THE SHORT-TERM PHYSICAL EFFECTS OF STREAM RESTORATION AT BIG BEEF CREEK, KITSAP COUNTY, WASHINGTON

by

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ABSTRACT

The short-term physical effects of stream restoration at Big Beef Creek, Kitsap County, Washington

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I employed a large-scale stream channel cross section survey, aerial photo analysis, real-time kinematic GPS survey, and physical measures of aquatic habitat to monitor the effects of multiple restoration treatments on the stream channel at lower Big Beef Creek, Kitsap, County, Washington. The stream plan view changed from primarily single thread to a braided pattern with total channel length increasing by 43% over the study period. Pond area increased 25% and became 95% more accessible to fish. Physical effects on channel varied. In the main channel, bank erosion and streambed aggradation increased (367% and 87%, respectively) after wood placement, but bank erosion was less important than reported by previous studies of the channel. The main channel changed from net-transport to net-depositional in response to wood placement, in combination with a heavy sediment load delivered from upstream, during the 2016-17 water years. In side channels, streambed degradation was more important (and variable) as stream discharge became directed to them from the aggrading main channel. Results of physical habitat surveys also varied. The percent of habitat units observed as pools increased over the entire reach, however four times as many dry reaches of channel were measured post-project. Percent pool increased similarly at placed wood locations, although 33% of the isolated pools observed in 2017 were directly associated with the structures. Pool area increased significantly with the number of days at or above bankfull flow, but not with wood placement. Similarly, maximum pool depth increased significantly with an increasing number of bankfull days and was similar comparing pools that received wood to those that didn't. North American Beaver (*Castor canadensis*) altered low water habitat conditions during the first summer post-treatment and complicate any prediction of future outcomes. The results of this study serve to help answer outstanding questions about the placement of wood in streams as a restoration tool.

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Introduction

Around the world, river and stream restoration has become a billion dollar business (Jähnig et al. 2011; Bennett et al. 2016) with a focus on improving channel and floodplain function through the addition of wood, boulders, and the re-creation of morphological features and processes (Roni et al. 2002, 2008; Palmer et al. 2009; Jähnig et al. 2011). Additionally, where stream restoration efforts concurrently target species recovery, the reconnection of isolated habitats might address channel processes while simultaneously re-connecting habitat of imperiled species (Roni et al. 2002).

In the Pacific Northwest (PNW) multiple listings of Pacific salmon and steelhead (*Oncorhynchus* spp.) under the Endangered Species Act (ESA; Table 1), have led to some of the largest investments in stream restoration in North America (Roni et al. 2002; Katz et al. 2007; Bennett et al. 2016), but the lack of recording basic project details and limited monitoring severely limit opportunities to learn from and improve on these actions (Bernhardt et al. 2007; Jähnig et al. 2011; Bennett et al. 2016). Despite this considerable investment in stream restoration, the benefits of these efforts to Pacific salmon and steelhead populations remain largely uncertain (Katz et al. 2007; Anderson et al. 2015).

In response to this uncertainty, some 17 intensively monitored watershed (IMW) studies have been implemented around the Pacific Northwest to test the efficacy of a broad range of stream restoration actions on salmonid populations (Bennett et al. 2016; Figure 1).

Table 1. Pacific Salmon species listed under the Endangered Species Act across the Pacific Northwest.

Species	Population	Listing Status	Date Listed
Steelhead (*Oncorhynchus mykiss*)	Puget Sound	Threatened	May 2007
	Lower Columbia River	Threatened	March 1998
	Middle Columbia River	Threatened	March 1999
	Snake River	Threatened	August 1997
	Upper Columbia River	Threatened	June 2009
Chum Salmon (*O. keta*)	Hood Canal Summer run	Threatened	March 1999
	Columbia River	Threatened	March 1999
Coho Salmon (*O. kisutch*)	Lower Columbia River	Threatened	June 2005
Chinook Salmon (*O. tsawytscha*)	Lower Columbia River	Threatened	March 1999
	Puget Sound	Threatened	March 1999
	Snake River spring/summer/fall runs	Threatened	April 1992
	Upper Columbia River spring run	Endangered	March 1999
Sockeye Salmon (*O. nerka*)	Snake River	Endangered	November 1991
	Lake Ozette	Threatened	March 1999
Bull Trout (*Salvelinus confluentus*)	Columbia/Snake River	Threatened	June 1998
	Coastal-Puget Sound	Threatened	November 1999

Big Beef Creek (BBC) is one of four streams comprising the Hood Canal IMW (HCIMW) complex in Washington State (Figure 1) where a Before-After-Control-Impact (BACI) study design focuses primarily on Coho Salmon (*O. kisutch*), utilizing a life cycle monitoring approach (Anderson et al. 2015; Bennett et al. 2016).

Salmon habitat data under this project are collected utilizing a modified version of the United States Environmental Protection Agency's (EPA) environmental monitoring and assessment protocol (EMAP) as well as additional monitoring associated directly with restoration projects (Anderson et al. 2015). As an example of this 'project monitoring', the reconnection of the floodplain and the addition of wood structures along lower BBC during 2015-2016 offered a unique opportunity to both re-examine channel processes reported by historic studies (e.g., Cederholm 1972; Madej 1978, 1982), while simultaneously documenting how these actions affected current channel processes that drive the formation of and act to maintain habitat for Pacific salmon. Asking the research question; 'How will the physical channel respond to restoration treatments at lower BBC?', I initiated a large-scale cross section survey of the channel in 2013, two years before project implementation. Having re-located a number of his original cross section markers, my approach directly follows Cederholm's (1972) assessment of the physical effects of stream channelization and might more effectively address reach-level effects of wood placement than studies more focused on the structures themselves (Nichols and Ketcheson 2013).

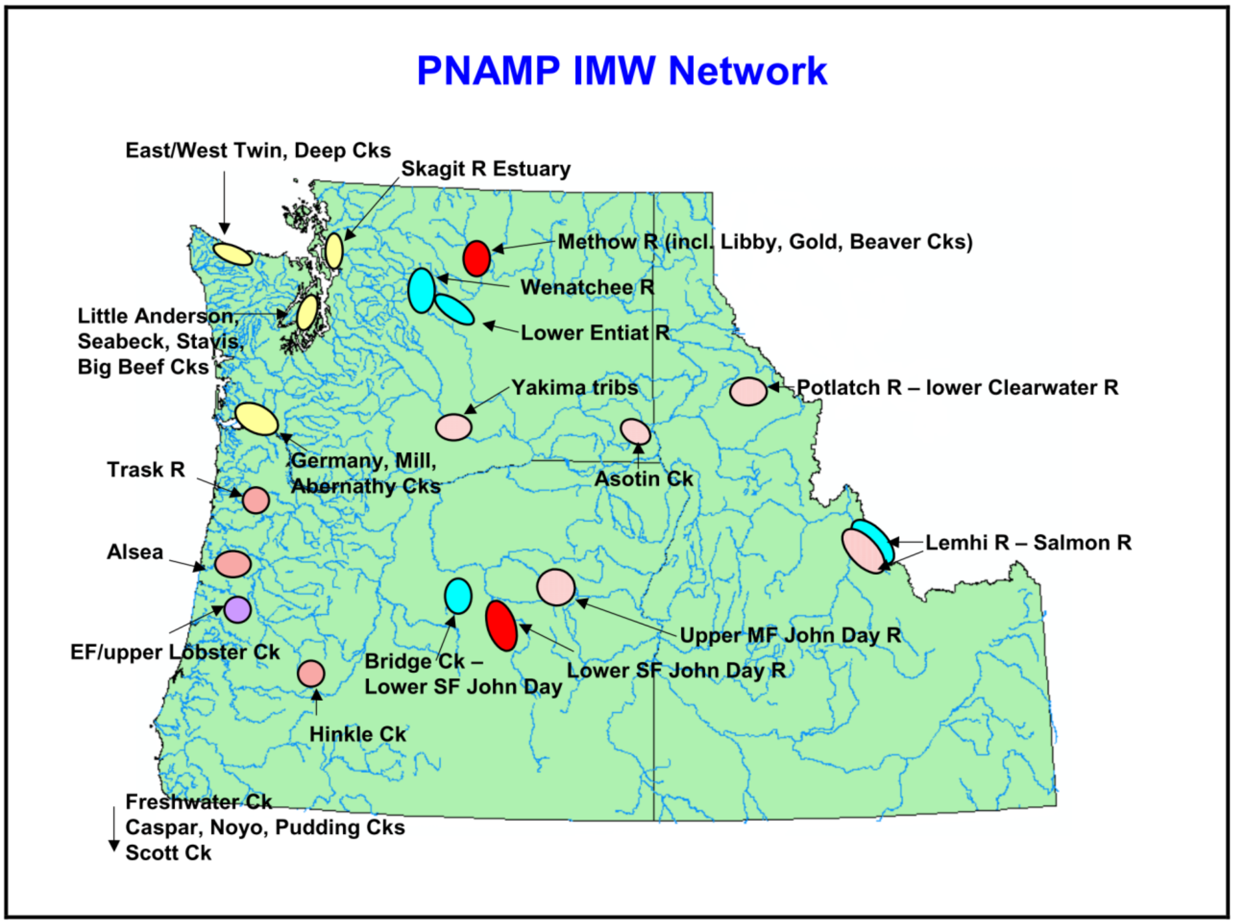


Figure 1. Proposed network of intensively monitored watersheds across the Pacific Northwest. Those colored yellow on the map have been in process since 2004 and include the Hood Canal IMW (Image courtesy of PNAMP).

Literature Review

Driven by the Intensively Monitored Watershed studies (IMW), as well as worldwide efforts intended to decipher the effects of stream restoration actions on fluvial processes and ecological integrity, a healthy debate exists within the literature as to what constitutes a 'success' or a 'failure' relative to said restoration actions (Jähnig et al. 2011). This debate is multi-faceted and will likely take on new direction as restoration science progresses. Rather than arguing what constitutes a success over a failure in stream restoration, I wish to impress on the reader the challenges associated with making such an evaluation (also see : Bennett et al. 2016).

Evaluating a stream restoration project is not a neutral or necessarily systematic act, it's important to know whether the evaluation is gauged toward: (1) measuring the impact of public policy, (2) explaining and justifying restoration actions to the local community, or (3) improving scientific knowledge (Morandi et al. 2014). Any evaluation strategy (choice of monitoring framework, metrics, and reference) should be adapted to standards associated with the evaluation goal (Morandi et al. 2014). Citing two main issues regarding the evaluation of restoration projects: (1) evaluations contribute to fundamental scientific knowledge regardless of their intended goal, and (2) evaluations provide feedback and guidance for future restoration work and adaptive management, these authors further stress the crucial nature of assessing whether restoration objectives have been achieved (Morandi et al. 2014).

