Creation of a side channel increases habitat heterogeneity in Lagunitas Creek, Marin County, California

FINAL DRAFT

Stephanie Clarke, Chris Williams, Rachael Ryan, Jessie Moravek

LDARCH 227

Abstract

Side channel restoration projects can increase the extent of complex habitats across a river landscape. We measured habitat complexity in the main channel and a recently constructed side channel along Lagunitas Creek, Marin County, California, and found that the side channel added habitat complexity to the overall site in terms of stream gradient, grain size distribution, pool size, cross-sectional depth, cross-sectional velocity, canopy cover, large woody debris, undercut banks, and riparian vegetation. This side channel habitat is especially important in providing overwintering habitat for juvenile salmonids, particularly endangered coho salmon *(Oncorhynchus kisutch)*. Overwinter survival has been identified as a limiting factor for the Lagunitas Creek coho population, where juveniles risk getting swept away in the simplified main channel. Our results from low-flow conditions indicate that juvenile coho may benefit from increased habitat complexity during the summer as well, and these findings contribute to understanding the role of constructed side channels as a river restoration method.

Table of Contents

Problem Statement

California has some of the most extensive water infrastructure in the world; dams, canals, levees and culverts have been constructed to provide various human services, at high ecological costs. Impacts of human modifications of rivers are widespread and pervasive: alteration of flow regimes has homogenized flora and fauna (Moyle and Mount 2007), sediment retainment by dams has led to "hungry water" incising channels (Kondolf 1997), and disconnection of floodplains has restricted spawning and rearing habitat for native fishes (Jeffres et al. 2008; Goertler et al. 2018). The cumulation of these impacts is the loss of habitat complexity within rivers. Dynamic physical processes that operate at various spatial and temporal scales generate different patches of instream habitats (Poole 2002) that can support diverse aquatic communities (Thoms 2006).

Habitat complexity is important for persistence of some of California's most threatened aquatic species, such as salmonids. Studies have shown that variation in adult spawning and juvenile rearing habitats lead to greater stability in abundance across time and differential growth and survival rates (Quinn and Peterson 1996; Wheaton et al. 2004; Goertler et al. 2018). Pacific salmon species in California have been decimated in the last century, with Central California Coast coho salmon *(Oncorhynchus kisutch)* on the brink of extinction (Miller 2010). In response, there have been millions of dollars spent in improving salmon habitat, specifically coho salmon habitat. Given the benefits that diverse habitats confer to salmon survival, there is a growing interest in restoring habitats with greater complexity and increased variation.

One of the most common areas of restoration of salmon habitat has been to increase habitat heterogeneity through creation or reconnection of floodplains and side channels. Side channels can differ in physical habitat structure, organic matter content and water chemistry from the main channel (Sobotka and Phelps 2017). In rivers modified by dams, side channel creation is especially appealing as it is a way of increasing habitat variation in a modified system where dams are unlikely to be removed. Natural side channel habitats benefit juvenile salmon by providing refuge from high winter flows, which increases survival (Peterson 1982a). They also contribute to growth in the summer, as juveniles can exploit asynchronous habitat dynamics, such as spatiotemporal variation between side channel and main channel habitats (Baldock et al. 2016). This variation is critical in dynamic environments, where previously unused habitats may become favourable under different environmental conditions (Brennan et al. 2019). Constructed side channels have successfully created suitable juvenile coho habitat (Morley et al. 2005), but few studies have assessed whether constructed side channels increase overall habitat complexity of a stream, as is found in natural systems.

Our study seeks to address the gap in assessment of side channel restoration by evaluating within and between-channel habitat complexity in a constructed side channel and a reach of the adjacent main channel. Our objectives are twofold: first, we compare various elements of stream habitat between a constructed side channel and a stretch of the adjacent main channel to assess differences in habitat; second, we evaluate how habitat variation of the entire site is increased by the construction of the side channel. The habitat elements we measured include stream gradient, cumulative grain size distribution, pool size, cross-sectional depth, cross-sectional velocity, canopy cover, large woody debris, undercut banks, riparian vegetation. Critiques of studies investigating benefits of habitat complexity include the tendency to focus on one structural element of habitat and only quantify the density of that element (St. Pierre and

Kovalenko 2014). A wide range of habitat components collectively contribute to habitat complexity, and the variation in these components throughout a reach can be a determining factor for salmon abundance (St. Pierre and Kovalenko 2014), which is why our study uses a multitude of habitat metrics to assess complexity.

By understanding how variation in habitat changes between the two channels, we can evaluate the "value-added" by this constructed side channel. We can use these methods to expand evaluation of other constructed side channels in streams throughout California and begin to understand the biological consequences of this type of restoration.

Methods

Study Site

Lagunitas Creek is a small coastal watershed located in Marin County, CA, with a catchment area of 213 km² (Figure 1) (Downs et al. 2018). The watershed has been modified by various human activities that have degraded the instream habitat. Deforestation, ranching and agriculture dominated land-use from 1850-1920 and led to increased erosion and sediment input (Downs et al. 2018). Starting in the 1920's, human settlement started to intensify, resulting in increased flow impoundment that has changed sediment transport patterns and the natural flow regime (Downs et al. 2018). Currently there are three dams in the Lagunitas watershed, two on mainstem Lagunitas Creek. Peters Dam regulates flow on mainstem Lagunitas Creek where our study site is located. Despite extensive human impacts, small populations of endangered Central California Coast coho salmon, threatened Central California Coast steelhead trout *(O. mykiss)* and endangered freshwater shrimp *(Syncaris pacifica)* persist (Miller 2010). The Lagunitas coho population is the southernmost wild spawning population of coho salmon, thus conservation efforts are focused on maintaining and restoring high quality juvenile salmon habitat.

The non-profit organization Salmon Protection and Watershed Network (SPAWN), a branch of Turtle Island Restoration Network, undertook a major restoration project to improve habitat quality for coho, specifically to provide refuge from high winter flows for juvenile coho (Figure 2). They constructed an approximately 360m floodplain side channel adjacent to a reach of the Lagunitas Creek mainstem. Construction was completed in October 2018, and the added channel was exposed to high flows in the winter of 2018-19. In the summer, most of the floodplain is dry but there is a small, 100m perennial reach of the constructed channel that provides habitat for coho, shrimp and other native fishes. While the goal of the ephemeral and perennial side channel construction was specifically to create overwinter habitat for juvenile coho that protects them from high flows, there may be additional benefits provided to juveniles in the summer by increasing habitat complexity. Our study focused on quantifying the habitat variation in the perennial side channel (hereafter "side channel") and a 100m reach of the main channel adjacent to the side channel during the low flow season.

Geomorphic Surveys

We surveyed two cross-sections spanning both the main channel and side channel using a measuring tape, stadia rod, and auto level on a tripod to measure distance and elevation coordinates along the cross sections (Figures 4a, 4b). Using these same methods, we created longitudinal profiles of the main channel and the side channel showing bed slope (Figures 5a, 5b). Equations used to create the cross-sections and profiles are shown in Appendix A, Equations 1-6. At each pool identified from the longitudinal survey, we recorded the length and maximum width of the pool using a measuring tape and recorded maximum pool depth with a meter stick. We omitted measurement of one pool on the mainstem as we could not access it through the woody debris.

We determined cumulative grain size distribution using pebble counts. We briefly surveyed the study reaches and delineated facies (Figure 3). We classified facies as "fine" if it looked like >90% of the sediment in that section was less than 8mm in diameter and did not do pebble counts in that section. Within facies where a pebble count was feasible, we conducted a pebble count, measuring grain size of 100 randomly selected stones encountered on a random walk, and measuring the intermediate axis diameter with a hand ruler. We used the following binned size classes to sort the measured pebbles, in millimeters: <8, 8, 11.3, 16, 22.6, 32, 45, 64, 90, 128, 180, 256 (Kondolf and Lisle 2016). For each facies, we plotted the grain size distribution and found the median grain size (d_{50}). Classifications of fine, medium and coarse gravel on the facies map are according to the Wenthworth scale (Figure 3).

Hydrology and Depth

We used both historical flow records for the USGS stream gage at Lagunitas Creek at Samuel P. Taylor State Park (gage 11460400) (Equations 10,11) and regression equations (Equation 12) to estimate the flow for the 2-year flood, a flow commonly used as indicative of a geomorphically important flow. USGS regression flow was calculated from USGS streamstats website (U.S. Geological Survey 2016). We modified the upstream stream gage flow data to correctly apply to the project site by taking the ratio of the stream gage and project site drainage areas (both taken from the USGS streamstats website).

We measured velocity at five cross sections approximately equally spaced in each study reach (Figure 2). Two velocity cross sections were at the same location as geomorphic surveys. At each cross section, we measured the channel width, and measured velocity at ten equidistant points along the channel transect, at six tenths of the depth. We measured velocity with a Pygmy Flow Meter, which recorded the number of revolutions of its turbine during a period of 30 seconds (Figures 6, 7). To convert revolutions per second to velocity, equation 7 was used (Appendix A, Equation 7). We also recorded depth at each velocity measurement location.

