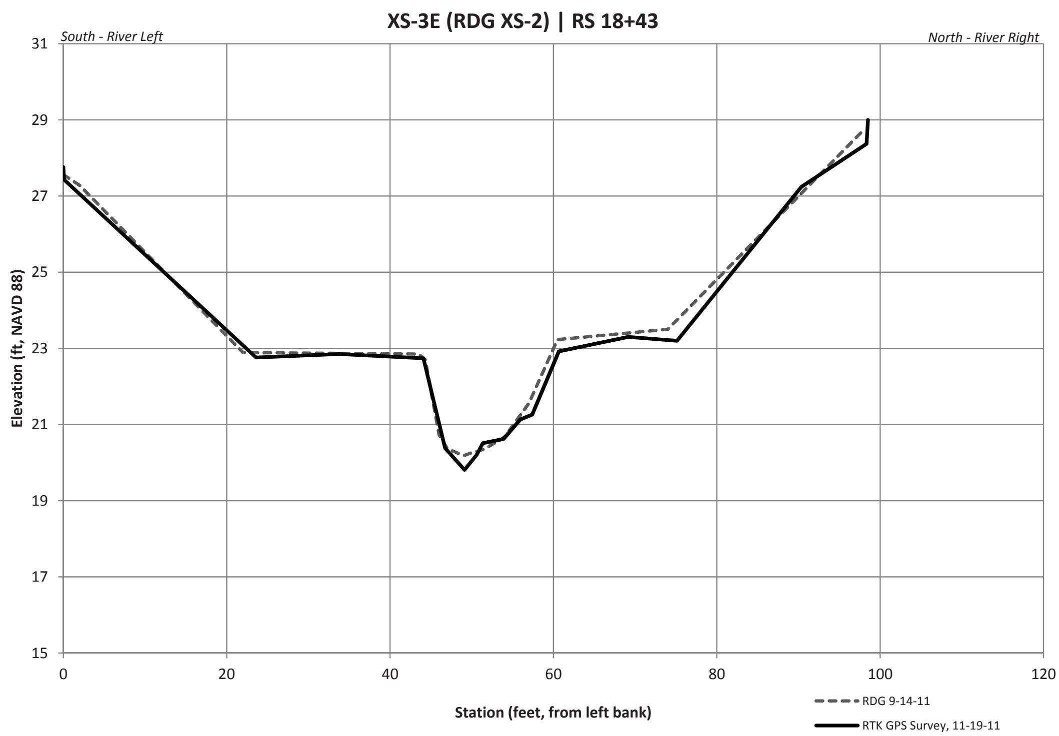
APPENDIX A
Cross Section Plots

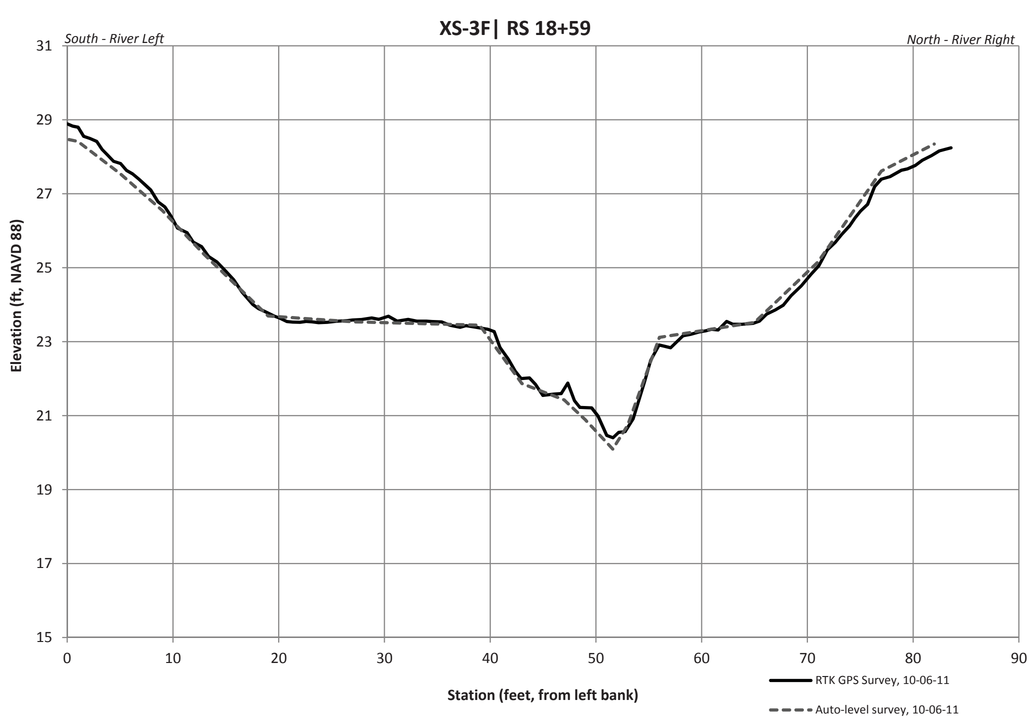

XS-3A | RS 14+41
South - River Left
North - River Right
Elevation (ft, NAVD 88)
Station (feet, from left bank)
RTK GPS Survey, 10-6-11
