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11 years later: An assessment of upstream channel changes since the dam's removal

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In California's Central Valley, dams block 95 percent of historic salmonid habitat. To restore access by spring-run chinook salmon (*Onocorhynchus tshawytscha*) and other anadromous fish to approximately 12 miles of upstream spawning habitat on Clear Creek (drainage areas 720 km^2), the US Bureau of Reclamation removed the McCormick-Saeltzer Dam in November 2000. Previous studies—the most recent in 2004—identified significant sediment mobilization since dam removal at, and above, the former dam site. In October 2011, we resurveyed two previously established cross sections at 26 m and 103.3 m upstream of the dam site and conducted a long profile of the thalweg from the dam site to 175 m upstream. We also replicated previous site photographs, drew vegetation maps and compared 2010 aerial photographs to those from 1998 and 2004 to assess vegetation change and erosion patterns. Our results documented little incremental erosion at and upstream of the dam site since 2004, suggesting that sediment mobilization post-dam removal has largely stopped. Establishment of riparian vegetation may be stabilizing remaining sediment deposits.

INTRODUCTION

Habitat loss is a major factor contributing to the decline of chinook salmon (*Onocorhynchus tshawytscha)* and other anadromous fish populations in California (NMFS 1996, Myers et al. 1998, NMFS 2009). These population declines have motivated efforts to restore suitable habitat (DWR 1997) in places like California's Central Valley, where dams block 95 percent of historic salmonid spawning habitat (Brown n.d.).

Dam removal to improve salmonid access to upstream spawning habitat has become an increasingly popular restoration tool. When a dam is removed, sediment formerly impounded behind the dam may be mobilized and deposited downstream.[1] After this initial sediment mobilization, additional sediment is likely to be mobilized during large floods, resulting in channel widening. Once a flood of a given level has occurred, more sediment is unlikely to be mobilized until a larger flood occurs (Heinz Center 2002). Existing literature suggests that most of this adjustment occurs in the first five or ten years after dam removal, but studies have suggested that complete adjustment may take decades (Williams and Wolman 1984, Bednarek 2001).

If deposited on spawning gravels, fine sediment mobilized by dam removal can degrade downstream habitat until it is remobilized by future high flows. In the long term, dam removal allows for the re-establishment of more natural sediment flow and the resupply of sediment into starved downstream reaches (Bednarek 2001). Therefore, the short-term negative impacts of fine sediment releases after dam removal must be weighed against the longer term positive impacts of restoring access to upstream spawning habitat and re-establishing natural sediment supply. Overall, a stronger scientific understanding of geomorphic response to dam removal is needed to help guide dam removal policy and planning (Bednarek 2001, Heinz Center 2002).

[1] Dams impound reservoirs of very slow moving water, which experience very different geomorphic processes than free flowing channels. Slow moving water causes transported sediment to drop out of the water column, resulting in aggradation within reservoirs and sediment-starved reaches below dams (Bednarek 2001).

Greater cognizance of geomorphic adjustment processes in former reservoirs of removed dams provides insight toward understanding the short and long-term effects of dam removal.[2] Measuring ongoing geomorphic adjustment at the former McCormick-Saeltzer Dam (Saeltzer Dam) site in Clear Creek near Redding, California, can help project planners assess the likely magnitude and timing of such adjustment in anticipation of assessing future dam removals on other streams.

Saeltzer Dam was removed in 2000 as part of the larger Lower Clear Creek Coordinated Resource Management Program (CCRMP) (BLM 2008).[3] The principal objective of the dam removal was to restore spring-run Chinook salmon access to 12 miles of spawning habitat between Saeltzer Dam and the Whiskeytown Dam, upstream (Figure 1). Spring-run Chinook salmon are state and federally threatened, and are unable to survive in the reaches below the dam due to low summer flows and high summer water temperatures (BLM 2008).

Prior to dam removal, accumulated sediment was removed from behind the dam in an attempt by project planners to limit negative impacts on downstream spawning habitat for other anadromous fishes. Post-project assessments to measure geomorphic changes at the dam site were conducted in 2001, 2003 and 2004 (Table 1). These assessments evaluated potential adverse downstream habitat impacts by studying sediment mobilization in the reach at, and upstream, of Saeltzer Dam. Since 2003, no surveys have been undertaken in the former reservoir area, but creek flows have been nearly equal to those which mobilized significant sediment loads in 2002 and 2003 (Ferry and Miller 2003, Miller and Vizcaino 2004, Figure 14). This study aims to determine if, consistent with existing literature, the rapid rate of erosion and channel adjustment experienced in the early years after Saeltzer Dam's removal has slowed. In October

[2] Other relevant information includes studies of downstream effects and sediment and biota passage through the former dam site.
[3] The CCRMP included the Saeltzer Dam removal, ongoing gravel injections, watershed fuel load reductions, and a downstream floodplain restoration project (BLM 2008).

2011, we visited the former dam site to evaluate ongoing geomorphic response to the dam's removal.

SITE DESCRIPTION AND BACKGROUND

Located in Shasta County, California, Clear Creek originates in the mountains east of Trinity Lake and drains a 278 mi^2 (720 km^2) watershed. The first major tributary to the Sacramento River downstream of Shasta Dam, Clear Creek is a west bank tributary flowing approximately 35 miles (56 km) to its confluence with the Sacramento River (Figure 1).

Clear Creek has been heavily impacted by direct and indirect anthropogenic interventions for over a century (Brown n.d.). Dredge mining for gold and gravel has altered the channel form by removing point bars, floodplains and riparian vegetation (Pittman and Matthews 2005 *in* Gilbreath 2006). In some areas, the stream is straight and highly entrenched (NRCS 1999); in others, multiple flow channels and open extraction pits exist (NRCS 1999, Pittman and Matthews 2005 *in* Gilbreath 2006).

The creek provides habitat for state and federally threatened spring-run Chinook salmon (Brown, n.d.), as well as other anadromous fishes including steelhead and fall and winter-run Chinook salmon. Spring-run Chinook migrate upstream in the spring but wait to spawn until temperatures drop in fall. They require cool water temperatures to survive the intervening summer months, and typically need to reach high elevations to find suitable habitat (Newton and Brown 2004, Bjornn and Reiser 1991).

Two dams, McCormick-Saeltzer Dam (Saeltzer Dam) and Whiskeytown Dam, have historically restricted salmonid access to upstream habitat on Clear Creek. The 282-foot (86 m) high Whiskeytown Dam, at River Mile 18 (approximately 12 miles (19 km) upstream of the former Saeltzer Dam), is an earth-fill dam constructed in 1963 as part of the Bureau of Reclamation's Trinity River Project (NPS 2008). It traps all coarse and fine sediment from the upper watershed and diverts up to 80 percent of the natural flow to Lower Clear Creek into its reservoir (NRCS 1999, BLM 2008), thus significantly reducing the magnitude and frequency of channel forming flow events (Hepler 2001).[4] The sediment supply deficit has been partially mitigated by gravel augmentation, but the stream lacks complexity created by woody debris deposition during flood events (BLM 2008).[5]

Completed in 1912, the privately owned Saeltzer Dam was located at River Mile 6.2. (Figure 1a). The approximately 15-foot (4.6 m) high, 200-ft (61 m) long concrete and timber crib gravity structure diverted water for a variety of uses over time: irrigation, dredge mining, cleaning mined gravels and watering livestock (Hepler 2001, Hepler 2004 *in* Gilbreath 2006). The dam prevented coarse sediment from moving downstream and blocked anadromous fish migration to upstream spawning habitat between Saeltzer and Whiskeytown Dams. A series of attempts (in 1912, 1958 and 1992) to improve fish passage with ladders failed. In 1992, the Central Valley Project Improvement Act authorized the Bureau of Reclamation to increase anadromous fish populations in the Central Valley within 10 years, specifically identifying improved fish access above Saeltzer Dam (Hepler 2001). In 1999, less than one percent of spring-run Chinook salmon in Clear Creek successfully passed upstream of the dam (Hepler 2001). Under increasing pressure from state and federal agencies, the dam and its associated water rights were purchased; and Saeltzer Dam was removed in November 2000 (Hepler 2001).

In 2002, US Fish and Wildlife surveys estimated that over 70 percent of spring-run Chinook in Clear Creek passed upstream of the former dam site (Newton and Brown 2003).[6] Thus, the project has been successful in its primary goal of restoring spring-run Chinook salmonid access to the 12-mile reach between Saeltzer and Whiskeytown Dams.

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[4] A pilot Whiskeytown Dam re-operation plan to reestablish a more natural channel flow regime and reduce sediment starvation is expected to begin in 2013 (Brown 2011).
[5] Since the removal of Saeltzer Dam, minimum instream flows have been maintained to assist the establishment of spring-run Chinook salmon in lower Clear Creek (BLM 2008).
[6] From 2000 to 2008, between 20 and 200 spring-run Chinook were counted in lower Clear Creek (BLM 2008).

With the primary goal achieved, we were interested in assessing the potentially deleterious downstream impacts from removing Saeltzer Dam. Before removal, approximately 12,500 yd^3 (9,500 m^3) of accumulated sediment was excavated from behind the dam in efforts to avoid downstream channel aggradation of fine sediment on spawning gravels, and to encourage rapid re-establishment of a functional channel gradient (Hepler 2001).[7] Erosion control measures were taken to promote vegetation growth, including riprap, silt fences, seeding, mulching and topsoil. Pre-project estimates indicated that sediment availability for future erosion from the former reservoir area (Figure 1b) would be minimal – 6,000 yd^3 (4,600 m^3) – and that the potential for adverse affects downstream was low (Hepler 2001 *in* Gilbreath 2006).

Due to actively spawning fall-run Chinook salmon, we were unable to survey downstream reaches for signs of fine sediment deposition. We nonetheless believe that the time series of surveys at and above the dam site to which this report contributes provide a useful assessment of whether geomorphic adjustment at the dam site – a likely source of downstream fine sediment deposition – is ongoing.[8]

KEY FINDINGS FROM PREVIOUS STUDIES

For this study, we were primarily interested in geomorphic changes at the Saeltzer Dam site. Previous work at the dam site included a post project assessment by Stillwater Sciences in 2001, University of California, Berkeley graduate student papers in 2003 and 2004 (Ferry and

[7] Original sediment excavation plans were for the removal of approximately 19,000 m^3 (25,000 yd^3) of sediment, but excavators hit bedrock up to eight feet higher than expected during project work (BLM 2000, Hepler 2001).

[8] While not explicitly a focus of this report, a number of studies have been conducted approximately one mile downstream of the dam site at a reach called Renshaw's Riffle. Past research has documented up to three feet of aggradation in the riffle post-dam removal (Gilbreath 2006). Because tracer studies were not conducted it is not possible to make firm conclusions about whether this aggradation is a result of deposition of sediment eroded from the dam site. More recently, geomorphic monitoring indicates that the 2008 Moon Fire and subsequent salvage logging has led to a large increase in fine sediment deposition on salmonid spawning habitat in Clear Creek. In the fire's wake, steelhead juvenile productivity has declined 86 percent on Clear Creek and spring-run Chinook juvenile productivity has declined 35 percent (Brown 2011).

Miller 2003, Miller and Vizcaino 2004), and field work by Graham Matthews and Associates in 2000 and 2004 (Table 1).

Stillwater Sciences 2001

Stillwater Sciences (Stillwater) surveyed the reservoir and dam area in 2000 prior to dam removal, then returned and resurveyed the area in spring 2001, following the unusually low 2001 peak flow season (peak flow 1250 cfs). They found no significant changes to channel morphology (122 yd^3 (93 m^3) of erosion from January to May 2001) and estimated that only 5,900 yd^3 (4,500 m^3) of eroded sediment was available for downstream transport from the reach just upstream of the former dam site (Stillwater 2001).

Ferry and Miller 2003/Miller and Vizcaino 2004[9]

Between 2001 and 2003, three flows greater than the 2-year flood (2,800 cfs (78 m^3s^{-1})) occurred (Ferry and Miller 2003), including a three-year event (Pittman and Mathews 2005 *in* Gilbreath 2006). Ferry and Miller (2003) and Miller and Vizcaino (2004) documented significant geomorphic changes at and upstream of the dam site. They attributed these changes mainly to the large flows that had not been experienced prior to the 2001 survey. The 2003 study documented post-2001 incision of more than 3 feet (1 m) over a 1,050 ft (320 m) length upstream from the former dam site to an active head cut. It documented lateral erosion of 49-59 ft (15-18 m) in the same area.

The 2004 survey estimated that 51,900 yd^3 (39,750 m^3) of sediment had eroded from the former reservoir deposit in the reach extending approximately 1500 ft (457 m) upstream of the former dam site (Figure 1a (areas A, B, and C); Miller and Vizcaino 2004), nearly an order of magnitude higher than Stillwater's 2001 estimates of available sediment. Miller and Vizcaino estimated that 40 percent of the eroded sediment (20,900 yd^3 (16,000 m^3)) was sand, which can

[9] Miller and Vizcaino published their findings in 2004, but their fieldwork was conducted in Fall 2003.

have particularly negative downstream impacts on salmonid spawning gravels (Miller and Vizcaino 2004 *in* Gilbreath 2006).

Both studies suggested that because sediment had been excavated down to bedrock during dam removal, incision was limited and banks eroded laterally. The desiccation of remnant riparian vegetation, which had initially helped to stabilize newly exposed banks following dam removal, likely contributed to the availability of sediment for mobilization during high flow periods after Stillwater's 2001 study (Miller and Ferry 2003, Miller and Vizcaino 2004).