Habitat Surveys

We defined large woody debris as non-transient wood in the stream channel, or wood that was anchored in some way and would not be moved by low flows. We measured the diameter of each non-transient stem. Stems less than 2cm in diameter were considered transient and therefore not included in the dataset. We classified stems into three groups: small wood, 2–20 cm in diameter; medium wood 20–50 cm in diameter, and large wood, ≥ 50 cm in diameter (modified based on Kiffney et al. 2009). We calculated woody debris loading by the total number of stems divided by reach length and width (Montgomery et al. 1995) (Appendix A, Equation 8). We also calculated loading of each size class of woody debris. In both woody debris counts and load analysis, we decided to include stems less than 10cm in diameter. Both Montgomery et al. and Kiffney et al. recommend excluding stems <10cm because these are often transient debris but we included smaller stems because most of the woody debris structures created in the side channel restoration purposefully utilized anchored willow cuts that were 7cm diameter stems (Figure 8). By including smaller stems, we more accurately represented the true non-transient woody debris load in the side channel.

We identified where banks were undercut and measured the length of the undercut bank. We measured the depth of the undercut in at least one location in the undercut, but usually in three to six locations depending on the length of the undercut. We measured depth with a meter stick at the surface of the water. Some undercut banks had been intentionally constructed in the side channel as habitat for freshwater shrimp (Figure 9). These were indicated in our dataset but were included in analysis with naturally formed undercuts.

We surveyed riparian vegetation at three evenly spaced locations along both sides of each channel (six total quadrats per channel). We conducted vegetation surveys within 1x1 meter square quadrats. At each survey location, we placed the quadrat touching the water on one end and extending one meter up into the riparian vegetation (Figure 10). This quadrat placement was to examine the plant community most directly influenced by the stream. Although some riparian plants in the side channel, such as willows, were purposefully planted by the SPAWN restoration team, we made no effort to exclude purposefully planted vegetation from naturally established vegetation, because all types of vegetation are part of the riparian plant community regardless of how they got there. Within each quadrat, we estimated percent vegetation cover, and identified and listed each type of plant. Plants were identified using the Lagunitas Creek plant ID guide from iNaturalist, as well as Google reverse photo search. We identified plants to species where possible and otherwise to genus. We quantified plant diversity using species richness (number of species per site). We also calculated alpha, beta, and gamma diversity for each channel (Hunter and Gibbs 2006). Alpha diversity shows species diversity within a local, specific area. Beta diversity is defined as the ratio of local diversity to regional diversity (Appendix A, Equation 9). Gamma diversity is the sum of all local diversities across a landscape.

We measured canopy cover using a spherical densiometer in the center of each velocity transect. We recorded data as the number of open dots based on a total of 46 dots on the densiometer. The percent coverage was the number of covered dots divided by the total number of dots. We measured coverage in all four cardinal directions and then averaged.

Statistical Analyses

To analyze the habitat heterogeneity in the side channel and main channel, we calculated the mean, standard deviation, and coefficient of variation of cross-sectional depth, velocity and undercut bank depth and canopy cover. We assessed heterogeneity in large woody debris by comparing debris load by size class and channel.

Results

Geomorphic Surveys

We observed greater variation in grain size in the side channel than the main channel, which prompted more pebble counts in the side channel to accurately characterize the bed. The pebble counts in the side channel resulted in d_{50} values of 10, 10, 20, and 30mm, while the two pebble counts in the main channel resulted in d_{50} values of 20mm each. The two 10mm d_{50} pebble counts in the side channel had large portions of fine gravel, which could not be accurately measured. All other samples had large amounts of medium gravel (8-16mm) and coarse gravel (16-64mm), and the 30mm d_{50} pebble count also had some small cobbles (64-128mm). Figure 11 illustrates the grain size distributions for all pebble counts.

Figures 4a and 4b show two cross sections looking downstream that span across both the main channel and side channel, and the site map (Figure 3) shows their locations. Cross-section 1 shows a pool along the left edge of water of the main channel, which then goes over an island between the main channel and side channel, and then over another island before entering the floodplain. Cross-section 2, which is located 43.5 m downstream of cross-section 1, shows a wide and uniform main channel that then crosses an island and enters a deep pool in the side channel. In cross-section 2, there is a 3m difference in elevation between the side channel and the main channel.

Figure 5a shows a longitudinal profile of the main channel, and Figure 5b shows a longitudinal profile of the side channel. The average slope of the main channel is 0.38%, and the average slope of the side channel is 0.83%. The side channel had four distinct pools compared to three distinct pools in the main channel. One pool in the main channel was not measured as it was completely blocked by a log jam. Figure 12 shows that the maximum depth in measurable pools is similar between the two channels, but the side channel has three smaller pools of various depths and a deep pool, while the main channel only has two deep pools (that were measured).

Hydrology and Depth

The USGS 2-year flow analysis resulted in 2160 ft^3/s (Equation 13), and the stream gage data resulted in 2176 ft^3/s (Equations 11 and 12). These values represent the combined flow for the side and main channels. Figure 13 illustrates the calculated historical flow at the site based on USGS stream gage data (U.S. Geological Survey 2016).

The cross-sectional depths from the five transects reveal greater variation in depth across the stream in the main channel than the side channel (Figure 14). The average depth for the entire reach is similar for both the side and main channels, but the standard deviation and coefficient of variation are greater in the main channel and the side channel does not add much variation in depth (Table 1). The side channel has lower velocity overall compared to the main channel, including some areas of almost no velocity, and the total coefficient of variation is greater in the side channel, although this could be caused by cross-section two; looking at individual cross-sections, it appears that the main channel has more variation in velocity across the channel besides cross-section two (Figure 15, Table 1). Looking at the two reaches combined, the addition of the side channel increases the coefficient of variation in velocity.

Habitat Surveys

The side channel had a greater woody debris load (0.174 stems/m^2) than the main channel (0.116 stems/m^2). We also calculated load for large, medium, and small size classes for the main channel and the side channel (Figure 16).

The length of bank that is undercut is approximately four times greater in the side channel than the main channel, at 30m of undercut banks compared to 7m. In addition, while the mean depth is similar between the channels, the variation in the depth of the undercut banks is greater in the side channel (Figure 17), illustrating that the side channel adds variation in undercut bank habitat to the combined reaches (Table 1).

Twenty-five riparian plant species were identified on both the main channel and side channel (Table 2). Seventeen species were identified in both the main channel and side channel, but only eight species overlapped between the two sites. Alpha, beta, and gamma diversity were calculated for the two habitats (Table 3). In the mainstem, average percent cover was 41 percent, and average percent cover in the side channel was 82 percent.

The average canopy cover in the mainstem was 97 percent cover and the standard deviation 7.2, while the average canopy cover in the side channel was 85 percent cover and standard Deviation 17.8. The coefficient of variation of canopy cover in the mainstem was 0.074, in the side channel 0.21, and overall 0.16.

Discussion

Geomorphic Surveys

The cross-sectional width of the main channel is larger than that of the side channel with greater depth variation, and the side channel is at a greater elevation than the main channel. The large difference in elevation could have potential implications for subsurface flow, depending on the substrate permeability, which is outside the scope of this study. In addition, the higher elevation of the banks in the side channel can enhance floodplain connectivity; overbank flow at lower discharges may inundate the island between the side and main channels and create floodplain habitat. Ephemeral floodplain habitat is highly valuable for juvenile salmon growth and overwinter survival and growth; thus the addition of the side channel benefits juvenile coho salmon (Jeffres et al. 2008).

Although both the main and side channel have pools and bars, the surveyed section of the main channel has larger distances between its pools. Over the 100 m surveyed, the main channel has three deep pools and the side channel has two deep pools with more variance in bed slope between its pools than the main channel. Additionally, the side channel has a steeper slope than that of the main channel. A steeper slope allows for sediment and gravel to be transported during high flows more readily but can also lead to higher water velocities. This is interesting as our cross-sectional velocities showed slower water velocities in the side channel, which could mean that the steeper slope has greater impacts on velocity during high flow seasons. The side channel has more pool habitat closer together than the main channel, which we suspect adds valuable habitat for salmonids (Peterson 1982b, 1982a). The combination of the wider, shallow main channel gradient and the narrower, steep side channel gradient provides greater heterogeneity in habitat in this stretch of river than the main channel alone could provide.

Variation in pool habitat is also increased by the construction of the side channel, which has four pools of varying depths compared to the three large, deep pools in the main channel (only two of which were measured). Distribution and depth of pools in a reach is important for providing refuge for various species, and variation in pool depth can provide opportunities for different species make-up. For example, the larger, deeper pools in the main channel may be dominated by larger fishes such as 1+ year old steelhead, which we observed in the deep main channel pools this summer. These types of pools may be ideal habitats for smaller salmonids and other resident fishes such as California roach *(Hesperoleucus symmetricus),* but the larger fish may outcompete or exclude these fishes. Smaller pools as found in the side channel can provide habitats with reduced competition and different resources. The differences in pool habitat between the side and main channel are a clear example of how the side channel increases habitat heterogeneity to the potential benefit of fish diversity.

High flows from storms can deposit upstream sediment or erode current sediment, which can affect coho salmon habitat. The 2176 ft^3/s 2-year flow from stream gages and 2160 ft^3/s flow from the regression equations only differ by 0.7%, which indicates that the 2176 ft^3/s is accurate. The presence of the constructed side channel can spread the high flows and base flows across a wider area, generating pockets of slower moving water where there is instream structure such as woody debris in the side channel. This can create better heterogeneity in velocity experienced by organisms, which can have bioenergetic effects. Additionally, the side channel contains a wider variety of grain sizes, further increasing heterogeneity. Macroinvertebrate biodiversity has been linked to substrate diversity in some systems, which can provide a greater resource base for foraging fish such as juvenile coho (Duan et al. 2008).