A review of 345 studies investigating the effectiveness of stream rehabilitation (termed *stream restoration* throughout this paper) concluded that the failure of many of these projects to meet stated objectives was attributable to: (1) inadequate assessment of historic conditions and factors limiting biotic production, (2) poor understanding of watershed-scale processes that influence localized projects, and (3) monitoring at inappropriate spatial and temporal scales (Roni et al. 2008). The authors were unable to draw firm conclusions on several specific types of restoration actions because of: (1) limited information provided on physical habitat, water quality, and biota and (2) the short duration and limited scope of most published evaluations (Roni et al. 2008). However, their findings suggest that: (1) the reconnection of isolated habitats, floodplain rehabilitation, and instream habitat improvement projects have proven effective for improving habitat and increasing local fish abundance under many circumstances, and (2) techniques such as riparian rehabilitation, road improvements (sediment reduction), dam removal, and restoration of natural flood regimes have shown promise for restoring natural processes that create and maintain habitats, but that the number of publications related to these types of actions is lacking (Roni et al. 2008). They conclude that protecting high-quality habitats and restoring connectivity and catchment processes before implementing instream habitat improvement projects might be appropriate in the interim (Roni et al. 2008; Anderson et al. 2015).

The published literature might mostly reflect positive results in the area of stream restoration (Roni et al. 2008, 2015). A single, published study was dedicated to the evaluation of the occurrence and causes of failure of 161 instream structures among 15 streams located in southwest Oregon, and southwest Washington States following high streamflow that ranged between a 2 and 10 year event in magnitude (Frissell and Nawa 1992). These authors report a median failure rate of 18.5% and an median damage (impairment + failure) rate of 60% for instream structures but note that the incidence of impairment or outright failure varied widely among streams (Frissell and Nawa 1992). Manner of failure was varied and displayed no relationship to structure type, however damage was frequently observed in low-gradient channels and widespread in streams with signs of catchment-wide disturbance, high sediment loads, or highly erodible bank materials (Frissell and Nawa 1992). Similar to the concept of protecting quality habitat, restoring connectivity and catchment processes before implementing instream projects meant to influence habitat (Roni et al. 2008a; Anderson et al. 2015), these authors suggest that the restoration of fourth order and larger alluvial streams (those with the greatest potential for fish production in the PNW) will require the reestablishment of natural catchment and riparian processes over the long-term (Frissell and Nawa 1992).

Stream restoration actions are widespread, numerous, and likely to continue. After many years of human impacts (e.g., damming and channelization) to the physical and ecological processes in rivers (Gregory 2006; Morandi et al. 2014), repairing environmental degradation has become a priority in western industrialized societies (Morandi et al. 2014). Beyond salmon recovery, legal requirements such as the US Clean Water Act (1972), the Canadian Water Act (1985), and the EU Water Framework Directive (2000) have driven the use of river restoration as a management tool that aims to meet the standards set forth in these mandates (Morandi et al. 2014). However, analysis of spatially referenced, project level data of more than 23,000 stream restoration actions at over 35,000 locations (Washington, Oregon, Idaho, and Montana) that were mostly initiated between 1991 and 2005 suggest that stream restoration actions are moving forward with little or no knowledge of specific linkages between restoration actions and the responses of target species (Katz et al. 2007). The authors call for implementation monitoring to inform targeted effectiveness monitoring required to address this lack of mechanistic understanding (Katz et al. 2007)

Less rigorous approaches to monitoring stream restoration actions may lead to bias. A recent survey of water managers in Germany revealed that self-evaluation of restoration projects was overly positive, with 40% of the respondents admitting that their evaluation was based on gut feeling, and that only 45% of restoration measures were monitored or occasionally checked (Jähnig et al. 2011). Other respondents to this survey reported successes in the form of landscape aesthetic value or benefit to the public, or just portrayed a “condemned to success” attitude (Jähnig et al. 2011). However, such subjective measures did not correspond with objective measures made by field investigations at these projects: while study results agreed with many others that reported improvements in the hydromorphology (see Vogel 2011), the lack of objectively recorded data meant that water managers could not reasonably evaluate restoration success (Jähnig et al. 2011). Based upon their findings, these authors argue that : (1) project goals should be thoughtfully formulated prior to implementation and (2) it is necessary to monitor river restoration success from different perspectives (Jähnig et al. 2011).

Similarly, in the United States, interviews with 317 stream restoration project managers from across the country indicated that while less than half of all projects set measurable objectives for their projects, nearly two-thirds of all interviewees felt that their projects had been ‘‘completely successful” (Bernhardt et al. 2007). Data revealed highly successful projects as those that had high levels of community involvement and an advisory committee (Bernhardt et al. 2007). A key finding from these interviews was that the mere publishing of more scientific papers would not likely lead to meaningful improvements in restoration practice—the authors recommend direct, collaborative involvement between scientists, managers, and practitioners to forward progress in the science and application of stream restoration (Bernhardt et al. 2007).

In examination of 44 pilot projects (physical restoration measures aimed to restore or enhance the ecological condition of waterbodies) that included an evidence-based evaluation of success, researchers indicated that: (1) evaluation strategies are often too poor in quality to understand the link between a project and ecological changes, (2) contradictory conclusions are often drawn, making the determination of success or failure difficult, and (3) the most positive conclusions about the effects of restoration generally come from the poorest evaluation strategies (Morandi et al. 2014). Poor evaluation strategies were not based in science, the choice of metrics more related to the political authority in charge of the evaluation than to river characteristics or restoration measures (Morandi et al. 2014). The results of the study emphasized the difficulty in producing an evaluation of stream restoration success without clearly defined standards and ecological references related to the objectives of the project (Morandi et al. 2014)

There is no lack of decision matrices and/or strategies designed to guide the evaluation of stream restoration projects, with objectives that can be quite variable. Some emphasize the measurement of geomorphic characteristics of the restored stream reach based on the understanding that the interactions between channel, floodplain, and stream discharge provide a framework on which aquatic and riparian function is supported (Kondolf and Micheli 1995). These authors cite a growing body of literature that argues for geomorphic factors as primary determinants of spatial and successional patterns of biological communities to back this emphasis in their evaluation criteria (Kondolf and Micheli 1995).

Other strategies emphasize an ecological perspective. Believing healthy, self-sustaining river systems as important providers of goods and services upon which human life depends, Palmer et al. (2005) propose five criteria for measuring success; (1) projects should be conceived on a specified guiding image of a more dynamic/healthy river that could exist at the site, (2) measurably improved ecological condition, (3) the river system must be more self-sustaining and resilient to perturbation allowing for only minimal maintenance, (4) no lasting harm should be inflicted on the ecosystem during the construction phase, and (5) both pre- and post-assessment must be completed and the data made public. While further providing literature-based guidelines and indicators that could be used in the evaluation of these five measures of success, the authors emphasize that conservation of streams/rivers (before they become degraded) remain a priority (Palmer et al. 2005).

Some may focus even more broadly, considering stakeholder interactions with the project. One such strategy to assess river restoration success considers 49 indicators across 17 indicator categories as related to 13 restoration objectives (Woolsey et al. 2007). This robust assessment begins at the planning phase and considers acceptance by the public and aesthetic landscape value among a host of other indicators that focus largely on hydrologic/geomorphic conditions and biological communities. These authors cite the vital nature of stream restoration assessment for adaptive management, evaluation of project efficiency, optimizing future efforts, and gaining acceptance with the public (Woolsey et al. 2007).

In 2011, the Washington State Salmon Recovery Funding Board (SRFBD) offered protocols for the effectiveness monitoring of a range of salmonid habitat restoration actions. Operating under the definition of a restoration project as that of Morandi et al. (2014)—a homogenous group of restoration actions aiming to achieve one or several restoration objectives (a project can be implemented at different times or at different sites)—and the restoration objectives of my target project (PRISM 2018), my interest lies with the protocols for monitoring the effectiveness of instream habitat and floodplain enhancement projects (Crawford 2011a, 2011b).

Indicators and decision criteria advanced by these protocols (Table 2) are designed to answer a series of questions. For instream habitat projects, questions answered by this approach include: (1) Have artificial instream structures (AIS, aka placed wood structure) as designed remained in the stream for up to ten years for the sampled instream structure projects? (2) Has juvenile salmon abundance increased significantly in the impact area for the sampled instream structure projects within ten years? and (3) Has stream morphology improved significantly in the treated stream reach for the sampled instream structure projects within ten years (Crawford 2011b)? And at floodplain enhancement projects (Crawford 2011a), a longer list:

- How many acres of new off-channel or floodplain habitat have been created?

- What flood stage is necessary for the newly accessible habitat to be available?
- What is the frequency and duration of inundation for the new habitat?
- Has the removal and/or setback reduced channel constraints and increased flood flow capacity for ten years?
- Has the channel become more frequently connected with the floodplain?
- Has additional off-channel habitat been created within 10 years?
- Has the floodprone width increased?
- What is the level of fish use?
- What species and life stage use the newly available habitat?

The approach designed to assess the effectiveness of instream habitat projects tests the null hypothesis that the placement of wood structures in the stream has had no effect upon: (1) Improving stream morphology and fish habitat as measured by thalweg residual pool vertical profile area and mean residual depth, and (2) Increasing juvenile abundance in the impacted area (Crawford 2011b). Similarly, at floodplain enhancement projects, the null hypothesis that the removal or setback of dikes, riprap, roads, or landfills, or reconnected side channels along the stream has had no significant effect upon: (1) providing slow water habitat for juvenile rearing, (2) improving stream morphology and fish habitat as measured by thalweg residual pool vertical profile area, mean residual depth, and flood-prone width, (3) increasing the presence and connection of off-channel and side channel habitat as measured through hydraulic modeling and visual observation and repeated topographic and field surveys, and (4) increasing juvenile fish abundance in the impacted area is tested (Crawford 2011a; Table 2).

Table 2. Indicators and decision criteria designed to assess the effectiveness of instream habitat projects and floodplain enhancement projects as put forth by the Washington Salmon Recovery Board (adapted from Crawford 2011a, 2011b; O'Neal et al. 2016).

Project Category	Indicators Tested	Decision Criteria
Instream Habitat Projects	• Mean thalweg residual pool vertical profile area • Mean residual depth • Log_{10} volume of large wood • Stability of structure placement	Linear regression or Paired t-test for preproject mean against postproject mean, alpha = 0.10 for one-sided test; 20% increase over baseline considered biologically significant
Floodplain Enhancement Projects	• Mean thalweg residual pool vertical profile area • Mean residual depth • Bank-full height • Bank-full width • Flood prone width • Proportion of the reach with three-layer riparian vegetation • Mean canopy density along the banks • Level of habitat connection	Linear regression or Paired t-test for preproject mean against postproject mean, alpha = 0.10 for one-sided test; 20% increase over baseline considered biologically significant

As defined by these strategies, the stream channel seems to be considered separate from its floodplain—by virtue of separate protocols to assess the effectiveness of restoration projects located at either—and thus side channels are considered separate from the channel when assessing the effectiveness of restoration actions. This approach might reflect different levels of salmon productivity or population use among habitat types (Bellmore et al. 2013) or observed increases in Coho Salmon production within restored/reconnected examples of these areas (Henning et al. 2007; Roni et al. 2008; O'Neal et al. 2016). However, it might deviate from traditional geomorphic models that consider interactions between channel, floodplain, stream discharge, and sediment availability as a framework on which aquatic and riparian function is supported (Leopold et al. 1992; Kondolf and Micheli 1995; Lane and Richards 1997; White et al.

