The Blackwood Creek Reach 6 Restoration Project's Influence on Reach Scale Sediment Scour and Storage Characteristics

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The Blackwood Creek Reach 6 Restoration Project’s Influence on Reach Scale Sediment Scour and Storage Characteristics

by

David Raymond Immeker

A plan B paper submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Watershed Science

Approved:

__________________________  __________________________
John C. Schmidt              Tom Lachmar
Major Professor              Committee Member

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Chris Luecke
Committee Member

UTAH STATE UNIVERSITY

Logan, Utah

2012
ABSTRACT

The Blackwood Creek Reach 6 Restoration Project’s Influence on Reach Scale Sediment Scour and Storage Characteristics

By

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Utah State University, 2012

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Department: Watershed Sciences

Stream restoration activities in Reach 6 of Blackwood Creek involved constructing a new stream channel in a reach that had been eroding and adjusting to historic land uses since the 1960s. In 2010, the spring after restoration work was completed, the project had a 2.3-year recurrence peak flow of 12.3 m$^3$/s. This post-project assessment looks at the impacts of restoration work in Reach 6 in the short time since the project was completed. Project objectives for restoration work were to: increase the extent of floodplain inundation for seasonal flooding, reduce the rate of bank erosion, and to encourage sediment deposition, particularly fine sediment, on the floodplain.

Using HEC-RAS, a one dimensional hydrologic model, I predict that the extent of flooding over a wide range of recurrences will increase as a result of restoration work, with the largest proportional increase for small magnitude, high recurrence floods. To assess the impact restoration activities will have on stream channel erosion, the average predicted shear stress was compared between pre-restoration and post-restoration conditions. This work indicates that there will be a decrease in average shear stress for all floods, with a 39% decrease for the 1.5-year recurrence flow and a 48% decrease for a 20-year recurrence flow. In 2010, areas of deposition...
and scour were mapped in Reach 6 to assess whether the project reach was accumulating sediment on the floodplain. I found that 1,129 m$^3$ of sediment had been deposited and 142 m$^3$ of sediment has been scoured. Of the 1,541 Mg of sediment deposited within Reach 6, 40% was gravel and coarser sizes, 50% was sand, 7% was silt, and 2% was clay.
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Chapter 1-Introduction

Stream restoration post-project appraisals have been defined as “systematic assessments of built restoration projects, which provide feedback on performance of restoration approaches to improve future restoration efforts” (Kondolf et al., 2011). Monitoring the status and performance of stream restoration projects with a post-project appraisal allows us to learn from our mistakes or successes and make better informed decisions in the future. Downs and Kondolf (2002) propose that performing post-project appraisals can “evaluate river restoration schemes in relation to their compliance with design, their short-term performance attainment, and their longer-term geomorphological compatibility with the catchment hydrology and sediment transport processes.” Wohl et al. (2005) propose that stream restoration projects can be viewed as experiments and that only by systematically monitoring each project can we learn from each project’s successes and failures.

Most restoration projects are not monitored. As of 2005, over $1 billion were being spent annually on stream restoration projects in the United States, and yet, once completed, few projects receive any sort of post-project appraisal (Bernhardt et al. 2005). In a survey of California restoration projects, the National River Restoration Science Synthesis group found that only 11% of restoration projects in their survey were monitored (National River Restoration Science Synthesis, 2006). In order to determine whether a restoration project was successful in achieving its objectives or if it was performing as designed, some level of monitoring is required. In addition, it is useful for project objectives to be stated in the planning phase of a restoration project. Projects with stated, quantifiable objectives have a standard to which the project can be compared to determine if the project was successful (Kondolf, 1995).
In the summer of 2008 and 2009, the US Forest Service implemented a stream restoration project in Blackwood Canyon on the west shore of Lake Tahoe, California. This watershed was selected for restoration, because it has been identified as the second largest sediment producing watershed in the Lake Tahoe basin (Simon et. al, 2004). In 2003, Swanson (2003) classified the reaches of lower Blackwood Creek based upon a geomorphic analysis. Reach 6 was the number assigned to the stream reach that is the subject of this post-project appraisal. This restoration project entailed reconstructing the stream channel and floodplain, because this segment had experienced high erosion rates since the 1960s (Swanson, 2003; Kiesse, 2011).

Restoration work entailed constructing a series of large rock-log roughness structures that were designed and positioned to redirect flows into a more sinuous, less entrenched, channel. A more sinuous flow path at higher base level was constructed between the roughness structures. The design of the project allows the position of the channel to shift laterally. Excessive movement of the channel in response to sediment and woody debris inputs expected during rain-on-snow flood conditions is limited by roughness structures. Channel and floodplain aggradation is expected over the long term, given that watershed conditions upstream are thought to still be recovering from land use impacts. Roughness structures are multi-purposed. Their positioning discourages high energy flows from directly eroding high terrace cut banks composed primarily of sand and mud, and creates lee side low velocity regions that encourage sediment deposition (USFS, 2011, Craig Oehrli, USFS Hydrologist, personal communication). In spring 2010, following the completion of the project, Reach 6 was inundated by a 2.3-year recurrence flood of 12.3 m$^3$/s. After flows receded, areas of deposition and erosion were observed on the floodplain.

The goal of this analysis is to evaluate whether the restoration project in Reach 6 of Blackwood Creek was successful in meeting its objectives and whether the project performed
consistent with the project design. To determine this, project objectives were taken from the project environmental assessment report (USDA, 2008). From the objectives, monitoring questions were developed to determine if the project has, in the short term, been successful in achieving these objectives. In the year after the restoration project was completed, the project area did begin to respond by forming many new areas of deposition and scour on the floodplain and along the channel.

1.1 Blackwood Creek Watershed

The Blackwood Creek watershed drains into the western part of Lake Tahoe in the Sierra Nevada Mountains of California. The western part of the watershed is the primary drainage divide of the Sierra Nevada, and Blackwood Creek drains to the east (Figure 1). The watershed area is 29 km² and ranges in elevation from 2,706 m at Twin Peaks to 1,897 m at Lake Tahoe.

The Blackwood Creek watershed is predominantly underlain by volcanic rocks with a predominance of andesitic and basaltic rocks. Overlying the volcanic parent material are numerous fluvial and glacial deposits. The Blackwood Creek valley has a U-shape, typical of most of the valleys in the region that were extensively glaciated. There are many extensive and large landslides in the valley (Swanson, 2003).

Soils in the watershed are predominantly derived from volcanic parent material. Steeper slopes higher in the watershed tend to have less well developed thin soils with many locations of exposed bedrock. Lower in the valley, soils are more developed and deeper. Many of the lower elevation areas are composed of soils that have formed on glacial outwash and alluvial fans.

Flood flows are typically caused by one of two processes. The spring melt each year typically creates the annual instantaneous peak flow. The highest spring snowmelt peak flow for
Figure 1. An overview map showing the location of Reach 6 in the Blackwood Creek watershed on the west shore of Lake Tahoe, near the California/Nevada state line.
the period of record for the USGS gage at the mouth of Blackwood Canyon was 27 m$^3$/s on May 16, 1996. Rarer but larger peak flows occur in some years and are usually caused by rain-on-snow events. The highest instantaneous peak flow recorded for Blackwood Creek was 83 m$^3$/s on January 1, 1997, during a rain-on-snow event.

1.2 Recent Land Use History

The Blackwood Creek watershed was heavily used from the late 1800s to approximately 1970 for livestock grazing, logging, and gravel mining (Table 1). The earliest documented sheep grazing in Blackwood Canyon dates back to 1865, and in 1889, clear cut logging began in the lower 2.5 km of the watershed. Through the 1960s, grazing ceased but logging increased in intensity. In 1960, a gravel mine began operating along Blackwood Creek and the adjacent floodplain, and Blackwood Creek was diverted around the mine in a diversion channel (Tetra Tech, 1999).

By the late 1800s, most suitable land in Blackwood Canyon was grazed by sheep. A report written in 1905 commented that Blackwood Canyon was being heavily grazed. In 1944, a US Forest Service report on Blackwood Canyon expressed concern over the deterioration of meadows and increased erosion from overgrazing. In 1959, a US Forest Service range report recommended closing Blackwood Canyon to grazing due to deterioration of meadows and valley bottoms from overgrazing. By 1963, nearly all grazing in Blackwood Canyon had stopped (Tetra Tech, 1999).

Extensive logging in Blackwood Canyon began in the 1950s when most of the watershed was still privately owned. By 1956, enough timber was being generated from Blackwood Canyon that a sawmill was built along Blackwood Creek. To provide timber to the mill, an
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1865</td>
<td>Earliest recorded sheep grazing in Blackwood Creek watershed</td>
</tr>
<tr>
<td>1889-1905</td>
<td>Clear-cut logging along Blackwood Creek in lowest 2.4 km of the watershed</td>
</tr>
<tr>
<td>1953-1962</td>
<td>Extensive logging and logging road construction throughout Blackwood Canyon</td>
</tr>
<tr>
<td>1960</td>
<td>Gravel mining starts 1.5 km upstream of Reach 6 and Blackwood Creek diverted around gravel mining operation in diversion channel</td>
</tr>
<tr>
<td>1962</td>
<td>Grazing ends in Blackwood watershed</td>
</tr>
<tr>
<td>1968</td>
<td>California Department of Fish and Game removes woody debris and beaver dams from Blackwood Creek to remove fish passage barriers</td>
</tr>
<tr>
<td>1968</td>
<td>Gravel mine ceases operation</td>
</tr>
<tr>
<td>1969</td>
<td>Diversion channel around gravel mine is cut off and Blackwood Creek is diverted back into its original alignment, through the gravel pit</td>
</tr>
<tr>
<td>1971</td>
<td>Large scale logging ceases in Blackwood watershed</td>
</tr>
<tr>
<td>1971</td>
<td>Woody debris removed from channel downstream from gravel mine location, through Reach 6 by Lake Tahoe Area Council for fish passage</td>
</tr>
</tbody>
</table>

Table 1. This table summarizes some of the significant historic periods in Blackwood Canyon.

An extensive system of roads was constructed throughout the canyon that can be clearly seen in the 1969 aerial photo of the Blackwood Creek watershed. By 1969, most of the lower elevation, easily accessible portions of the watershed had been logged, including the floodplain. By 1970, the US Forest Service had acquired nearly the entire Blackwood Creek watershed, and large scale logging operations stopped (Tetra Tech, 1999). Logging on the floodplain removed many trees that would have eventually died, fallen, and become important roughness elements that would have reduced velocities during flood flows over the floodplain and along the stream. In addition to commercial logging, in the late 1960s, woody debris was removed from Blackwood Creek, downstream from the gravel mine location, in an effort to remove fish passage barriers.

Several reports have proposed that logging and overgrazing have impacted the hydrologic response time and erosion rate in the watershed. Swanson (2003) hypothesized that the extensive network of roads and skid trails in the watershed contributed to channel and floodplain instability by more effectively routing water to Blackwood Creek. This would have produced a flashier
response to rain and could lead to higher peak flows in Blackwood Creek. In addition, Kiesse (2011) believes that overgrazing and logging would have increased the upland erosion rate and provided additional sediment to the creek. However, he also believes that, while overgrazing and increased erosion due to grazing and logging may have contributed to the channel instability in Blackwood Creek, it was not the primary factor responsible. The primary channel instability trigger is thought to be in-stream gravel mining at the head of the valley.

With development and associated road building in the Lake Tahoe basin in the 1950s and 1960s came the demand for aggregate. A mining operation in Blackwood Canyon began in 1960. The location of the gravel mine, 1.5 km up valley from Reach 6, was along Blackwood Creek where the channel slope decreases and the valley bottom widens substantially. In 2001, Swanson Hydrology and Geomorphology surveyed a long profile of the thalweg of Blackwood Creek where it flows through the former gravel mine pit. They found that the 1,090-m reach upstream of the gravel mine had a slope of 0.0120, while the slope for the 510-m long channel in the gravel mine decreased to 0.0036. On the down valley side of a landslide that is downstream from the gravel mine site, the channel slope once again increases to 0.0106 for 490 m (Swanson, 2003). This reach of low channel slope has been an area of coarse bedload aggradation since the landslide occurred and was therefore a logical location to locate a gravel mining operation (Tetra Tech, 1999). This decrease in channel slope and valley widening was caused naturally by a landslide coming off the north side of Blackwood Canyon and covering the valley bottom, around 300 to 15,000 YBP (Swanson, 2003). The landslide caused a natural discontinuity in sediment transport with substantial bedload deposition up valley from the landslide.