Graham Mathews and Associates (GMA) 2000 and 2004

GMA surveyed the former impoundment area (the former reservoir immediately upstream of the dam site) in November 2000 and October 2004 (Figure 1a). A comparison of these surveys showed results similar to those described by Ferry and Miller (2003) and Miller and Vizcaino (2004). GMA calculated a net sediment volume change of 49,000 yd^3 (37,500 m^3) in the former impoundment area (Gilbreath 2006). A long profile found incision extending upstream at least 4,000 feet (1,200 m) and aggradation extending downstream at least 9,000 feet (2,700 m), into areas of known salmonid spawning habitat.

METHODS

Study Reach

Our study reach, which includes the former site of Saeltzer Dam and its reservoir, is approximately 1970 feet (600 m) long.[10] It extends upstream of the dam site in the former reservoir impoundment, and is a meandering reach.[11] We conducted fieldwork on October 22 and 23, 2011 in the lower 1,460 feet (445 m) of the study reach (Figure 1a; areas A, B and C). We

[10] Our study reach overlaps that from previous studies at the former Saeltzer Dam site.
[11] Linear distance not in-stream distance.

further analyzed areas A, B, C and D using aerial images from 1998, 2004 and 2010 from Google Earth Pro.

Lateral Channel Movement and Incision

We replicated the first two of Miller and Vizcaino's five 2003 cross sections using a level and rod (Figures 2, 3, 4, 5). These two cross sections were marked with rebar stakes on the right bank.[12] We conducted a long profile of the thalweg from the dam site to 575 feet (175 m) upstream (Figures 3, 6). We compared these survey results to those presented by Miller and Vizcaino (2003, Figures 4, 5, 6).

Erosion and Deposition

We compared erosion and deposition between 1997 and 2003, and between 2003 and 2011 (Figures 7a, 7b, 7c). We mapped areas of potential erosion and deposition in the field, based on visual cues including un-vegetated sheer banks and gravel bars. Using the 2004 aerial imagery, we re-interpreted a hand-drawn map of erosion and deposition observations from Ferry and Miller 2003 (Appendix A). Similarly, 2011 erosion and deposition field maps were overlain on aerial imagery from 2010, and used to determine incremental patterns of erosion and deposition since 2003/04.

By observing rock characteristics and different substrate types along the stream channel, we also generated a rudimentary field facies map.[13] We later geo-referenced the facies map in GIS to create an anecdotal assessment of substrate distribution in the study area and to map exposed bedrock (Figures B1, B2). Detailed methods and results for substrate facies mapping can be found in Appendix B.

[12] Strong flows, time constraints, heavy brush and inability to locate additional markers prevented us from surveying the remaining three upstream cross sections. As in the Ferry and Miller (2003) and Miller and Vizcaino (2004) studies, we used the upstream corner of a concrete box (remnant of a failed fish ladder) on the right bank as the benchmark for these surveys.

[13] Due to time limitations, we did not conduct pebble counts.

Vegetation and Channel Change

Additionally, we replicated post-dam removal photos from Ferry and Miller (2003) to document ongoing geomorphic and vegetation changes in area A (Figures 8, 9, 10). Using GIS tools, we geo-referenced the 1997, 2004 and 2010 aerial photos to analyze observed changes in vegetation cover (Figures 11a, 11b) and channel form (Figures 12a, 12b, 12c) since 1998. Channel edges were drawn from the geo-referenced aerial images for 1997, 2004 and 2011. By layering the stream channel outlines, changes in form were made particularly evident in areas C and D (Figure 1a, 12a, 12b, 12c). Both channel form and vegetation establishment in 2011 were confirmed through field maps and observation.[14]

RESULTS AND DISCUSSION

Lateral Channel Movement 1998-2003

Ferry and Miller (2003) and Miller and Vizcaino (2004) described substantial channel change between 1998 and 2003 (Figure 12a). Changes in channel form are best described in four distinct areas: A, B, C, and D (Figure 1a):

A. In the first 490 feet (150 m) upstream from the former dam site (area A), the channel moved north by approximately 65 to 100 feet (20 to 30 m) as measured from the channel center.

B. In the next 330 feet (100 m) (area B), the creek has abandoned the southeastern (river left) high flow channel upon draining of the reservoir. (This dry high flow channel was noted during the Ferry and Miller (2003) study.) The deeper northwestern channel previously cut southeast through a former bar island. In the field, Ferry and Miller

[14] The most recent available aerial imagery of the study area is from 2010. All 2011 field observation data is displayed on 2010 photographs. We do not have reason to believe the channel changed significantly in this time span. We used a 2010 aerial photograph from the USGS seamless server to confirm spatial referencing of the historical imagery.

(2003) observed substantial erosion on the left (northwest) bank in this area.[15] They proposed that erosion in this area was due to death of riparian vegetation upon lowering of the reservoir water level. The banks in this area are comprised of unconsolidated fine sediment and cobbles, which would be easily eroded during periods of high flows without stabilization provided by vegetation (Ferry and Miller 2003).

C. In the northernmost 660 feet (200 m) of the reach (area C), the channel shifted north by approximately 160 feet (50 m). This was accompanied by observations in 2003 (Ferry and Miller) of substantial erosion on the left (north) bank in this area, and deposition on the right (south) bank.

D. In the third bend, approximately 2300 feet (700 m) upstream of the dam site in area D, the channel moved approximately 160 feet (50 m) east. This may be related to a meander cutoff that occurred just upstream during this time period (Figures 13a, 13b, 13c).[16] Meander cutoffs result in a steeper channel grade, and an associated increase in water velocity and sediment transport (Knighton 1998). This increase in velocity likely caused the major eastward shift of area D between 1998 and 2004.

Lateral Channel Movement 2004-2010/2011

Conversely, channel change from 2004 to 2010 (Figure 12b) was relatively minor compared to that observed from 1998 to 2004 (Figure 12a); except in area D, where significant braiding has occurred since 2004.

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[15] Aerial photographs from 2004 (to which Ferry and Miller did not have access in 2003) indicated that the channel was moving in the opposite direction. One possible explanation is that Ferry and Miller observed the eroded area left behind by the channel as it migrated and assumed it was erosion on the channel's cutting edge.

[16] In the course of our aerial photo analysis, we observed that a meander immediately upstream was cut off between 1998 and 2004, during the same time period when the dam was removed. Since the previous studies did not look this far upstream, and we did not notice this cutoff until after the completion of our field work (and thus did not get the chance to look at it in person), it is difficult to conclude whether this cutoff is related to the dam removal.

A. The channel in area A is primarily lined with exposed bedrock on the south bank, and unconsolidated fine sediment and cobbles on the north bank. There is evidence of slight widening since 2003 – approximately five meters into the north bank in the western most portion of area A (Figure 12b). Comparison of cross sections 1 and 2 between 2003 and 2011 show little change to creek channel and bank profiles (Figures 4, 5). The area of northward channel widening is evident in the lower left corner of cross section 2 (Figure 5). It is notable that only the low-flow channel has widened, and the north bank (where significant erosion occurred from 2001 to 2003) has remained stable. It is also notable that the high flow channel (visible on the right side in the 2003 cross section, also visible in the 1998 channel form, Figure 12a) is not present in the 2011 cross section (Figure 5). Insufficient data collection in this cross section in 2011 makes it difficult to assess whether the high flow channel's "non-presence" indicates that it has filled since 2003, but in the course of our field surveys, we did not note any grade breaks in this portion of the cross section.

B. The channel in area B has continued to cut west (Figures 12b, 12c). We noted a small area of active erosion on the right bank in this location, corresponding to a similar area of deposition on the left bank[17] (Figure 7b). The presence of bedrock on the right bank will likely prevent further movement of the channel in this area (Figure A2).

We also observed erosion on the upper left bank in area B. This is in the same location as that observed by Ferry and Miller in 2003 (Figure 7c). Their method for recording erosion and deposition was unclear (Appendix B) and it is difficult to determine whether this bank has eroded since 2003, or if all erosion occurred prior to 2003. However, the presence of large vegetation on the bar between this eroded bank and

[17] We were unable to survey cross section 3 in this location. Thus, we cannot determine if the volume of erosion is equal to the volume of deposition. Qualitatively, though, observation of the area appears that this is the case.

the channel suggests that any recent erosion has been minimal. A better determination of upper bank stability can be made if cross section 3 is resurveyed in the future (Figure 2).

C. In area C, the channel has continued to move north, toward the outside of the meander bend (Figure 7a). We observed corresponding erosion along the left bank and deposition on the right. The large area of deposition that was evident in 2003 on the south bank in area C eventually stabilized into the large bar present in 2011 (Figures 12a, 7b).

D. Substantial braiding was observed in area D (Figure 12c). We suspect that this may be deposition of sediment transported due to the meander cutoff just upstream. The channel steepening associated with meander cutoffs results in increased water velocity and sediment transport (Knighton 1998). The increased velocity continued to push the channel in area D eastward, while the increased sediment transport likely resulted in increased sediment deposition, creating the braided channel observed in 2011.

Incision

Our assessment of incremental incision into the channel bed since 2003 is inconclusive. While our cross sections confirmed that the thalweg has not incised since 2003, our long profile was consistently 1.6 to 3.3 feet (.5 to 1 m) lower than the long profile surveyed in 2003 (Figure 6). Attempts to better align the long profiles show that there may have been some shifting of the pattern of bars and pools in the reach immediately above the dam site (Figure 6), but it is difficult to draw any solid conclusions given our uncertainty in the alignment of the long profiles.[18]

[18] We likely mistook the immediate location of the former dam site (which we used as 0 on the x-axis), and our profile was therefore not properly aligned with long profiles surveyed in previous years. None of the long profiles made indicate a positioning landmark other than the dam site. In making our long profile, we did note the location of cross section 2, and could use this as a stable point to line up our cross section with that from 2003, since we knew from our cross sectional surveys that no incision had occurred in this location. However, it should be noted that the area at the dam site is mostly bedrock, but shows incision of almost 1.6 ft (0.5 m) even after shifting long profile alignment. Given the error inherent in attempting to shift a long profile horizontally without any clear benchmarks, and the low number of data points surveyed in this area in 2003, it is difficult to draw any solid conclusions from the long profiles.

Vegetation Change

Comparison of imagery (Figures 8, 9, 10) reveals that significant riparian vegetation die-off occurred in the years immediately following dam removal, as noted in previous studies (Ferry and Miller 2003, Miller and Vizcaino 2004). Dams and associated upstream reservoirs lead to a saturation of surrounding sediment down to bedrock and a localized rise in the water table. After dam removal (and reservoir emptying), the water table subsides, potentially stranding and leading to the mortality of riparian vegetation along the margins of the former reservoir (Shafroth et al. 2002). Ferry and Miller (2003) and Miller and Vizcaino (2004) both cite this die-off as a probable and major contributor to the observed erosion in this time period. From 2003 to present day, considerable riparian vegetation had become established, most of which appears to be several years old. The presence of this vegetation confirms that significant erosion has not recently occurred, and suggests a reinforcing pattern of bank stability in which vegetation reduces the availability of bank sediment for mobilization and in turn grows larger each season, leading to even greater bank stability.

Rate of Geomorphic Adjustment

Following dam removal, a series of geomorphic processes may occur in the reach at and above the dam site as a stream moves toward a state of quasi-equilibrium (Stanley and Doyle 2002 *in* Ferry and Miller 2004). Previous studies of the former Saeltzer Dam site have confirmed that this process of adjustment was underway by 2003, dominated by lateral erosion due to excavation of sediment down (or close to) bedrock (Ferry and Miller 2004). We believe the dam site has moved into a state of quasi-equilibrium in the past eight and a half years (April 2003 to October 2011), based on the following observations:

- We documented little change in cross sections 1 and 2, compared to the rapid change observed in 2003.

- Aerial imagery analysis resulted in small incremental patterns of lateral erosion in areas that had already been eroding in 2003.[19] The magnitude of sediment mobilization was far more substantial in just the two years between 2001 and 2003 (evident in cross section comparison from those respective studies). It is particularly notable that the major post-dam channel adjustments were delayed until large flows came through the area in 2001-2003 (Ferry and Miller 2003, Miller and Vizcaino 2004, Figure 14). These major adjustments appear to have all occurred within two seasons of moderately large flows.
- There has been substantial re-establishment of riparian vegetation throughout the study reach, mainly *Salix spp.* (willow) (Figures 8, 9, 10). Much of this vegetation appears to be several years old, suggesting a reinforcing pattern of bank stability in which vegetation reduces the availability of bank sediment for mobilization and in turn grows larger each season, which leads to even greater bank stability.
- Creek high flows between 2003 and 2011 occurred at levels that were, from 2001 to 2003, sufficient to mobilize sediment. On December 30, 2005, for example, there was a significant flow event (4,400 cfs) that approached the high flow volumes seen in the winter and spring of 2003—flow volumes that had caused substantial geomorphic change in the creek (Figure 14). The highest flows recorded from 2000 to 2001 were likely too low to trigger substantial post-dam sediment movement and geomorphic adjustment.