2010) along with process-based principles of stream restoration for salmon recovery (Beechie et al. 2010; Anderson et al. 2015).

Many—perhaps most—of the stream restoration actions aimed at salmon recovery are based on perceptions of 'good' or 'desirable' habitat types, or on a limited selection of stream restoration techniques developed over the past several decades (Roni et al. 2008a; Beechie et al. 2010). In the same way, many restoration designs/evaluations might be based upon those same perceptions. In review of 109 studies that reported on physical response to instream structures, researchers report significant increases (>50%) in pool frequency, pool depth, woody debris, habitat heterogeneity, complexity, spawning gravel, sediment retention, and organic matter retention after placement of instream structures (Roni et al. 2008, 2015). This analysis however, does not separate constructed habitats from those that are formed and maintained through natural processes after the restoration treatment is complete (i.e., the difference between pools dug by backhoe and those scoured by complex flow patterns around structures added to the existing system). With a very strong tendency to report responses in pool area/frequency/depth in evaluations of instream restoration projects designed at increasing salmon habitat (Cederholm et al. 1997; Roni and Quinn 2001; Roni et al. 2015; O'Neal et al. 2016; Jones et al. 2017), it seems critical to understand and communicate the method of pool formation along with any metrics that describe the habitat and its maintenance over time.

Similarly, in review of 83 published studies that reported on some type of physical response (other than structure stability), Roni et al. (2015) only identified three investigations into the response of a stream channel to the placement of wood without cabling/anchoring or minimal disturbance to the streambed during construction (see: Nichols and Ketcheson 2013; Carah et al. 2014; Jones et al. 2017). A trend toward 'less engineered' approaches to stream restoration (particularly non/less-rigid wood structure placement in streams < 20 m width; (Bisson et al. 2003; Kail et al. 2007; Roni et al. 2008, 2015) then, might strengthen the argument by Morandi et al. (2014) that clear ecological references be observed from the setting of project objectives through the reporting of any evaluation of project effectiveness. While wood 'placed' in the stream channel as part of a constructed habitat might have clear project objectives associated with it (i.e., maintenance of a specific habitat type), wood that is placed by modern approaches may not. Project objectives might be described as 'to improve channel heterogeneity' or 'promote sediment stability' while offering a specific number of pools expected to be created over the restoration reach (PRISM 2018).

In summary, the determination of 'success' or 'failure' at stream restoration projects is not a neutral act, requiring evaluation strategies to be designed early in the project planning process and be based on clearly-defined objectives (Morandi et al. 2014). The published literature might mostly reflect positive results from stream restoration actions (Roni et al. 2008a, 2015), and thus debate surrounds the efficacy of stream restoration projects to meet their objectives (Katz et al. 2007; Anderson et al. 2015). However, stream restoration actions are widespread, numerous, and likely to continue. Restoration projects and their associated evaluations might be limited by perceptions of 'good', 'bad', and 'desirable' habitat conditions (Roni et al. 2008; Beechie et al. 2010; Jähnig et al. 2011). Less rigorous approaches (or those that are politically driven) to monitoring/evaluating stream restoration actions might lead to bias and/or contradictory results making the determination of success or failure difficult (Jähnig et al. 2011; Morandi et al. 2014). However, robust monitoring guidance exists within the literature (i.e., Kondolf and Micheli 1995; Palmer et al. 2005; Woolsey et al. 2007) and has been developed institutionally (Crawford 2011a, 2011b; O'Neal et al. 2016). More than 100 years of controversy surrounding the placement of wood in streams to create fish habitat (Roni et al. 2015) coupled with trends toward 'less engineered' restoration treatments (Bisson et al. 2003; Kail et al. 2007; Roni et al. 2008, 2015) signals gaps in our understanding of how stream channels respond to these efforts.

Extensive reviews of the literature have suggested that future research into the effects of placed wood on stream channels/physical habitat should focus on addressing the following questions:

- How do responses differ among types of wood placement (i.e., anchored vs. not-anchored)?
- What amounts/types/sizes of wood are needed to achieve a physical response in different sizes and types of stream channels?
- How quickly might a response be observed and how long might observed 'improvements' be expected to last?
- What are the stream channel types or geomorphic settings where wood placement might result in minimal or even detrimental physical effects (i.e., increased erosion and habitat degradation)? (Roni et al. 2008, 2015)

The following investigation into the effects of wood placement at lower Big Beef Creek—under the umbrella of the HCIMW—is additive to and will help guide detailed long-term/region-wide physical monitoring efforts called for by these authors to answer these questions (Roni et al. 2008, 2015).

Study Area

Area Description

Big Beef Creek—a gravel bedded stream—drains 38 km^2 of forested/rural-residential landscape located on the west-central Kitsap Peninsula in Washington State (Figure 2). The glacial and human histories of this landscape have naturally divided the catchment into distinct sections (Cederholm 1972; Madej 1978, 1982; Quinn and Peterson 1996; Booth et al. 2003; Anderson et al. 2015)

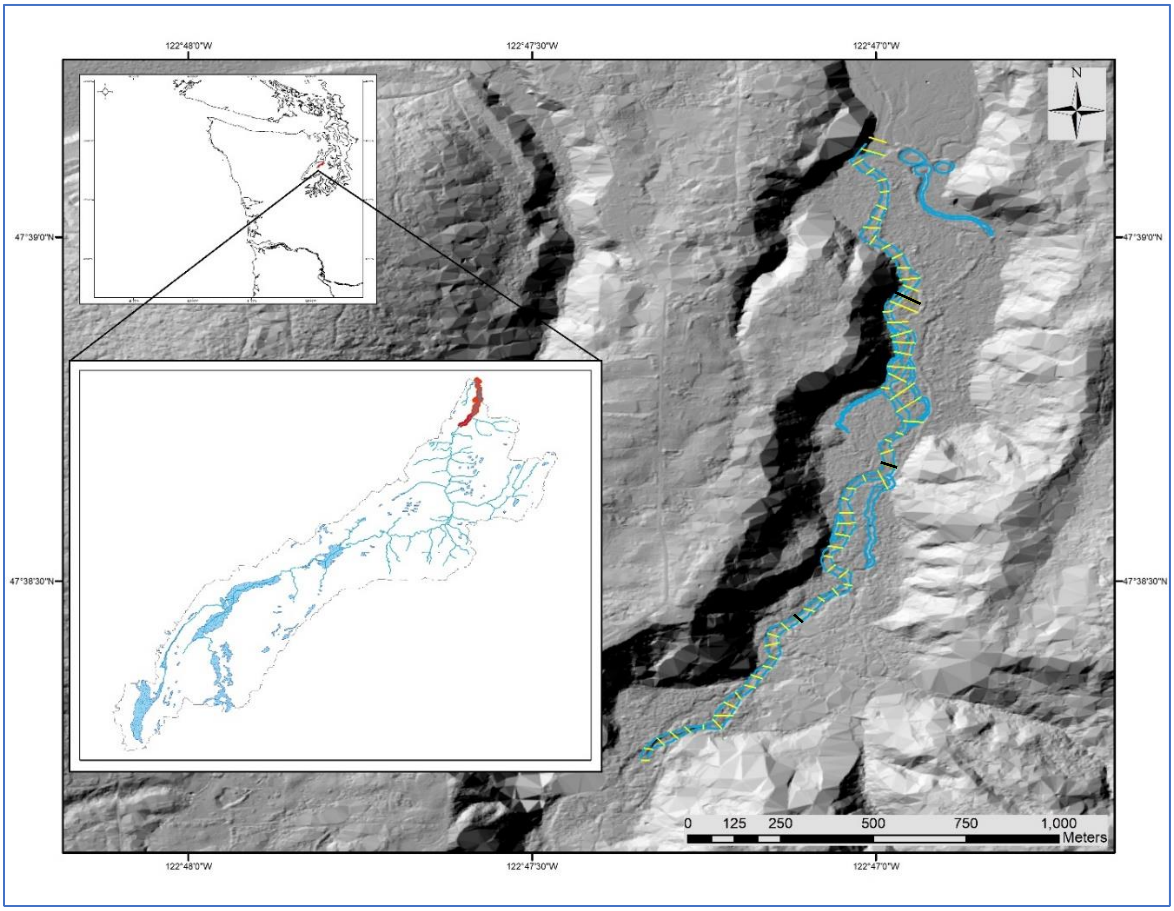


Figure 2. Location map of the BBC catchment located on the Kitsap peninsula in western Washington State. The 2013-15 channel configuration is shown in the zoomed image with channel cross section stations 3-66 indicated with yellow lines (black lines denote upstream cross section of sub-reaches 1-4). Note the experimental spawning channel and ponds associated with the University of Washington's BBC Research Station which has recently suspended operations (upper right of image).

The upper section, marked by broad marshes (Figures 2 and 3) and gentle slope, lies within Russell-age recessional outwash terrain formed by a continuous south-flowing outwash stream (Haugerud and Tabor 2008). Stranded alluvial flats (mapped as 'al'; Figure 4; Table 3) in the middle reach of the creek and deformed outwash flats near lake William Symington suggest at least 23 m of late Holocene uplift above the Seattle fault (Haugerud 2009). No obvious sources of sediment delivery to the modern upper channel and a natural marshy area (now dammed as lake William Symington) at the head of channel transition, suggests that most of the coarse sediment delivered to the lower channel originates from tributaries (up to and including the LB tributary to lake William Symington), mass-wasting, and localized bank/bed erosion in both recent and historic times. Measurements of the slowly advancing delta that formed in the upstream end of the lake (post-dam construction) seem to confirm this observation (Madej 1978).