Auto level survey, 10-19-11

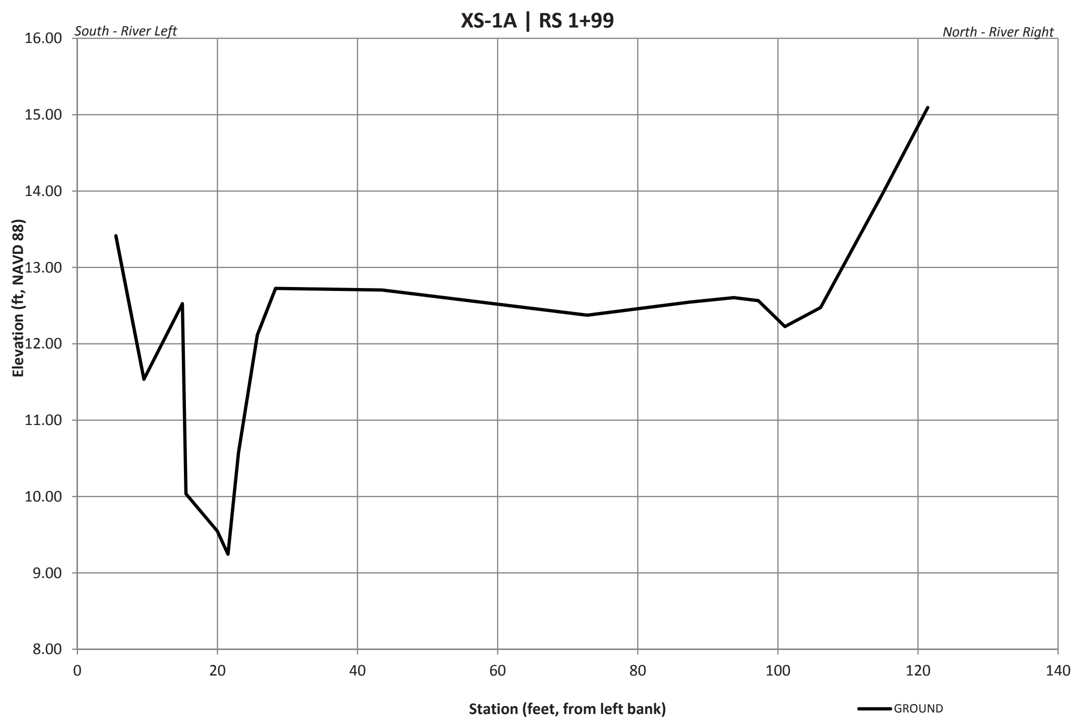

XS-3B (RDG XS-1) | 14+76
South - River Left
North - River Right
Elevation (ft, NAVD 88)
Station (feet, from left bank)
RDG Survey, 9-14-11
RTK GPS Survey, 11-19-11