One open question is whether larger flows than those experienced over the past decade will lead to additional erosion at, and upstream of, the dam site. Historically, flows on Clear Creek have exceeded those experienced since the dam was removed on multiple occasions. Peak flows exceeded 5,000 cfs in five of the seven years from 1993-1999 (Figure 14). We were interested in determining whether the rapid movement of sediment observed from 2001 to 2004 has continued, or if, as existing theory predicts, the period of rapid adjustment has ended and the

[19] We were not able to reliably estimate 2004 to 2011 erosion volume at, and upstream of, the dam site because we only resurveyed two of the five previously surveyed cross sections (these cross sections are in the erosion volume estimation calculation).

area has reached a state of quasi-equilibrium that is unlikely to be upset until the creek experiences larger flows than those of the last 11 years.[20] Knowledge of how long this site took to adjust to dam removal could be useful in estimating how long deleterious effect will last downstream.

Lastly, we intend for the rudimentary facies map (Figure B1) to provide a baseline for future research on ongoing geomorphic change in the reach. It might be particularly useful for evaluating the long-term impacts, if any, of upstream sediment mobilization resulting from the planned re-operation of Whiskeytown Dam, and the impacts from the 2008 Moon Fire which included subsequent salvage logging and upstream gravel injections.

CONCLUSION

Approximately eleven years after the removal of Saeltzer Dam, and more than seven years after the last published study at the former dam site, we found that the Clear Creek reach at, and upstream of, the former dam appears to be moving from a pattern of intense modification to a pattern of relative stability. In a meandering reach such as this study site, geomorphology would predict some amount of channel movement and associated lateral erosion and deposition even in an undisturbed regime. Thus, the challenge is determining when the period of intense post-dam adjustment has ended and the natural range of channel movement has returned for this site. Without pre-dam data on channel movement, the pre-disturbance rate of change for this area is impossible to determine. However, based on the channel position and cross sectional evidence we collected, we believe that no major channel adjustments have occurred since Ferry and Miller's 2003 fieldwork. This stability is consistent with the existing literature, which suggests that rapid adjustment to dam removal is followed by relative stability (Williams and Wolman 1984, Heinz Center 2002). This stability is unlikely to be upset until higher flows than those seen

[20] Quasi-equilibrium is the state of relative balance in which erosion and deposition (aggradation and degradation) rates are roughly equal in a stream reach (EPA, n.d.)

in the past 11 years occur in Clear Creek. The extent to which establishment of riparian vegetation will prevent erosion in these future high flow events remains to be seen, but these high flows are possible as the Whiskeytown Dam has a circular spillway that allows approximately 10,000 cfs to release into lower Clear Creek during large storm events that fill the Whiskeytown Reservoir (BLM 2008).

While lateral bank erosion and deposition continues to a limited extent, channel widening and incision—at least at and immediately above the dam site—has not increased since 2003. Establishment of riparian vegetation appears to be a contributing factor to reinforcing bank stability at the study site.

In general, the changes at the study site appear to be beneficial. The extent to which the short-term fine sediment mobilization and downstream deposition on salmonid spawning gravels that may have occurred in this period will have negative impacts on Clear Creek remains to be seen—these negative impacts are likely to be transient as future high flows clear fine sediment from downstream reaches. In addition, the increase in upstream spawning habitat above the dam site is likely to outweigh these short-term downstream impacts (upstream habitat is critical to threatened spring-run Chinook salmon, and the downstream habitat is used by more common anadromous fishes (fall-run and winter-run Chinook salmon and steelhead)). It is important that ongoing monitoring continue at Clear Creek to assess these long-term impacts.

Overall, removal of Saeltzer Dam on Clear Creek—and the ongoing appraisals of its impacts—provide a valuable case study for dam removal project planners. In this case, the chronology of channel adjustment at Saeltzer Dam can be compared to temporal and spatial geomorphic modifications at other dam removal sites to enhance our capacity to better predict and adaptively manage river and stream response to future dam removal projects.

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LIST OF FIGURES AND TABLES

APPENDIX A

APPENDIX B

FIGURES AND TABLES

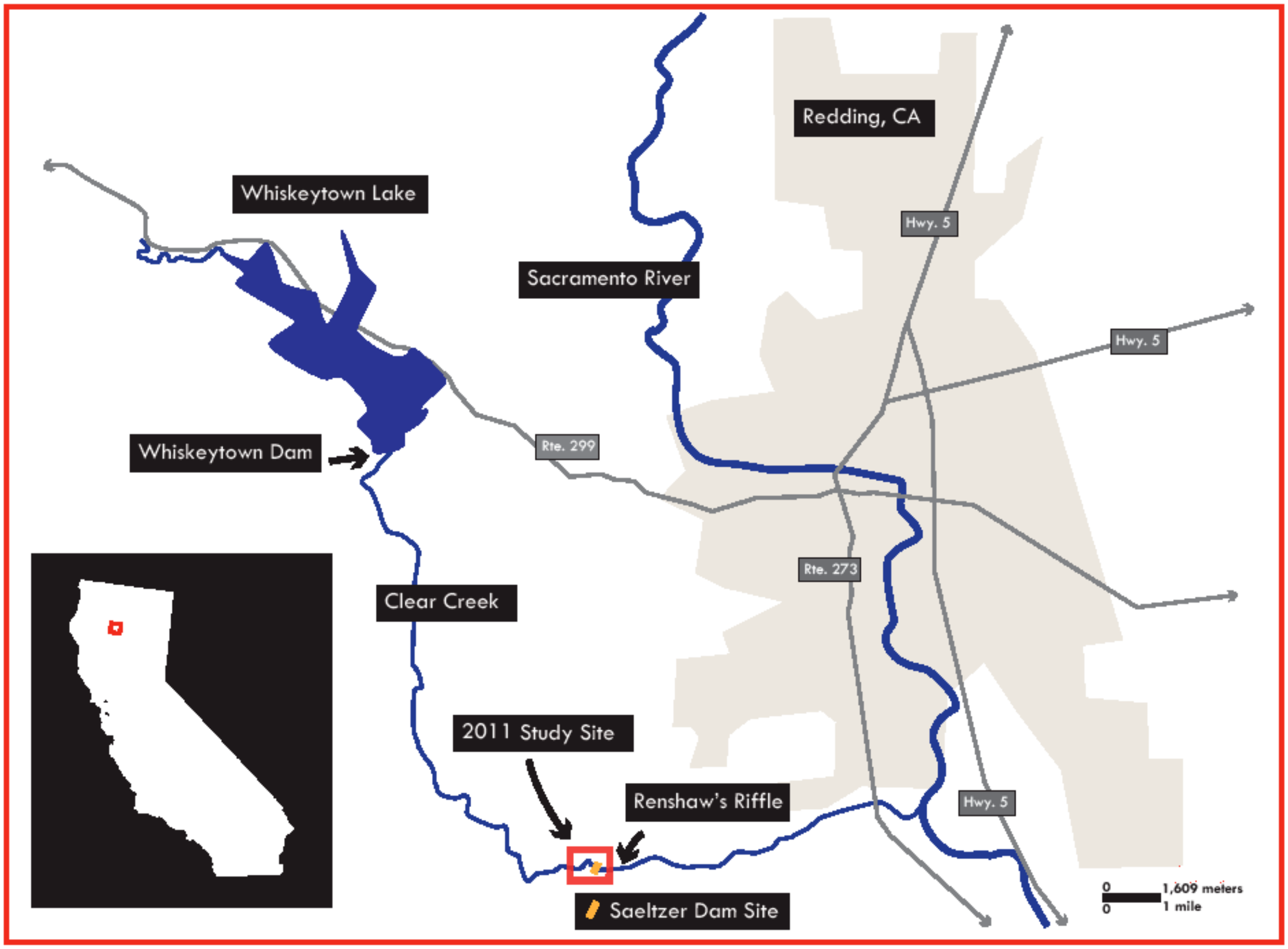


Figure 1.
2011 study region and former Saeltzer Dam site

STUDY	YEAR	METHOD	PRIMARY FINDING(S)	NOTES
Stillwater Science	2001	Pre- and post-removal survey of the dam site (in 2000 and 2001, respectively)	No significant change in channel morphology 5,900 yd3 of eroded sediment available for downstream transport	2001 was an unusually low peak flow season (1,250 cfs)
Ferry and Miller	2003	Five cross sections were taken upstream of the dam site (Figure 2)	Significant geomorphic change at and upstream of dam site 3 foot incision 49-59 foot lateral erosion	Between 2001-2003, three flows greater than the 2-year flood occurred (>2,800 cfs) One 3-year flood occurred
Miller and Vizcaino	2004		51,900 yd3 of eroded sediment available for downstream transport 40% (20,900 yd3) of erosion is sand Bedrock limited incision, emphasized lateral erosion (Figures 15, 16, B2)	Continuation of Ferry and Miller 2003 High sand content of sediment has especially negative impacts to downstream salmonid spawning habitat
Graham Matthews and Associates (GMA)	2000, 2004	Survey and long profile of former dam site and upstream impoundment area	49,000 yd3 net change in sediment Incision 4,000 feet upstream Aggradation downstream 9,000 feet into known salmonid spawning habitat	

Table 1.
Previous studies and findings.

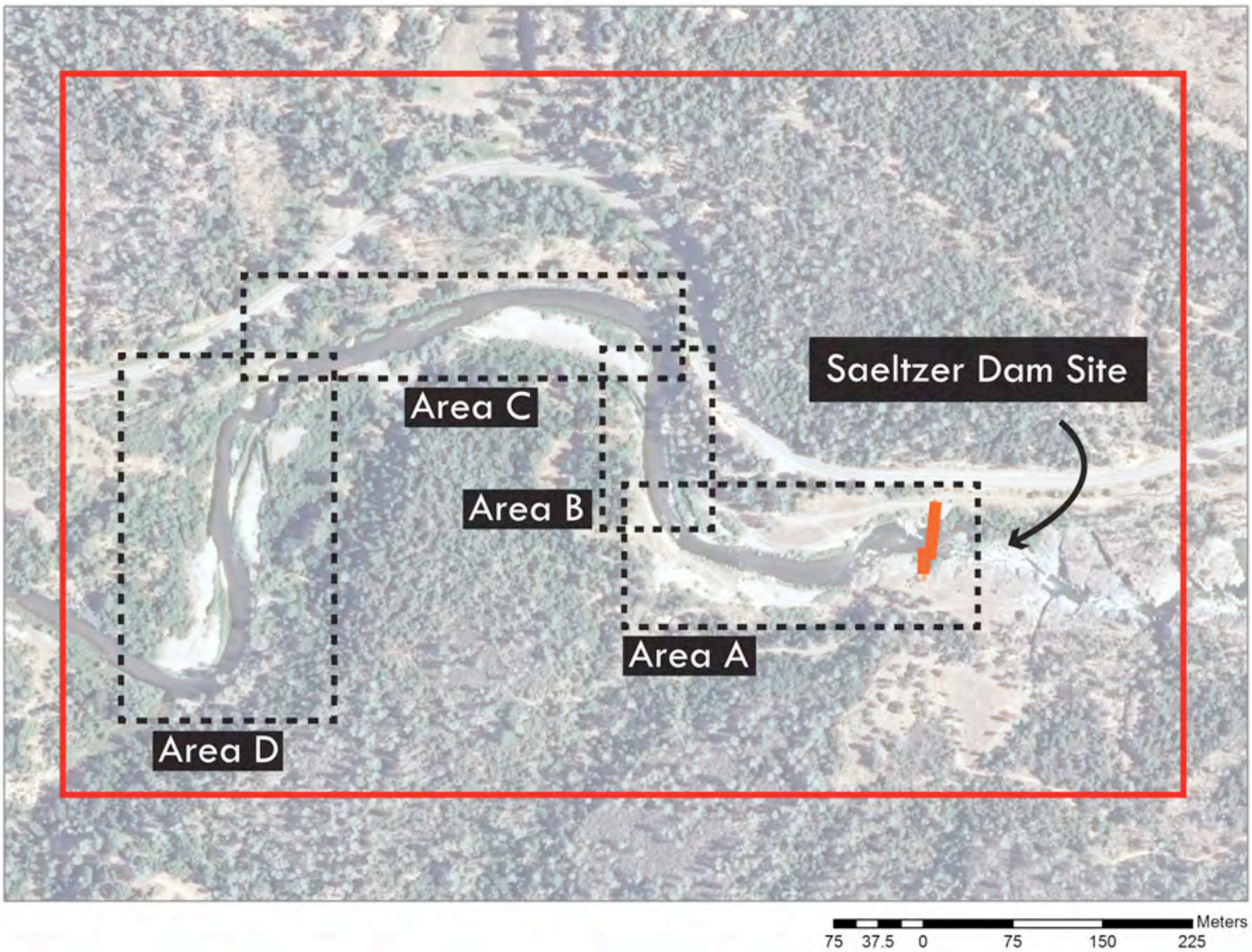


Figure 1a.
2011 study site and Saeltzer Dam location.