Velocity and Depth

Another important aspect of habitat is the channel depth and velocity; areas of slow velocity can be important for refuge for fish that expend energy feeding or swimming against the current, while different depths across a channel width can indicate variation in habitat features (Peterson 1982b, 1982a). There is greater variation in the cross-sectional depths across the stream in the main channel, which is consistent with natural processes of depositional gravel bars and scouring of pools. The side channel has a more uniform depth across the channel, potentially because it has not been exposed to multiple years of high flows that can move the sediment.

Variation in velocity across a stream section is higher in the side channel overall, however for each individual cross-section, variation in velocity is only higher in the side channel for cross-section two. This could be because velocity in the side channel was so low, there was little variation. While the main channel may offer more opportunities for velocity breaks across a channel width, it is more necessary in the main channel because the velocities are higher. From a total site perspective, the slower velocities in the side channel add an element of habitat complexity not found in the main channel. Our measurements were done in the early fall at low-flow, but if this trend holds in the winter during high flows, the side channel can offer an important refuge from the higher velocities in the main channel.

While the goal of this restoration was to provide velocity refuge for juveniles in the winter, our results from the low-flow period still show a level of heterogeneity in velocity that can have bioenergetic consequences, as fish can use less energy to swim in low velocity environments and they can alter their foraging techniques.

Habitat Surveys

One of the most important habitat features for juvenile salmon is the presence of complex cover, including logs, branches and undercut banks (Brusven et al. 1986; McMahon and Hartman 1989; Dolloff and Reeves 1990). Juvenile coho extensively use areas of cover in the summer and winter for protection from predators and as thermal and velocity refuges, thus habitats with greater cover complexity can support more juvenile coho (McMahon and Hartman 1989).

Total woody debris load in the side channel (0.174 stems/m^2) was greater than in the main channel (0.116 stems/m^2). However, when we split woody debris into size classes (large, medium, and small), large woody debris load was higher in the main channel (0.016 stems/m^2) than the side channel (0.005 stems/m^2), likely due to a large logjam at the beginning of the main channel reach. Medium woody debris load showed a similar pattern, likely for the same reason. In contrast, small woody debris load was much higher in the side channel (0.162 stems/m^2) than the main channel (0.071 stems/m^2), likely due to the small willow stems installed during restoration as woody debris. Splitting the woody debris loading by size class demonstrates the complex differences in habitat structure between the main channel and the side channel; the main channel has more large wood, but the side channel has more small stems. This demonstrates that the side channel adds habitat complexity to the river landscape in the form of different types of woody debris assemblages.

Undercut banks also provide cover complexity to a channel and provide valuable cover from predators and thermal refuge for small fish (Brusven et al. 1986). Freshwater shrimp are commonly found in willow roots that are exposed in undercut banks, making them valuable shrimp habitat. The main channel has fewer undercut banks, which is unsurprising considering the intentional construction of undercut banks in the side channel, specifically for freshwater shrimp habitat. The side channel has more undercut banks, and greater variation in undercut bank depth, which can lead to differences in microhabitat. We suspect this difference will only be exacerbated with high flows that further scour the undercut banks in the side channel.

Although alpha diversity was the same in the side channel and the main channel, plant species assemblages were very different. This can partially be attributed to differences in canopy cover and light availability: canopy cover in the side channel was about 85 percent, while cover in the main channel was 97 percent. Given that the side channel was actively cleared and re-planted in 2018, it is unsurprising that the canopy is clearer, and the plant community has responded accordingly. The differing plant communities between the side and main channels could also be partially attributed to active planting in the side channel during restoration--records from the SPAWN restoration team indicate they focused on planting locally sourced willows and some grass. It is likely that the community of plants in the side channel, both that were actively planted, and which have naturally colonized, are early successional colonizer species (e.g. smartweed, thistle, goldenrod, curlydock) that respond to disturbance and increased light availability. In the main channel, we found more later successional species that prefer shade (poison oak, alder, thimbleberry, snowberry).

The presence of the side channel has clearly increased overall landscape biodiversity in terms of riparian vegetation. Although alpha diversity in both the side and main channels was 17 species, gamma diversity, or overall landscape diversity, was 25 species. Thus, the side channel adds a considerable number of additional species to the overall river habitat that would not otherwise be found in the main channel. In an unregulated stream system with a natural pattern of scouring floods, newly-created side channels with low canopy cover and freshly-exposed banks would be relatively common and would naturally create habitat for early-successional plant species, increasing overall landscape diversity in the same way this restoration project has artificially done.

It is important to note that in several years, the vegetation community in this side channel will look very different (Corenblit et al. 2010; Stella et al. 2013). For example, willows will become much taller and out-compete sun-loving species, and the side channel will begin to look more like the main channel in terms of shade-loving, relatively sparse riparian vegetation. At that point, overall gamma (landscape) biodiversity will decrease. In a natural stream system with regular scouring floods, there would be multiple side channel habitats at varying stages of succession, which would increase overall biodiversity and habitat diversity across the landscape. In this modified system, in order to imitate the varying stages of succession in side channel habitats that would be present in natural streams, restoration efforts must be continuous and mobile. Restoration of several other sites for the next decade and ongoing management at this current site can create a mosaic of side channels at different stages of succession that would ultimately increase landscape biodiversity and habitat diversity, resembling a natural stream system.

Conclusions

The construction of the side channel increased overall landscape habitat complexity by adding variation in size class distribution of woody debris, increasing the length and depth of undercut banks, and providing slow moving pools that could act as refugia for fish. Riparian vegetation in the side channel was characterized by early-successional, sun-loving species, as opposed to the shaded main channel. Additionally, the side channel added to diversity in the main channel and increased landscape biodiversity. Geomorphic surveys identified that the side channel added deep pools and steeper slope habitat, which can allow for differential sediment and gravel transport during high flows as compared to the main channel. In a system with natural water flows, similar side channel habitats would be created by scouring flows. In a regulated stream, the restored side channel has created a similar type of disturbance and the associated habitat complexity.

Further research into this site should investigate the biological response of certain target species such as coho salmon and freshwater shrimp to increased habitat complexity in the side channel. This research could also be expanded to assess side channels in other river systems, since side channel construction is a common practice in California streams.

References Cited

Baldock, J.R., Armstrong, J.B., Schindler, D.E., and Carter, J.L. 2016. Juvenile coho salmon track a seasonally shifting thermal mosaic across a river floodplain. Freshw. Biol. **61**: 1454–1465. doi:10.1111/fwb.12784.

Brennan, S.R., Schindler, D.E., Cline, T.J., Walsworth, T.E., Buck, G., and Fernandez, D.P. 2019. Shifting habitat mosaics and fish production across river basins. Science (80-.). **364**(6442): 783–786.

Brusven, M.A., Meehan, W.R., and Ward, J.F. 1986. Summer Use of Simulated Undercut Banks by Juvenile Chinook Salmon in an Artificial Idaho Channel. North Am. J. Fish. Manag. **6**(1): 32–37. doi:10.1577/1548-8659(1986)6<32:suosub>2.0.co;2.

Corenblit, D., Steiger, J., and Tabacchi, E. 2010. Biogeomorphologic succession dynamics in a Mediterranean river system. Ecography (Cop.). **33**(6): 1136–1148. Wiley Online Library.

Dolloff, C.A., and Reeves, G.H. 1990. Microhabitat Partitioning among Stream-Dwelling Juvenile Coho Salmon, Oncorhynchus kisutch, and Dolly Varden, Salvelinus malma. Can. J. Fish. Aquat. Sci. **47**: 2297–2306.

Downs, P.W., Dusterhoff, S.R., Leverich, G.T., Soar, P.J., and Napolitano, M.B. 2018. Fluvial system dynamics derived from distributed sediment budgets: perspectives from an uncertainty-bounded application. Earth Surf. Process. Landforms **43**(6): 1335–1354. doi:10.1002/esp.4319.

Duan, X., Wang, Z., and Tian, S. 2008. Effect of streambed substrate on macroinvertebrate biodiversity. Front. Environ. Sci. Eng. China **2**(1): 122–128. doi:10.1007/s11783-008-0023-y.

Goertler, P.A.L., Sommer, T.R., Satterthwaite, W.H., and Schreier, B.M. 2018. Seasonal floodplain-tidal slough complex supports size variation for juvenile Chinook salmon (Oncorhynchus tshawytscha). Ecol. Freshw. Fish **27**(2). doi:10.1111/eff.12372.

Hunter Jr, M. L., & Gibbs, J. P. (2006). Fundamentals of conservation biology. John Wiley & Sons.

Jeffres, C.A., Opperman, J.J., and Moyle, P.B. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environ. Biol. Fishes **83**: 449–458. doi:10.1007/s10641-008-9367-1.

Kiffney, P.M., Pess, G.R., Anderson, J.H., Faulds, P., Burton, K., and Riley, S.C. 2009. Changes in fish communities following recolonization of the Cedar River, WA, USA by Pacific salmon after 103 years of local extirpation. River Res. Appl. **25**(4): 438–452. Wiley Online Library.

Kondolf, G.M. 1997. Hungry water: Effects of dams and gravel mining on river channels. Environ. Manage. **21**(4): 533–551. doi:10.1007/s002679900048.