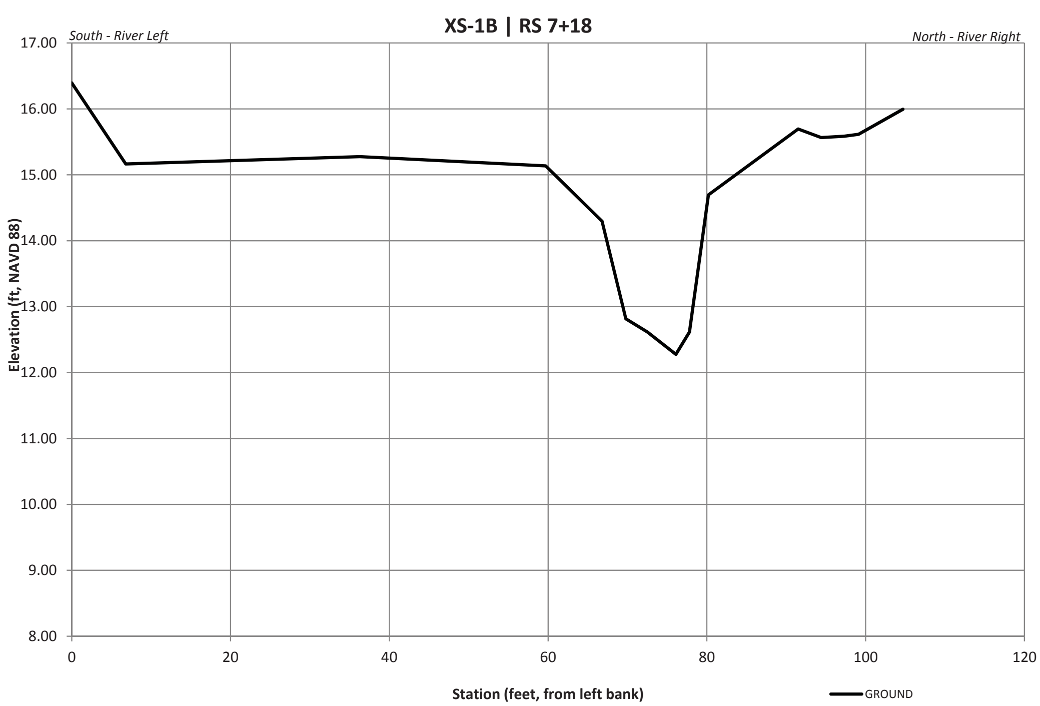

XS-3C | RS 15+49
South - River Left
North - River Right
Elevation (ft, NAVD 88)
27
25
23
21
19
17
15
0
10
20
30
40
50
60
70
Station (feet, from left bank)
RTK GPS Survey, 10-06-11
Auto-level survey, 10-19-11


XS-3D | RS 16+64
South - River Left
North - River Right
Elevation (ft, NAVD 88)
29
27
25
23
21
19
17
15
0
10
20
30
40
50
60
70
Station (feet, from left bank)
RTK GPS Survey, 10-6-11
Auto-level Survey, 10-6-11