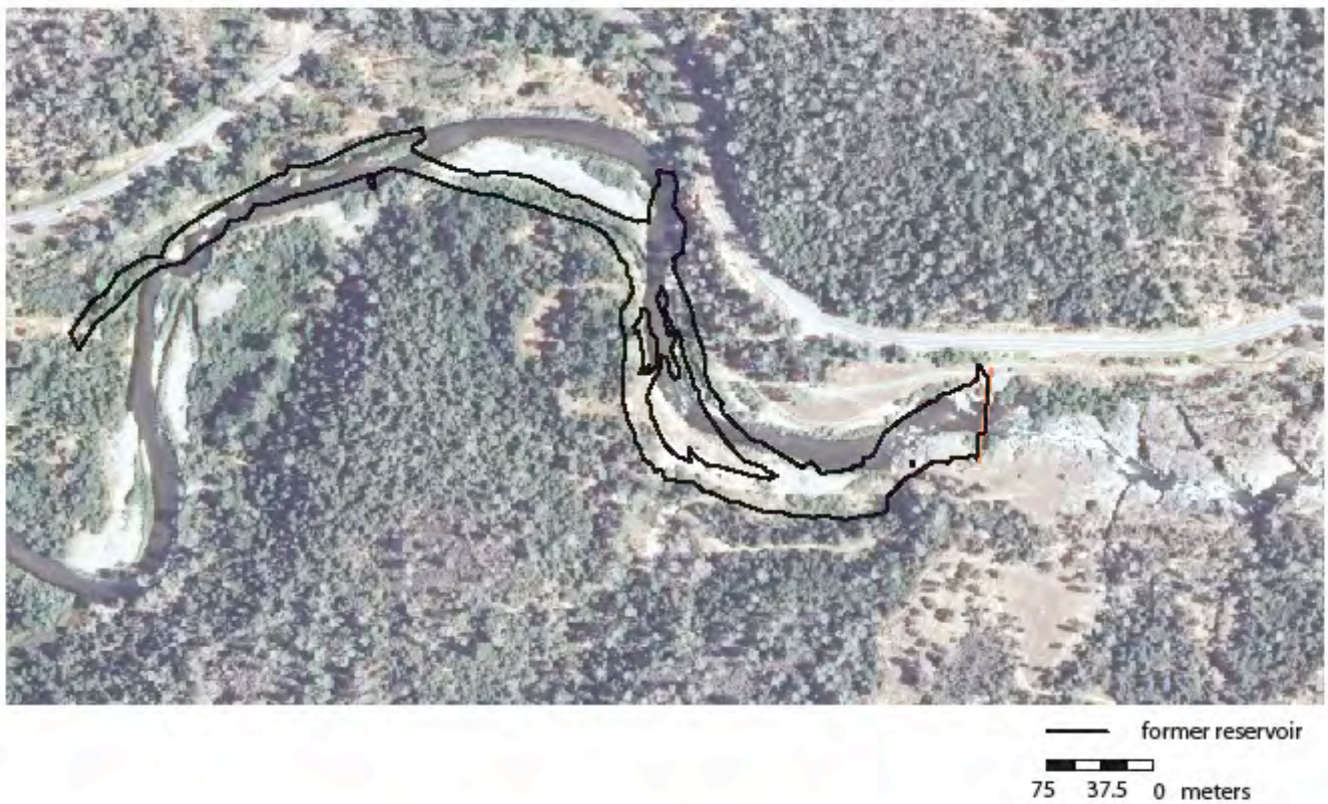


Figure 1b.
Approximate extent of former reservoir impoundment.

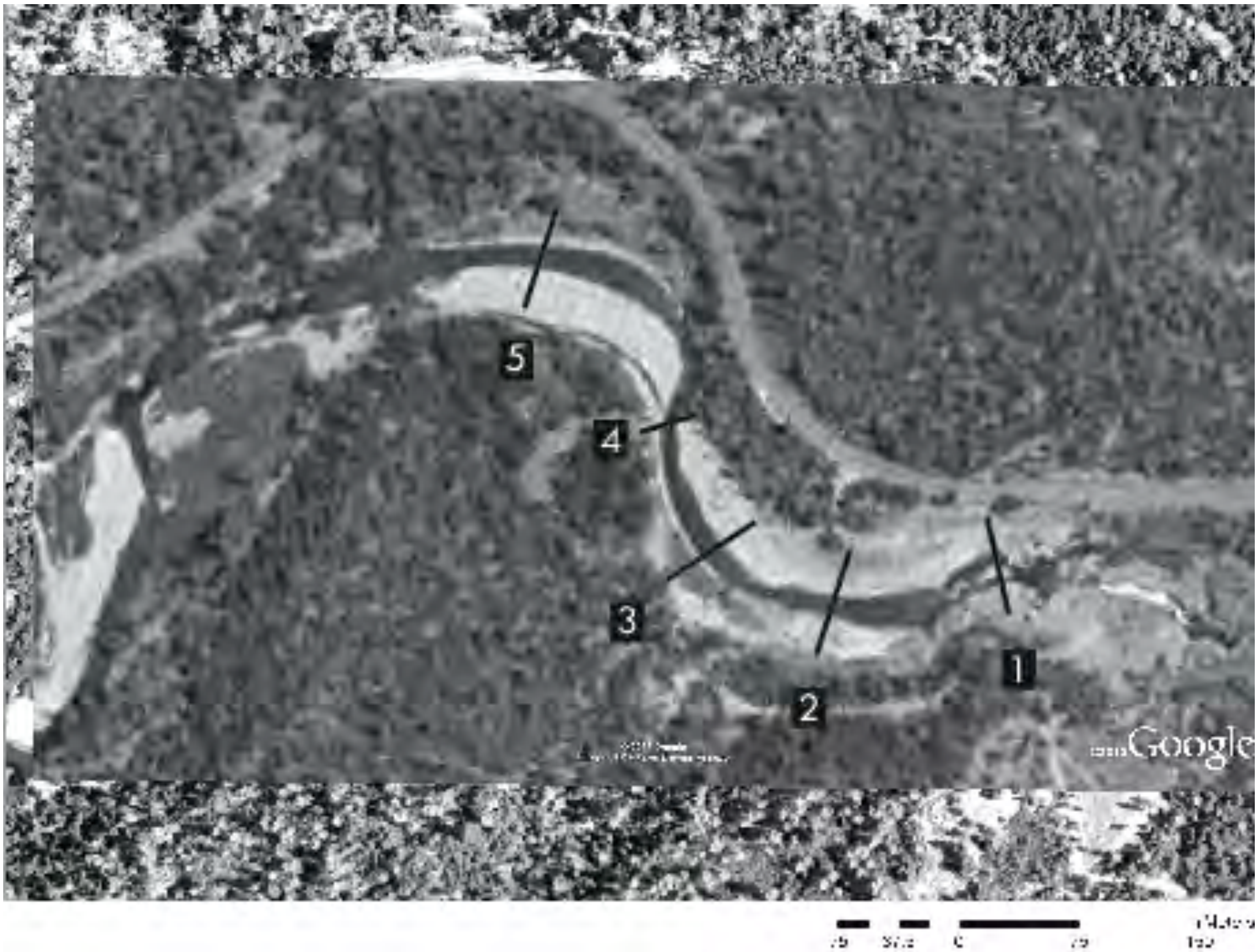


Figure 2.
Five cross sections conducted in 2003 by Ferry and Miller (cited in Miller and Vizcaino 2004).

Figure 3.
2011 cross sections 1 and 2, and long profile of thalweg.

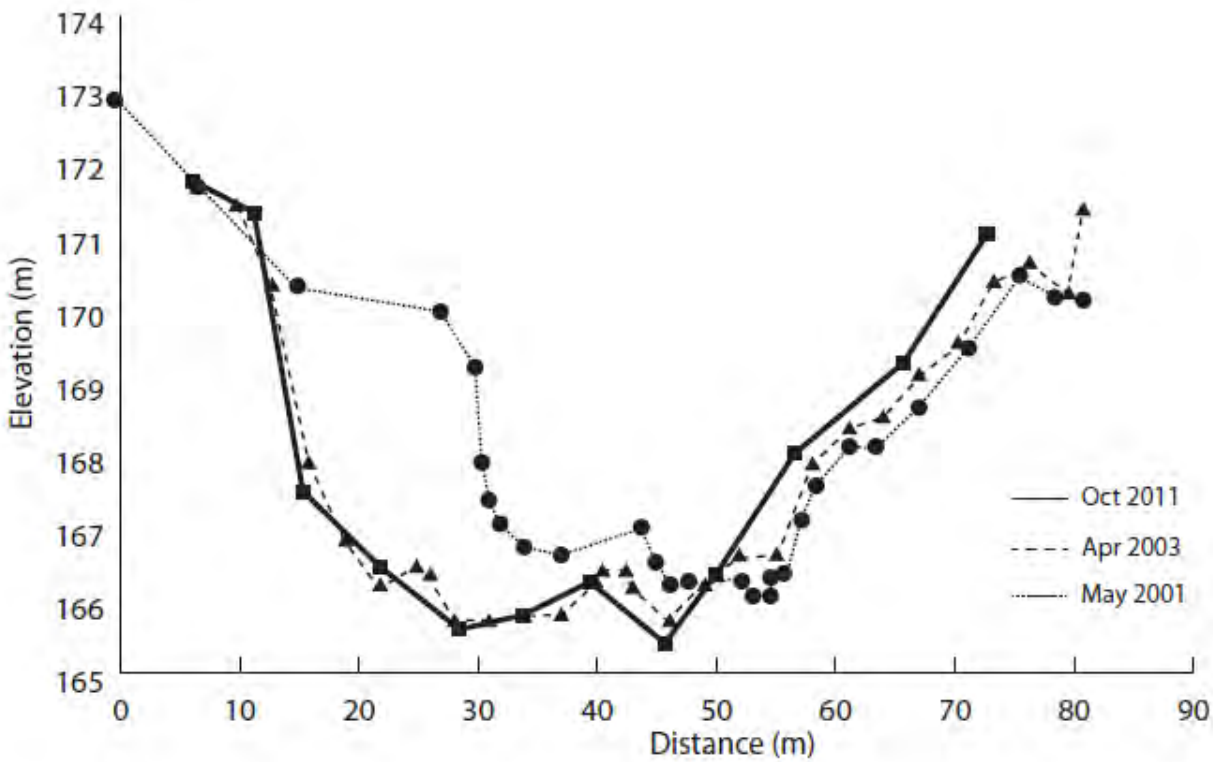


Figure 4.
Cross-section 1.

2011 results are compared to those from 2001 and 2003. Our 2011 cross section was based on the rebar stake used in Miller and Vizcaino's 2003 fieldwork. The graph of their cross section 1 is missing from the published report. Based on maps in the 2003 and 2004 reports, we determined that Ferry and Miller's 2003 cross section 1 is in approximately the same location, so we use it here for comparison. Cross section 1 in 2003 was cut at an angle across the channel, while we surveyed perpendicular to the channel. Thus the 2003 channel appears slightly larger in this graphic, although we have no reason to believe that is actually the case (since aggradation on steep slopes is extremely unlikely).

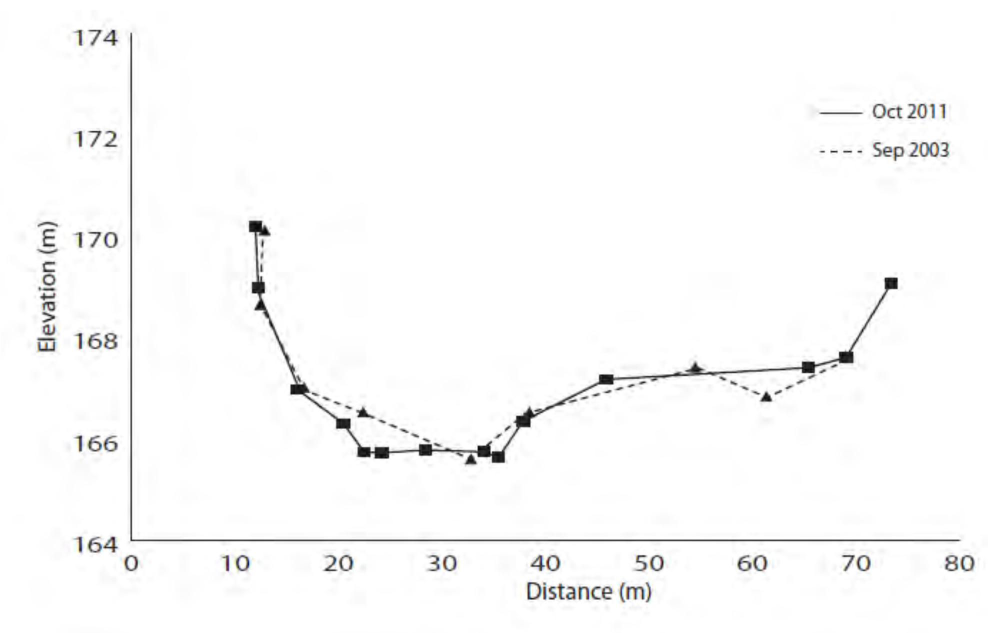


Figure 5.
Cross-section 2.
2011 findings are compared to those from Miller and Vizcaino's 2003 cross section. (Note: Stillwater's 2001 study did not survey this cross section).