In 1960, Blackwood Creek was diverted into a diversion canal around the gravel mine. The aerial photos of the stream reach through the gravel mine pit before mining show that the
stream had a sinuosity of 1.59. The diversion canal that was built around the gravel pit was much straighter (sinuosity decreased to 1.14) and therefore must have had a greater slope through the reach. The increase in slope increased the stream competence, and the stream therefore was able to transport bedload coming in from upstream that was previously deposited in the low slope reach upstream of the landslide. This means that areas downstream of the landslide began receiving bedload that was previously being deposited on the low slope reach upstream from the landslide (Tetra Tech, 1999; Swanson, 2003; Kiesse, 2011; Gavigan, 2007). Additionally, Kiesse (2011) believes that the diversion canal itself was likely an additional source of coarse material to the downstream reach as the diversion canal widened and incised.

Several watershed assessments written on Blackwood Canyon propose that gravel mining activities, and specifically the re-routing of Blackwood Creek through the diversion canal, had the greatest impact on the destabilization of Blackwood Creek (Tetra Tech, 1999; Tetra Tech, 2001; Swanson, 2003; Gavigan, 2007; Kiesse, 2011). By routing an abundance of bedload through the diversion canal, reaches immediately downstream of the gravel mine pit began receiving more bedload than had been occurring previously. Before, these reaches received a minimal amount of bedload because of the upstream geomorphic controls described earlier. The combined effects of adding bed load and logging near the stream then set channel and floodplain destabilization in motion. Invading bedload would have been deposited onto the inside of meanders during periods of high flow. The building point bars caused erosive power to be applied to the outside of meanders. As bank erosion and point bar formation progressed, the channel slope would have decreased. In addition, the material eroded from the outside of meanders would then add to the excess of sediment in the channel and be transported downstream to Reach 6. This excess of sediment aggraded the channel and may have even
decreased the width to depth ratio temporarily. The combination of an aggrading channel and flood flows passing over a smoother, less erosion-resistant floodplain enhanced destabilization by allowing the creek to cut off meanders, thus shortening and steepening the channel bed. Once the channel had straightened and steepened, Blackwood Creek then had more competence and incised its bed. After incision, flood flows, that previously were able to dissipate over the floodplain, were contained within the channel. The increase in shear stress within the channel caused increased bank erosion in all reaches downstream from the gravel mine and a new lower elevation floodplain began to form (Tetra Tech, 1999; Swanson, 2003; Gavigan, 2007; Kiesse, 2011).

1.3 Aerial Photo Record of Reach 6

Comparing changes between the 1939 and 2007 air photos shows that there was a decrease in sinuosity from 1.80 to 1.23 in 68 years (Table 2). In addition, the floodplain in 1939 appears to be covered in dense vegetation. Accounts of the floodplain in the early 1940s indicate that most of the valley bottom floodplain was composed of a series of meadows intermixed with cottonwood forests (Tetra Tech, 1999). While the species present in the 1939 aerial photo cannot be determined, it is clear that the extensively vegetated floodplain present in 1939 had been replaced by 2007 with open gravel washes that were mostly devoid of vegetation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Channel Length (m)</th>
<th>Sinuosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1939</td>
<td>985</td>
<td>1.80</td>
</tr>
<tr>
<td>1969</td>
<td>894</td>
<td>1.63</td>
</tr>
<tr>
<td>1986</td>
<td>835</td>
<td>1.53</td>
</tr>
<tr>
<td>1995</td>
<td>777</td>
<td>1.42</td>
</tr>
<tr>
<td>2001</td>
<td>731</td>
<td>1.34</td>
</tr>
<tr>
<td>2007</td>
<td>674</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 2. This table shows the decrease in sinuosity observed in Reach 6 as identified in the available aerial photos.
The 1939 aerial photo (Figure 2) is the earliest aerial photo of Reach 6. In this photo, the floodplain appears to have a uniform cover of vegetation on it. The dense vegetation, in addition to the lower quality photography, makes it difficult to locate the channel accurately in some locations. Comparing the 1939 aerial photos to the 1969 aerial photo (Figure 3) shows that in the intervening 30 years, a large portion of the floodplain directly adjacent to the channel was logged. In 1939, the channel sinuosity was 1.8, and by 1969, sinuosity had decreased slightly to 1.63.

![Image of 1939 aerial photo of Blackwood Creek Reach 6.](image)

*Figure 2. The 1939 aerial photo of Blackwood Creek Reach 6. The blue line is the alignment of the channel and the red lines show the extent of the Reach 6 restoration project area. Sinuosity in this photo was 1.80 and by 2007, sinuosity decreased to 1.23 as the channel straightened. Note the dense vegetation found on both sides of the channel. Stream flow is to the east.*

Comparing the 1969 aerial photo to the 1986 photo (Figure 4) shows that that the channel in Reach 6 had begun to change substantially. In the upper half of Reach 6, the channel had cut across several meanders and much of the vegetation that existed on the floodplain adjacent to the channel had been removed and been replaced by un-vegetated gravel washes. In the lower half of reach 6, the channel was still in the same location. During the 17-year period between the 1969
Figure 3. The 1969 aerial photo of Blackwood Creek Reach 6. The blue line is the alignment of the channel and the red lines show the extent of the Reach 6 restoration project area. Note logging on the floodplain in the western portion of the photo. Stream flow is to the east.

Figure 4. The 1986 aerial photo of Blackwood Creek Reach 6. The blue line is the alignment of the channel and the red lines show the extent of the Reach 6 restoration project area. Note how unvegetated washes have formed near the channel. Stream flow is to the east.
aerial photos and the 1986 photos, there were four peak flows that exceeded the five-year recurrence flow (24 m$^3$/s) in Reach 6. The highest peak flow in Reach 6 during this period was in 1981 at 49 m$^3$/s. Channel sinuosity continued to decrease in this time period, from 1.63 in 1969 to 1.53 in 1986.

![1995 aerial photo of Blackwood Creek Reach 6](image)

*Figure 5. The 1995 aerial photo of Blackwood Creek Reach 6. The blue line is the alignment of the channel and the red lines show the extent of the Reach 6 restoration project area. Stream flow is to the east.*

In the nine years between the 1986 aerial photo and the 1995 aerial photo (Figure 5), Reach 6 appeared to have changed little. During this time, there were no flows greater than the five-year recurrence, and the highest flow was 17 m$^3$/s in 1995. Sinuosity continued to decrease during this time from 1.53 to 1.42, due mainly to one meander being cut off.

Between the 1995 aerial photo and the 2001 aerial photo (Figure 6), the flood of record occurred in Reach 6 at 78 m$^3$/s with an estimated return interval of 41 years. In this six-year period, most of the vegetation that was growing on the floodplain adjacent to the channel has been replaced by open gravel washes. During this time, the channel continued to straighten and sinuosity decreased from 1.42 to 1.34.
Figure 6. The 2001 aerial photo of Blackwood Creek Reach 6. The blue line is the alignment of the channel and the red lines show the extent of the Reach 6 restoration project area. Between this photo and the 1995 photo was the flood of record at 78 m$^3$/s. Stream flow is to the east.

Figure 7. The 2007 aerial photo of Blackwood Creek Reach 6. The blue line is the alignment of the channel and the red lines show the extent of the Reach 6 restoration project area. By 2007, sinuosity had decreased to 1.23, compared to 1.80 that was seen in 1939. Stream flow is to the east.
Tetra Tech’s analysis (1999) of Reach 6 found that flows in excess of the 100-year recurrence flood would be contained within the larger capacity channel and the previous floodplain had become a terrace. In 1998, they attempted to find several historic cross sections in Reach 6. Cross section pins located in the middle of the reach could not be located due to receding channel banks due to high rates of bank erosion. They were able to locate and re-survey one cross section at the upstream end of Reach 6 in 1998. This showed that in the two years since 1996, the channel top width had increased from 12.5 m to 24 m and the cross-sectional area had increased 60% from 12.0 m$^2$ to 19.3 m$^2$.

Between the 2001 and 2007 aerial photos (Figure 7), the channel continued to straighten and decreased in sinuosity from 1.42 to 1.23. Only one flow exceeded the five-year recurrence interval during this period, and this flow was the second largest flow on record at 60 m$^3$/s. Combining aerial photos and repeat cross section surveys, Kiesse (2011) estimated that 12,848 m$^3$ of sediment was eroded out of Reach 6 between 1995 and 2001 and 1,649 m$^3$ was eroded out between 2001 and 2007.

Comparing this series of aerial photos of Reach 6 shows some of the changes that have occurred related to floodplain vegetation and channel sinuosity. While the cross-sectional area of the channel and floodplain cannot be ascertained from aerial photos, the changes in channel sinuosity and straightening over time can be seen between the 1939 photo and the 2007 photo. In addition to the decline in sinuosity, the decline in floodplain vegetation can be identified as the well-vegetated floodplain in the 1939 photo is replaced with unvegetated gravel washes by 2007.
1.4 Previous Restoration Work in Blackwood Canyon

The Blackwood Creek watershed has been the site of several watershed restoration projects. Most of these projects have been smaller in scale and have addressed erosion in the uplands of the watershed. The gravel mine area and the Barker Road crossing of Blackwood Creek (3.7 km upstream from Lake Tahoe) have been the primary locations for restoration work done along the stream channel (Figure 1). In 1979, the diversion channel was filled and a cement grade control structure was constructed where the creek flowed into the gravel mine site. The purpose of this structure was to prevent channel incision upstream from the lowered bed elevation of the gravel pits and allow fish passage upstream. In 2003, this cement structure was removed and a more natural functioning sequence of rock weirs was constructed that provides better fish passage. Between 1966 and 2006, this crossing consisted of a single culvert located in a causeway that extended across the floodplain. In 2005, the culvert crossing was replaced with a bridge designed to pass a 100-year recurrence flow. In conjunction with the crossing replacement, a new channel was constructed at the bridge to join the upstream and downstream channel segments.

In 2008 and 2009, the Reach 6 restoration project was implemented that is the focus of this paper. This reach was selected, because it had experienced significant straightening, incision, and bank erosion since the 1980s. The project involved constructing a new stream channel through the reach that would decrease the channel slope and increase sinuosity. Additionally, the bed elevation of the channel was raised (relative to the existing channel it replaced) and set closer to its historic channel-floodplain connection elevation. Since an excess of sediment was identified as a primary contributor to the destabilization of the reach, a design was implemented that would promote aggradation of sediment on the new channel’s floodplain. An impact of
raising the channel bed elevation is that depressions were left on the floodplain. The intention was that at flood flows, the project reach would rebuild its floodplain by promoting aggradation on the floodplain throughout the reach. In addition, the project was intended to arrest the high rate of bank erosion that was continuing through the reach.

1.5 Previous Post-Project Assessment Work

Post-project appraisals take on many forms. Smith and Prestegaard (2005) performed a post-project appraisal of a stream restoration project on a reach of Deep Run in northeast Maryland. Comparing the pre-restoration condition to the as-built condition, they found that channel capacity had decreased by 30% and the sinuosity had increased slightly. One year after the project was constructed, they observed that the channel had made several adjustments in planform and cross-section area. Additionally, it was observed that several of the structures used to reduce bank erosion or maintain grade control were being compromised as channel location and capacity adjusted.