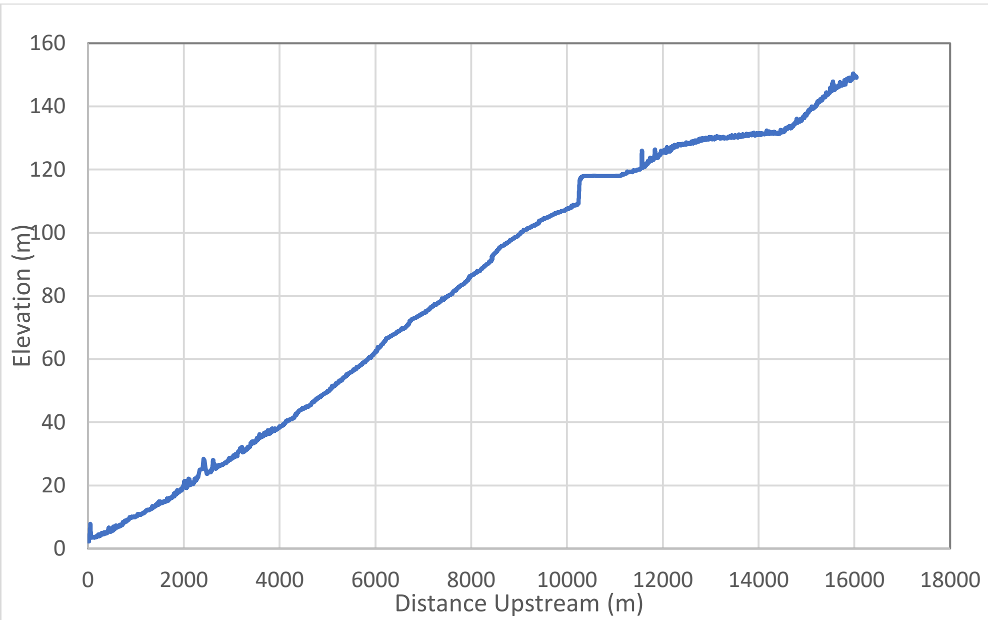


Figure 3 Longitudinal profile of the BBC channel. Noise in the line—pronounced near 2500m upstream—reflects errors in the GIS layer used to produce it or channel changes since the layer was created. Lake William Symington appears between 10-12,000 m on the plot. Mean channel gradient (% slope) below the dam is about 0.01 and 0.008 within the study reach (about 0-2000 m).

The lower section of BBC cuts into the landscape, with the modern stream flowing northerly for about 10 km to Hood Canal. Transition to the lower section begins with a canyon reach where wood and ≤ gravel-sized sediments are relatively rare. Glacial till is sometimes exposed on the streambed within this reach. A channel headcut (upstream moving erosion of the streambed) has developed in an exposed till layer where the valley-bottom expands, and stream/sediment flows are increased by valley-wall tributaries. This feature affects upstream migration of spawning salmon at some stream discharges and contributes to the bedload of the stream. The reach downstream of this point is characterized by erodible terraces (stranded alluvial flats) that are hydraulically disconnected (Haugerud 2009) from the channel and have been perceived to be major contributors to downstream sediment deposits (Cederholm 1972). Further downstream, the channel is periodically constricted by these stranded alluvial deposits, large alluvial fans, and debris flow deposits as testament to the erodible nature of this landscape (Haugerud 2009; Figure 4). My study reach includes channel reaches confined by the lowermost alluvial fan/debris flow deposit along with the relatively broad floodplain conditions downstream of river km 1.0 (Figures 2 and 4).

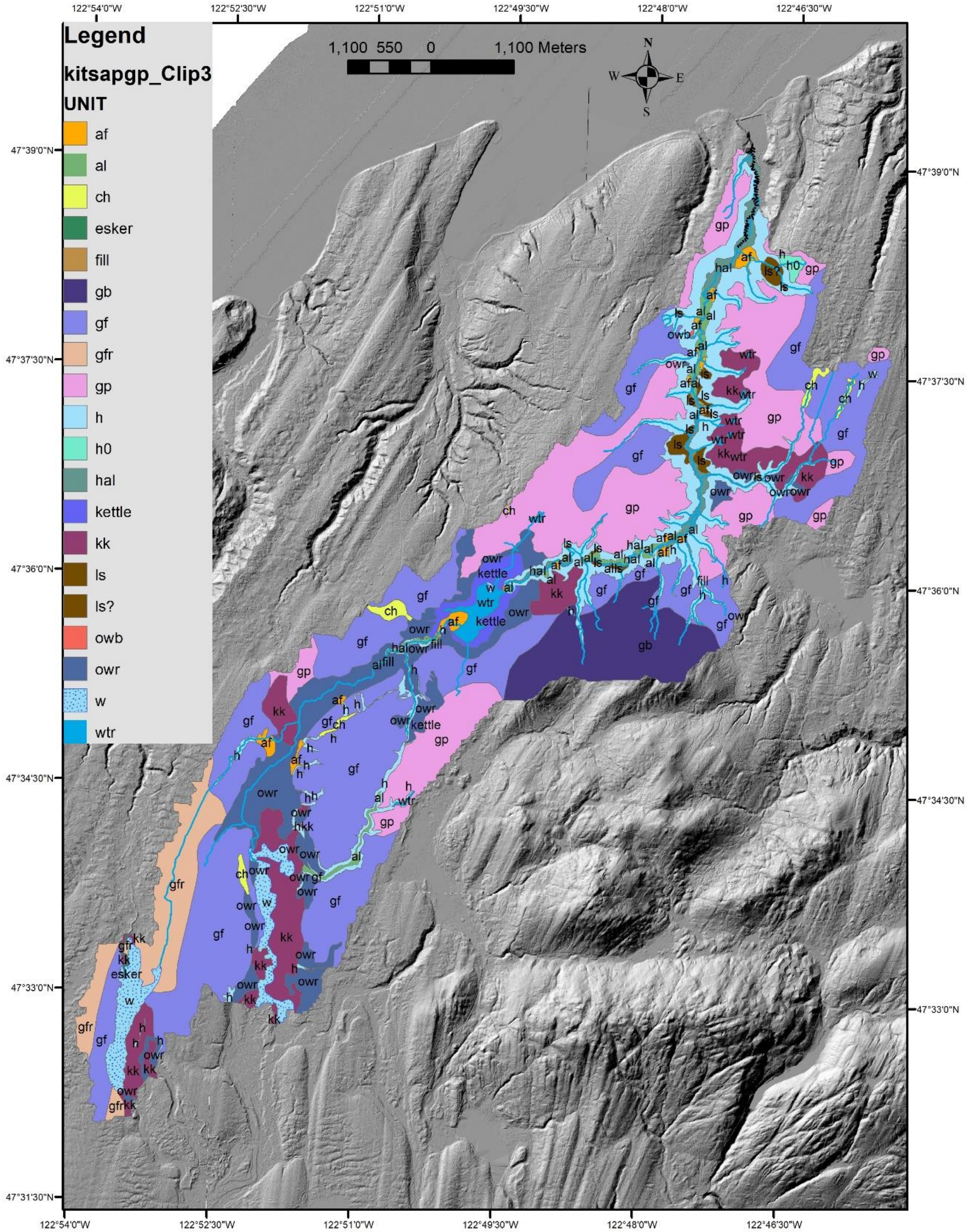


Figure 4. Geomorphic units mapped within the BBC catchment (from Haugerud 2009). See Table 3 for description of units.

Table 3. Count and definition of geomorphic units comprising the BBC catchment (from Haugerud 2009).

Unit Code	Count (%)	Definition
af	16 (0.2)	Alluvial fan - Moderately sloping (nearly 2-5°) surface, mostly conic, at drainage confluences and along toes of valley walls. Slope suggests sediment transport is dominated by debris flow or infrequent floods.
al	34 (0.19)	Alluvial flat - Stream-shaped surface, either depositional or strath. Could be latest Pleistocene or Holocene in age.
ch	6 (0.18)	Channel—Smooth-walled channels, apparently water-carved, but without apparent source or sink for flowing water.
esker	1 (0.02)	Esker—Sinuous narrow ridge
fill	5 (0.005)	Artificial fill—Surface of fill bodies beneath highways and railways, mapped because of possibility of failure during severe seismic shaking
gb	1 (26.84)	Glaciated bedrock surface—Ice-modified ground that has lumps or transverse ribs (eroded bedding) indicative of erosion from bedrock rather than from unconsolidated material
gf	18 (36.43)	Fluted glaciated surface - Characterized by well-organized flutes that have elongation ratios (length/width) typically greater than 10.
gfr	4 (9.14)	Rippled fluted glaciated surface—Fluted glacial surface that has transverse ripples or “chatter marks.”
gp	10 (10.17)	Pockmarked glaciated surface—Weakly fluted ground that has irregular pits and lumps.
h	30 (2.56)	Hillslope—Steep (commonly, 20-35º) surface that appears to be dominated by colluviation, debris-flow, shallow-landslide, and other mass-movement processes. Mostly with distinct breaks in slope at upslope and downslope margins. Cut into adjacent topography.
hal	5 (0.4)	Holocene alluvial flat—Stream valley floor. Recognized by low slope, planarity, and position in topographic lows along active drainage paths.
kettle	3 (0.28)	Kettle—Closed depression that has moderately to steeply sloping sides; commonly embedded in outwash flat
kk	14 (2.7)	Kame-kettle surface—Irregular ground characterized by steep-walled closed depressions (kettles), collapse features, eskers, and common alluvial flats
ls	17 (0.18)	Landslide—Surface of deep-seated landslide, recognized by uphill scarps, bulbous toes, position in hillslope hollows, and (locally) rumpled surface. Queried where identity as landslide is less certain.
owb	1 (0.003)	Outwash flat of Bretz age—Alluvial flat graded to glacial Lake Bretz. Queried where Bretz age is less certain
owr	28 (2.23)	Outwash flat of Russell age—Alluvial flat graded to glacial Lake Russell.
w	4 (1.15)	Wetland—Planar surface of low slope. Identification as wetland corroborated by approximate correspondence with third-party wetland inventories (Kitsap County GIS, 2006) and limited field checking.
wtr	9 (0.17)	Water
h0	1 (0.04)	Older hillslope—Position and lower gradient argue that older hillslope developed in a regime of lower slope stability, perhaps without vegetation cover

Land Use and Development

Big Beef Creek was dammed in 1965 at the transition between the upper and lower sections creating Lake William Symington as a central water feature for a housing development (Williams 1970). The dam was redesigned/rebuilt in 1992—while information relative to changes to the structure are not readily available—period news articles suggest that changes to the spillway were blamed for considerable erosion to downstream bluffs. During the original construction of the dam, the stream was channelized for about 500m below the structure. The dam is laddered for fish passage.

At the same time, the University of Washington (UW) developed lowermost 1.0 km of BBC where it meets Hood Canal (Madej 1978; Figures 2 and 5). Until operations were recently halted, the UW's BBC Research Station provided a setting for many ecological investigations. Examples include: (1) The effects of real-estate development on fish populations and other biological indicators (Williams 1970), (2) the physical and biological effects of stream channelization (Cederholm 1972), (3) the response of a stream channel to an increased sediment load (Madej 1978, 1982), and the influence of habitat complexity and size on the survival of Coho Salmon (Quinn and Peterson 1996). Shortly after construction of the research station the then Washington Department of Fisheries (WDF) channelized about 0.6 km of the creek that became braided (probably within existing blind tidal channels) after being diked from its channel (Cederholm 1972; Madej 1978, 1982). Windfalls and logjams had contributed to the aggradation of bed material leading to negative effects on salmon populations via gravel instability (loss of redds) and predation by dogs (Cederholm 1972). During the summer of 1970 an additional 800 m^3 of bed material was excavated at the mouth of the creek and a fence-type weir was constructed to aid in the early investigations of salmonid response to land-use changes within the catchment (Cederholm 1972). Excavation of bed material from around the location of the weir has continued periodically since then, the last occurrence in 2014.