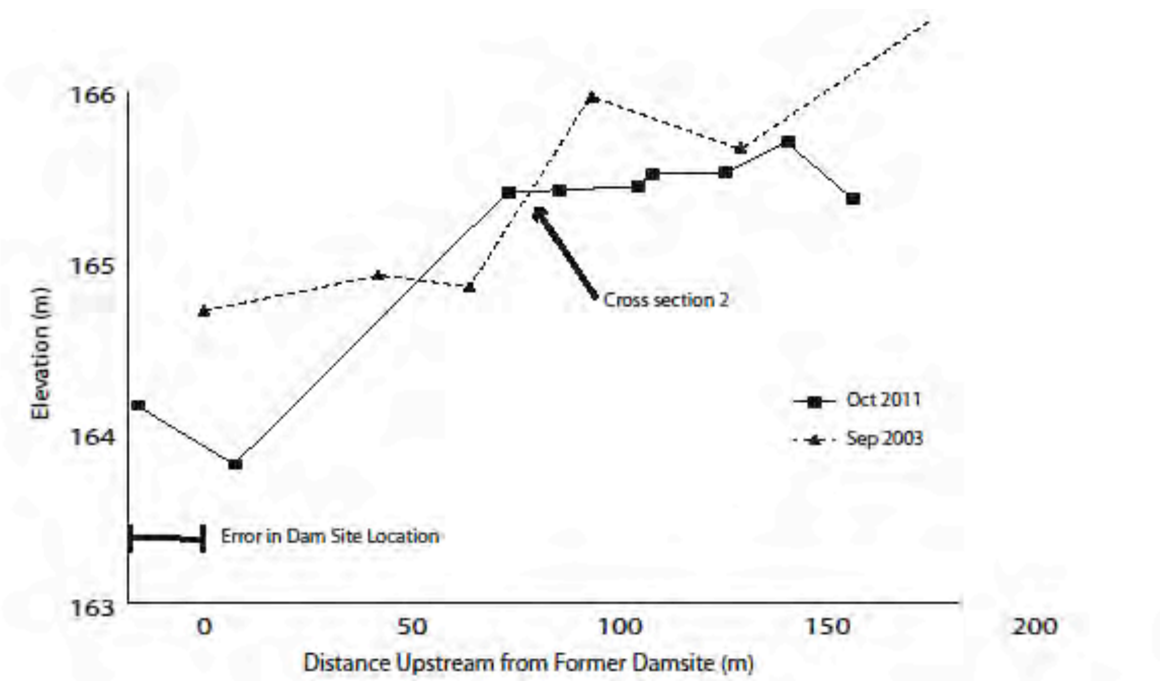


Figure 6.
Long profile of thalweg upstream of the former dam site.
Surveying downstream of the former dam site was impossible due to deep, fast moving water. Long profiles are located based on the former dam site, but there was likely large amount of error in locating the former dam site, resulting in uncertainty in the alignment of the two long profiles.

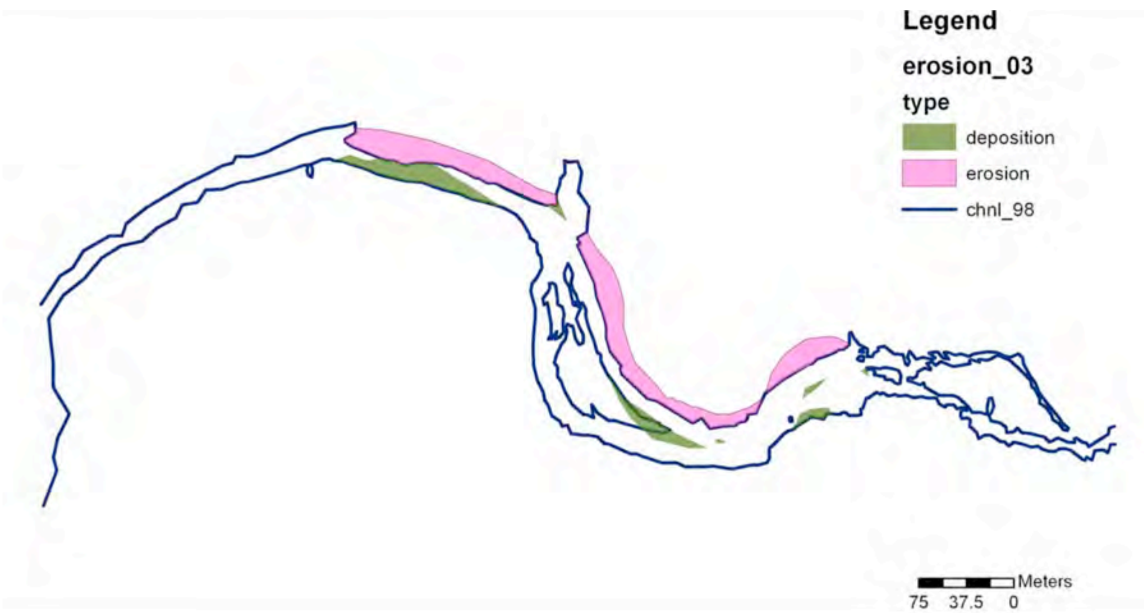


Figure 7a.
Areas of erosion and deposition in 2003/04
Interpreted from Ferry and Miller 2003). Interpretation methods are described in Appendix A.

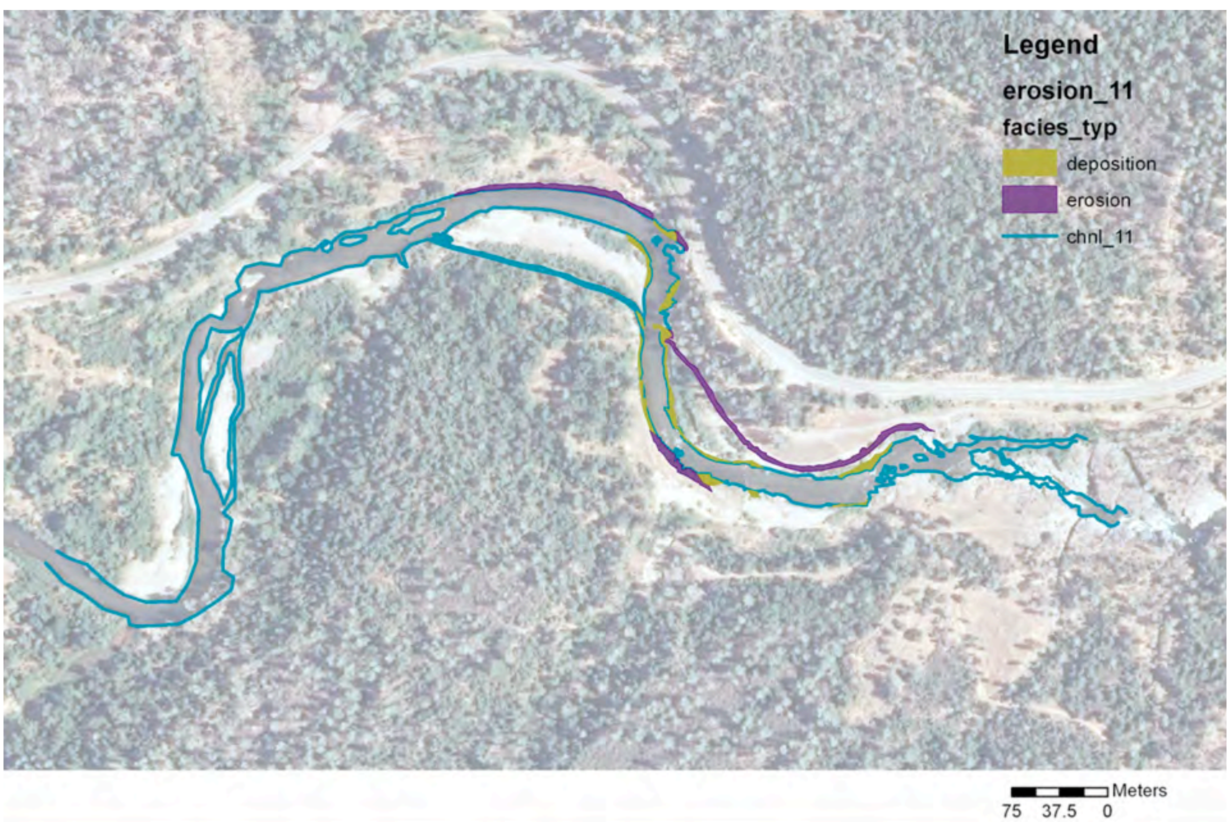


Figure 7b.
Areas of erosion and deposition in 2011.

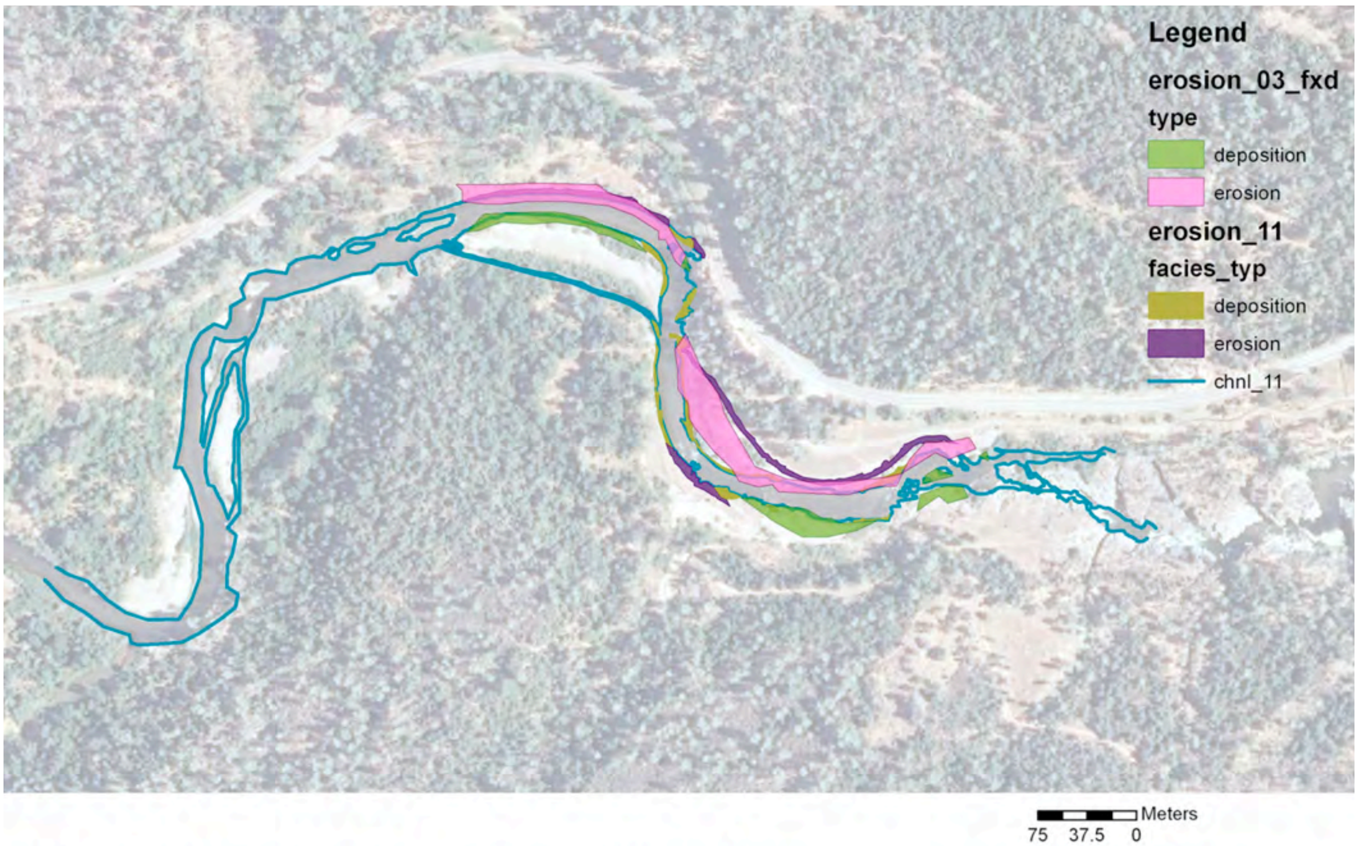


Figure 7c.
Compared areas of erosion and deposition, between 2003/04 and 2011, on the 2011 channel.
Note increased erosion in Areas A and C from 2003 to 2011.

(A) Pre-2000

(B) April 2003

(C) October 2011

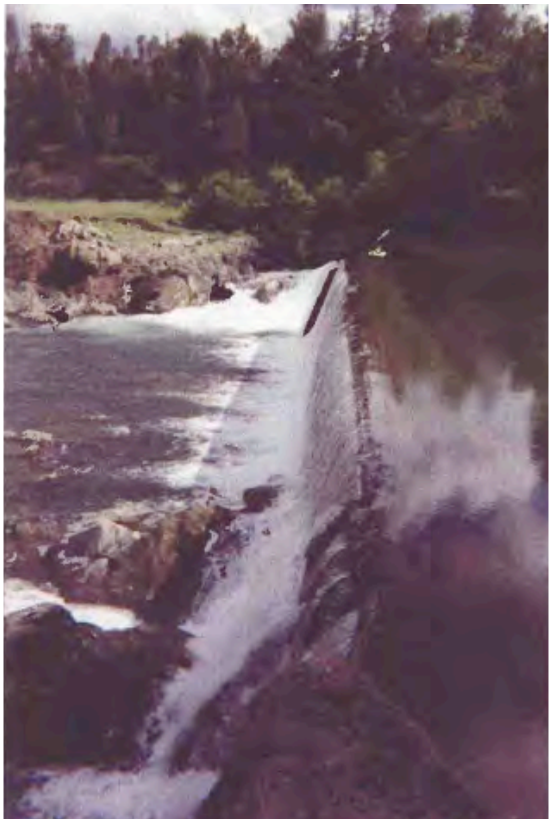
Figure 8.
Upstream view, Saeltzer Dam. (A) Pre-2000 before removal; (B) April 2003; and (C) October 2011. Pre-dam removal and 2003 photos from Ferry and Miller 2003. Note extensive vegetation growth from 2003 to 2011.