Hydraulic models can be used during post-project appraisals to predict water surface elevations and flow velocities generated by a specified flow. Klein et al. (2007) used the MIKE II hydrologic model as part of a post-project appraisal of a restoration project on the Lower Red River in north-central Idaho. This project involved constructing a new channel using the natural channel design (Rosgen, 2006) methodology. To determine if the restored reach was achieving its project objectives, the authors modeled a range of flows for the pre- and post-restoration channels to determine the predicted water surface elevation (in relation to the floodplain elevation), extent of floodplain inundation, and bankfull flow velocities. They found that the distance between the water surface elevation and the top of bank elevation was less for both
bankfull flows and low flows for post restoration conditions in 2000 (immediately after restoration work was completed) and in 2003. Comparing the modeled area inundated by water shows an increase of 150% from pre-restoration conditions. Immediately post-restoration, mean bankfull water velocity decreased significantly from pre-restoration conditions, as might be expected with a 60% increase in sinuosity.

Hydraulic models can also be used to predict the area inundated by water and shear stress generated by a specified flow. Elliott and Capesius (2009) used the HEC-RAS model to predict water surface elevation and shear stress generated in reaches of rivers in Colorado that had been altered by channel restoration activities. They compared the water surface elevations that were predicted by HEC-RAS for the 2-year, 5-year and 10-year recurrence peak flows. The model was calibrated to the observed water surface elevation during a rain-on-snow event that had occurred in the winter of 2005. The average boundary shear stress was also calculated in HEC-RAS for various cross sections. The shear stress was evaluated for the modeled flows and compared to the estimated critical shear stress. Using this method, they were able to determine whether the modeled flows produced shear stress that was greater than critical shear and were thus capable of transporting the bed material. Additionally, they were able to compare shear stresses generated at a cross section for the range of modeled flows to help understand the impact restoration work had at that location.

Thompkins and Kondolf (2007) used HEC-RAS to model flows in seven reconfigured compound channels in central California that were between two and 20 years old. They compiled cross sections and longitudinal surveys that had been surveyed after restoration work, in addition to surveying additional cross sections when there were insufficient cross sections to run the model. Manning’s n values were estimated from post-project monitoring that documented the
distribution and extent of vegetation along the channel and floodplain. For each stream, the
design flow for the low-flow channel and the 100-year recurrence flows were then modeled to
determine water surface elevations and flow velocities. The model results were then compared to
the project objectives (as stated in each project’s design documentation) for conveying flood
flows. They found that four of the projects were capable of passing their 100-year recurrence
flow. The remaining three projects had high channel and floodplain Manning’s roughness values
that produced high flood stages that could flood outside of the designed floodplain of the
compound channel. These projects were found to only partially achieve the stated project’s
objectives.

Endreny and Soulman (2011) used HEC-RAS while conducting a post-project
appraisal of a stream restoration project on Batavia Kill Creek in the Catskill Mountains in New
York. One of the goals of the project was to reduce bank erosion along Batavia Kill Creek. The
Creek flows into a reservoir used for drinking water and was found to have above normal
turbidity levels. The project was constructed using the natural channel design (Rosgen, 2006)
methodology and involved constructing numerous in-channel structures designed to deflect flow
away from banks and provide grade control. Using cross section and long profile survey data
from 2004, two years after the project was completed, HEC-RAS modeling of the 1.3-year
recurrence flow showed that flow depths in meander bend pools decreased from the as-built
condition. Modeling the shear forces and hydraulic slopes for the 1.3-year return flow at cross
vanes built during the project showed a hydraulic jump in the pools below the cross vanes and a
shear force greater than was found in the pools that were built on meander bends. The authors
attributed the decreased flow depth found in the meander bend pools to be the result of the
decrease in pool shear stress, leading to aggradation.
Buchanan et al. (2010) conducted a post-project appraisal of a stream restoration project implemented on Six Mile Creek in southern New York. Here, they modeled the water surface elevation and boundary shear stress for both pre-restoration and post-restoration conditions with HEC-RAS. The shear stress for the 1.5- and 7-year recurrence flows was modeled for both pre- and post-restoration topography and then compared to a calculated critical shear stress for the channel bed $D_{84}$. Using this method, they were able to show that the modeled 1.5-year recurrence flow in the post-restoration channel produced an average shear stress that was lower than the pre-restoration channel and the post-restoration shear stress was less than the calculated critical shear stress. One goal of the restoration project was to promote channel stability and reduce bed and bank erosion. In reality, hydrologic modeling did not match observed conditions as cross-section surveys of the post restoration channel showed channel widening and incision throughout the restoration reach. Modeled flood flows of the restoration channel also showed that, immediately post-construction, the design channel achieved another project goal of increasing floodplain inundation.

To assess the mass balance of areas of aggradation and degradation in the project reach, Buchanan et al. (2010) also mapped out areas of fill and scour. The boundaries of the deposits were then recorded using a GPS and the data were differentially corrected. To calculate a volume for regions of fill and scour, the authors estimated the average depth of each mapped unit and multiplied by the area of the deposit. Using this method, they estimated that 24.2 m$^3$ of sediment deposited in the reach while 883.6 m$^3$ was scoured from the reach. This gave a net loss of 859 m$^3$ for the restoration reach.
1.6 Research Objectives

The goal of this evaluation is to document if, in the short time since implementation, restoration work in Reach 6 was successful in changing an eroding, unstable reach of channel to one that is aggrading sediment. The following describes the specific research questions for this evaluation.

1. To what degree has the channel/floodplain restoration work in Reach 6 changed the areal extent of floodplain inundation when comparing the pre-project conditions to the post-project conditions?

2. Has restoration work reduced the potential for stream channel and cut bank erosion in Reach 6 through reductions in the average boundary shear stress generated in this reach?

3. What was the approximate volume of sediment deposition that occurred on the Reach 6 floodplain during the spring runoff of 2010?

4. What are the particle size characteristics of areas of sediment deposition on the floodplain, particularly as they relate to sand and mud (< 2mm)?
Chapter 2-Methods and Data Collection

2.1 Hydraulic Modeling

The Blackwood Creek Restoration Project environmental planning documents state that two of the objectives of restoration work in Reach 6 were to “reduce fine sediment and nutrient delivery rate to Lake Tahoe through stabilization of stream channels and reconnecting channels to floodplains…” and to “restore the degraded riparian plant community through the stabilization of stream channels and reconnecting channels to floodplains.” (USDA, 2008). From these stated objectives, two research questions were developed to determine if this project was successful in achieving its objectives. These questions are:

1. To what degree has the channel/floodplain restoration work in Reach 6 changed the areal extent of floodplain inundation when comparing the pre-project conditions to the post-project conditions?

2. Has restoration work reduced the potential for stream channel and cut bank erosion in Reach 6 through reductions in the average boundary shear stress generated in this reach?

To answer these questions, the project area was modeled using two software packages available from the US Army Corps of Engineers (ACE) Hydrologic Engineering Center, Hydrologic Engineering Center River Analysis Systems (HEC-RAS), and HEC Geo-RAS.

I conducted a flood frequency analysis using the log Pearson type III distribution. This analysis was carried out using the ACE Hydrologic Engineering Center’s Statistical Software Package (HEC-SSP) which performs a flood frequency analysis based upon the USGS bulletin 17B, “Guidelines for Determining Flood Flow Frequency” (USGS, 1982). Annual peak flows were taken from the USGS stream gage (USGS 10336660, Blackwood Creek near Tahoe City, California), located 2 km downstream from the Reach 6 project area, which has been in continuous use since 1960. In order to develop a collection of flood flows for Reach 6, I down
scaled the flows from the USGS gage to the watershed area for Reach 6 using the guidelines of the USGS (1997).

HEC-RAS version 4.1 is a one-dimensional hydraulic modeling program that predicts water surface elevations along a stream reach and shear stress for a given discharge assuming steady flow conditions. With gradually varied flow, HEC-RAS calculates the water surface elevation at each cross section by solving the energy equation using the standard step method. This iterative process assumes that there is mass continuity between cross sections and that changes in velocity and cross-sectional area are attributed to friction loss and expansion or contraction that occurs from one cross section to the next downstream.

The core set of data required to run the model is a series of cross sections that extend across the channel and the area that might be inundated adjacent to the channel, the channel slope and length along the channel center line where each cross section lies, and a friction coefficient value (US Army, 2010). To develop this required core set of model parameters, HEC Geo-RAS was used.

HEC Geo-RAS version 4.3 is a software package that runs as an extension in Environmental Systems Research Institute’s (ESRI) ArcGIS version 9.3 software. To use HEC Geo-RAS to develop the core set of model parameters, a Triangular Irregular Network (TIN) digital terrain model was needed that covers the stream channel and adjacent floodplain. The TIN for this project was generated from elevation data that consisted of 0.3-m contour lines and elevation points of the project area. A TIN is a three-dimensional surface composed of a series of interconnected triangles. For this work, the TIN was a terrain model of the channel and adjacent floodplain in Reach 6. Using HEC Geo-RAS and the three-dimensional surface of the TIN in ArcGIS, I was able to extract the information that is required to run HEC-RAS. In addition to
developing the information required to run HEC-RAS, HEC Geo-RAS has the ability to map the area inundated by water for a steady state flow modeled in HEC-RAS. To do this, the information generated from a HEC-RAS model run was loaded back into ArcGIS/HEC Geo-RAS. Using HEC Geo-RAS, a series of polygons of the inundated areas was created for a series of steady state flows.

Using this method, two TIN terrain models were created, one of the landscape as it was before restoration work, and another of the landscape as it was after restoration work. This method allowed me to compare what the modeled area inundated by water would be for identical flows by running each model with a known steady state flow. The model was run with a range of theoretical flows, and the area inundated by water was then compared between the pre-restoration conditions and the post-restoration conditions to see how the restoration project has influenced the areal extent of flood inundation.

In addition to modeling the water surface elevation, HEC-RAS has the capability to predict the average boundary shear stress generated at each cross section for a given steady flow. As HEC-RAS is a one dimensional model, calculations of shear stress do not take into account overall channel sinuosity or meander bend geometry, and therefore shear stress may be underestimated at meander bends (Richardson, 2002).

Shear stress at each cross section is calculated using equation (1):

\[
\tau = \gamma RS_f
\]

where \(\tau\) is the shear stress at the cross section in N/m\(^2\), \(\gamma\) is the unit weight of water in N/m\(^3\), \(R\) is the hydraulic radius of the cross section in meters and \(S_f\) is the friction slope at the cross section (the slope of the energy grade line at the cross section). Running a series of flows through HEC-
RAS allowed me to compare the shear stress generated in Reach 6 for the pre-restoration conditions and the post-restoration conditions for each flow.

2.2 Building the HEC-RAS/HEC Geo-RAS Model

One of the primary inputs required to run the HEC-RAS 1-D model is a series of cross sections that extend across the channel and floodplain. These have traditionally been generated by field surveying a number of cross sections in the stream reach to be modeled. While cross sections measured by field surveying may be accurate, it can be time consuming to gather them.

Another method available for generating the required cross sections is to use a TIN digital terrain model in ArcGIS. Terrain models created using LIDAR or stereophotogrammetry can depict the bare earth surface of a stream’s channel and floodplain, but these methods do not allow us to look into the channel below the surface of the water. To correct for this, additional surveyed information is required to depict the channel below the water surface. To account for this, Aggett and Wilson (2009) used a series of field surveyed cross sections and aerial photos to interpolate the bathymetry in a terrain model of a stream reach that was acquired with LIDAR.

On August 17, 2007, before construction was started, a series of overlapping aerial photos was acquired of Blackwood Creek that covered the Reach 6 project area. This imagery was processed by Aerial Data Inc. using stereophotogrammetry to create contour lines of the Reach 6 project area at the 0.3-m resolution. For this project, I brought the 0.3-m contour data set into ArcGIS where I created a TIN terrain model.

Using the USGS gage, 2 km downstream from Reach 6, at the mouth of Blackwood Canyon, shows the mean daily discharge was 0.04 m$^3$/s on the date that the 2007 aerial photos were taken. Analyzing the aerial photo shows that there was water in the pools at the time of
acquisition, but any water flowing between pools was minimal. This situation means that the contours developed using stereophotogrammetry were not able to show the bed of the channel through the water in the pools. To correct for the pool depths not accounted for in the contours, a long profile surveyed in October 2001 by Swanson Hydrology and Geomorphology was used. To account for pools in the TIN terrain model, pool depth contour lines were interpolated in ArcGIS at similar depths to what was measured in the long profile. The TIN was then created from the 0.3-m contour lines that accounted for pool depths.