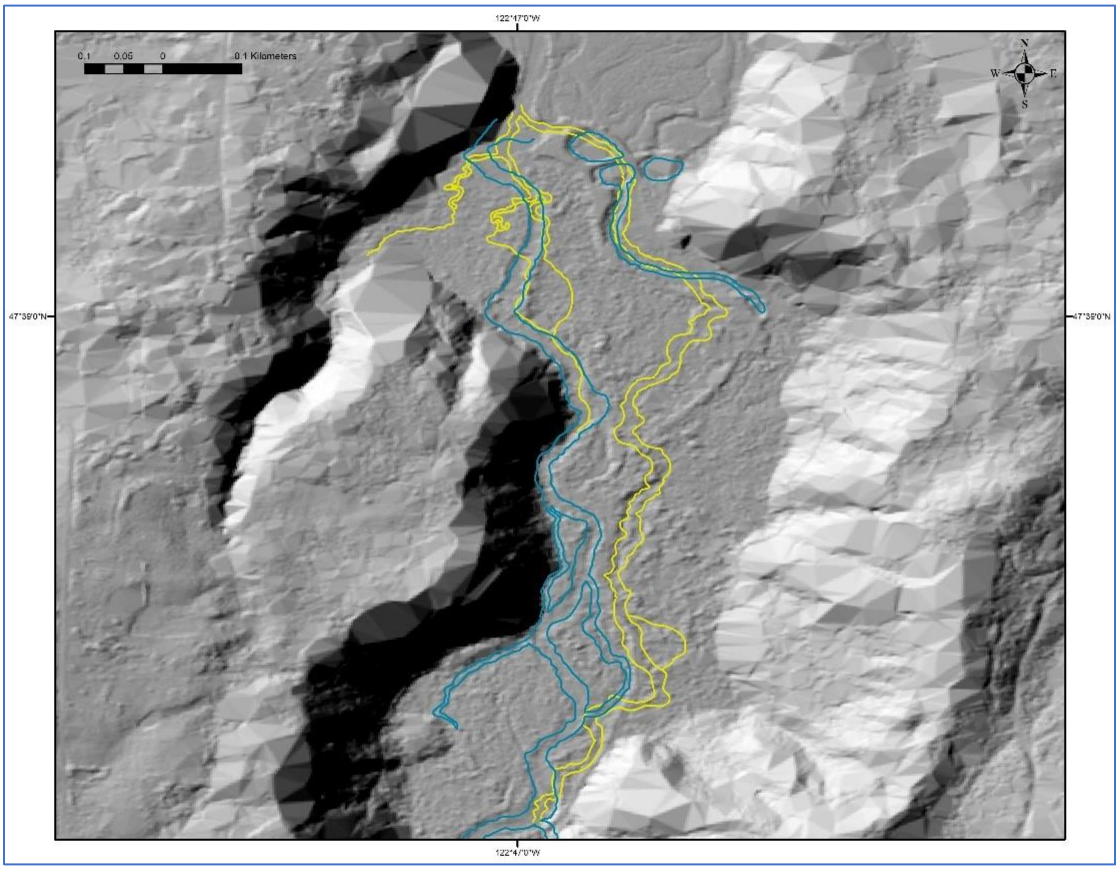


Figure 5. The approximate location of the pre-development channel at lower BBC (yellow) and the location of channels in 2015 (blue). Note the 3 ponds and artificial spawning channel associated with the research station facilities in the upper center image.

The WDFW continues to operate a weir-type salmon trap at the mouth of BBC today (updated mid-1980's; Matt Gillum, WDFW, personal communication). Trap data is primarily used to provide and index of Coho Salmon abundance within the greater Hood Canal catchment for harvest modeling efforts along with HCIMW monitoring. When the weir panels are in place at this structure it acts as a dam (Madej 1978, 1982; ENTRIX 2010) contributing to aggradation of the stream reach (Cederholm 1972; Madej 1978, 1982; ENTRIX 2010). Presently, salmonid-based research within the catchment include the HCIMW and investigations into the survival of steelhead (*O. mykiss*) outmigrants to Hood Canal and Puget Sound.

The catchment was 74% forested and 5% developed in 2010 with an estimated total channel length of 58 km (Krueger et al. 2010; Table 4). Additional timber harvest and land conversion has occurred since that time. The BBC catchment was most likely logged near the mouth at Hood Canal as early as 1860 following the establishment of the town of Seabeck and the first lumber production mill on Hood Canal. Camp Union (near the lake) became a central hub for a logging railroad by the 1920's and the catchment was logged to the streambanks by 1940. Logging began again in the late 1950's (Madej 1978, 1982) and continued through the early 1980's when land began being converted from timber to rural/residential use (much of the 'forested' extent reported above is in this land-use type). Harvest of a third crop of timber from the catchment has been occurring since the initiation of the HCIMW, however modern forestry practices intended to protect the waterway are being observed.

Table 4. Physical characteristics of the BBC Catchment (adapted from Krueger et al. 2010).

Attribute	Measure
Area (km^2)	38,8
Max. Elevation (m)	151
Geology	Quaternary sediment (glacial till and alluvium)
Mean Annual Precip.	105 cm/y
Forest – Developed (%)	74 F 5 D
Est. N Road Crossings	41
Total Reach Length (km)	58.0
N Reaches	109
Strahler Order	3
Drainage Pattern	dendritic
Drainage Density	1.5
Focal Species	Coho, Steelhead

Climate

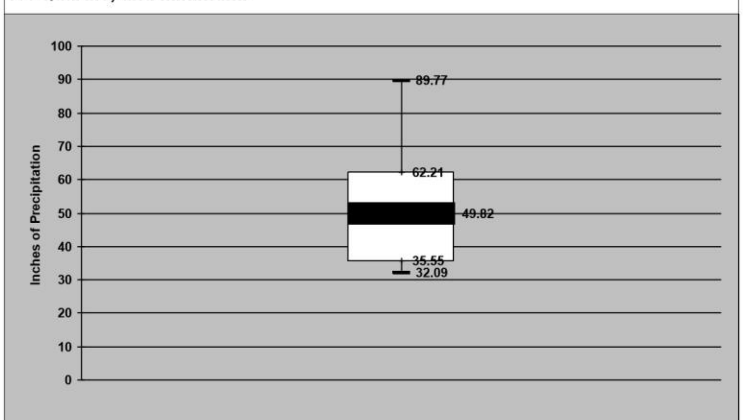
The Kitsap Peninsula has a characteristically marine climate typified by short, cool, dry summers and extended, mild, wet winters. Winter storms generally approach western Washington from the southwest, leading to relatively high winter rainfall from storms funneled into the region by a topographic gap formed by the Olympic Peninsula and the Black Hills (Kitsap Public Utility District et al. 1997). Moderated by the Pacific Ocean and inland marine waters, temperatures on the Kitsap Peninsula infrequently drop below freezing or exceed 27°C (Kitsap Public Utility District et al. 1997).

Precipitation

The Kitsap Public Utilities District (KPUD) maintains data from a countywide network of precipitation stations at their website (KPUDhydro n.d.). The median yearly precipitation total at the Bridletree station (Seabeck Creek catchment) was 49.82 over the past eight water years (Oct. 1 – Sept. 30) including the four years of my study period (Figure 6). The Bridletree station probably best represents the average precipitation conditions over BBC, however two tributaries to the creek (lower section) extend up the flanks of Green Mountain where localized precipitation amounts might be greater due to orographic effect (Kitsap Public Utility District et al. 1997).

Station No: 67
Station Name: Bridletree
Lat/Long: 47.6134 -122.820 Elv: 566
Local Number: 25N/01W-33M

Box Plot of Annual Total Precipitation Showing Maximum, 3rd Quartile, Median, 1st Quartile, and Minimum.



W YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL
2008	4.26	4.89	18.24	2.51	1.64	3.70	2.29	0.28	1.83	0.58	1.90	1.22	43.34
2009	2.82	5.61	3.32	1.09	2.52	4.30	3.16	5.32	0.42	0.02	1.22	2.29	32.09
2012	2.58	7.35	2.22	6.92	2.73	6.46	2.28	1.58	2.60	0.70	0.01	0.12	35.55
2013	5.24	12.10	16.24	3.72	3.59	3.75	4.26	1.27	2.15	0.00	1.70	8.19	62.21
2014	0.96	5.40	0.35	5.90	9.60	12.84	4.11	3.82	1.52	0.74	1.36	3.22	49.82
2015	10.13	7.70	12.14	5.04	8.36	5.96	1.89	0.48	0.32	0.63	2.74	1.35	56.74
2016	5.51	10.03	19.17	17.10	6.66	14.20	2.19	0.65	0.55	0.77	1.39	1.21	79.43
2017	18.35	16.53	4.82	8.59	13.22	13.98	8.46	3.04	1.81	0.01	0.15	0.81	89.77
MAX	18.35	16.53	19.17	17.10	13.22	14.20	8.46	5.32	2.60	0.77	2.74	8.19	89.77
MIN	0.96	4.89	0.35	1.09	1.64	3.70	1.89	0.28	0.32	0.00	0.01	0.12	32.09
NO YRS	8	8	8	8	8	8	8	8	8	8	8	8	8

Figure 6. Summary statistics for the Bridletree precipitation station near BBC, WY's 2008-17. Data and plot provided by Kitsap Public Utilities District (KPUDhydro n.d.).

Stream Discharge

Stream discharge (Q) data has been recorded at BBC near stream kilometer 1.6 since around 1969, however records are sometimes discontinuous. The KPUD assumed operation of the gaging station from the United States Geological Survey (USGS) in 2012 with real-time data for BBC available at their website (KPUDhydro n.d.). Stream discharge data plots representing my study period (WY2014-17) at lower BBC are presented in Figure (8). The peak Q (32.7 m^3/s) observed during the study period occurred in WY2016, after phase 1 wood placement but before the phase 2 effort (Table 5). Alteration of the gaging site by wood placement has limited the peak value the KPUD reports to the 1.5-year recurrence interval discharge (the 'bankfull' discharge) of 400 cfs (11.33 m^3/s). The peak Q observed in WY2016 ranked within the top 10 ever recorded at BBC (USGS 2018; Figure 7). A water year (WY) is defined as the period from October 1 – September 30. Streamflow data from previous studies of BBC mentioned by this effort are provided in Figure (9).

Table 5. Selected stream discharge statistics for BBC reported in cubic meters per second (m^3/s), WY's 2014-17. Data from Kitsap Utility District (KPUD) website (KPUDhydro n.d.).