(D) Pre-2000

(E) April 2003

(F) October 2011

Figure 9.
Downstream view, Saeltzer Dam. (D) Pre-2000, before removal; (E) April 2003; and (F) October 2011. Pre-dam removal and 2003 photos from Ferry and Miller 200. Note extensive vegetation growth since 2003.



(G) Pre-2000

(H) April 2003

(I) October 2011

Figure 10.
North to south bank view, Saeltzer Dam. (G) Pre-2000, before removal; (H) April 2003; and (I) October 2011. Pre-dam removal and 2003 photos from Ferry and Miller 2003. Note extensive vegetation growth since 2003.

Figure 11a.
1997 and 2004 aerial imagery, with notable areas of vegetation change.

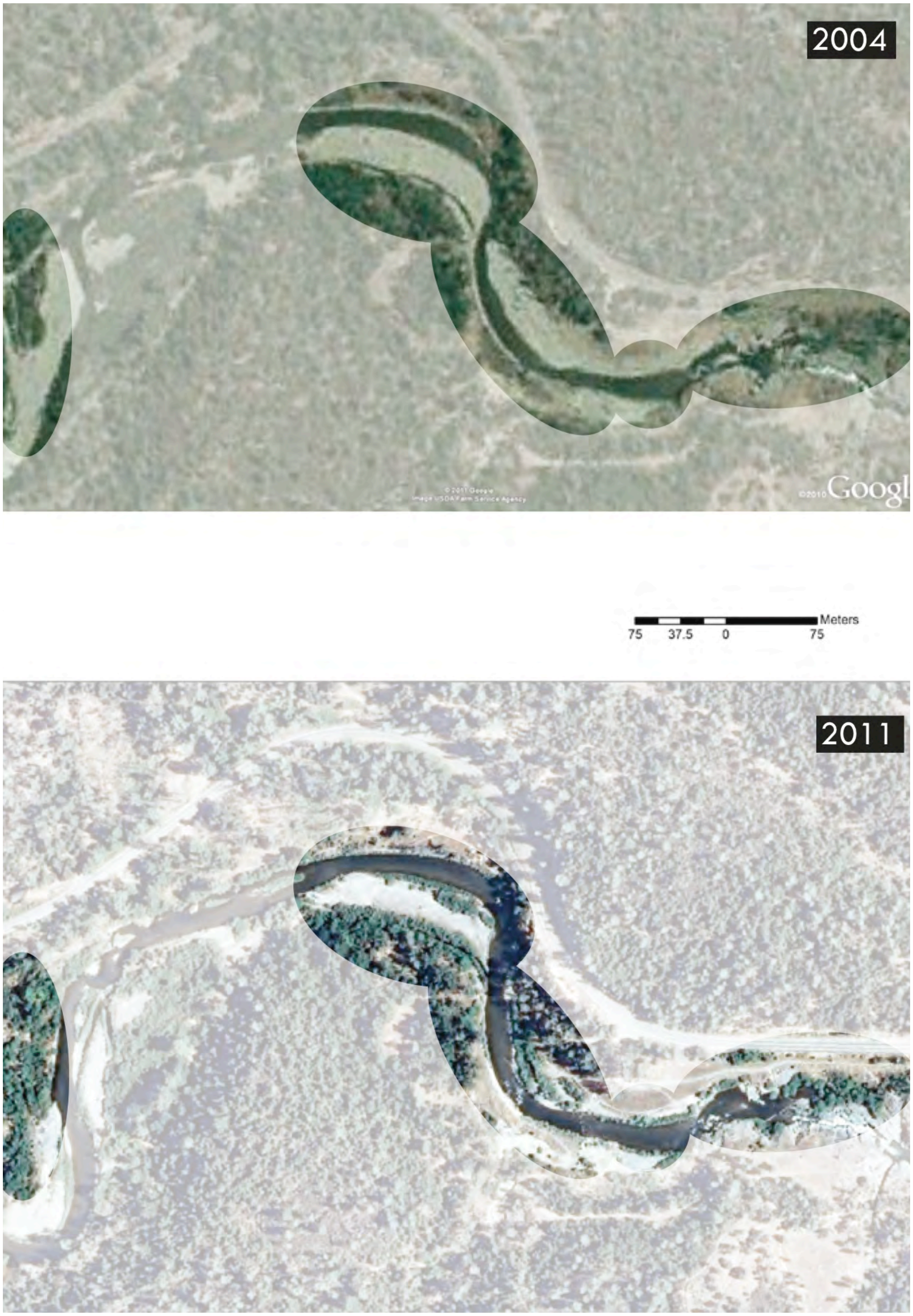


Figure 11b.
2004 and 2010 aerial imagery, with notable areas of vegetation change.

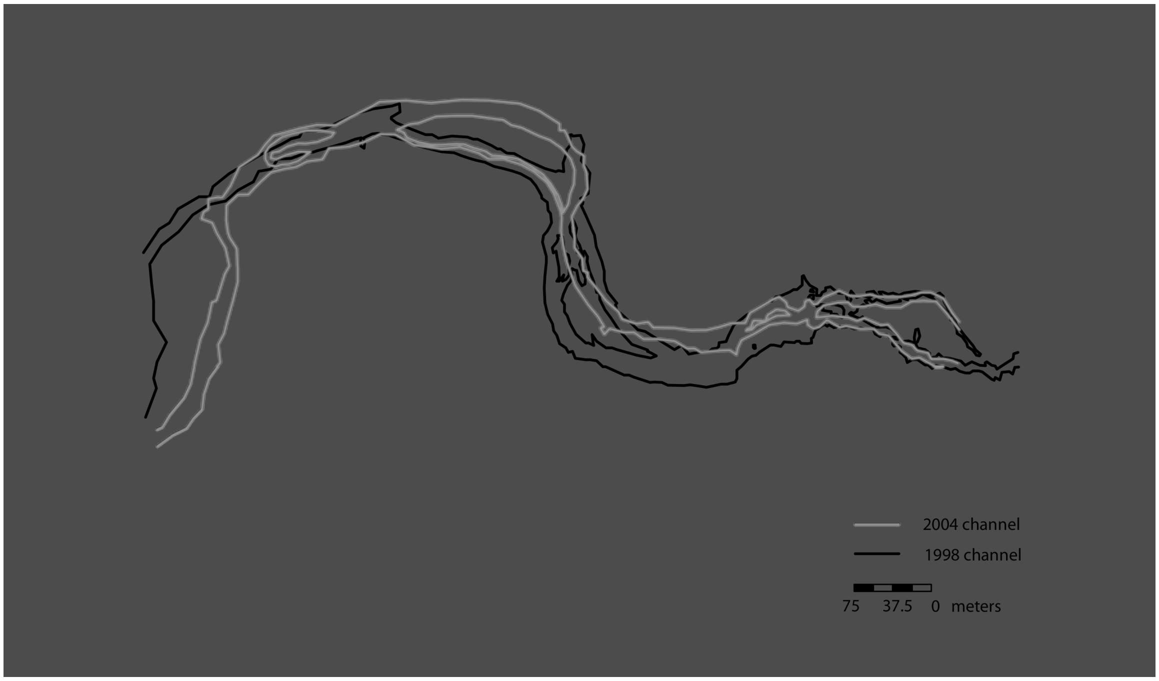


Figure 12a.
Channel change between 1998 and 2004.

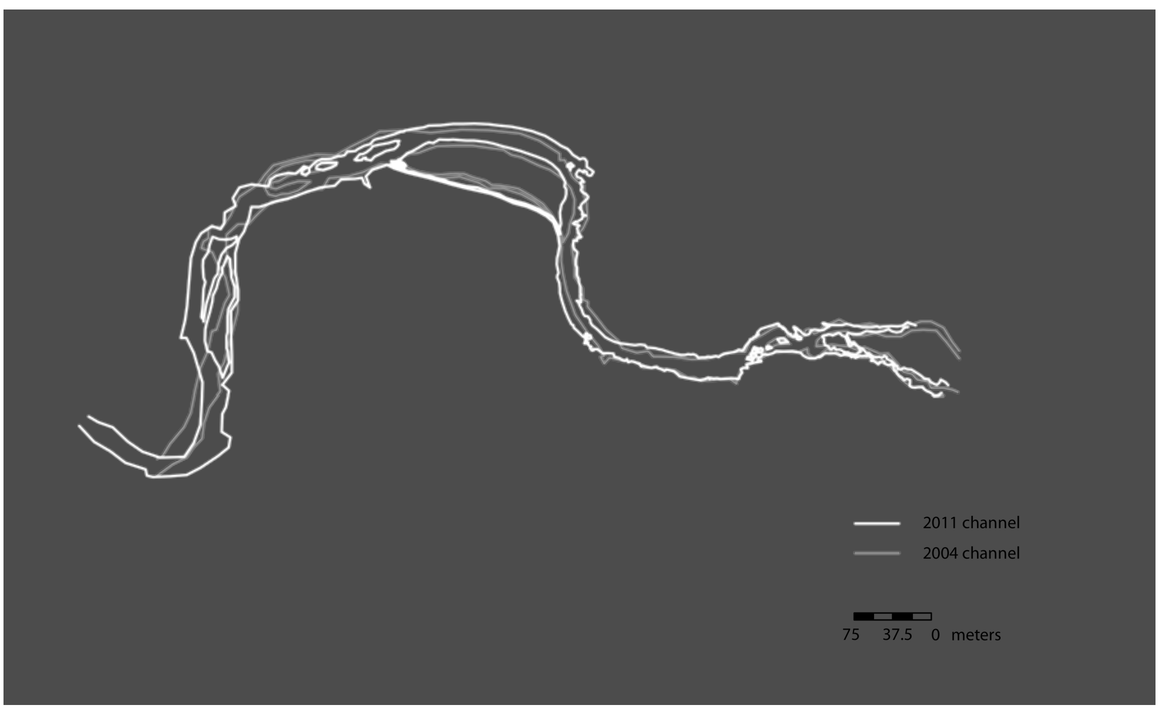


Figure 12b.
Channel change between 2004 and 2011.

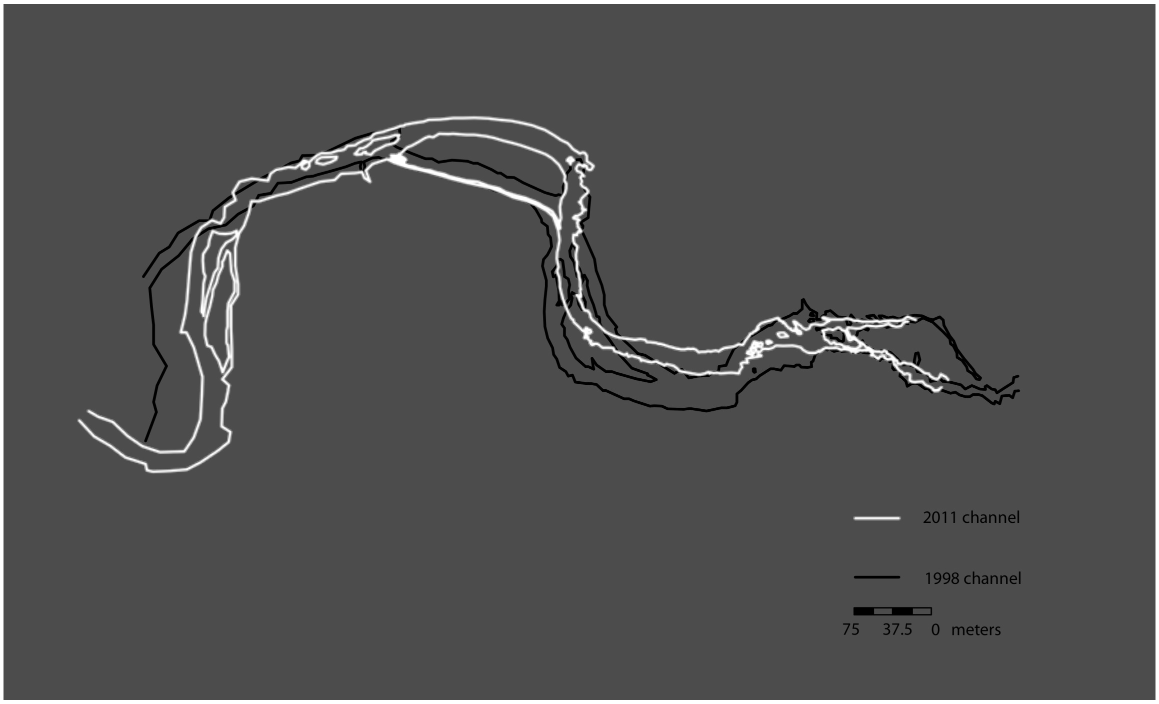


Figure 12c.
Channel change between 1997 and 2011.