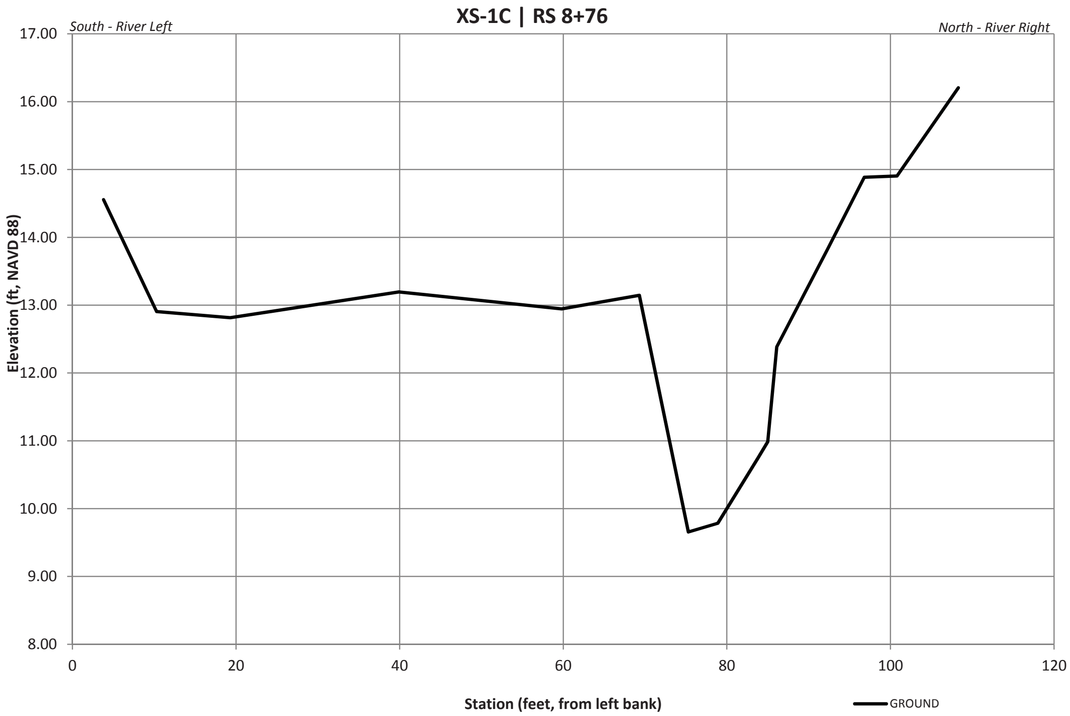

XS-3E (RDG XS-2) | RS 18+43
South - River Left
North - River Right
Elevation (ft, NAVD 88)
31
29
27
25
23
21
19
17
15
0
20
40
60
80
100
120
Station (feet, from left bank)
RDG 9-14-11
RTK GPS Survey, 11-19-11


XS-3F| RS 18+59
South - River Left
North - River Right
Elevation (ft, NAVD 88)
31
29
27
25
23
21
19
17
15
0
10
20
30
40
50
60
70
80
90
Station (feet, from left bank)
RTK GPS Survey, 10-06-11
Auto-level survey, 10-06-11