On November 3, 2010, after the restoration project was completed, another series of aerial photos was acquired and processed by Aerial Data Inc. They used stereophotogrammetry to create 0.3-m contour lines of Reach 6. On this date, the USGS gage at the mouth of Blackwood Canyon had a mean discharge of 0.22 m$^3$/s. Analyzing the aerial photo showed that there was water in the pools in Reach 6. As in the 2007 TIN Terrain model, the pools were not included in the derived contours as the stereophotogrammetry technique will not penetrate below the water surface. To correct for the pool depths not accounted for in the contours, a series of total station points collected in fall 2009 by Water Ways Consultants was used. I brought these points of known channel bed elevation into ArcGIS, and interpolated contour lines around them. Using these additional contour lines, I was able to create pools in the TIN that were similar to the surveyed pool depths. With the two TIN terrain models built and HEC Geo-RAS, I was able to extract the information that is needed to run HEC-RAS. Because the TIN terrain model is a three-dimensional surface, two-dimensional data (channel center line, channel banks, distance between cross sections along the channel center line) and three-dimensional (channel cross sections, channel slope) data can be extracted from the TIN (US Army, 2009).
Table 3. Table 3 shows the discharge measurements taken in July 2011 and the Manning’s n that was calculated for that discharge.

<table>
<thead>
<tr>
<th>Discharge m$^3$/s</th>
<th>Manning's n</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.18</td>
<td>0.0465</td>
</tr>
<tr>
<td>5.32</td>
<td>0.0325</td>
</tr>
<tr>
<td>2.01</td>
<td>0.0361</td>
</tr>
<tr>
<td>1.95</td>
<td>0.0664</td>
</tr>
</tbody>
</table>

With the terrain models built for the pre-construction and post-construction conditions, a Manning’s n value was selected. To select an n value for the channel, the slope of the channel was surveyed and a series of flow measurements were taken in July 2011 (Table 3). Using these measurements and the equation (2) for Manning’s n:

$$V = \frac{R^{2/3}S^{1/2}}{n}$$

(2)

where $V$ is the average water velocity in m$^3$/s, $R$ is the hydraulic radius of the channel with flow in meters, $S$ is the channel slope, and $n$ is Manning’s n (Chow, 1959). Multiplying both sides of equation (2) by $n$, and dividing by $V$, with $V$ equal to the discharge ($Q$) divided by the area ($A$), yields equation (3):

$$n = \frac{R^{2/3}S^{1/2}A}{Q}$$

(3)

Solving for $n$ with equation (3), using the cross section measurements and $Q$ from the discharges measured in Reach 6, gives an $n$ value for each discharge measurement. Taking the average of the calculated $n$ values, I got an $n$ of 0.045.

In Ven Te Chow’s Open Channel Hydraulics (Chow, 1959) the author provides a table of Manning’s n values for various natural stream channels and floodplains. Chow’s proposed range of values for “Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages” with a “Bottom: gravel, cobbles, and few boulders” is a
minimum of 0.03, a maximum of 0.05, and a normal value of 0.04. Comparing the field calculated channel $n$ value of 0.045 to Chow’s proposed values shows that this value is within his proposed range, but near the high end. As floodplain roughness is generally greater than channel roughness, the calculated channel $n$ value was doubled to give us a floodplain $n$ value of 0.09.

On the evening of June 6, 2010, I visited Reach 6 and took a series of photos between 17:30 and 19:00. The peak flow for the 2010 water year was 13.1 m$^3$/s and occurred on this date at 18:15, according to the USGS gage at the mouth of Blackwood Canyon. The peak flow in Reach 6 was estimated by scaling the peak flow at the gage to the watershed area of the lower end of Reach 6 which gave a flow of 12.3 m$^3$/s. In November 2011, these photos were used to determine the water surface elevation at several locations along the length of the constructed channel in Reach 6. The elevation of these locations was mapped using GPS, surveyed, and tied into the same datum used to build the HEC Geo-RAS terrain model. The 2010 HEC RAS model was then calibrated by adjusting the Manning’s $n$ value until the modeled water surface elevations were similar to the surveyed elevations for a flow of 12.3 m$^3$/s. This calibration lowered the original estimates of $n$ to 0.04 for the channel and 0.08 for the floodplain. Table 4 compares the surveyed elevations and modeled elevations for the series of points used in the model calibration to the 12.3 m$^3$/s discharge.

In summer 2010, after the spring snowmelt peak, field mapping was conducted to map the extent of the project that was inundated by water. Mapping was done by using the series of photos taken during the spring 2010 peak flow, then looking for high water stage indicators such as areas of organics deposited on the edges of the floodplain and floodplain surfaces that were re-organized or sorted by the passing of the high water stage. Since the restoration work was
<table>
<thead>
<tr>
<th>Distance Upstream from Bottom or Reach 6 Project Boundary (m)</th>
<th>Surveyed Water Surface Elevation (m)</th>
<th>HEC-RAS Modeled Water Surface Elevation (m)</th>
<th>Elevation Difference (Surveyed - Modeled) Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
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<td>1922.35</td>
<td>0.05</td>
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<tr>
<td>245</td>
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<td>765</td>
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<td>988</td>
<td>1,927.71</td>
<td>1927.69</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 4. This table compares the water surface elevation with the modeled water surface elevation once the HEC-RAS model was calibrated to a discharge of 12.3 m$^3$/s. Distance upstream is the distance up the channel from the downstream Reach 6 project boundary. The elevation difference is the surveyed elevation minus the modeled elevation.

completed in fall 2009, and this event was the first flow to inundate the floodplain, any indicators of high water stage in the project area were assumed to be from the spring 2010 peak flow.

The location of field indicators of high water stage were recorded with a Trimble GeoXT GPS, and the data were differentially corrected to remove any atmospheric disturbances at the time of acquisition. These data were then brought into ArcGIS, and a polygon of the area inundated by water was created from these field indicators. The mapped extent of flooding is very similar to the modeled area inundated by water for the same discharge. While the modeled flood did not capture all of the islands sticking up within the area of flooding, the outer limits of the mapped flood and the modeled flood were quite similar.

HEC-RAS was run with the 2007 and 2010 models using the flows shown in Table 5. For each flow that was modeled, HEC-RAS calculated the water surface at each cross section and the shear stress that was generated at that cross section. After the HEC-RAS model was run, the model output was brought back into HEC Geo-RAS. Using HEC Geo-RAS, I was able to convert the water surface elevation found at each cross section into a series of polygons of the
<table>
<thead>
<tr>
<th>Event</th>
<th>Flow (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5-year peak</td>
<td>7.4</td>
</tr>
<tr>
<td>2-year peak</td>
<td>10.7</td>
</tr>
<tr>
<td>2.3-year peak (spring 2010 peak)</td>
<td>12.3</td>
</tr>
<tr>
<td>3-year peak</td>
<td>16.0</td>
</tr>
<tr>
<td>4-year peak</td>
<td>20</td>
</tr>
<tr>
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<td>23</td>
</tr>
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<td>10-year peak</td>
<td>37</td>
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<tr>
<td>15-year peak</td>
<td>47</td>
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<tr>
<td>20-year peak</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 5. This table shows instantaneous peak flows at Reach 6 used to model the area inundated by water and shear stress. Flows were acquired from the USGS gage #10336660, Blackwood Creek Near Tahoe City California located at the mouth of Blackwood Canyon (USGS, 2011) and scaled down to the watershed for Reach 6.

area inundated by water. All the polygons were then trimmed to the upstream and downstream extents of the Reach 6 restoration project area. The area of each polygon was then calculated, and the 2007 and 2010 areas were compared for each flow.

Once the models were run in HEC-RAS, I also compared the average boundary shear stress generated by each flow. HEC-RAS calculates the shear stress at each cross section for a given flow, and gives a value for each cross section. Cross sections extended across the channel and floodplain. The number and location of cross sections is different in the pre-restoration and post-restoration models. In order to compare the difference in shear stress between the pre-restoration conditions and the post-restoration conditions, the mean cross section shear stress was calculated for each flow. Using these values, I compared how the shear stress had changed from pre-restoration conditions to post-restoration conditions for the same flow.

**2.3 Sediment Deposition/Scour Mapping and Sampling**

The Blackwood Creek Phase III, Stream and Floodplain Restoration Project Environmental Assessment states that one of the objectives of restoration work in Reach 6 was to
“Reduce fine sediment and nutrient delivery rate to Lake Tahoe through stabilization of stream channels and reconnecting channels to floodplains…” (USDA, 2008). From this objective, two research questions were developed that will be used to help us determine if this project was successful in achieving these objectives. These questions are:

1. What was the approximate volume of sediment deposition that occurred on the Reach 6 floodplain during the spring runoff of 2010?

2. What are the particle size characteristics of areas of sediment deposition on the floodplain, particularly as they relate to sand and mud (< 2mm)?

During the spring snowmelt of 2010, Blackwood Creek Reach 6 had a peak flow of 12.3 m$^3$/s (a 2.3-year recurrence peak flow). This was the highest peak flow to occur since the Reach 6 restoration project was completed in October 2009. After flows dropped in summer 2010, areas of scour and new areas of deposition were observed within the project area. In order to document the changes that occurred, I mapped the areal extent and average depth of areas of scour and deposition.

The areal extent of areas of deposition and scour was mapped in two ways. The boundaries of some deposit/scour areas were recorded using a Trimble GeoXT GPS. Once collected, these data were differentially corrected to remove any atmospheric disturbances at the time of acquisition and the data were brought into ArcGIS. Another technique used in mapping was to use a tape measure to measure the extent of the area of deposit/scour and hand draw the shape onto a base map of the project area. This hand-drawn map was then scanned and georeferenced in ArcGIS, and polygons were digitized around the hand-drawn areas. These digitized areas were then checked against field notes to determine if the area of the polygon digitized was similar in surface area to the surface area of the deposit/scour area measured in the field. This method of mapping polygons was used when satellite reception was poor or when
polygons were either small or long and narrow. In the latter case, measuring the polygon in the field was thought to be a better method of mapping as the opposing edges of the polygons were so close that they might be within the resolution of the GPS.

In many locations, adjacent deposition polygons share a common boundary. In these cases, the polygons were mapped as being distinct from one another by some distinguishing characteristic such as the estimated median surface grain size (D50) and/or the estimated average depth of the deposit at the time that the deposit was mapped.

Areas that were identified as being reorganized during the high flow, but were not predominantly an area of deposition or scour, were also mapped using these same methods. As these polygons contained a mixture of both deposition and scour, these polygons were labeled as mixed polygons.

In order to calculate volumes for deposition and scour in the project, I needed to have a thickness to assign to each polygon of deposition/scour. Average thicknesses for deposition polygons were measured using two methods. Deposits that were less coarse were probed for depth using a V-Star rod. This is a stainless steel rod with depth increments on the side. The rod was pressed vertically into the deposit until coarser, more resistant material under the deposit was encountered. In deposits of coarser material, shovels were used to dig through the deposit to identify the thickness of the deposit. In most locations, a boundary could be clearly identified between the underlying surface that was constructed during the restoration work and the overlying deposits which tended to be better sorted. The number of locations that thickness was measured varied for each polygon. Measurement locations were taken near the edges and in the middle of the mapped deposits. In some deposits, especially the fine sediment deposits, there were areas where the thickness of the deposit was much greater than the rest of the mapped
polygon boundary. This was frequently found on the downstream side of logs or rocks on the floodplain that created an area of low velocity water where fines would aggrade. These areas of thicker than normal deposits were considered outliers and were not used to determine the average deposit thickness.