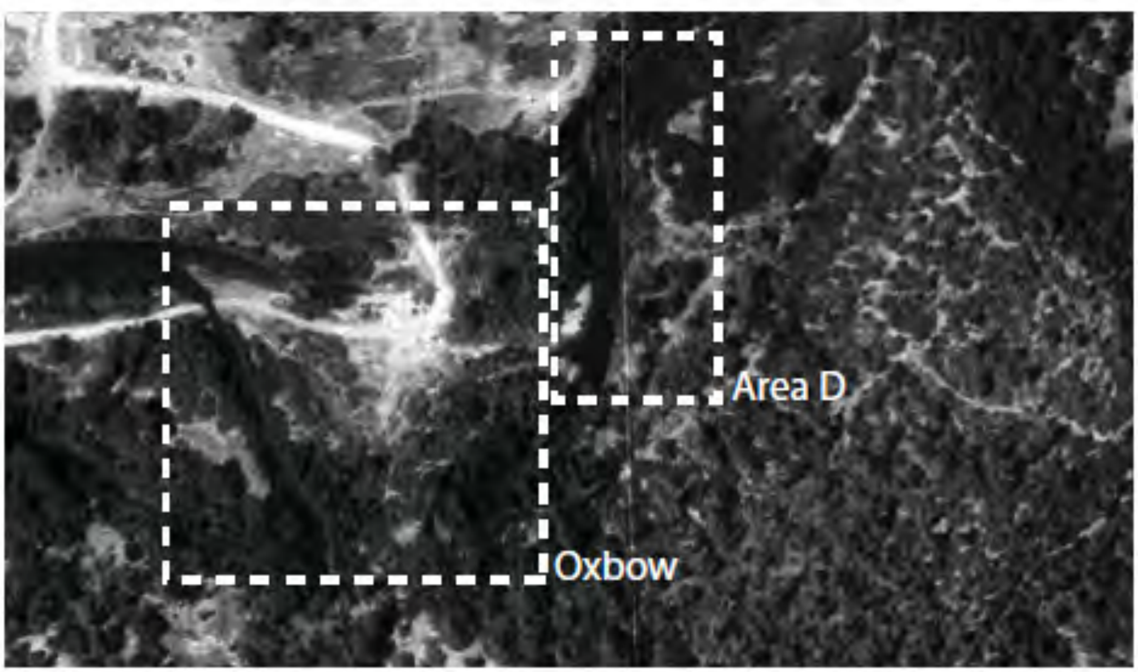


Figure 13a.
1998 Aerial photograph of area D and the Oxbow.

Figure 13b.
2004 Aerial photograph of area D and the Oxbow.

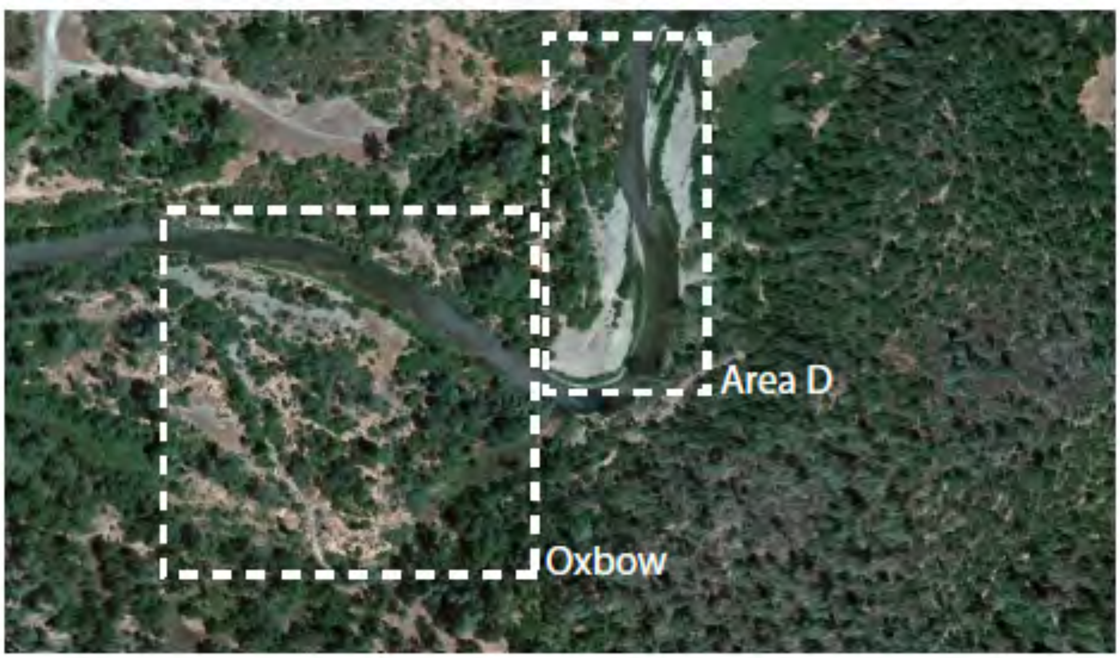


Figure 13c. 2010 Aerial photograph of area D and the Oxbow.

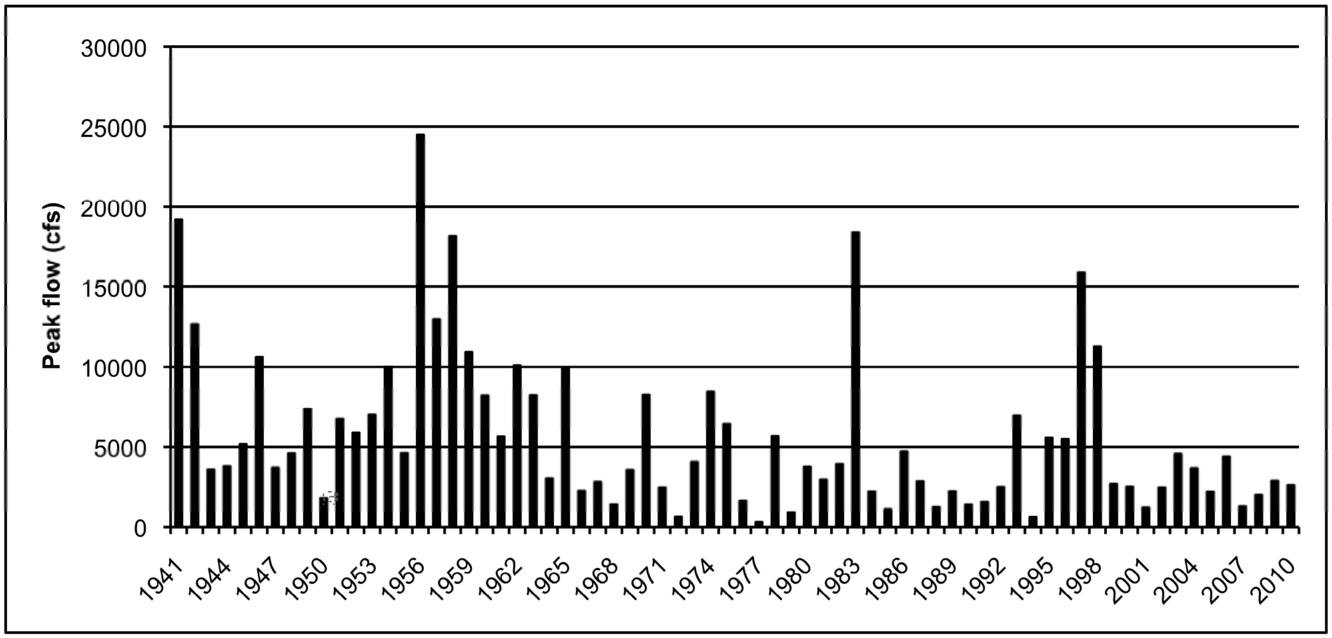


Figure 14.
Peak Annual Flow (cfs) 1941-2010.

From USGS gauge 11372000 on Clear Creek near Igo, CA. Note the 4,500 cfs flow recorded on December 31, 2005. In 2011, we found minimal incremental erosion from 2003 despite this substantial flow event.

APPENDIX A

Interpolation of 2003 erosion and deposition results for comparison in 2011

As discussed in the Methods section above, erosion and deposition mapping was done through field observation and translated into a digital GIS format. This allowed the data to be geo-referenced and analyzed. We compared erosion and deposition between 1998 and 2004, and between 2004 and 2011 (Figures 7a, 7b, 7c). To do so, it was necessary to interpret the erosion and deposition map made by Ferry and Miller in 2003 because their 2003 field observations were originally hand-drawn on a map of the 1998 channel form (Figure A1).

Ferry and Miller conducted field work in April 2003; we therefore assumed that their noted areas of erosion and deposition were in fact referenced from the 2003 channel. We overlaid their original map onto the 2004 aerial imagery from Google Earth Pro (Figure A2), and interpreted the areas of erosion and deposition to associate with the 2003/04 channel (Figure A3).

We then transposed these interpreted areas of 2003/04 erosion and deposition onto the 2011 channel[21] (Figure A4). This analysis demonstrates the relationship between 2003 areas of erosion and stream channel change noted in 2011, specifically in areas A and C.

Finally, by layering the interpreted 2003 areas and the observed 2011 areas of erosion and deposition, we observed incremental patterns of erosion and deposition since 2003/04, also in areas A and C (Figure A5). Results and discussion of this analysis can be found in those respective sections of the primary document.

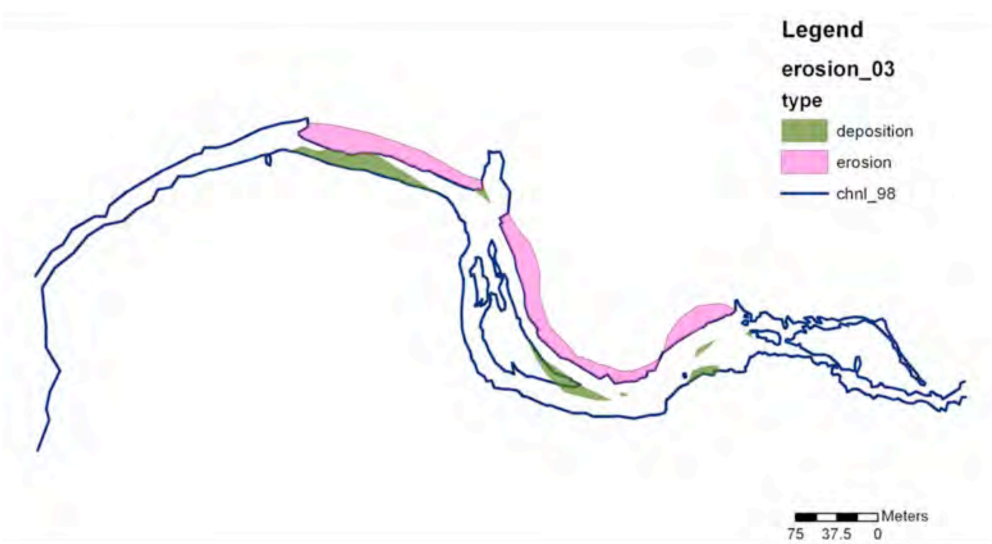


Figure A1 (7a).
Areas of erosion and deposition in 2003/04, interpreted from Ferry and Miller 2003.

[21] The most recent available aerial imagery of the study area is from 2010. All 2011 field observation data is displayed on 2010 photographs. We do not have reason to believe the channel changed significantly in this time span. We used a 2010 aerial photograph from the USGS seamless server to confirm spatial referencing of the historic imagery.

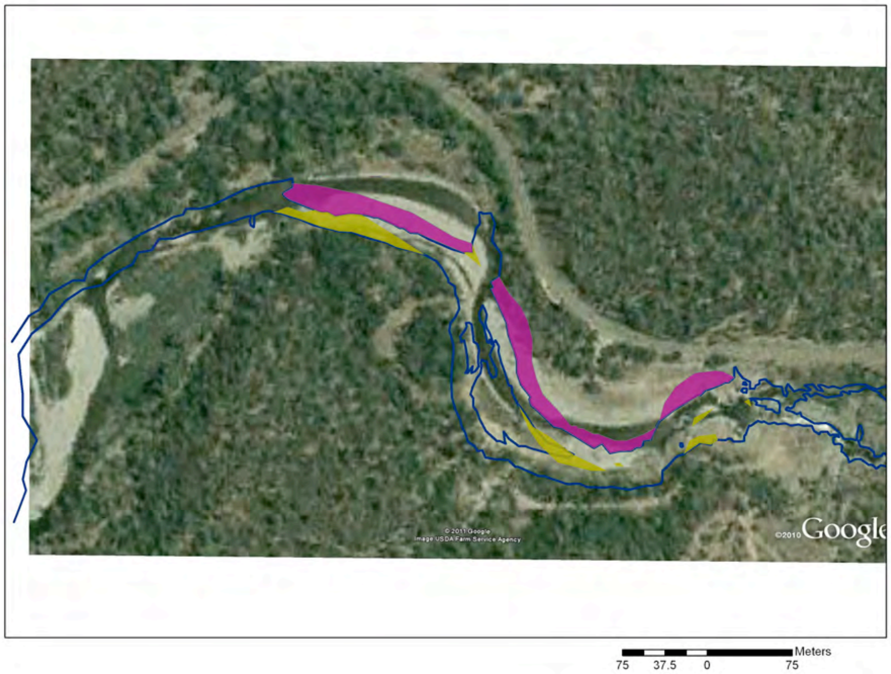


Figure A2.
Ferry and Miller's original 2003 erosion and deposition map overlaid on a 2004 aerial photograph.