Water Year	Days	Mean Q	WY Low Q (Date)		WY Peak Q (Date)		Number of bankfull days
2014	365	0.88	0.09	(9/12/14)	15.04	(3/6/2014)	3
2015	365	1.10	0.11	(8/10/15)	14.98	(12/10/14)	4
2016	366	2.18	0.08	(8/29/16)	32.7	(12/9/15)	22
2017	365	1.90	0.09	(9/15/17)	11.33*	(11/26/17)	8

*Damage to the gaging station by wood placed during the project limits what KPUD reports as a peak Q.

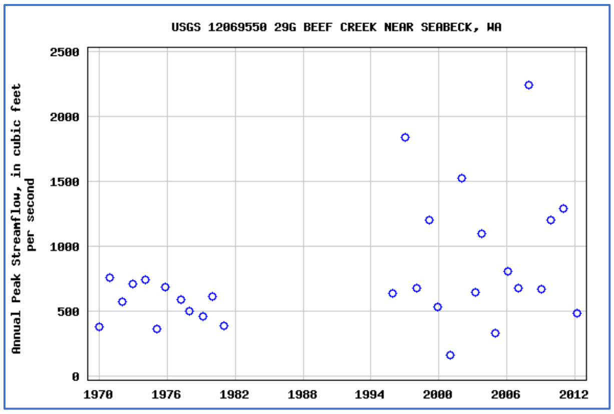


Figure 7. Peak discharge (Q) values recorded at BBC (1.6 km above the mouth), 1970-2012. Data and plot provided by (USGS 2018).

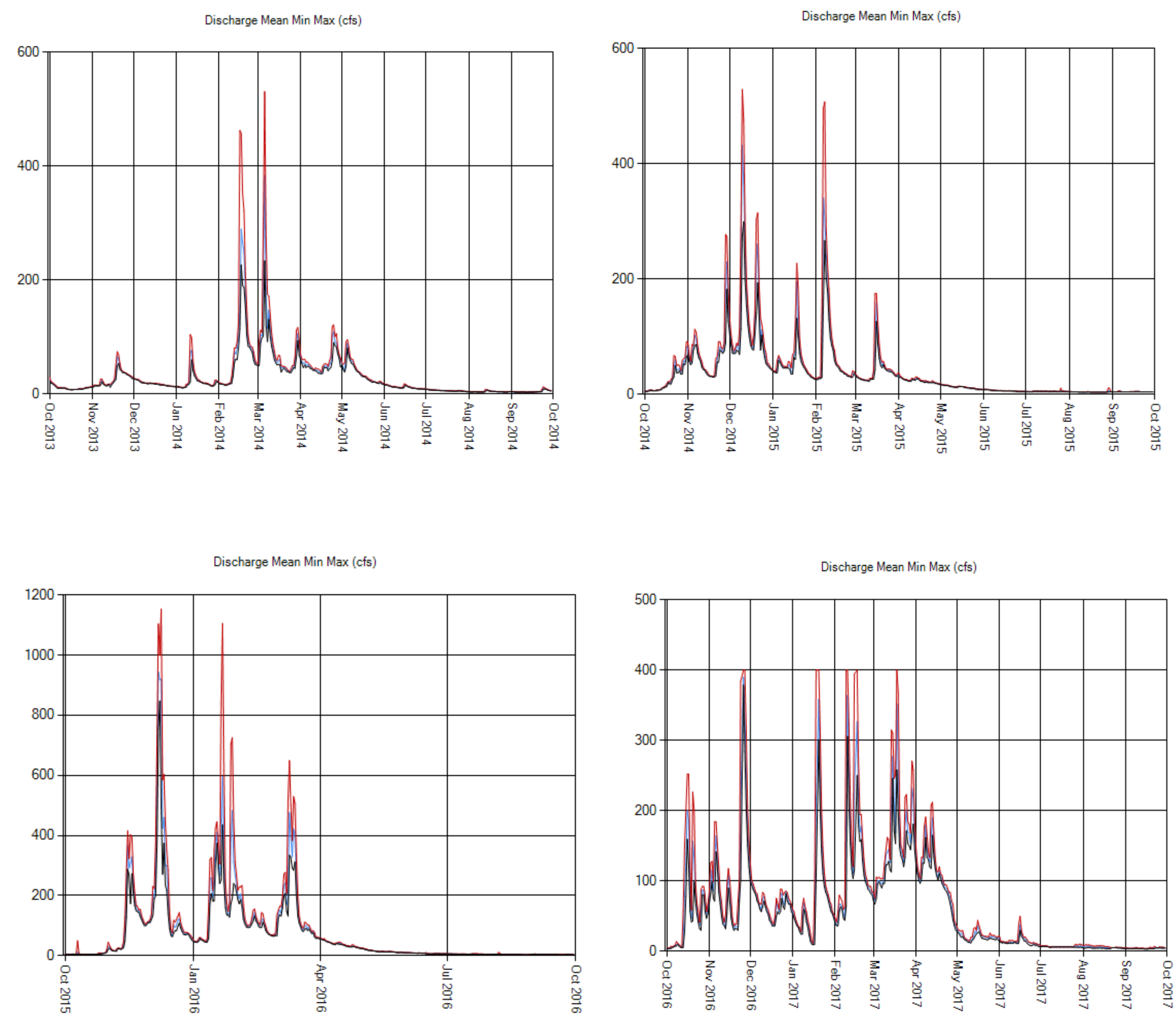


Figure 8. Stream discharge summary for water years 2014-2017 at BBC in cubic feet per second (cfs). Data and plots from Kitsap Utility District (KPUD) website (KPUDhydro n.d.). Note that peak Q in WY2017 is only reported to 400cfs after the placement of wood in the stream affected the gaging station.

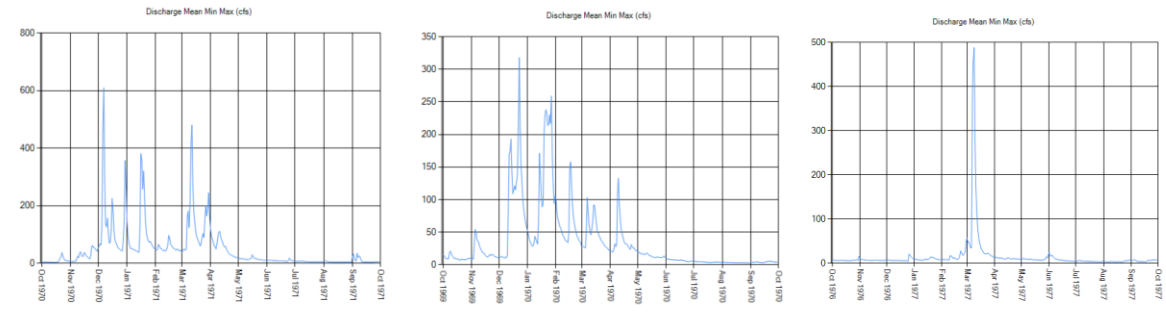


Figure 9. Stream discharge summary reported in cfs at BBC for WY's 1970-71 and 1977. Data and plots from Kitsap Utility District (KPUD) website (KPUDhydro n.d.). These plots represent the conditions encountered by (Cederholm 1972; Madej 1978, 1982) during their respective study years.

Restoration History

Completed in 2002, the ‘Big Beef Creek Preservation Project’ set a project goal to preserve the UW BBC Research Station as an active fisheries research center for use in the development and practice of studies investigating wild Hood Canal salmon. Citing loss of natural wetland function (including sediment entrapment), the proposal was to preserve some 120,000m^2 of wetland habitat by removing all/part of an elevated well access roadway that dissects the floodplain. Total project cost was $168,658 (PRISM 2018).

The re-introduction of summer Chum Salmon to BBC was completed in 2005 at a cost of $175,000. The re-establishment of the experimental spawning channel associated with the UW Big Beef Creek Research Station was the only ‘physical’ component of this project (PRISM 2018).

Also completed in 2005 was the development and analysis of an orthophoto for the BBC catchment ($40,000). Citing salmon recovery goals: (1) establish specific thresholds for catchment impervious surface and native forest cover, (2) reduce peak flows, (3) retrofitting of the Seabeck highway causeway, and (4) setting riparian buffer width based upon floodplain width and channel migration zone (CMZ) project sponsors intended their products as aids in catchment planning (PRISM 2018).

The Washington Department of Fish and Wildlife (WDFW) acquired about 1.2 km^2 of uplands, wetlands, and lakes in the headwaters of four Hood Canal salmon streams (including BBC). This project was completed in 2006 at a cost of $840,000 (PRISM 2018).

In preparation for an extensive restoration effort, the ‘Lower Big Beef Creek Design’ was completed in 2011 at a cost of $79,000. Seeking to restore properly functioning floodplain and channel conditions within the lower 1.6 km of BBC, this design-phase project intended to: (1) minimize the elevated well-access road prism that dissects the floodplain, (2) reconnect several side channels and wetlands, and (3) install as many as 30 log jam structures (PRISM 2018).

The Great Peninsula Conservancy completed the ‘Big Beef Creek Preservation’ project in 2012. This project acquired one of the few remaining land parcels in private ownership along lower BBC and put it into conservation at a cost of $252,496 (PRISM 2018).

Completed in 2013 at a cost of $100, 000, the ‘UW research station wetlands restoration project’ relocated a well that services the facility in preparation for future project plans. The effort also lined the artificial spawning channel with boulders as mitigation for potential effects of future projects on summer Chum Salmon spawning habitat in the lowermost reaches of the system (PRISM 2018).

The ‘Final design’ of an extensive restoration effort was completed in 2014. This included the completion of the design/planning phase, survey work, and permitting costs for the phase 1 and 2 portions of ‘Lower Big Beef Creek Restoration’ over the lower 1.6 km of the creek. The cost of this effort was $70.061 (PRISM 2018).

Initially planned as a single phased project over the lower 1.6 km of the creek, ‘Lower Big Beef Creek Restoration’ became a three-phase project as additional catchment priorities were developed. Phases 1 and 2 were completed during the work windows of 2015 and 2016 respectively, while phase 3 work began during the summer of 2017 (ongoing scheduled to end 3/2019). Phase 1 and 2 project objectives included: (1) Remove the well access road dissecting the floodplain to eliminate channelization and restore habitat connectivity, (2) remove two buildings and 2523 m^3 of fill material—restore to wetland habitat, and (3) improve in-stream habitat complexity by adding (to the channel) 10 new wood structures and reinforcing 13 existing structures with additional wood placement (Figures 10-11). The phase 3 objectives aim to promote sediment stability and enhance channel complexity to improve winter habitat conditions for juvenile salmon through additional wood placement at key locations between the lower project site and the channel headcut near Lake William Symington. Additionally, livestock-fencing and riparian plantings are planned along a productive tributary in the upper catchment. Costs of the three phase of the project were $1,370,810 (phases 1, 2) with an additional $229,840 to complete phase 3 (PRISM 2018).