A random approach was used to determine the number of measurements taken. No standard number of measurements was used. The number of measurements taken was determined in the field based on my professional judgment regarding how many measurements were needed to determine an average thickness for that particular polygon. The number of measurements was based upon the size of the polygon and the variability of the measurements as they were taken. Individual measurements were not recorded; rather, measurements were taken until a reasonable estimate of the average thickness could be determined. Larger deposits were sampled in more locations than smaller deposits, and the thicker deposits were sampled in more locations than thinner deposits. Deposits that were found to have greater variability in the measured depth were sampled more extensively than were deposits that had more uniform thickness measurements. The smallest polygons were sampled in at least four locations, and the largest polygons were sampled in more than 20 locations.

For estimates of areas of scour, assumptions had to be made as to the shape of the landscape before it was removed. Many of the areas of scour were associated with side channels across the floodplain and areas of bank scour adjacent to the main channel. At the locations of new side channels across the floodplain, it was assumed that the channel formed in material that was previously at the same elevation as the surrounding material. These new side channels were mapped (for surface area and depth) as an area of scour. For areas of bank erosion, it was assumed that the banks in the area scoured were similar in shape to the banks immediately
upstream and downstream that showed no signs of scour. In addition, photos taken immediately post-project were referenced to assist in determining the extent of deposition and scour.

In order to characterize the grain size distribution of areas of deposition in the project, samples were gathered within the mapped areas of deposition. To do this, the deposits were first categorized by their surface grain size. Deposits were classified into one of three classes based upon a visual estimate of the D50 of the surface of the deposit. Fine deposits, i.e. sand and mud, had a surface D50 of less than 2mm, medium deposits had a surface D50 of 2mm to 16mm, i.e. very fine, fine and medium gravels and coarse deposits had a D50 greater than 16mm, i.e. coarse gravel, very coarse gravel and cobbles. ArcGIS was then used to select the polygons with the largest surface area within each of the three size classes. Nine samples were gathered in the fine size class, nine samples were taken in the medium size class, and ten samples were gathered in the coarse size class.

In an effort to not bias the sampling location, the following method was used to select the location on the deposit to sample. First, the long axis of the mapped deposit was measured and a number from 0 to 100 was drawn from a bag. This number was then used to select the percent along the tape measure where I would next place the tape measure. At the selected location, the tape measure was stretched perpendicular to the first alignment. Once again, a number was drawn and used to determine the percent along the second tape measure alignment where the sample would be taken. Using this method, 28 bulk samples were gathered in one-gallon Zip-Lock bags. At each sampling location the top layer of the deposit was removed before the sample was collected to try to remove any armoring that may be present. This layer removed was equal to two times the estimated D50 of the surface deposit.
Bunte and Abt (2001) propose that the minimum bulk sample size mass required to obtain a representative sample can frequently be approximated by taking 20 to 100 times the mass of the $D_{\text{max}}$ (the single largest particle in the sample). Table 6 compares the dry sample mass to the $D_{\text{max}}$ mass of the medium and coarse samples. Of the 19 samples, two did not achieve the minimum of 20 times the total sample mass, and all the medium samples fell within the 20 to 100 times minimum range they proposed. As the main goal of this project was to determine the grain size characteristics of the fine size class, all samples collected were used, including the two whose sample mass was less than 20 times $D_{\text{max}}$. Field sieving was not used as samples needed to be wet sieved in order to remove all the finer material from the coarser material in the sample, and therefore needed to be processed in a laboratory.

While it is impossible to precisely characterize the areas of scour in the project area, an effort was made to try to determine what the grain-size distribution may have been. With the exception of the imported boulders (imported material was predominantly greater than 30 cm in diameter), all materials used in the construction of the project in Reach 6 came from the site. This means the mixture of mud, sand, gravel, and cobbles present within the Reach 6 channel and floodplain before restoration is also present within the project area after restoration. To try to characterize what the grain-size distribution may have been for the areas of scour, three locations were chosen to sample. All three locations were in areas that did not appear to have been submerged by the spring 2010 high water stage and were immediately adjacent to areas of bank scour that were mapped along the main channel. Material from these three locations was collected and combined together for processing as one sample.

The bulk sediment samples collected in Reach 6 were then processed for grain size analysis by the Desert Research Institute (DRI) in Reno, NV. First, the samples were oven dried
<table>
<thead>
<tr>
<th>Sample ID #</th>
<th>Size Class</th>
<th>Total Sediment Dry Mass (g)</th>
<th>D&lt;sub&gt;max&lt;/sub&gt; (g)</th>
<th>Total Sediment Dry Mass (g)/D&lt;sub&gt;max&lt;/sub&gt;(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C11-802</td>
<td>Coarse</td>
<td>3,043</td>
<td>290</td>
<td>10.5</td>
</tr>
<tr>
<td>C11-803</td>
<td>Coarse</td>
<td>3,691</td>
<td>78</td>
<td>47.3</td>
</tr>
<tr>
<td>C11-804</td>
<td>Coarse</td>
<td>5,264</td>
<td>189</td>
<td>27.9</td>
</tr>
<tr>
<td>C11-805</td>
<td>Coarse</td>
<td>4,805</td>
<td>222</td>
<td>21.6</td>
</tr>
<tr>
<td>C11-806</td>
<td>Coarse</td>
<td>5,361</td>
<td>756</td>
<td>7.1</td>
</tr>
<tr>
<td>C11-807</td>
<td>Coarse</td>
<td>4,067</td>
<td>120</td>
<td>33.9</td>
</tr>
<tr>
<td>C11-808</td>
<td>Coarse</td>
<td>4,468</td>
<td>152</td>
<td>29.4</td>
</tr>
<tr>
<td>C11-809</td>
<td>Coarse</td>
<td>3,565</td>
<td>126</td>
<td>28.3</td>
</tr>
<tr>
<td>C11-810</td>
<td>Coarse</td>
<td>4,099</td>
<td>198</td>
<td>20.7</td>
</tr>
<tr>
<td>C11-811</td>
<td>Coarse</td>
<td>2,971</td>
<td>78</td>
<td>38.1</td>
</tr>
<tr>
<td>C11-812</td>
<td>Med</td>
<td>3,917</td>
<td>162</td>
<td>24.2</td>
</tr>
<tr>
<td>C11-813</td>
<td>Med</td>
<td>3,887</td>
<td>75</td>
<td>51.8</td>
</tr>
<tr>
<td>C11-814</td>
<td>Med</td>
<td>3,310</td>
<td>25</td>
<td>132.4</td>
</tr>
<tr>
<td>C11-815</td>
<td>Med</td>
<td>3,512</td>
<td>152</td>
<td>23.1</td>
</tr>
<tr>
<td>C11-816</td>
<td>Med</td>
<td>2,945</td>
<td>72</td>
<td>40.9</td>
</tr>
<tr>
<td>C11-817</td>
<td>Med</td>
<td>3,524</td>
<td>62</td>
<td>56.8</td>
</tr>
<tr>
<td>C11-818</td>
<td>Med</td>
<td>2,399</td>
<td>18</td>
<td>133.3</td>
</tr>
<tr>
<td>C11-819</td>
<td>Med</td>
<td>3,427</td>
<td>97</td>
<td>35.3</td>
</tr>
<tr>
<td>C11-820</td>
<td>Med</td>
<td>1,114</td>
<td>20</td>
<td>55.7</td>
</tr>
</tbody>
</table>

Table 6. This table compares the dry bulk sample mass to the mass of the largest single particle in the sample for bulk samples.

overnight. If organic matter was present, it was burned off. The samples were then dry sieved with a 2-mm sieve to separate the gravel and cobbles from the finer fraction. The sand and mud was then wet sieved with a 62.5-um sieve to separate the sand from the mud, and each sample was then dried and weighed. From the mud (<62.5um) portion of the sample, a subsample volume was taken to run through a Micromeritics Saturn DigiSizer 5200 laser particle size analyzer. Using this method, I estimated the percent of silt and clay from the analyzed mud subsample by volume. I then used these percents to determine the percent silt and clay for the entire <62.5 um portion of the sample, with the assumption that the subsample was representative of the <62.5 um portion.
I combined the grain-size distribution data for sand, gravel and cobble (percent by weight) with size distribution data for the silt and clay (percent by volume). To combine these I assumed that the density of the silts and clays is similar to the other material in the sample. This is a common assumption made by researchers and should be a reasonable assumption as the common density range proposed for clays is 2.6 - 2.8 g/cm$^3$ (US Department of Energy, 2011). This density range is close to the density range proposed for andesitic rocks (2.65 g/cm$^3$) (Edumine, 2011) that are prevalent in the watershed (California Geologic Survey, 2005). With this assumption, I combined the <62.5 um grain-size distribution data (a distribution by volume) with the grain-size distribution of the gravel+ and sand (done by weight). Combining these gave me a grain-size distribution of each sample by weight.

In order to develop a weight to volume ratio for the sample, the volume of each sample was measured. Using the grain-size distribution data by weight (in grams) and the volume of the sample (in liters), I was able to determine the density in g/L of each particle size class for each sample. Samples were then grouped according to their surface D50 used in the sediment deposit/scour mapping, and the average density (g/L) of each particle size in the size distribution was calculated. I then took the volume of each sediment feature mapped and multiplied by the density for a given particle-size class to determine the weight of that volume within the sediment feature.
Chapter 3-Results and Discussion

3.1 Hydraulic Modeling

The area inundated by water at Reach 6 has increased at all flood flows that were modeled for this project (Table 7). The lowest peak flow modeled was the 1.5-year peak flow at 7.4 m$^3$/s. This discharge produced the greatest percentage increase in water inundation between pre-restoration conditions and post-restoration conditions with a 106% increase (area of flooding increased from 14,200 m$^2$ to 29,300 m$^2$). The largest peak flow modeled was the 20-year peak flow at 55 m$^3$/s, and this saw an increase in flooded area of 27% from 38,200 m$^2$ to 48,400 m$^2$.

Looking at Table 7 shows a trend where, for the range of flows modeled, the lowest magnitude peak flows have the greatest percentage increase in the change between pre-restoration flooded area extent and post-restoration flooded area extent, and the largest magnitude peak flows have the smallest increase. Figure 8 shows the flood frequency graph of the scaled flows for Reach 6.

<table>
<thead>
<tr>
<th>Event</th>
<th>Flow (m$^3$/s)</th>
<th>Pre-Restoration Flooded Area (m$^2$)</th>
<th>Post-Restoration Flooded Area (m$^2$)</th>
<th>Increase or Decrease in Flooded Area after Restoration</th>
<th>Change in Flooded Area (m$^2$) from Pre-Restoration to Post-Restoration</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5-year peak</td>
<td>7.4</td>
<td>14,200</td>
<td>29,300</td>
<td>Increase</td>
<td>15,100</td>
<td>106</td>
</tr>
<tr>
<td>2-year peak</td>
<td>10.7</td>
<td>16,100</td>
<td>32,300</td>
<td>Increase</td>
<td>16,300</td>
<td>101</td>
</tr>
<tr>
<td>2.3-year peak (spring</td>
<td>12.3</td>
<td>16,800</td>
<td>33,100</td>
<td>Increase</td>
<td>16,400</td>
<td>97</td>
</tr>
<tr>
<td>2010 peak)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-year peak</td>
<td>16</td>
<td>18,800</td>
<td>34,700</td>
<td>Increase</td>
<td>15,900</td>
<td>85</td>
</tr>
<tr>
<td>4-year peak</td>
<td>20</td>
<td>21,000</td>
<td>36,400</td>
<td>Increase</td>
<td>15,400</td>
<td>74</td>
</tr>
<tr>
<td>5-year peak</td>
<td>23</td>
<td>25,400</td>
<td>37,700</td>
<td>Increase</td>
<td>12,300</td>
<td>48</td>
</tr>
<tr>
<td>10-year peak</td>
<td>37</td>
<td>31,400</td>
<td>43,000</td>
<td>Increase</td>
<td>11,600</td>
<td>37</td>
</tr>
<tr>
<td>15-year peak</td>
<td>47</td>
<td>35,600</td>
<td>46,300</td>
<td>Increase</td>
<td>10,800</td>
<td>30</td>
</tr>
<tr>
<td>20-year peak</td>
<td>55</td>
<td>38,200</td>
<td>48,400</td>
<td>Increase</td>
<td>10,200</td>
<td>27</td>
</tr>
</tbody>
</table>

*Table 7. This table compares the modeled flooded area between the 2007 pre-restoration conditions and the 2010 post-restoration conditions for a range of flows.*

The average cross section shear stress has decreased for all flood peak flows that were modeled for this project (Table 8). The 1.5-year recurrence peak flow is 7.4 m$^3$/s and saw a
Figure 8. Log Pearson type III flood frequency analysis for the downstream end of Blackwood Creek Reach 6. Instantaneous peak flows were taken from the USGS gage #10336660, Blackwood Creek Near Tahoe City California located at the mouth of Blackwood Canyon (USGS, 2011) and scaled down to the watershed for Reach 6.