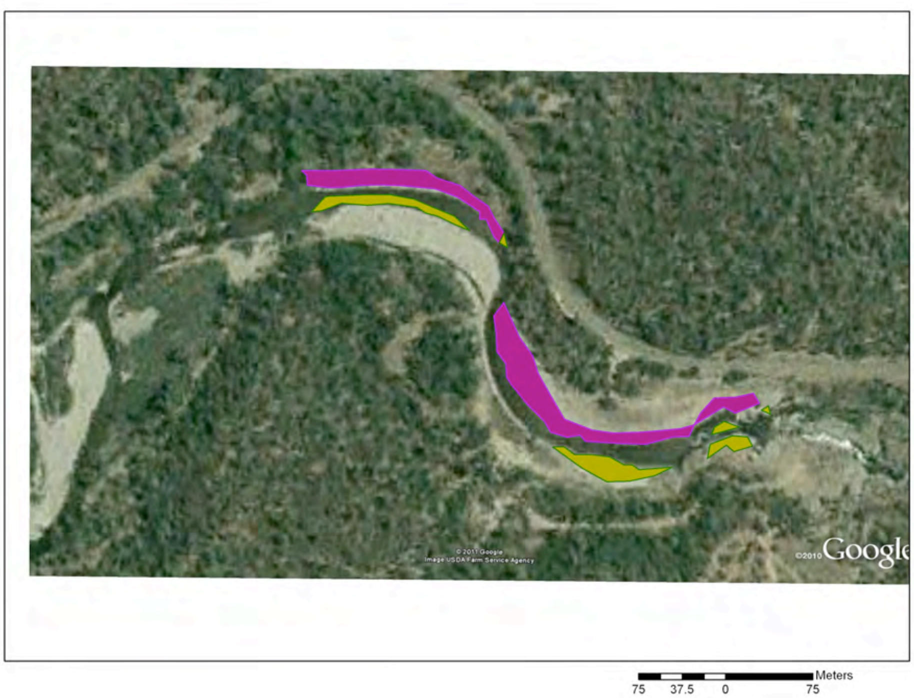


Figure A3.
Interpretation of Ferry and Miller's areas of erosion and deposition to the 2004 channel.

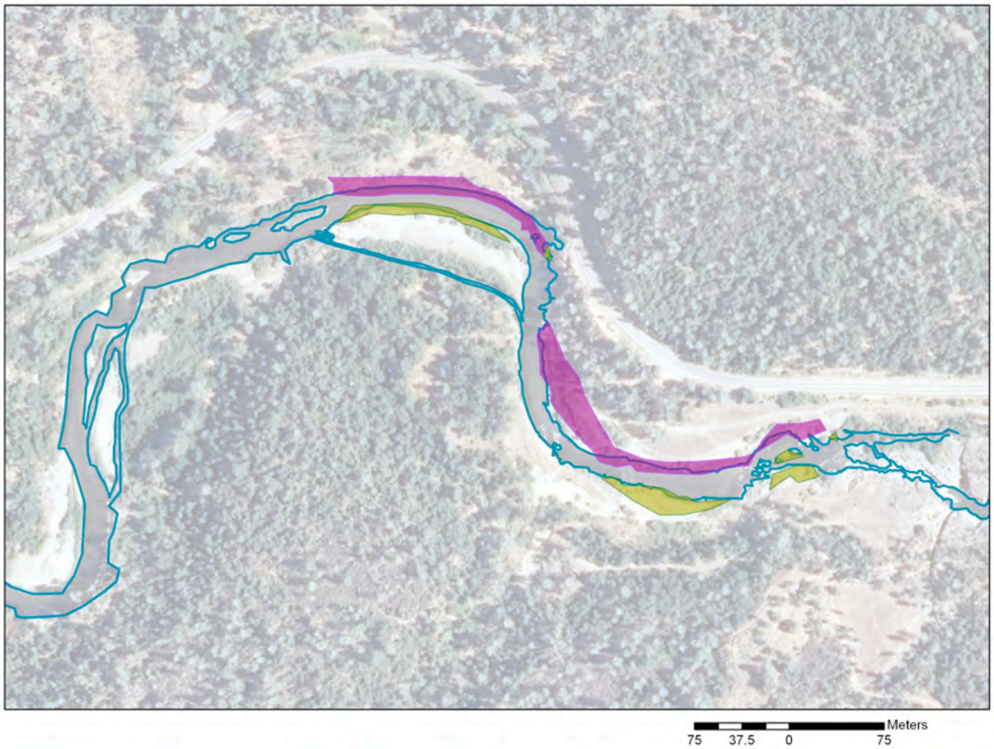


Figure A4.
Interpreted 2003/04 erosion and deposition compared with the 2011 channel form.

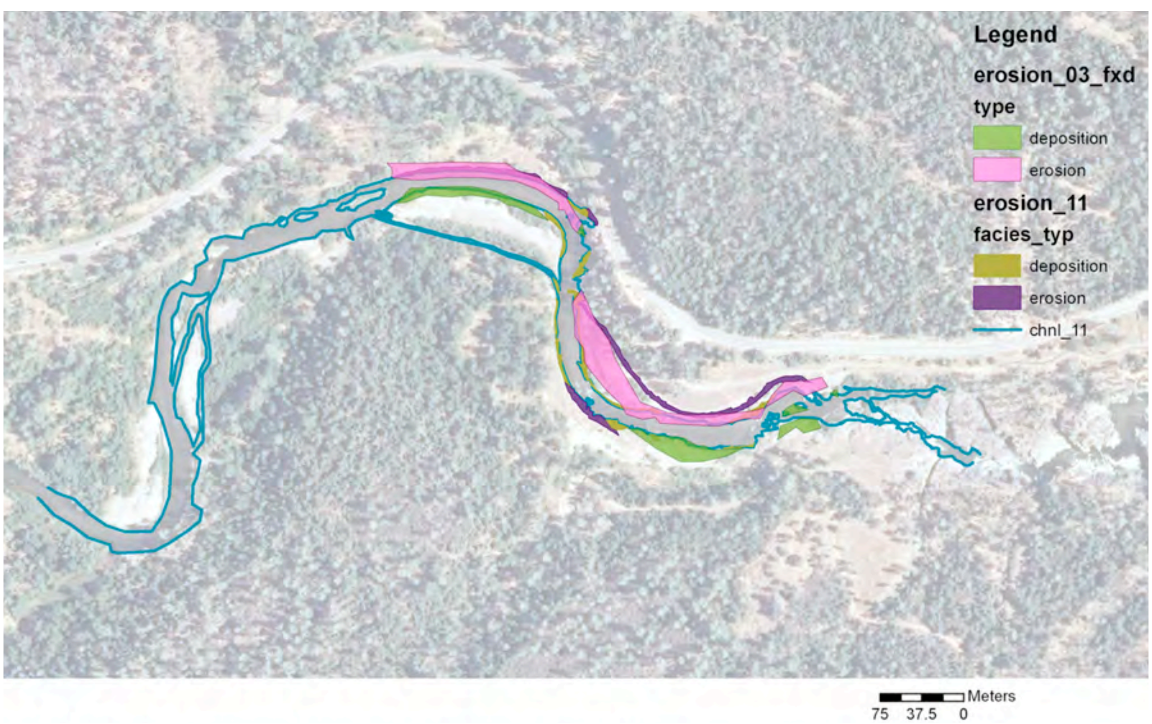


Figure A5 (7c).
Compared areas of erosion and deposition, between 2003/04 and 2011, on the 2011 channel.

APPENDIX B

2011 Facies map and substrate classification (Study areas A, B and C).

Facies mapping involves identifying the location and size of each patch of rock, and then characterizing each patch based on its grain size (Buffington and Montgomery, 1999 in Clayton-Niedernman and Gilbreath, 2005). A pebble count method is commonly used to characterize a patch by its grain size. A sample of 100 stones is generally appropriate to reproduce accurate median grain sized (d50), however accurate results may require samples of up to 400 stones (Kondolf et al, 2003 in Clayton-Niedernman and Gilbreath, 2005).

Our method for creating facies map of the study area did not include a pebble count and is therefore rudimentary in regard to classification. For this reason, we chose not to include it in our study of geomorphic adjustment and bank stabilization. Our recorded areas of differing substrate type, however, are distinct and reliable for at least an anecdotal assessment of substrate distribution in the study area.

We mapped substrate facies and areas of exposed bedrock through field observation, and translated these results into a geo-referenced GIS format (Figure B1). We visually referenced substrate facies definitions as they are described in Figure 6 of Clayton-Niedernman and Gilbreath's 2005 study. This, at the very least, allows anecdotal consistency in the Clear Creek data collection.

Eight substrate types were observed: sand, mixed gravel embedded in sand, small cobble and mixed gravel, medium cobble, large cobble, boulder, bedrock, and dam rubble. Total observed area for each substrate type was calculated in square meters (Table B1).

Small cobble with mixed gravel was the dominant type, primarily observed in those areas where channel change occurred between 1998 and 2011 (Figure 12c). Exposed bedrock was also significant (Figure B2), as we believe its presence aids in stabilization since 2004. Our 2011 observations of areas of erosion and deposition further support this conclusion (Figure 7b).

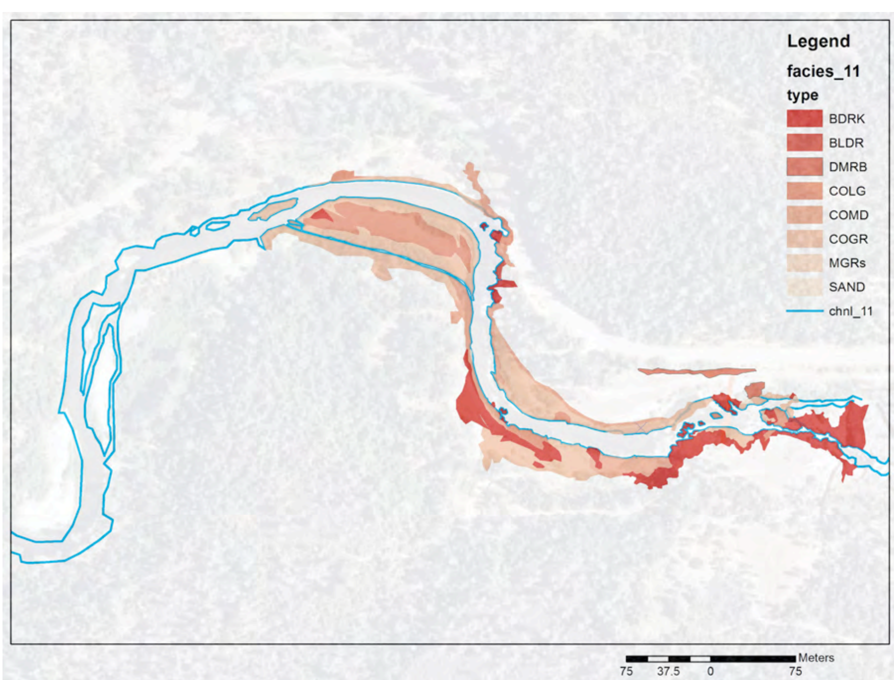


Figure B1.
2011 Substrate facies map.

SUBSTRATE TYPE	CODE	TOTAL AREA m2 (square meters)
Sand	SAND	54
Mixed gravel embedded in sand	MGRs	157
Small cobble and mixed gravel	COGR	11784
Medium Cobble	COMD	3328
Large Cobble	COLG	4058
Boulder	BLDR	76
Bedrock	BDRK	6267
Dam Rubble	DMRB	603

Table B1.
2011 Substrate facies classification and approximate area.

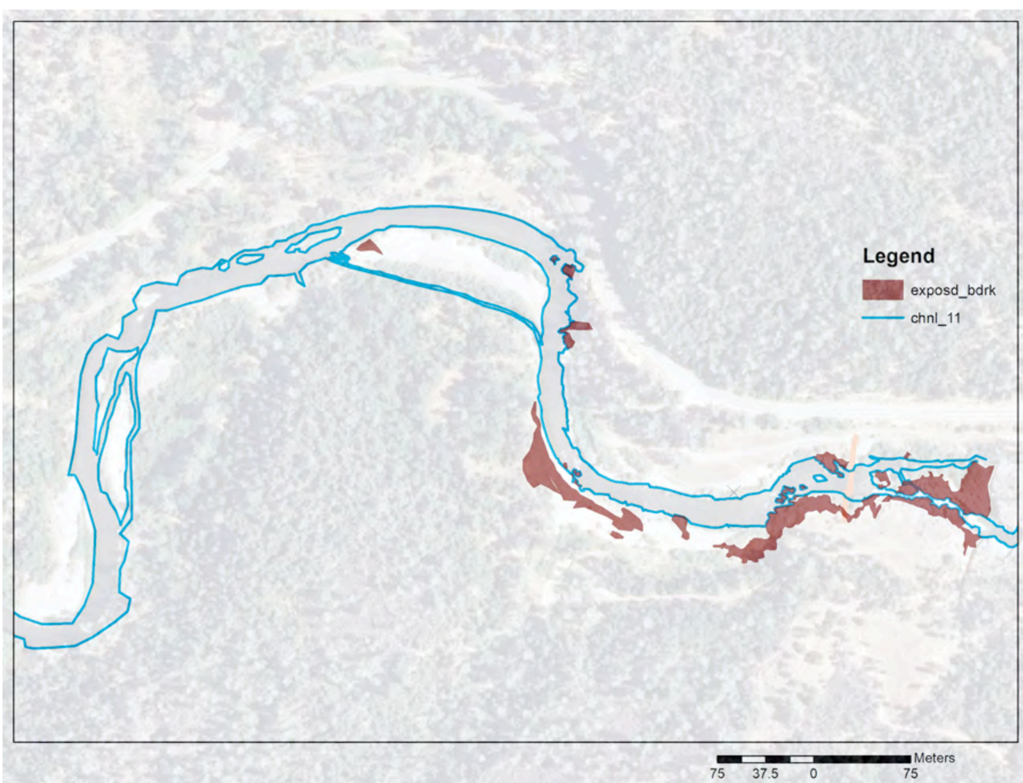


Figure B2.
2011 Exposed bedrock.