Figure 10. Example of wood structures built during phase 1 of the lower BBC restoration. This set of structures were built around posts driven into the streambed with a backhoe and included 'slash bundles' of smaller logs bound together with rope at their base (the complete restoration design may be viewed at PRISM 2018). Photographs are of the same structure depicted in the plan and were taken two years after construction in 2015 - facing upstream (left) and downstream (right). A backwater pool is present underneath the wood in the photographs and this structure has wracked additional wood since construction. Upper image (blue arrow indicates flow direction from McCullough 2015).

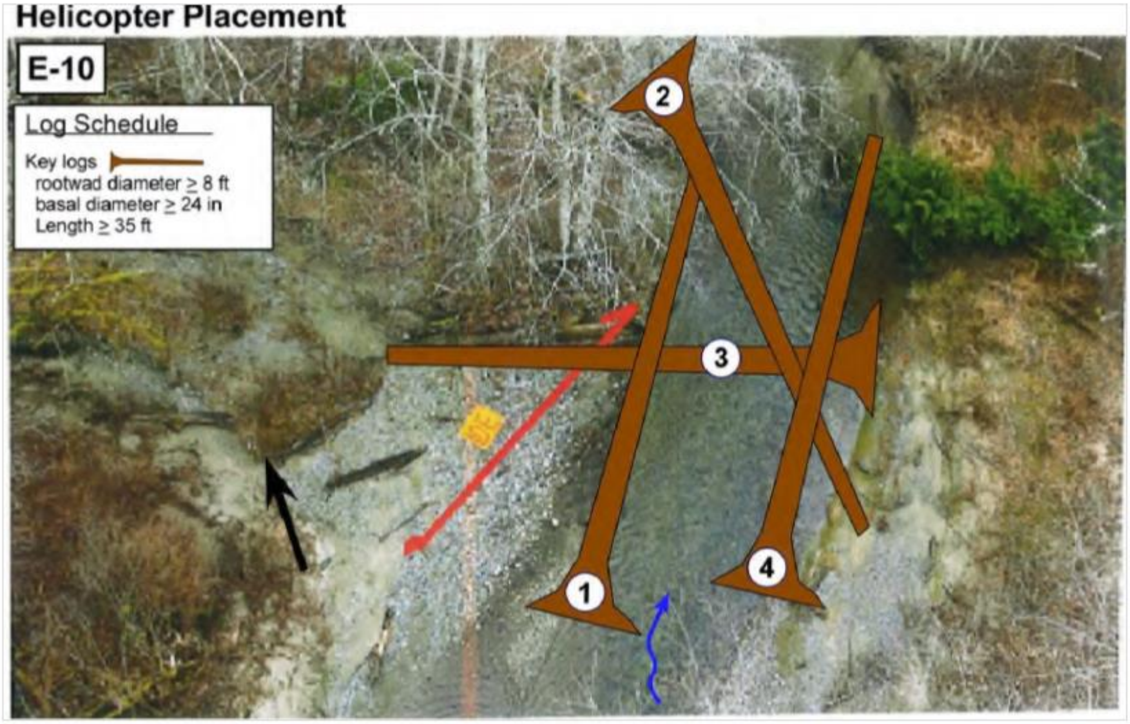


Figure 11. Example of wood structures built during phase 2 of the lower BBC restoration. This set of structures were placed by helicopter and included 'slash bundles' of smaller logs bound together with rope at their base (Seen best in center image on the left, the complete restoration design may be viewed at PRISM 2018). Photographs are of the same structure depicted in the plan and were taken one year after placement in 2016 - facing upstream (left) and downstream (right). The slash bundles associated with this structure is becoming buried in the sediment, a small pool is associated with the root wad in the middle of the left image, and aggradation of bed materials around the structure contributed to the activation of a previously abandoned channel reach (black arrow upper image). Upper image (blue arrow indicates flow direction from McCullough 2015).

Methods

Floodplain Habitat

Beaver pond/wetland locations were located on aerial imagery (years1990, 2013, 2015, 2017) and polygon features were created within the ESRI ArcGIS® environment to represent their area and change over time. Extensive field reconnaissance in all years but 1990 aided in the generation of these files. Beaver dam locations/elevations were collected as line files with Trimble GeoExplorer® real-time kinematic global positioning system (RTKGPS) (± 1 m) during 2016-17.

Channel Locations were identified and mapped with RTKGPS (2 m horizontal accuracy) at study start, in 2016 when new channels began appearing on the landscape, and again in 2017 to document further change over that WY. These data were smoothed within the ESRI ArcGIS® environment using integrated tools affording a more accurate determination of channel lengths.

Stream Channel Cross Section Survey

The primary tool that I utilized to monitor response of the stream channel at lower Big Beef Creek to restoration actions completed in 2015 and 2016 was the stream channel cross section. The shape of a stream channel cross section (at any location) is a function of the streamflow, the character and composition of bed and bank materials (including vegetation), and the quantity and character of the sediment moving through the section (Leopold et al. 1992). Furthermore, the mean bed elevation (channel depth) at a stream channel cross section not only depends on streamflow but is closely related to changes in width, depth, velocity, and sediment load during the passage of high flow events (Leopold et al. 1992).

Stream channel cross sections have been used as the primary tool in calculations of geometric, hydraulic, and sediment transport parameters (Madej 1978, 1982; Leopold et al. 1992; Hardy et al. 2005), to provide a method of repeatable measures to evaluate the effects of management actions on streams and rivers (Cederholm 1972; Olson-Rutz and Marlow 1992), and in channel and road crossing design (Hardy et al. 2005). As management actions in streams have turned toward restoration, the channel cross section has further emerged as a monitoring tool in the evaluation of change in stream channel morphology around engineered structures placed in streams (Nichols and Ketcheson 2013). Noting changes in channel bed morphology further away from the structures they studied, these investigators modified their study design to include between structure cross sections. However, these additional stream channel cross sections lacked background information relative to their natural variability in response to streamflow and sediment (Nichols and Ketcheson 2013).

My design followed the approach of, and utilized many of the same stream channel cross sections as, Cederholm (1972) to evaluate the physical response of the stream channel to channelization. Madej (1978, 1982) similarly studied changes in sediment transport rates in BBC related to an increased sediment yield from recent land use changes. In comparison with topographic surveys completed at the same time, Cederholm (1972) reported a 13% over-reporting of upstream sediment yield, a 7% under-reporting of streambed degradation, along with an 8% under-reporting of streambank erosion values when utilizing the stream channel cross section technique to estimate—and identify sources of—volumetric change of bed material at lower BBC.

Stream channel cross section data was collected at 48 (2013-2015) and 64 (2016-2017) locations spaced approximately 33 m (stations 3-50) and 30 m (stations 51-66) apart along the previously channelized section of the stream and continuing upstream of the wood placement sites (Figure 2). I utilized maps from Cederholm (1972) and any remaining monuments marking his original cross section survey to duplicate effort as accurately as possible. A permanent benchmark and a series of elevation control points were established throughout the study area using a combination of Trimble GeoExplorer® real-time kinematic global positioning system (RTKGPS) accurate to within 5 cm vertical and simple transit techniques utilizing a rod and level. The benchmark and control points were intended to facilitate reference to a datum point (MHW NAVD88) and allowed for greater consistency in the re-survey process.

The end points of each cross section were monumented with wooden stakes and flagging tape (where Cederholm's monuments were missing) and located with RTKGPS to 1m horizontal accuracy. End points were set approximately 2 m inland from the ordinary high-water mark (OHW) on both right and left banks (RB, LB) of the channel as identified in 2013 (stations 3-50) and 2016 (stations 51-66). A compass bearing along the line between the RB and LB monuments was collected to aid in their relocation or replacement. Where the location of the stream channel had changed since these previous surveys, channel cross sections were extended in length to include the new channel location. This technique was further utilized in subsequent years to capture side channel activation, new channel creation, and bank erosion when feasible.

Stream channel cross section data was collected yearly (2013-17) during late-summer low-flow conditions utilizing rod, level, and tape procedures. A CST/berger Lasermark® automatic self-leveling rotary laser rated at ± 0.6 cm over 900 m was used to complete a transit upstream through the study reach and back downstream to close at the primary benchmark each year. Channel cross section data was collected as side-shots from the transit line completed with the instrument. A tape was also laid along the channel thalweg (a line following the deepest part of the channel) during 2016 to provide a detailed survey of water surface gradient and more precise thalweg elevations than those gathered only at channel cross sections.

Elevation data was collected along each cross section at maximum intervals of 1 m within channels and 2 m on islands. Within those intervals additional data was collected where breaks in slope occurred as to model the stream channel as accurately as possible. Additionally, elevation data was collected at the thalweg and OHW in all years, and at all water surface heights along the channel cross section in 2016-17.

Changes in channel cross section area were determined for each station by WY using WinXSPRO, an interactive Windows® software package designed to analyze stream channel cross section data for geometric, hydraulic, and sediment transport parameters (Hardy et al. 2005). The software allows the user to subdivide the channel cross section into multiple subsections (Hardy et al. 2005), permitting the evaluation of three parameters; (1) bank erosion, (2) streambed aggradation, and (3) streambed degradation and is comparable to the analysis done by Cederholm (1972) investigating channel response associated with stream channelization at lower BBC (Figure 12).

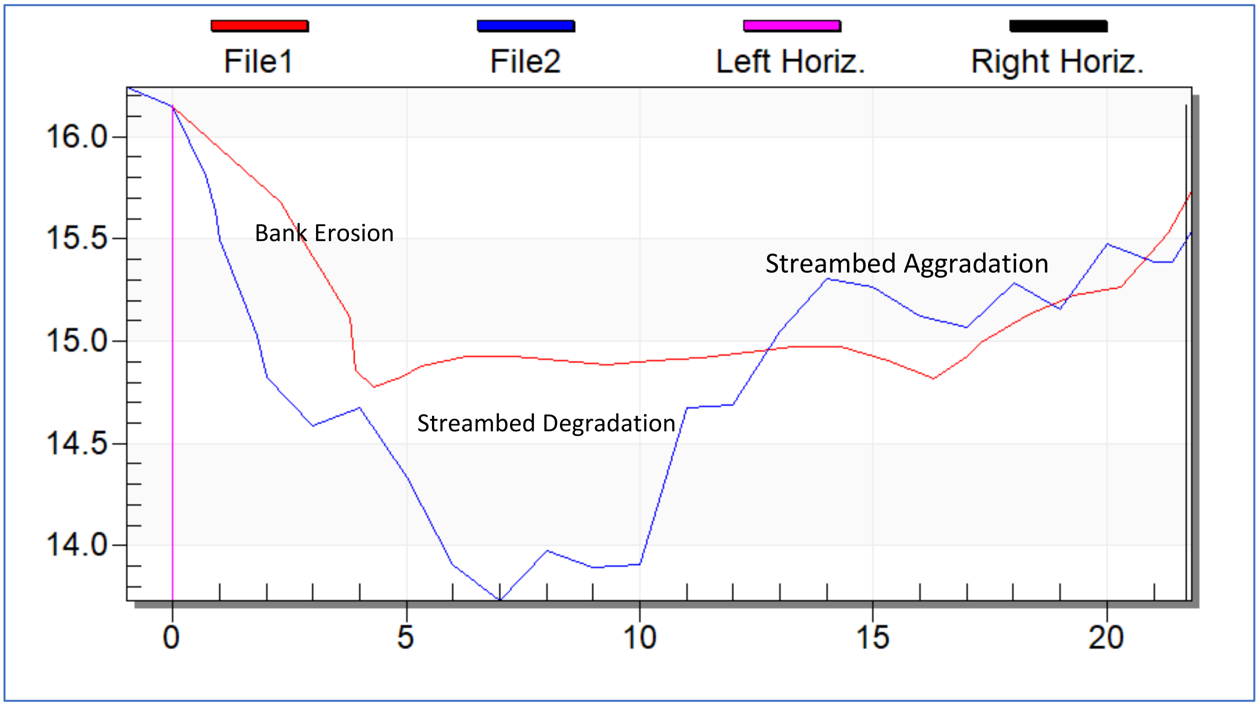


Figure 12. Methodology for determining bank erosion, streambed aggradation, and streambed degradation on plots of channel cross section from lower BBC, WY's 2014-17.