Kondolf, G.M., and Lisle, T.E. 2016. Measuring bed sediment. *In* Tools in Fluvial Geomorphology, Second. *Edited by* G.M. Kondolf and H. Piegay. John Wiley & Sons, Ltd. pp. 278–305.

McMahon, T.E., and Hartman, G. 1989. Influence of Cover Complexity and Current Velocity on Winter Habitat Use by Juvenile Coho Salmon (Oncorhynchus kisutch). Can. J. Aquat. Sci. **46**: 1551–1557.

Miller, G. 2010. In central California, coho salmon are on the brink. Science **327**(5965): 512–3. American Association for the Advancement of Science. doi:10.1126/science.327.5965.512.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., and Pess, G. 1995. Pool Spacing in Forest Channels. Water Resour. Res. **31**(4): 1097–1105. doi:10.1029/94WR03285.

Morley, S.A., Garcia, P.S., Bennett, T.R., and Roni, P. 2005. Juvenile salmonid (Oncorhynchus spp.) use of constructed and natural side channels in Pacific Northwest rivers. Can. J. Fish. Aquat. Sci. **62**(12): 2811–2821. doi:10.1139/f05-185.

Moyle, P.B., and Mount, J.F. 2007. Homogenous rivers, homogenous faunas. Proc. Natl. Acad. Sci. **104**(14): 5711–5712. doi:10.1029/20033WR002583.

Peterson, N.P. 1982a. Population characteristics of juvenile coho salmon (Oncorhynchus kisutch) overwintering in riverine ponds. Can. J. Fish. Aquat. Sci. **39**(9): 1303–1307. NRC Research Press.

Peterson, N.P. 1982b. Immigration of juvenile coho salmon (Oncorhynchus kisutch) into riverine ponds. Can. J. Fish. Aquat. Sci. **39**(9): 1308–1310. NRC Research Press.

St. Pierre, J.I., and Kovalenko, K.E. 2014. Effect of habitat complexity attributes on species richness. Ecosphere **5**(2): 1–10. doi:10.1890/ES13-00323.1.

Poole, G.C. 2002. Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. Freshw. Biol. **47**(4): 641–660. doi:10.1046/j.1365-2427.2002.00922.x.

Quinn, T.P., and Peterson, N.P. 1996. The influence of habitat complexity and fish size on over-winter survival and growth of individually marked juvenile coho salmon (Oncorhynchus kisutch) in Big Beef Creek, Washington. Can. J. Fish. Aquat. Sci. **53**(7): 1555–1564. doi:10.1139/f96-092.

Sobotka, M.J., and Phelps, Q.E. 2017. A Comparison of Main and Side Channel Physical and Water Quality Metrics and Habitat Complexity in the Middle Mississippi River. River Res. Appl. **33**(6): 879-888.

Stella, J.C., Rodríguez-González, P.M., Dufour, S., and Bendix, J. 2013. Riparian vegetation research in Mediterranean-climate regions: common patterns, ecological processes, and considerations for management. Hydrobiologia **719**(1): 291–315. Springer.

Thoms, M.C. 2006. Variability in riverine ecosystems. River Res. Appl. **22**(2): 115–121. doi:10.1002/rra.900.

U.S. Geological Survey, 2001, National Water Information System data available on the World Wide Web (Water Data for the Nation). Accessed Oct 29, 2019, at URL https://nwis.waterdata.usgs.gov/nwis/peak?site_no=11460400&agency_cd=USGS&set_logscale_y=1&date_format=YYYY-MM-DD&rdb_compression=file&hn2_compression=file&submitted_form=brief_list

Wheaton, J.M., Pasternack, G.B., and Merz, J.E. 2004. Use of habitat heterogeneity in salmonid spawning habitat rehabilitation design. Fifth Int. Symp. Ecohydraulics Aquat. Habitats Anal. Restor.: 791–796.

Figure Captions

Figure 1: Location of Lagunitas watershed in the San Francisco Bay Area and the Lagunitas and Olema Creek subwatersheds (inset; not included: Nicasio Creek subwatershed). The red dot indicates the location of the SPAWN side channel where our study was conducted.

Figure 2: Constructed side channel looking downstream from the location of the first turning point for the longitudinal survey. SPAWN offices are visible.

Figure 3: Hand drawn facies and sampling site map from field sampling efforts. Side channel is on the left and main channel on the right.

Figure 4a: Cross section 1 spanning across main channel, side channel and floodplain from left bank to right bank, looking downstream.

Figure 4b: Cross section 2 spanning across main channel and side channel from left bank to right bank, looking downstream.

Figure 5a: Longitudinal profile of main channel.

Figure 5b: Longitudinal profile of side channel.

Figure 6: Velocity measurement across the side channel. Looking downstream of side channel.

Figure 7: Velocity measurement in the main channel.

Figure 8: Example of large woody debris and a large pool in the side channel. Looking upstream of side-channel.

Figure 9: Constructed pile of large woody debris (and some non-transient woody debris) in the side channel. Constructed undercut banks covered in anti-erosion mesh are visible on the right and left banks.

Figure 10: Vegetation survey in main channel, example of quadrat placement.

Figure 11: Cumulative Size Distribution for all Pebble Counts in Side and Main Channel

Figure 12: Maximum depth of pools (meters) in the main channel and side channel

Figure 13: Historical Flow at the Site based on USGS stream gage data, gage 11460400 at Samuel P. Taylor State Park.

Figure 14: Boxplot showing variation in channel depth across the five velocity cross sections in the main channel and the side channel.

Figure 15: Boxplots showing variation in velocity across five velocity transects in the main channel and the side channel.

Figure 16: Woody Debris load by size class. Woody debris load calculated according to Montgomery et al. 1995 (see Equation 9). Size classes according to Kiffney et al. 2009.

Figure 17: Depth of undercut banks identified in the main channel and the side channel. Depth was measured with a meter stick at the surface level of the water.

Tables

Table 1: Summary statistics for habitat elements: cross-sectional depth and velocity, and undercut banks.

Habitat Element	Statistic	Side Channel	Main Channel
Cross-sectional Depth (m)	Mean	0.018	0.020
	Standard Deviation	0.013	0.016
	Coefficient of Variation	0.723	0.840
Cross-sectional Velocity (m/s)	Mean	0.183	0.133
	Standard Deviation	0.114	0.145
	Coefficient of Variation	1.612	0.921
Undercut Bank Depth (cm)	Mean	23.731	24.542
	Standard Deviation	11.501	3.952
	Coefficient of Variation	0.485	0.161

Table 2: Riparian vegetation species list

Species List	Side Channel	Mainstem
Acanthomintha spp.	x	
Alnus rubra		x
Calletriche stagnalis		x
Cirsium vulgare	x	
Conium maculatum	x	
Convolvulus spp.		x
Cyperus spp.	x	x
Dysphania ambrosioides	x	
Grass	x	x
Hedera helix		x
Helminthotheca echioides	x	x
Hordeum brachyantherum	x	
Ludwigia decurrens	x	
Persicaria spp.	x	x
Pteridum spp.		x
Rubus armeniacus	x	x
Rubus parviflorus		x
Rumex crispus	x	x
Salix spp.	x	x
Solidago californica	x	
Symphoricarpos albus		x
Toxicodendron diversilobum		x
Trifolium spp.	x	
Urtica dioica	x	x
Veronica beccabunga	x	x

Table 3: Metrics of riparian vegetation diversity using species richness in the side channel, main channel, and overall Site

Alpha Diversity (Side Channel)	17
Alpha Diversity (Main Channel)	17
Beta Diversity	18
Gamma Diversity	25

Figures

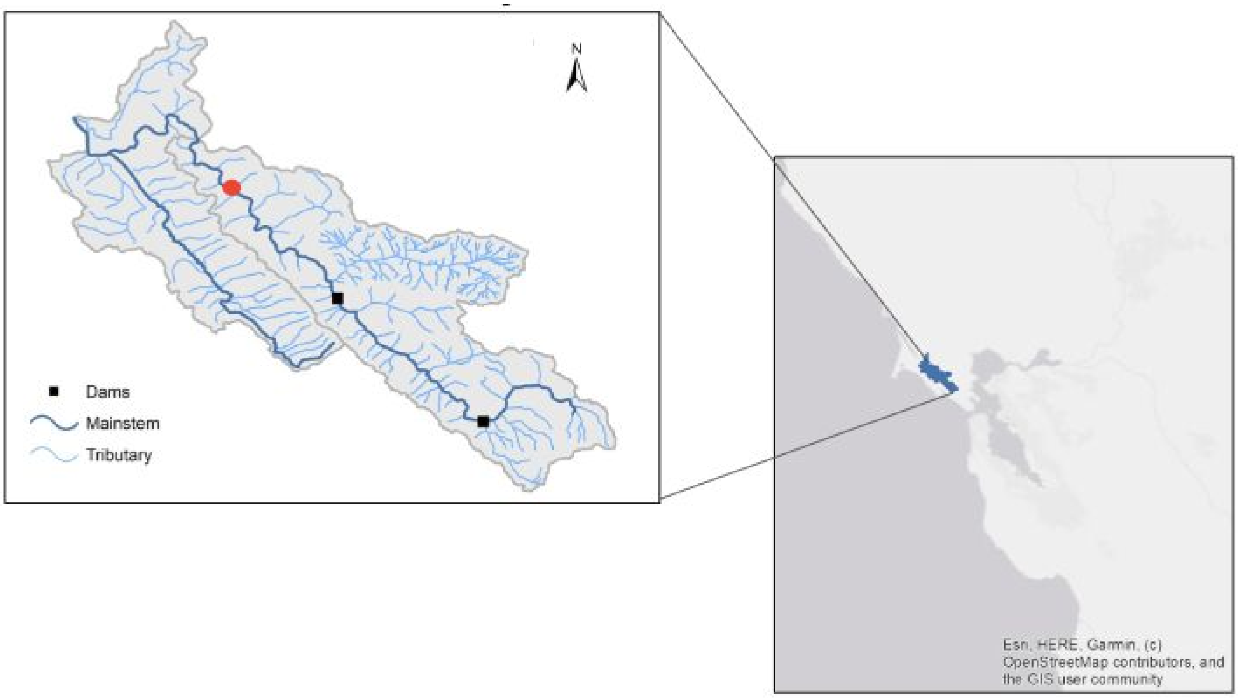

Figure 1: Location of Lagunitas watershed in the San Francisco Bay Area and the Lagunitas and Olema Creek subwatersheds (inset; not included: Nicasio Creek subwatershed). The red dot indicates the location of the SPAWN side channel where our study was conducted.