<table>
<thead>
<tr>
<th>Event</th>
<th>Flow m$^3$/s</th>
<th>Pre-Restoration (N/m$^2$)</th>
<th>Post-Restoration (N/m$^2$)</th>
<th>Increase or Decrease in Shear Stress after Restoration?</th>
<th>Percent change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5-year peak</td>
<td>7.4</td>
<td>37.5</td>
<td>23</td>
<td>Decrease</td>
<td>-39%</td>
</tr>
<tr>
<td>2-year peak</td>
<td>10.7</td>
<td>43.2</td>
<td>26.3</td>
<td>Decrease</td>
<td>-39%</td>
</tr>
<tr>
<td>2.3-year peak (peak flow of spring 2010)</td>
<td>12.3</td>
<td>45.7</td>
<td>28</td>
<td>Decrease</td>
<td>-39%</td>
</tr>
<tr>
<td>3-year peak</td>
<td>16</td>
<td>50.4</td>
<td>29.9</td>
<td>Decrease</td>
<td>-41%</td>
</tr>
<tr>
<td>4-year peak</td>
<td>20</td>
<td>52.7</td>
<td>29.5</td>
<td>Decrease</td>
<td>-44%</td>
</tr>
<tr>
<td>5-year peak</td>
<td>23</td>
<td>54</td>
<td>31.4</td>
<td>Decrease</td>
<td>-42%</td>
</tr>
<tr>
<td>10-year peak</td>
<td>37</td>
<td>58.2</td>
<td>33</td>
<td>Decrease</td>
<td>-43%</td>
</tr>
<tr>
<td>15-year peak</td>
<td>47</td>
<td>64.8</td>
<td>36.2</td>
<td>Decrease</td>
<td>-44%</td>
</tr>
<tr>
<td>20-year peak</td>
<td>55</td>
<td>69.4</td>
<td>36.3</td>
<td>Decrease</td>
<td>-48%</td>
</tr>
</tbody>
</table>

Table 8. This table shows the average cross-sectional shear stress that was modeled in HEC-RAS for pre-restoration conditions and post-restoration conditions for a range of flows.
decrease in average cross-sectional shear stress of 39%. The greatest difference was for the 20-year recurrence peak flow that had a decrease in average cross-sectional shear stress between pre-restoration and post-restoration conditions of 48%. Figure 9 shows that the modeled values for average cross-sectional shear stress increased with discharge for both the pre-restoration conditions and post-restoration conditions. This figure also shows that as discharge increased, the difference between pre-restoration and post-restoration conditions also increased as the pre-restoration average cross-sectional shear stress increased more rapidly. This means that for the range of modeled values, the difference in average cross-sectional shear stress is less for the lower recurrence peak flows and greater for the less common, longer recurrence peak flow.

3.2 Sediment Deposition/Scour Mapping and Sampling

Comparing the area of the mapped regions of deposition, scour, and mixed areas (areas showing a mixture of deposition and scour), shows that there are 11,560 m$^2$ of deposition, 591 m$^2$ of scour and 729 m$^2$ of mixed (Table 9). This change means that there was nearly 20 times more deposition area than scour area. Comparing the calculated volumes shows that there was
1,129 m$^3$ of deposition and 142 m$^3$ of scour in Reach 6. This means that there was roughly seven times more deposition volume than scour volume. While the area of scour mapped and volume of scour calculated were both less than for deposition, the difference between them is less once the volume of the deposits is calculated. This was because the areas of scour tended have a greater average depth, as many of the mapped areas of scour were where bank erosion occurred. The greatest depth assigned to any area of deposition or scour was 1.5 m where bank erosion occurred. While there is, of course, some uncertainty involved with the mapping of areas of sediment deposition and scour and in estimating the thickness of such areas, there seems to be a clear trend in this data of a greater volume of deposition than volume of scour.

<table>
<thead>
<tr>
<th></th>
<th>Surface Area (m$^2$)</th>
<th>Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit</td>
<td>11,560</td>
<td>1,129</td>
</tr>
<tr>
<td>Scour</td>
<td>591</td>
<td>142</td>
</tr>
<tr>
<td>Mix</td>
<td>729</td>
<td>na</td>
</tr>
</tbody>
</table>

*Table 9. This table shows the area and volume of areas of deposition, scour and mixed areas (areas showing a mixture of deposition and scour) that were mapped in the summer of 2010 in Reach 6.*

Combining the sediment deposition/scour volumes with the sediment sampling data shows some of the characteristics of the deposited material and the scoured material. Looking at Table 10 shows that there were 623 Mg of gravel and coarser (>2mm), 776 Mg of sand, 114 Mg of silt and 28 Mg of clay deposited in Reach 6, and there were 188 Mg of gravel and coarser

<table>
<thead>
<tr>
<th>Total Weight in Deposit</th>
<th>Total Weight in Scour</th>
<th>More Deposition or Scour?</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel+</td>
<td>Sand</td>
<td>Silt</td>
<td>Clay</td>
</tr>
<tr>
<td>623 Mg</td>
<td>776 Mg</td>
<td>114 Mg</td>
<td>28 Mg</td>
</tr>
<tr>
<td>188 Mg</td>
<td>83 Mg</td>
<td>7 Mg</td>
<td>3 Mg</td>
</tr>
</tbody>
</table>

*Table 10. This table shows weight in megagrams of the gravel and coarser, sand, silt and clay in the areas of deposit and scour. Also shown is whether there was more deposition or scour for each size class and what the difference was between the two values.*
Figure 10. Map showing the modeled area inundated with water by the HEC-RAS/HEC Geo-RAS modeled 2.3-year, 12.3 m$^3$/s flow and the areas of deposition, scour and areas that had both deposition and scour that were mapped in the summer of 2010.

>2mm), 83 Mg of sand, 7 Mg of silt and 3 Mg of clay scoured. Of the four size classes used in this study, sand was the class that had the greatest amount of deposition with 776 Mg. As was stated previously, there is greater uncertainty with the grain-size distribution information for the scoured areas because this estimate is for material that is no longer there.

Comparing the weight of each size class of deposition and scour shows that all size classes had more deposition than scour. The greatest difference between deposition and scour
was for the sand size class where there was a difference of 693 Mg between deposition and scour. Figure 11 displays the relative weights of scour and deposition by size class.

Looking at the locations of deposition and scour (Figure 10) shows several patterns. The coarse deposits that were mapped tended to be adjacent to the channel. This pattern is expected as flows over the floodplain would be slower than along the channel and would therefore be less competent to transport larger particles. The majority of fine deposits were mapped in depressions on the floodplain that were left during construction of the restoration project and down-valley from the roughness structures. Here, far from the thalweg, where flow velocities would be low and cross section area is high, is where I would expect finer material to drop out of suspension.

In the upstream portion of Reach 6 there are more coarse and medium deposits on the floodplain than are found downstream. Because of the deposition of sediment on the upstream portion of the reach, it is likely that there is less sediment making it to the downstream portions, and therefore, fewer coarse and medium deposits are mapped there. Scour regions tended to fall along the edges of the constructed channel where flow velocities would have been highest at the

![Figure 11. The weight in megagrams of the deposition and scour for each size class used in this study as well as the total weight of deposition and scour.](image-url)
2.3-year recurrence flow. Scour also occurred in two locations where flow cut across a meander and formed a cut off channel.

### 3.3 Discussion

This post project appraisal has shown that since restoration work concluded, more sediment has aggraded than scoured out of the reach. In addition, the extent of flooding increased for all flows modeled, with the most significant increase for the smallest modeled flood, a 1.5 year return flow. This shift in extent of flooding and changing the reach from one that was scouring more than it aggraded into one that is now aggrading more than it scours is consistent with the goals of the project. In the long term, if the project continues to aggrade, it has the potential to rebuild its floodplain by continuing to deposit sediment on the floodplain. The project was constructed under the assumption that a surplus of sediment is still being supplied to the reach from upstream reaches and over time the supply will decrease as the upstream reaches continue to recover. The Reach 6 restoration project was designed to absorb much of the sediment currently being supplied to the reach. If aggradation continues, the depressions on the floodplain may fill in and the rock-log floodplain roughness structures will be buried.

The design of the Reach 6 restoration project included building rock-log floodplain roughness structures. These are intended to provide roughness on the floodplain until native vegetation can colonize and proved roughness. Willows, cottonwoods and aspen were planted throughout the project area in 2009, at the end of construction. If they continue to grow, these will provide floodplain roughness as they mature in the future. In addition to planted material, it is anticipated that the floodplain will become colonized by seeds, broken roots, and branches that
deposit as sediment aggrades on the floodplain. This was observed in 2010 as several locations where aggradation occurred also showed natural willows colonization.

One long term concern of the project is that the decrease in slope brought about by the longer, more sinuous channel may promote excessive aggradation on the channel bed. Surplus sediment aggradation in the channel is believed to be a primary cause of destabilization in Reach 6 and it is not unreasonable to think that this could happen again. If the bed aggrades, then the channel capacity would decrease and the extent of flooding could increase even further. If this were to occur, then the potential for cutting off meanders would increase. The rock-log structures that extend from the terrace, out onto the floodplain will prevent the channel from forming a new channel directly down valley through the project area but will not prevent shorted meander cut-offs.

In two locations, sediment mapping showed that new channels were starting to form that cut across meanders. The western channel formed as flood flows overtopped a rock structure and further incision is limited due to the rock structure that it flows over. The eastern channel formed across a gravel meander bend. This channel has the potential to change and should be monitored for future changes. The two cut off channels that showed up in the sediment mapping appear to have remained stable as of summer 2010. These locations are a potential location where change may occur and should be monitored for future change. If the channel bed does aggrade, then I might expect the cut-off channels to enlarge as more flow is diverted into them. Monitoring these channels for future change should include surveying the size of each to determine if they are enlarging over time and establishing photo points that capture the channels.

Within the project area are a series of rock-log structures that are tied into the terrace. One potential failure that could occur is if one of these structures was to be flanked. If erosion
occurs along the terrace edge then a new flow path could be established around one of these structures and directly into the finely textured forest soils. If this were to occur, the effectiveness of the structure in deflecting flood flows back towards the channel would be eliminated and a substantial amount of erosion would occur. Monitoring for this event should include photo points and visiting the site at flood flows to look for any signs that this is occurring.

In order to monitor long term changes of Reach 6, a long profile was surveyed of the thalweg in Reach 6 and 12 cross sections were established in summer 2011. The long profile and cross sections will be useful in monitoring changes in the channel and will allow for monitoring future channel aggradation. In addition, a series of total station points were recorded in 2010 by Water Ways Consultants. These repeatable points document location and elevation of points on the channel bed and some portions of the floodplain. Repeating these points in the future will assist in determining if the channel is aggrading or changing in an unanticipated way. In 2009, photo points were established in Reach 6. Repeating these will assist in monitoring changes along the channel and floodplain, in addition to monitoring the growth of planted vegetation and determining whether the project is being colonized by vegetation. There is a 2010 aerial photo of the completed project. Additional aerial photos could be collected to monitor larger scale changes in the channel planform or extent of vegetative cover.