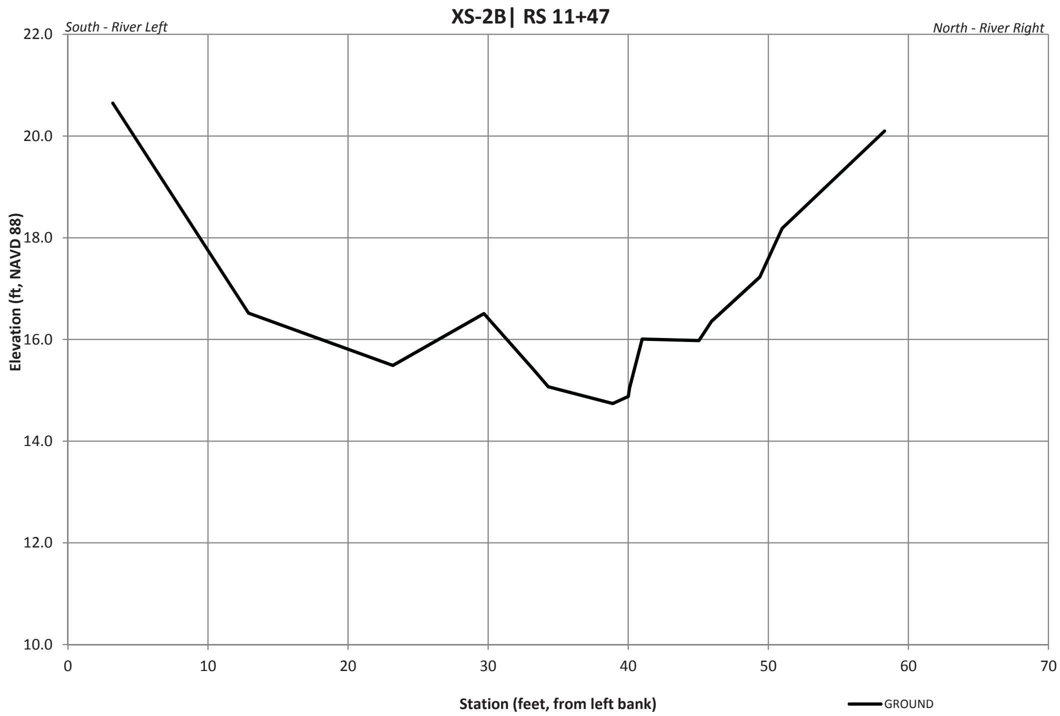


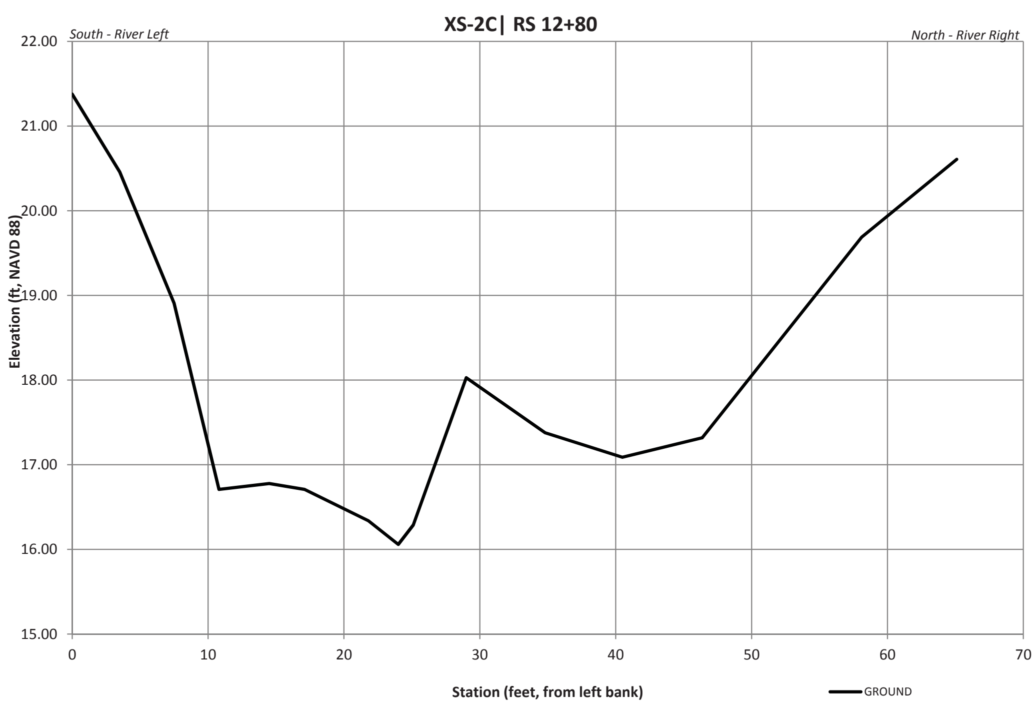


APPENDIX A - CROSS SECTION PLOTS



APPENDIX A - CROSS SECTION PLOTS


XS-2B| RS 11+47
South - River Left
North - River Right
Elevation (ft, NAVD 88)
22.0
20.0
18.0
16.0
14.0
12.0
10.0
0
10
20
30
40
50
60
70
Station (feet, from left bank)
GROUND


XS-2C| RS 12+80
South - River Left
North - River Right
Elevation (ft, NAVD 88)
22.00
21.00
20.00
19.00
18.00
17.00
16.00
15.00
0
10
20
30
40
50
60
70
Station (feet, from left bank)
GROUND