Figure 2: Constructed side channel looking downstream from the location of the first turning point for the longitudinal survey. SPAWN offices are visible.

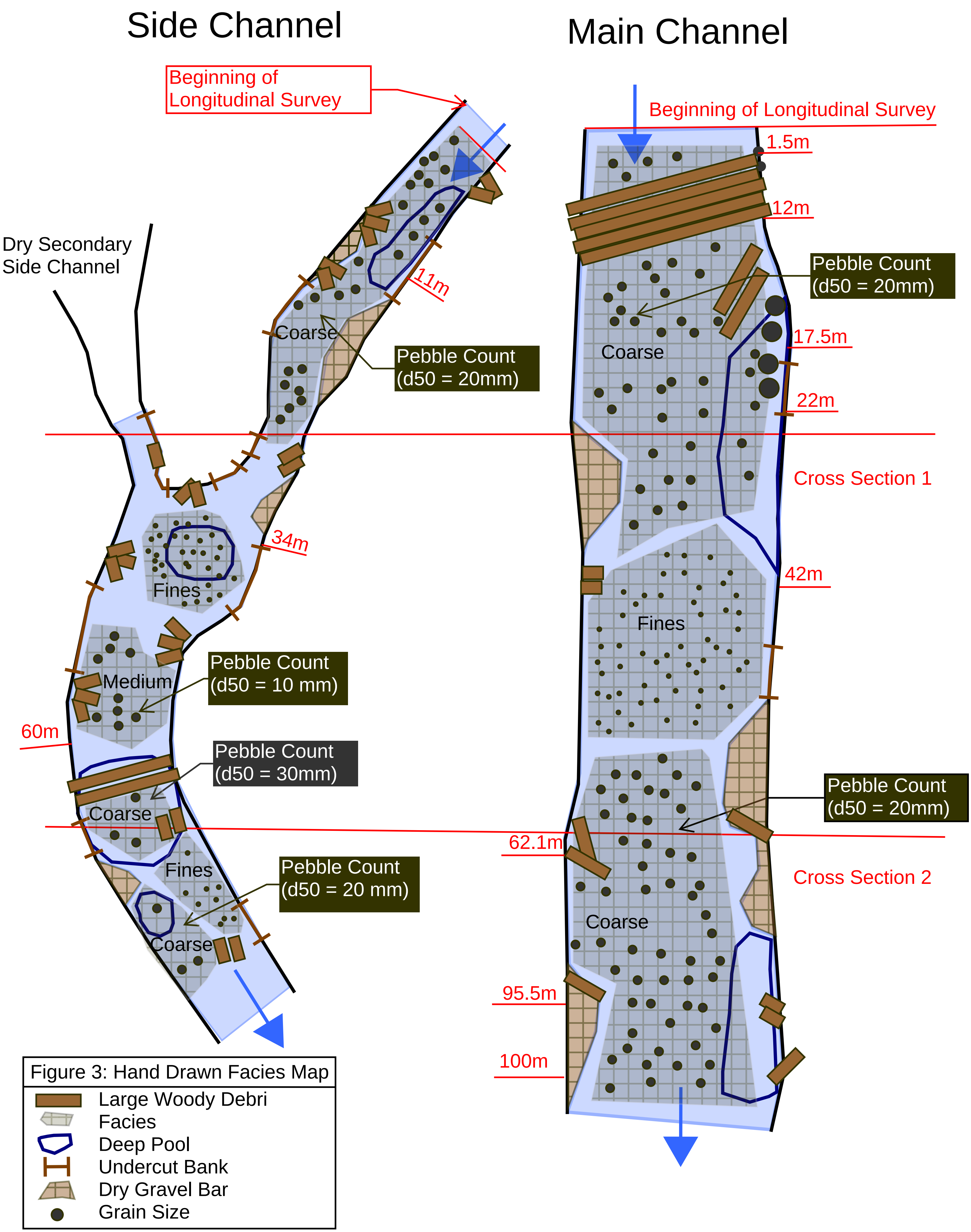

Figure 3: Hand Drawn Facies Map

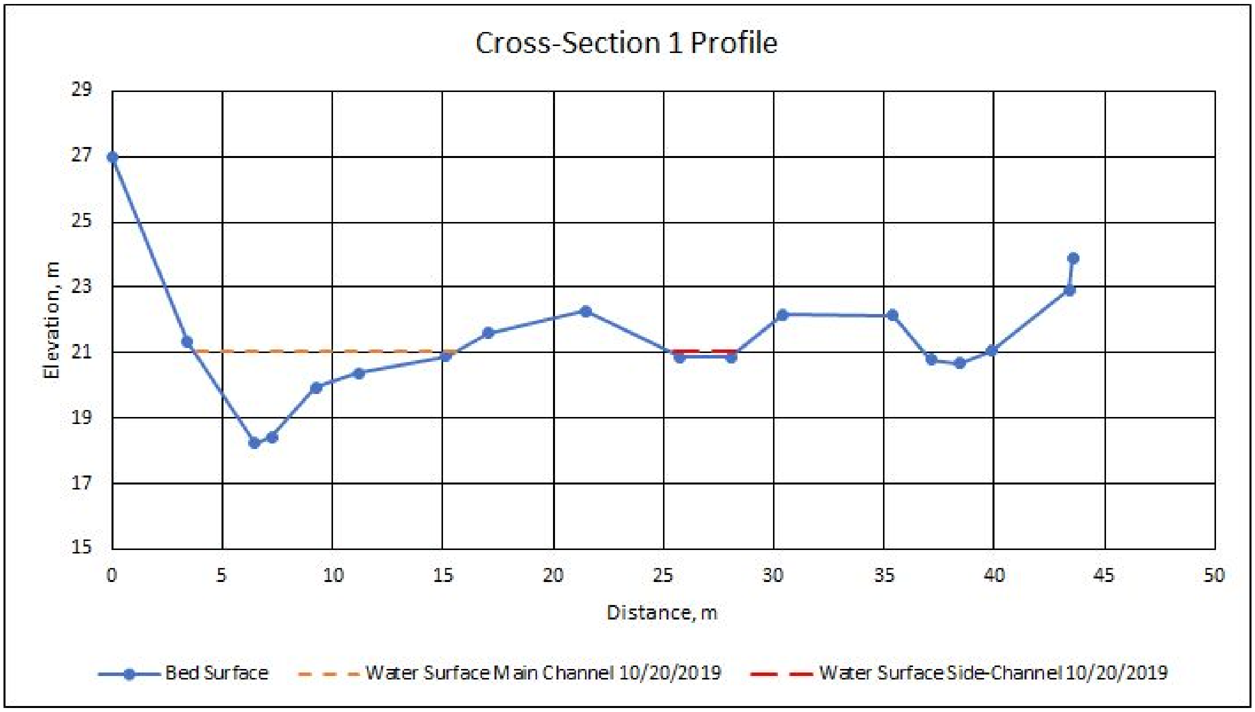

Figure 4a: Cross-section 1 spanning across main channel, side channel and floodplain, from left bank to right bank, looking downstream