**Chapter 4: Conclusion**

The Reach 6 restoration project was designed to reconnect the channel to the adjacent floodplain. Hydrologic modeling using HEC-RAS has shown that restoration work in Blackwood Creek Reach 6 has increased the extent of flooding in the reach. The 1.5-year flow (the smallest peak flow modeled for this project) had the greatest percent increase in area inundated by water as it more than doubled between pre-restoration conditions and post-restoration conditions. At
higher, less frequent flows, the percent increase in flooded area between pre-restoration conditions and post-restoration conditions was less, but the post-restoration project still produced a larger area of flooding.

The Reach 6 restoration project was also designed to reduce shear stress in the reach. Hydrologic modeling of Reach 6 showed that for all modeled flows, shear stress was less for the post-restoration conditions for all flows modeled. With the lowering of the relative shear stress in Reach 6, it is likely that the potential for continued erosion in the reach has decreased. Additional evidence of this can be found in the extensive deposits that formed on the floodplain after the first spring peak flow following completion of the project. While this work shows that the average cross-sectional shear stress has decreased, the pattern of deposition and scour observed in Reach 6 shows that there are still regions of high shear stress. In several locations along the channel, scour was observed where higher velocities and shear stress caused erosion along the channel banks. Lower shear stress can be assumed in many locations where fines were deposited on the floodplain. Most of these locations were downstream from roughness structures that were built as part of the restoration project.

Another objective of the Reach 6 restoration project was to promote aggradation on the floodplain. Comparing the volumes shows that there was more deposition than scour, with 1,129 m$^3$ of deposition within the project area and 142 m$^3$ of scour. Mapping of areas of deposition and scour within the reach had a level of uncertainty to it. Errors could have been made in mapping the areal extent of the deposits or in assigning an average depth to the mapped deposits. Even if the total volume of scour was subsequently deposited in the project area again and mapped as a deposit, there would still be 987 m$^3$ of new sediment deposition in the project area. This shows a
clear indication that there was significantly more deposition in the project area than there was scour.

One of the reasons that restoration work in Reach 6 was initiated was to arrest the erosion of finer bank material. The project implemented in 2009 was designed to promote aggradation onto the floodplain in an effort to rebuild surfaces that had previously eroded away. Of particular interest was the finer fraction of sediment deposited. Of the 1,541 Mg of sediment deposited within the project area, 40.4% was gravel and coarser, 50.4% was sand, 7.4% was silt and 1.8% was clay. This means that 776 Mg of sand, 114 Mg of silt and 28 Mg of clay were deposited in the project reach. Looking at this another way, 918 Mg or 59.6% of the sediment deposited in Reach 6 during the spring 2010 peak flow was <2mm.

Overlaying the mapped areas of deposition and scour with the inundated area modeled for the 2.3-year recurrence flow shows a few patterns. The larger fine deposits fell along the margins of the flooded area and also in deeper regions on the floodplain. Coarser deposits were only mapped adjacent to the channel where velocities were great enough to transport them.

References Cited


Gavigan, T., 2007, Total Maximum Daily Load for Bedded Sediment, Blackwood Creek; California Regional Water Quality Control Board, Lahontan Region

Kiesse, M., 2011, Restoration in Blackwood Creek Reach 6: Initial Monitoring Results and Analysis


USGS, 1982, Guidelines for determining flood flow frequency, Bulletin 17B of the Hydrology Subcommittee. Interagency Advisory Committee on Water Data

Appendix

Pre-Restoration Area Inundated by Water

Figure 12. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 2.3-year, 12.3 m³/s flow, the peak flow that occurred in the spring of 2010. The area inundated by water is 17,150 m².

Figure 13. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 1.5-year, 7.4 m³/s flow. The area inundated by water is 14,836 m².
Figure 14. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 2-year, 10.7 m$^3$/s flow. The area inundated by water is 19,951 m$^2$.

Figure 15. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 3-year, 16 m$^3$/s flow. The area inundated by water is 19,951 m$^2$. 
Figure 16. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 4-year, 20 m$^3$/s flow. The area inundated by water is 22,952 m$^2$.

Figure 17. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 5-year, 23 m$^3$/s flow. The area inundated by water is 29,731 m$^2$. 
Figure 18. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 10-year, 37 m$^3$/s flow. The area inundated by water is 39,237 m$^2$.

Figure 19. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 15-year, 47 m$^3$/s flow. The area inundated by water is 41,377 m$^2$. 
Figure 20. August 17, 2007 aerial photo of Blackwood Creek Reach 6 (before restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 20-year, 55 m³/s flow. The area inundated by water is 43,664 m².
Post-Restoration Area Inundated by Water

Figure 21. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 2.3-year, 12.3 m$^3$/s flow, the peak flow that occurred in the spring of 2010. The area inundated by water is 32,276 m$^2$.

Figure 22. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 1.5-year, 7.4 m$^3$/s flow. The area inundated by water is 29,394 m$^2$. 
Figure 23. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 2-year, 10.7 m³/s flow. The area inundated by water is 34,188 m².

Figure 24. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 3-year, 16 m³/s flow. The area inundated by water is 34,188 m².
Figure 25. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 4-year, 20 m$^3$/s flow. The area inundated by water is 35,566 m$^2$.

Figure 26. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 5-year, 23 m$^3$/s flow. The area inundated by water is 41,374 m$^2$. 
Figure 27. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 10-year, 37 $m^3/s$ flow. The area inundated by water is 50,235 m$^2$.

Figure 28. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 15-year, 47 $m^3/s$ flow. The area inundated by water is 52,004 m$^2$. 
Figure 29. November 3, 2010 aerial photo of Blackwood Creek Reach 6 (after restoration work) with the area inundated by water for a HEC-RAS/HEC Geo-RAS modeled 20-year, 55 m³/s flow. The area inundated by water is 54,379 m².
Terrain Models Used for HEC-RAS Modeling

Figure 30. Pre-restoration (2007) triangular irregular network (TIN) generated from one foot contour lines. This TIN was used in HEC-RAS/HEC Geo-RAS modeling.

Figure 31. Post-restoration (2010) triangular irregular network (TIN) generated from one foot contour lines. This TIN was used in HEC-RAS/HEC Geo-RAS modeling.
Figure 32. West half of the map showing the unique number assigned to each polygon.
Figure 33. East half of the map showing the unique number assigned to each polygon.

1969 Gravel Mine and Reach 6 Overview
Figure 34. Map showing Blackwood Creek from the gravel mine, downstream to Reach 6. Blackwood Creek is in the diversion channel (in red) in this 1969 aerial photo.

Gravel Mine Location Maps from 1939 and 1969
Figure 35. Gravel mine location in 1939 before gravel mining started.

Figure 36. Gravel mine in 1969 with Blackwood Creek in the diversion channel around the mine. This aerial photo shows the same location as the 1939 photo above.

Sediment Deposition/Scour Mapping Summary Data
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<tr>
<td>Deposit</td>
<td>Medium</td>
<td>15.48</td>
<td>0.10</td>
<td>1.58</td>
<td>101</td>
</tr>
<tr>
<td>Deposit</td>
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<td>18.69</td>
<td>0.30</td>
<td>5.61</td>
<td>29</td>
</tr>
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<td>Medium</td>
<td>26.82</td>
<td>0.10</td>
<td>2.55</td>
<td>103</td>
</tr>
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<td>0.10</td>
<td>3.17</td>
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<td>2.75</td>
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<td>7.75</td>
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<td>0.50</td>
<td>34.54</td>
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</tr>
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<td>0.08</td>
<td>6.55</td>
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<td>Deposit</td>
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<td>0.15</td>
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<td>0.05</td>
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<td>0.10</td>
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<td>0.05</td>
<td>11.03</td>
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</tr>
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<td>0.10</td>
<td>29.94</td>
<td>116</td>
</tr>
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</tr>
<tr>
<td>Deposit</td>
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<td>0.20</td>
<td>4.07</td>
<td>49</td>
</tr>
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<td>Deposit</td>
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<td>4.16</td>
<td>10</td>
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<td>0.41</td>
<td>43.70</td>
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</tr>
<tr>
<td>Deposit</td>
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<td>26.39</td>
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</tr>
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<tr>
<td>Deposit</td>
<td>Coarse</td>
<td>398.31</td>
<td>0.11</td>
<td>45.41</td>
<td>124</td>
</tr>
</tbody>
</table>

Table 11. This table shows the surface grain size class, area, depth, volume and polygon number of deposition polygons that were mapped in the summer of 2010.
<table>
<thead>
<tr>
<th>Type of Polygon (Deposit or Scour)?</th>
<th>Surface Grain Size</th>
<th>Polygon Area (m²)</th>
<th>Average Polygon Depth (m)</th>
<th>Volume Assigned to Polygon (m³)</th>
<th>Polygon Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scour</td>
<td>na</td>
<td>6.15</td>
<td>0.60</td>
<td>3.69</td>
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<tr>
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<td>1.03</td>
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<td>Scour</td>
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<td>9.87</td>
<td>1.50</td>
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<td>1.00</td>
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<td>39</td>
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<td>1.57</td>
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<td>0.20</td>
<td>2.29</td>
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<td>0.10</td>
<td>1.51</td>
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<tr>
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<td>na</td>
<td>15.96</td>
<td>0.25</td>
<td>4.05</td>
<td>87</td>
</tr>
<tr>
<td>Scour</td>
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<td>17.40</td>
<td>0.15</td>
<td>2.61</td>
<td>25</td>
</tr>
<tr>
<td>Scour</td>
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<td>20.29</td>
<td>0.15</td>
<td>3.04</td>
<td>42</td>
</tr>
<tr>
<td>Scour</td>
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<td>20.47</td>
<td>0.15</td>
<td>3.07</td>
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<tr>
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<td>0.20</td>
<td>4.17</td>
<td>80</td>
</tr>
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<td>0.15</td>
<td>3.66</td>
<td>121</td>
</tr>
<tr>
<td>Scour</td>
<td>na</td>
<td>24.86</td>
<td>0.30</td>
<td>7.46</td>
<td>27</td>
</tr>
<tr>
<td>Scour</td>
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<td>29.84</td>
<td>0.25</td>
<td>7.58</td>
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<td>Scour</td>
<td>na</td>
<td>30.11</td>
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<td>6.02</td>
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</tr>
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<td>32.82</td>
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<td>9</td>
</tr>
<tr>
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<td>0.15</td>
<td>5.37</td>
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</tr>
<tr>
<td>Scour</td>
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<td>36.42</td>
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<td>70</td>
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<tr>
<td>Scour</td>
<td>na</td>
<td>67.41</td>
<td>0.10</td>
<td>6.88</td>
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<tr>
<td>Scour</td>
<td>na</td>
<td>89.77</td>
<td>0.25</td>
<td>22.80</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 12. This table shows the area, depth, volume and polygon number of scour polygons that were mapped in the summer of 2010.
Figure 37. Map showing the location where sediment samples were taken in the summer of 2010.
HEC-RAS Model Run Outputs

Pre-restoration HEC-RAS model run summary for a 3-year recurrence flow of 16 m$^3$/s.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 919.999  Profile: PF 3
Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 907.2966  Profile: PF 3
Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 894.2064  Profile: PF 3
Note: Manning's n values were composited to a single value in the main channel.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 866.0478  Profile: PF 3
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 851.7308  Profile: PF 3
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 837.3942  Profile: PF 3
Warning: The energy loss was greater than 1.0 ft (0.3 m). between the current and previous cross section. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 804.3423  Profile: PF 3
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 748.9328  Profile: PF 3

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 734.1041  Profile: PF 3

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 718.8632  Profile: PF 3

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 670.7289  Profile: PF 3

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 653.0986  Profile: PF 3

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 635.0583  Profile: PF 3

Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 621.2635  Profile: PF 3

Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 605.3036  Profile: PF 3

Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 589.1367  Profile: PF 3

Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning’s n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007   RS: 564.0449   Profile: PF 3
Warning: Divided flow computed for this cross-section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007   RS: 542.7491   Profile: PF 3
Warning: Divided flow computed for this cross-section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning’s n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007   RS: 529.6509   Profile: PF 3
Warning: Divided flow computed for this cross-section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning’s n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007   RS: 511.5188   Profile: PF 3
Warning: Divided flow computed for this cross-section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning’s n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007   RS: 489.3688   Profile: PF 3
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 471.0776 Profile: PF 3

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 454.2979 Profile: PF 3

Warning: Divided flow computed for this cross-section.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 431.2071 Profile: PF 3

Warning: Divided flow computed for this cross-section.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 410.6381 Profile: PF 3

Warning: Divided flow computed for this cross-section.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 394.9552 Profile: PF 3

Warning: Divided flow computed for this cross-section.