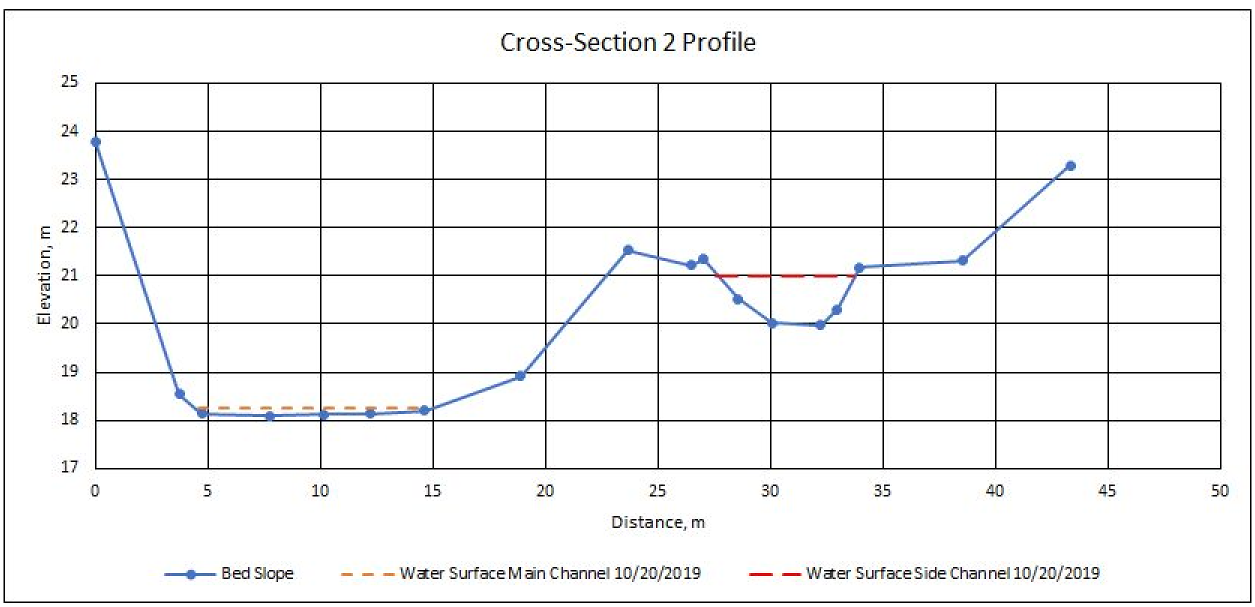

Figure 4b: Cross-section 2 spanning across main channel and side channel, from left bank to right bank, looking downstream

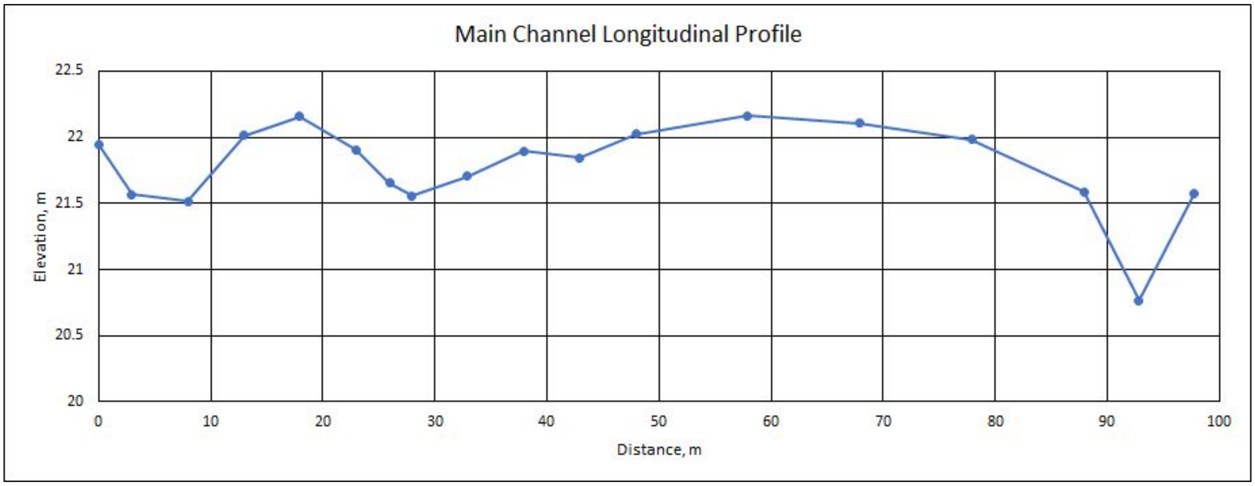

Figure 5a: Longitudinal profile of main channel.

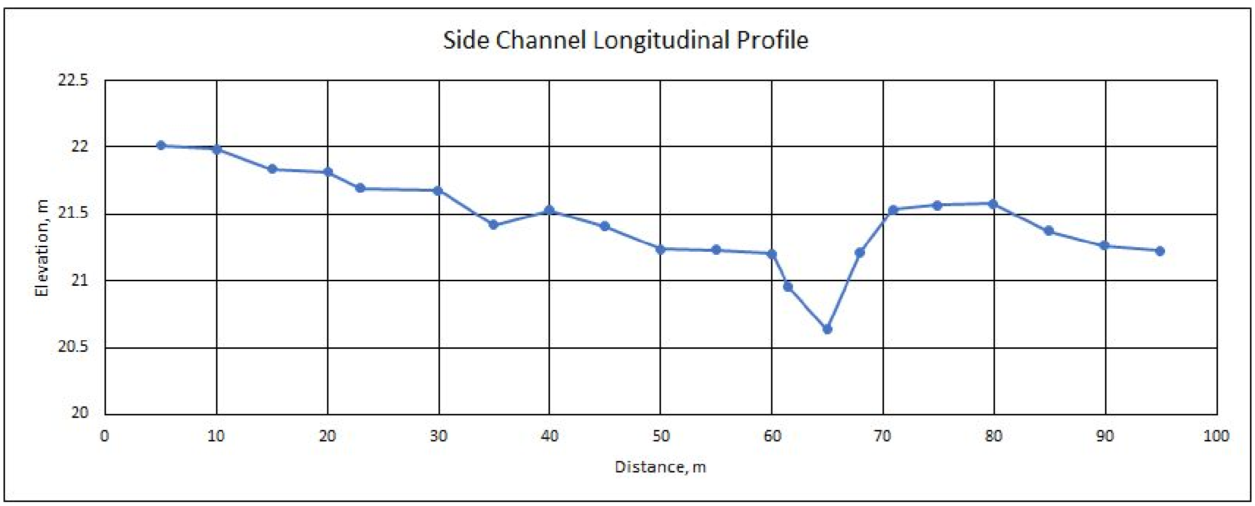

Figure 5b: Longitudinal profile of side channel.

Figure 6: Velocity measurement across the side channel. Looking downstream of side channel.

Velocity measured at discharge of 8cfs on 10/20/19.

Figure 7: Velocity measurement in the main channel. Velocity measured at discharge of 8cfs on 10/20/19.

Figure 8: Example of large woody debris and a large pool in the side channel. Looking upstream of side-channel.

Figure 9: Constructed pile of large woody debris (and some non-transient woody debris) in the side channel. Constructed undercut banks covered in anti-erosion mesh are visible on the right and left banks.

Figure 10: Vegetation survey in main channel, example of quadrat placement.

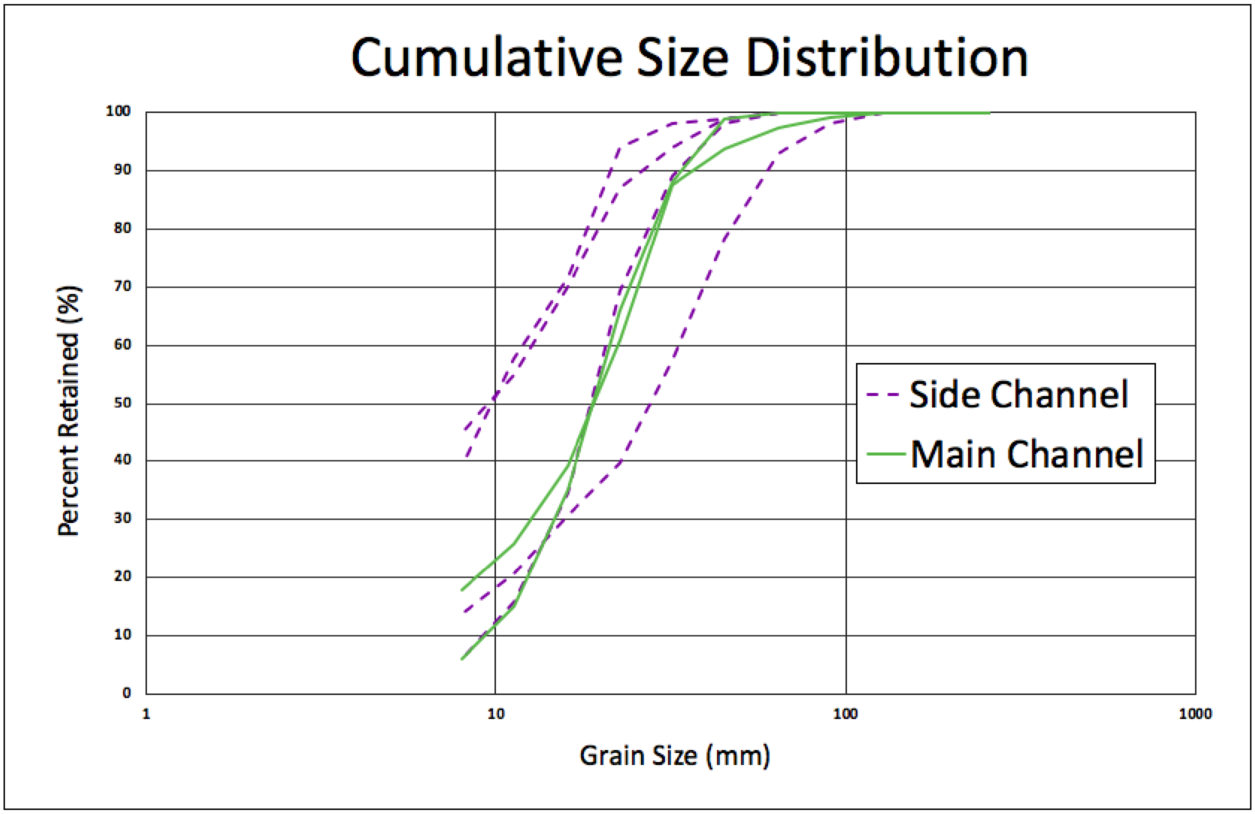

Figure 11: Cumulative Size Distribution for all Pebble Counts in Side and Main Channel

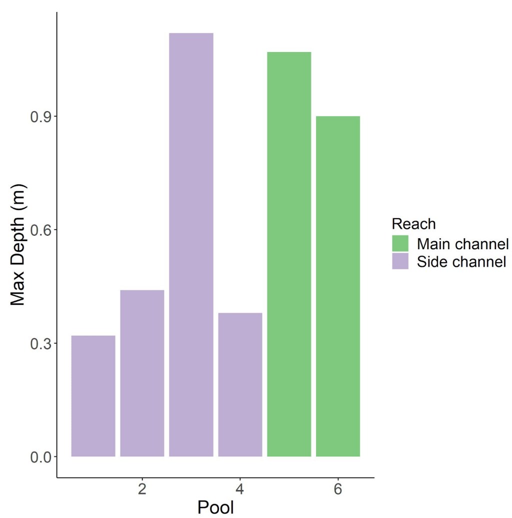

Figure 12: Maximum depth of pools (meters) in the main channel and side channel measured at discharge of 8 cfs on 10/20/19.

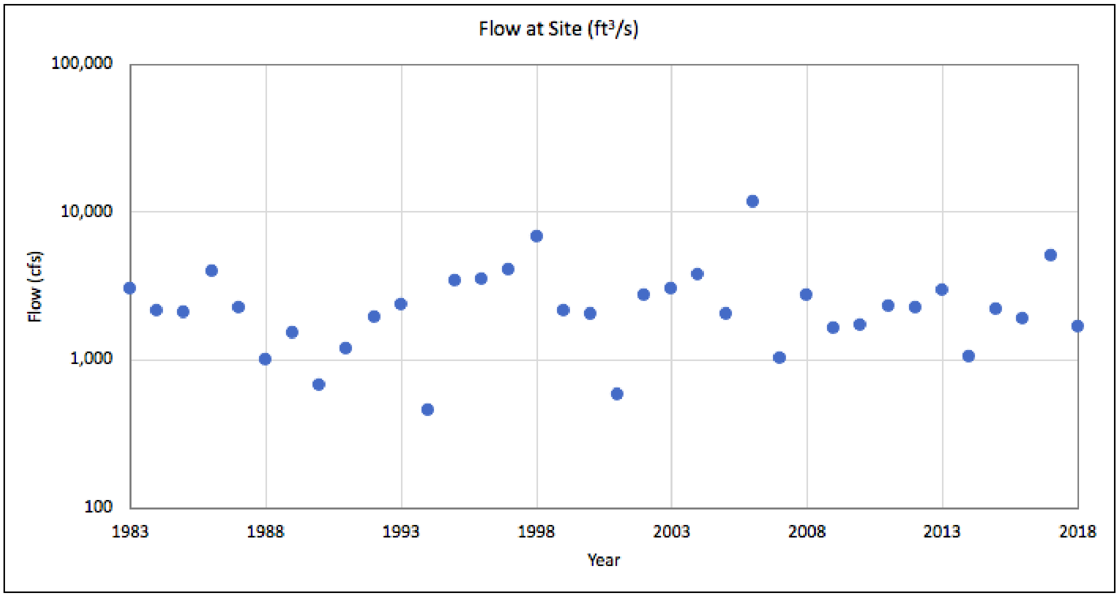

Figure 13: Historical Flow at the Site based on USGS stream gage data, gage 11460400 at Samuel P. Taylor State Park.

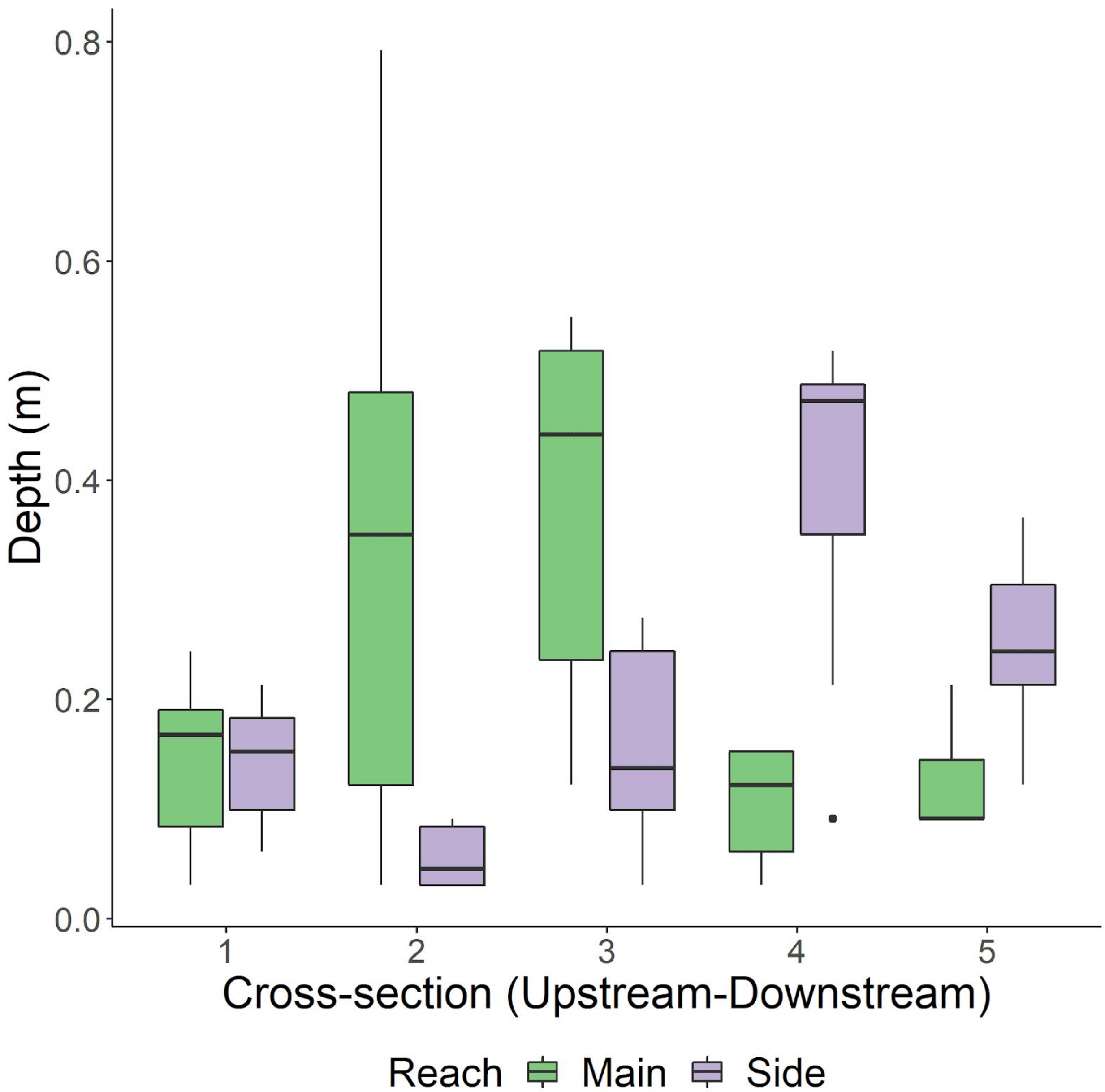

Figure 14: Boxplot showing variation in channel depth across the five velocity cross sections in the main channel and the side channel. Depth measured at discharge of 8 cfs on 10/20/19.