Warning: The energy loss was greater than 1.0 ft (0.3 m) between the current and previous cross section. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 376.5406 Profile: PF 3

Warning: Divided flow computed for this cross-section.

Warning: The energy loss was greater than 1.0 ft (0.3 m) between the current and previous cross section. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 353.7027 Profile: PF 3
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 338.4825  Profile: PF 3
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 321.2716  Profile: PF 3
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 301.3132  Profile: PF 3
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 277.0804  Profile: PF 3
Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 250.8588  Profile: PF 3
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 217.9387  Profile: PF 3
Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 197.4599  Profile: PF 3
Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 173.845 Profile: PF 3
Warning: The energy loss was greater than 1.0 ft (0.3 m) between the current and previous cross section. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 149.0853 Profile: PF 3
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 127.4677 Profile: PF 3
Warning: Divided flow computed for this cross-section.

Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 111.1129 Profile: PF 3
Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 92.49023 Profile: PF 3
Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007 RS: 66.48812 Profile: PF 3
Warning: Divided flow computed for this cross-section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Cr Reach: Reach 6 2007  RS: 40.73083  Profile: PF 3

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Table 13. Pre-restoration HEC-RAS model run summary for a 3-year recurrence flow of 16 m$^3$/s.

Post-restoration HEC-RAS model run summary for 3-year recurrence flow of 16 m$^3$/s.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1410.184  Profile: PF 4

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1398.095  Profile: PF 4

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1378.832  Profile: PF 4

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1362.123  Profile: PF 4

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1309.606  Profile: PF 4

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1294.026  Profile: PF 4

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1234.694  Profile: PF 4

Note: Manning's n values were composited to a single value in the main channel.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1206.949  Profile: PF 4

Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1194.896 Profile: PF 4

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1182.858 Profile: PF 4

Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1167.17 Profile: PF 4

Warning: The energy equation could not be balanced within the specified number of iterations. The program used critical depth for the water surface and continued on with the calculations.

Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Warning: During the standard step iterations, when the assumed water surface was set equal to critical depth, the calculated water surface came back below critical depth. This indicates that there is not a valid subcritical answer. The program defaulted to critical depth.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1154.608 Profile: PF 4

Warning: Multiple water surfaces were found that could balance the energy equation. The program selected the water surface whose main channel velocity head was the closest to the previously computed cross section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1139.053 Profile: PF 4
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1112.869 Profile: PF 4
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1095.714 Profile: PF 4
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1077.561 Profile: PF 4
Warning: The energy equation could not be balanced within the specified number of iterations. The program used critical depth for the water surface and continued on with the calculations.
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Warning: During the standard step iterations, when the assumed water surface was set equal to critical depth, the calculated water surface came back below critical depth. This indicates that there is not a valid subcritical answer. The program defaulted to critical depth.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 1068.084 Profile: PF 4
Warning: Multiple water surfaces were found that could balance the energy equation. The program selected the water surface whose main channel velocity head was the closest to the previously computed cross section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1059.787  Profile: PF 4
Warning: Divided flow computed for this cross-section.
Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1049.93  Profile: PF 4
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1037.566  Profile: PF 4
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1027.907  Profile: PF 4
Warning: The energy equation could not be balanced within the specified number of iterations. The program used critical depth for the water surface and continued on with the calculations.
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Warning: During the standard step iterations, when the assumed water surface was set equal to critical depth, the calculated water surface came back below critical depth. This indicates that there is not a valid subcritical answer. The program defaulted to critical depth.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1019.271  Profile: PF 4
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 1009.4  Profile: PF 4
Warning: Multiple water surfaces were found that could balance the energy equation. The program selected the water surface whose main channel velocity head was the closest to the previously computed cross section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 997.7851  Profile: PF 4
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 974.137  Profile: PF 4
Warning: The energy equation could not be balanced within the specified number of iterations. The program used critical depth for the water surface and continued on with the calculations.

Warning: Divided flow computed for this cross-section.
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The energy loss was greater than 1.0 ft (0.3 m) between the current and previous cross section. This may indicate the need for additional cross sections.

Warning: During the standard step iterations, when the assumed water surface was set equal to critical depth, the calculated water surface came back below critical depth. This indicates that there is not a valid subcritical answer. The program defaulted to critical depth.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 950.311 Profile: PF 4

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 929.8054 Profile: PF 4

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 922.7884 Profile: PF 4

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 914.9467 Profile: PF 4

Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 905.0219 Profile: PF 4

Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note:  Multiple critical depths were found at this location.  The critical depth with the lowest, valid, energy was used.

Location:  River: Blackwood Creek Reach: Reach 6 2010  RS: 894.9285  Profile: PF 4
Warning:  The velocity head has changed by more than 0.5 ft (0.15 m).  This may indicate the need for additional cross sections.
Warning:  The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4.  This may indicate the need for additional cross sections.
Note:  Manning's n values were composited to a single value in the main channel.
Note:  Multiple critical depths were found at this location.  The critical depth with the lowest, valid, energy was used.

Location:  River: Blackwood Creek Reach: Reach 6 2010  RS: 849.3234  Profile: PF 4
Warning:  The parabolic search method failed to converge on critical depth.  The program will try the cross section slice/secant method to find critical depth.
Note:  Multiple critical depths were found at this location.  The critical depth with the lowest, valid, energy was used.

Location:  River: Blackwood Creek  each: Reach 6 2010  RS: 840.0283  Profile: PF 4
Note:  Manning's n values were composited to a single value in the main channel.
Note:  Multiple critical depths were found at this location.  The critical depth with the lowest, valid, energy was used.

Location:  River: Blackwood Creek Reach: Reach 6 2010  RS: 829.5078  Profile: PF 4
Warning:  The velocity head has changed by more than 0.5 ft (0.15 m).  This may indicate the need for additional cross sections.
Warning:  The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4.  This may indicate the need for additional cross sections.
Note:  Manning's n values were composited to a single value in the main channel.
Note:  Multiple critical depths were found at this location.  The critical depth with the lowest, valid, energy was used.

Location:  River: Blackwood Creek Reach: Reach 6 2010  RS: 823.8342  Profile: PF 4
Note:  Multiple critical depths were found at this location.  The critical depth with the lowest, valid, energy was used.

Location:  River: Blackwood Creek Reach: Reach 6 2010  RS: 811.2727  Profile: PF 4
Warning:  Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 797.2588  Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 783.4055  Profile: PF 4
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 769.5674  Profile: PF 4
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 760.5866  Profile: PF 4
Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 753.01  Profile: PF 4
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 739.8454  Profile: PF 4
Warning: Multiple water surfaces were found that could balance the energy equation. The program selected the water surface whose main channel velocity head was the closest to the previously computed cross section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 726.5444  Profile: PF 4
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 715.2126 Profile: PF 4

Warning: The energy equation could not be balanced within the specified number of iterations. The program used critical depth for the water surface and continued on with the calculations.

Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Warning: During the standard step iterations, when the assumed water surface was set equal to critical depth, the calculated water surface came back below critical depth. This indicates that there is not a valid subcritical answer. The program defaulted to critical depth.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 700.655 Profile: PF 4

Warning: The energy equation could not be balanced within the specified number of iterations. The program selected the water surface that had the least amount of error between computed and assumed values.

Warning: Divided flow computed for this cross-section.

Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 670.1264 Profile: PF 4

Warning: Divided flow computed for this cross-section.
Warning: The energy loss was greater than 1.0 ft (0.3 m) between the current and previous cross section. This may indicate the need for additional cross sections.

Note: Manning’s n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 644.4757  Profile: PF 4
Warning: Divided flow computed for this cross-section.
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 630.6201  Profile: PF 4
Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 620.5234  Profile: PF 4
Warning: Multiple water surfaces were found that could balance the energy equation. The program selected the water surface whose main channel velocity head was the closest to the previously computed cross section.
Warning: Divided flow computed for this cross-section.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 608.8887  Profile: PF 4
Warning: Divided flow computed for this cross-section.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 589.2669  Profile: PF 4
Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 540.9506 Profile: PF 4
Warning: Divided flow computed for this cross-section.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 518.9864 Profile: PF 4
Warning: Divided flow computed for this cross-section.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 500.8333 Profile: PF 4
Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 483.0438 Profile: PF 4
Warning: Divided flow computed for this cross-section.
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 440.3534 Profile: PF 4
Warning: The energy equation could not be balanced within the specified number of iterations. The program used critical depth for the water surface and continued on with the calculations.
Warning: Divided flow computed for this cross-section.
Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Warning: During the standard step iterations, when the assumed water surface was set equal to critical depth, the calculated water surface came back below critical depth. This indicates that there is not a valid subcritical answer. The program defaulted to critical depth.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 411.0299  Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 400.6179  Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 381.1781  Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 362.3197  Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 345.6856  Profile: PF 4
Warning: Multiple water surfaces were found that could balance the energy equation. The program selected the water surface whose main channel velocity head was the closest to the previously computed cross section.

Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010  RS: 337.0753  Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 302.2373 Profile: PF 4

Warning: Divided flow computed for this cross-section.

Warning: The energy loss was greater than 1.0 ft (0.3 m) between the current and previous cross section. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 265.0171 Profile: PF 4

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 237.7307 Profile: PF 4

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 224.8561 Profile: PF 4

Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 215.7868 Profile: PF 4

Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 201.0855 Profile: PF 4

Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 184.8186 Profile: PF 4

Warning: Divided flow computed for this cross-section.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 161.2937 Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 146.5297 Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 128.9239 Profile: PF 4
Warning: Divided flow computed for this cross-section.

Warning: The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 115.6161 Profile: PF 4
Warning: Divided flow computed for this cross-section.

Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 104.3267 Profile: PF 4
Warning: Divided flow computed for this cross-section.

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 83.53954 Profile: PF 4
Warning: The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

Note: Manning's n values were composited to a single value in the main channel.
Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Location: River: Blackwood Creek Reach: Reach 6 2010 RS: 63.30714 Profile: PF 4

Note: Multiple critical depths were found at this location. The critical depth with the lowest, valid, energy was used.

Table 14. Post-restoration HEC-RAS model run summary for 3-year recurrence flow of 16 m$^3$/s.
HEC-RAS Modeled Shear Stress Summary

<table>
<thead>
<tr>
<th>Event</th>
<th>Flow m3/s</th>
<th>Pre-Restoration (N/m²)</th>
<th>Post-Restoration (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5-year peak</td>
<td>7.4</td>
<td>23.7</td>
<td>16.3</td>
</tr>
<tr>
<td>2-year peak</td>
<td>10.7</td>
<td>25.7</td>
<td>18.6</td>
</tr>
<tr>
<td>2.3-year peak (peak flow of spring 2010)</td>
<td>12.3</td>
<td>26.7</td>
<td>20.4</td>
</tr>
<tr>
<td>3-year peak</td>
<td>16.0</td>
<td>28.4</td>
<td>26.1</td>
</tr>
<tr>
<td>4-year peak</td>
<td>20</td>
<td>30.5</td>
<td>30.5</td>
</tr>
<tr>
<td>5-year peak</td>
<td>23</td>
<td>33.5</td>
<td>29.2</td>
</tr>
<tr>
<td>10-year peak</td>
<td>37</td>
<td>40.1</td>
<td>31.2</td>
</tr>
<tr>
<td>15-year peak</td>
<td>47</td>
<td>47.5</td>
<td>29.9</td>
</tr>
<tr>
<td>20-year peak</td>
<td>55</td>
<td>57.4</td>
<td>29.2</td>
</tr>
</tbody>
</table>

Table 15. This table shows the standard deviation of the cross section shear stresses calculated in HEC-RAS for each model run for both before restoration and after restoration conditions.