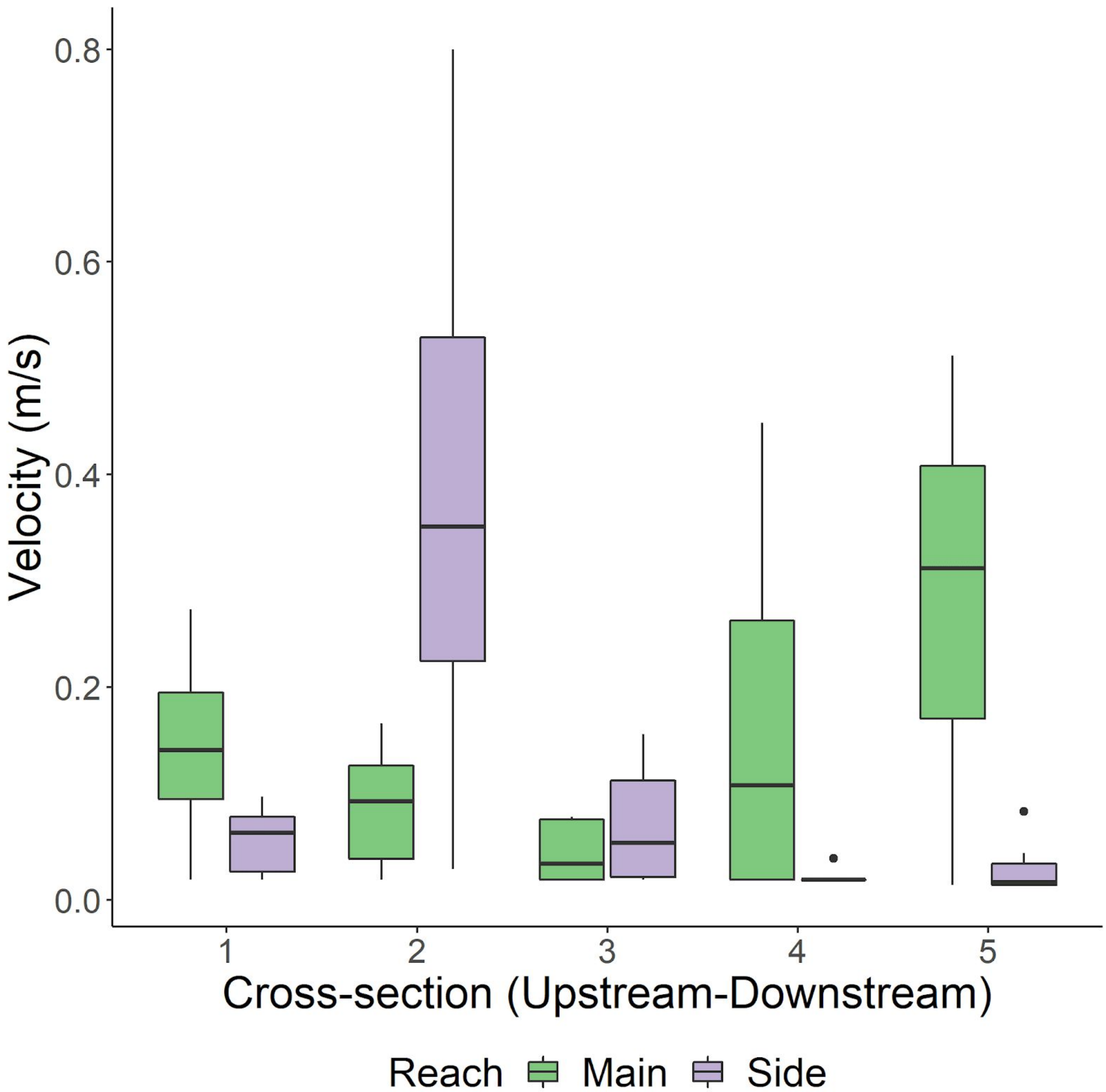

Figure 15: Boxplots showing variation in velocity across five velocity transects in the main channel and the side channel. Velocity measured at discharge of 8 cfs on 10/20/19.

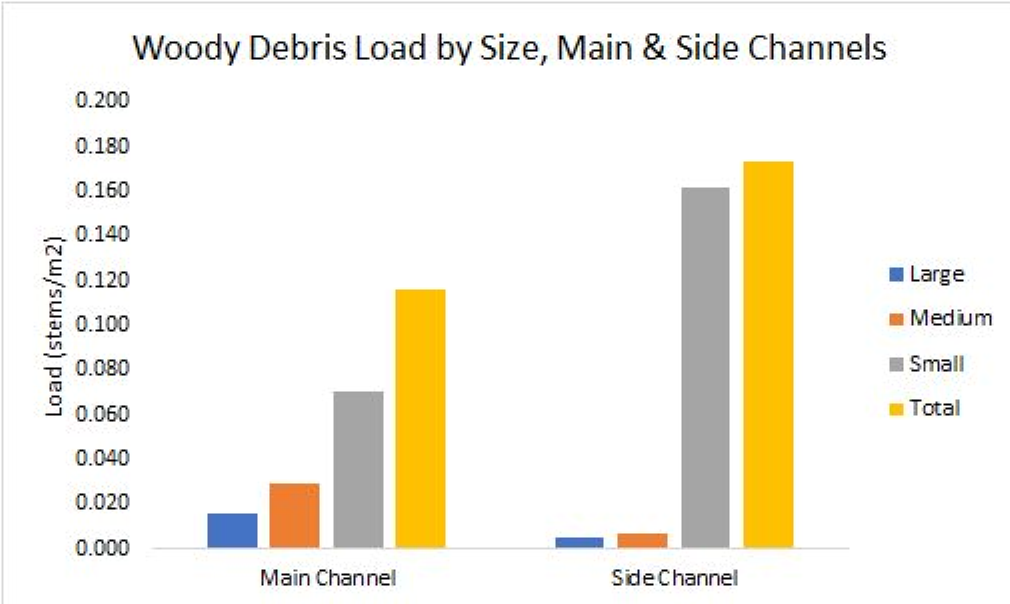

Figure 16: Woody Debris load by size class. Woody debris load calculated according to Montgomery et al. 1995 (see Equation 9). Size classes according to Kiffney et al. 2009.

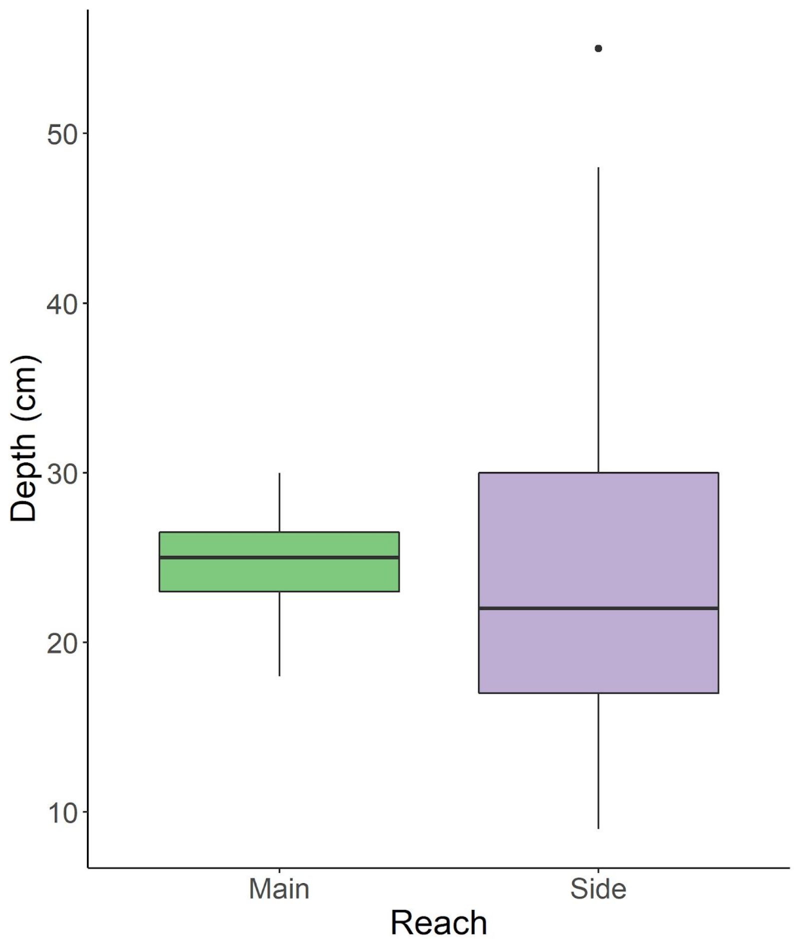

Figure 17: Depth of undercut banks identified in the main channel and the side channel. Depth was measured with a meter stick at the surface level of the water.

Appendices

Appendix A: Calculations

Equations 1-6 were used to create cross-sections (Figures 4a and 4b) and the longitudinal profiles (Figures 5a and 5b):

Equation 1: Height of instrument, HI, of cross-sections and longitudinal profile

$$HI = ELEV_{BM} + BS$$

Where: $ELEV_{BM}$ = elevation of benchmark, set at 74 m
BS = backsight

Equation 2: Elevation at location *i*, $ELEV_i$

$$ELEV_i = HI_i - FS_i$$

Where: FS_i = foresight at location *i*

Equation 3: Distance between points at location *i*, ΔL_i

$$\Delta L_i = L_i - L_{i-1}$$

Equation 4: Change in elevation at location *i*, Δz_i

$$\Delta z_i = ELEV_i - ELEV_{i-1}$$

Equation 5: Change in horizontal distance at location *i*, Δx_i

$$\Delta x_i = \mathrm{sqrt}(\Delta L_i^2 - \Delta z_i^2)$$

Equation 6: Horizontal distance from benchmark at location *i*, Lx_i

$$L_{xi} = L_{x(i-1)} + \Delta x_i$$

Equation 7: Conversion of revolutions per second (R) to velocity (V) from Rickly Hydrological Co. Manual

$$V = (0.9604R + 0.0312)*0.3048$$

Equation 8: Pool spacing (Montgomery et al. 1995)

Spacing = reach length / number of pools / average channel width

Equation 9: Large Woody Debris loading (Montgomery et al. 1995)

Loading = number of stems / reach length * average channel width

Equation 10: Beta diversity

Beta diversity = (α diversity 1 - # spp in common) + (α diversity 2 - # spp in common)

Equation 11: Non-exceedance probability

$$P_m = \frac{m}{n+1}$$

Where: m = rank of peak flow for each year (with 1 being the smallest peak flow)
n = number of years being ranked

Equation 12: Return period of peak flow

$$R = \frac{1}{1-P_m}$$

Equation 13: USGS Regression equation used by streamstats

$$Q_p = a_0(DRNAREA)^{b_0}(ELEV)^{c_0}(PRECIP)^{d_0}$$

Where: Q_p = P-percent annual exceedance probability flow, in ft^3/s

DRNAREA = drainage area, in square miles

ELEV = mean basin elevation, in feet

PRECIP = mean annual precipitation, in inches

a_0 b_0 c_0 d_0 = regression coefficients based on region