Vertical Thalweg Profile

I used thalweg elevations from stream channel cross sections and upstream distance as derived from the cumulative distance (33m [stations 3-50] or 30m [stations 51-66]) to represent the profile of the channel through my study reach. These data were divided to sub-reaches 1-3 (1-4 in WY2017) and analyzed for absolute and net change in the vertical thalweg profile area utilizing WinXSPRO software to again sub-divide by aggradation or degradation of the stream bed along the thalweg producing values for both of these variables by WY. Together, these observations offer estimates of both absolute and net change to the channel thalweg profile

Table 6. Description of four sub-reaches comprising the 2km study reach at lower Big Beef Creek 2013-17.

Sub-Reach	Confinement	Description
1	Moderate to none	Stations 3-18, sub-reach 1 largely comprises the channelized reach studied by Cederholm (1972). The WDFW weir is located about midway between stations 3 and 4. The channel has migrated in the upper end of the reach since the Cederholm (1972) study. Berms left from channelization and created naturally by stream processes confine most flows to the channel, however inflow to both RB and LB wetlands was observed over the study period.
2	Highly confined until road-berm removal in 2016 left this reach perched and unconfined	Stations 19-33, sub-reach 2 is characterized by road-berm confinement and the presence of both RB and LB side channels associated with the main channel. A LB overflow channel/beaver pond complex is also present that maintains streamflow year-round. Rip-rap had been used to harden banks in the past. A water intake structure was left in place after road berm removal and probably continues to harden the bank locally. The avulsion into the historic channel occurred within this reach. Rip-rap bank hardening was left along the RB of the channel post-project at and near station 33.
3	Moderate to high	Stations 34-50, sub-reach 3 is characterized by a LB side channel and an almost alluvial fan appearance as these channels on either side of the mainstem lay at lower elevation. A RB overflow channel is also present that maintains groundwater flow year-round. The upper end of this sub-reach becomes highly confined by an alluvial or debris flow fan that was deposited in the mainstem from the first RB tributary (travelling upstream). The stream gaging station is located within this highly-confined section.
4	High	Stations 51-66, sub-reach 4 was added in 2016 to accommodate additional wood placement associated with phase 3 of the lower Big Beef Creek restoration treatments. This sub-reach continues upstream along the alluvial/debris fan deposited to the valley floor along with the mouth of the tributary that provided the materials. Further upstream high/easily erodible terraces (probably formed when the channel was dammed by the debris flow fan [see Hoffman and Gabet 2007]) combined with valley walls confine the channel. Increased amounts of natural wood occur within this sub-reach.

This method assumes that the channel banks stay at a constant elevation and therefore might underestimate change within reaches that included berm or road removal along the channel edge. Sub-reaches were chosen because of their nearness to the weir, channel complexity, artificial confinement by the floodplain road berm, and completeness of the dataset in the case of sub-reach 4 where surveys began in 2016 rather than 2013 (Table 6).

Physical Habitat Survey

Individual habitat units were categorized and measured (by a single observer) beginning at the weir and continuing upstream about 1580 m in 2015 and 2060 m in 2016-2017 during late-summer low streamflow conditions. This effort included all available aquatic habitat from valley-wall to valley-wall. Stream-type habitats were classified using a modified version of the system offered by Bisson et al. (1982) that further typed pools within secondary channels (side-channels) along with including other habitat types omitted by this classification scheme but identifiable in the field (Table 7). These additional habitat types included (1) dry channels, (2) isolated pools, and (3) within-channel beaver ponds.

Physical habitat units were measured for surface area with a Laser Technology Inc. Impulse® laser rangefinder to the nearest 0.01 m. Length was measured in an upstream direction and three width measurements were taken perpendicular to that axis. Maximum depth of slow/deep habitats (pools) was collected in study years 2016-2017 utilizing a stadia rod graduated to the 0.005 m and rounded to the nearest 0.01 m.

*Table 7. Habitat classification scheme modified from Bisson et al. (1982). *Because pools were further classified in side channels, secondary channel pools are included here as reference only.*

Category	Habitat Type	Code	Description
Slow/deep	Lateral Scour Pool	PL	Where pool scour is caused by boulders, wood, or changes in channel direction
	Plunge Pool	PP	Where pool scour is caused by vertically dropping water
	Impounded Pool	PD	A pool area created by some sort of dam (includes debris dams, boulders, etc.)
	Backwater Pool	PB	A pool area that is disconnected from the main flow of the channel behind large obstructions such as rootwads or boulders
	Trench Pool	PT	A pool formed by bedrock or other hardened control (bathtub like), uniform flow
	*Secondary Channel Pool	PS	Any pool in a side-channel or braid
	Beaver Pond	BP	Within channel beaver pond, late summer/early fall
	Isolated Pool	PI	Depression within the channel substrate that contains water but is separated from the streamflow
Fast/ shallow	Glide	GL	Smooth surface, moderately shallow and uniform depth, cannot occur directly downstream of a pool
	Riffle	RI	Shallow, moderate velocity, moderate turbulence, ≤ 4% gradient, substrate (2-256 mm)
	Rapid	RA	> 4% gradient, swift flow, considerably turbulent, generally coarser substrate with boulders protruding through the surface at low flow
	Cascade	CA	Where shallow flow runs down a angled bedrock face or areas of uneven gradient consisting of a series of alternating small falls and shallow pools, typical substrate is bedrock, but may occur among boulders and debris dams
Other	Dry	DR	Dry channel

Statistical Analysis

Repeated measures ANOVA was used to compare pool area and maximum depth among channels, between WYs, and by wood placement (for pool area) following procedures outlined by Mangiafico (2016) using R programming language (R Core Team 2018). An identical process was carried out for non-pool habitat area. A *post hoc* Tukey's test was completed for each ANOVA to detect between group effects. Ecological data are rarely normally distributed (Studinski et al. 2012), and the data collected by this project were no different. Since skewness in the data was always in one direction, I stayed with the ANOVA tests. As a collection of t-tests, which is not at all sensitive to this assumption if the distribution of two groups are skewed the same (McDonald 2014), ANOVA provided results that were consistent with my extensive field observations of the site.

Results

Floodplain Habitat

Pond area (mostly beaver ponds impounded by dams) totaled about 53,000 m^2 in 2017 after restoration treatments were completed and winter had passed. This value represents a 25% increase since last measured in 2015 prior to treatment (Table 8). The whole of these habitats became accessible to fish (visually inspected) after restoration treatments were complete, a 95% increase in access over the 2015 condition.

Total channel length increased incrementally after restoration treatments and obtained a maximum (including where the channel flows through ponds) of 4713m in 2017, a 43% increase over background conditions (2013-15; Table 8).

Table 8. Total pond/wetland area and total channel length at lower BBC (1990, 2013-17). The value in parenthesis represents the percent change over the previous survey period. No ponds were observed on aerial photographs pre-dating 1990.

Year	Total Pond Area (m^2)	Accessible Pond Area (m^2)	Total Channel Length (m)
Pre-Treatment			
1990	9102 (1.00)	9102 (1.00)	NA
2013	27,119 (1.98)	20,924 (1.30)	3296 (NA)
2015	42,783 (0.58)	27,277 (0.30)	3296 (0.00)
Post-Treatment			
2016	NA	NA	3813 (0.16)
2017	53,266 (0.25)	53,266 (0.95)	4713 (0.24)

The plan view of the channel did not change measurably from 2013 through 2015 (Figures 13A-D). Overall, changes to the channel occurred after wood placement, but in combination with higher peak Q's and increased sediment delivery from upstream than were noted during the pre-treatment phase of this project. Changes occurred in 2016, one winter after phase 1 wood was placed in the channel during the summer of 2015. Net aggradation of the main channel from station 28 upstream to station 37 contributed to a partial LB channel avulsion near station 34. Additionally, and contributing to the main channel aggradation, bank erosion around wood structures that were placed between stations 29 and 30 redirected the channel thalweg into an existing RB side-channel where it remained for the duration of the study. The redirection of the channel thalweg, and thus the main path of water flow, left the main channel reach dry during the low water season from about station 26.25 to station 29.25 (Figures 13 C and D). The left bank side channel intersected by stations 21-25 was also dry or limited to isolated pools of water during the post-project low-flow season.

During WY2017 the channel avulsed in five additional locations (Figure 13D). Most importantly, after removal of the floodplain road berm, a potentially channel-capturing avulsion occurred into the pre-development channel. Big Beef Creek had previously avulsed at this same location during WY's 1999 and 2007; repairs to the road were made both times. This channel (floodplain avulsion channel) became the primary flow channel during summer low-flow conditions of WY2017 from the point of avulsion to the mouth of the stream. The new flow-path extended across the newly connected floodplain intersecting two beaver ponds (partially destroying the uppermost beaver dam, 'C' on Figure 13A) near the right valley-wall before continuing through the newly created wetland and along the weir access road where it intersected another series of large beaver ponds (B; Figure 13A). Active erosion was noted along the weir access road through the summer of 2017 as the dam containing the bulk of beaver pond B was raised (by the beaver) and the water height elevated.

Wood structures that were placed within the channel during 2016 appear to have directly contributed to three of the five WY2017 avulsions by retaining sediment within the main channel (creating a mid-channel bar) and thus directing flow toward channel banks that consisted of finer grained materials than the channel bed. The channel pattern at lower BBC changed from what was largely a single thread meandering channel (albeit constructed and maintained) to a braided channel pattern as a post-treatment condition (Figure 13D).

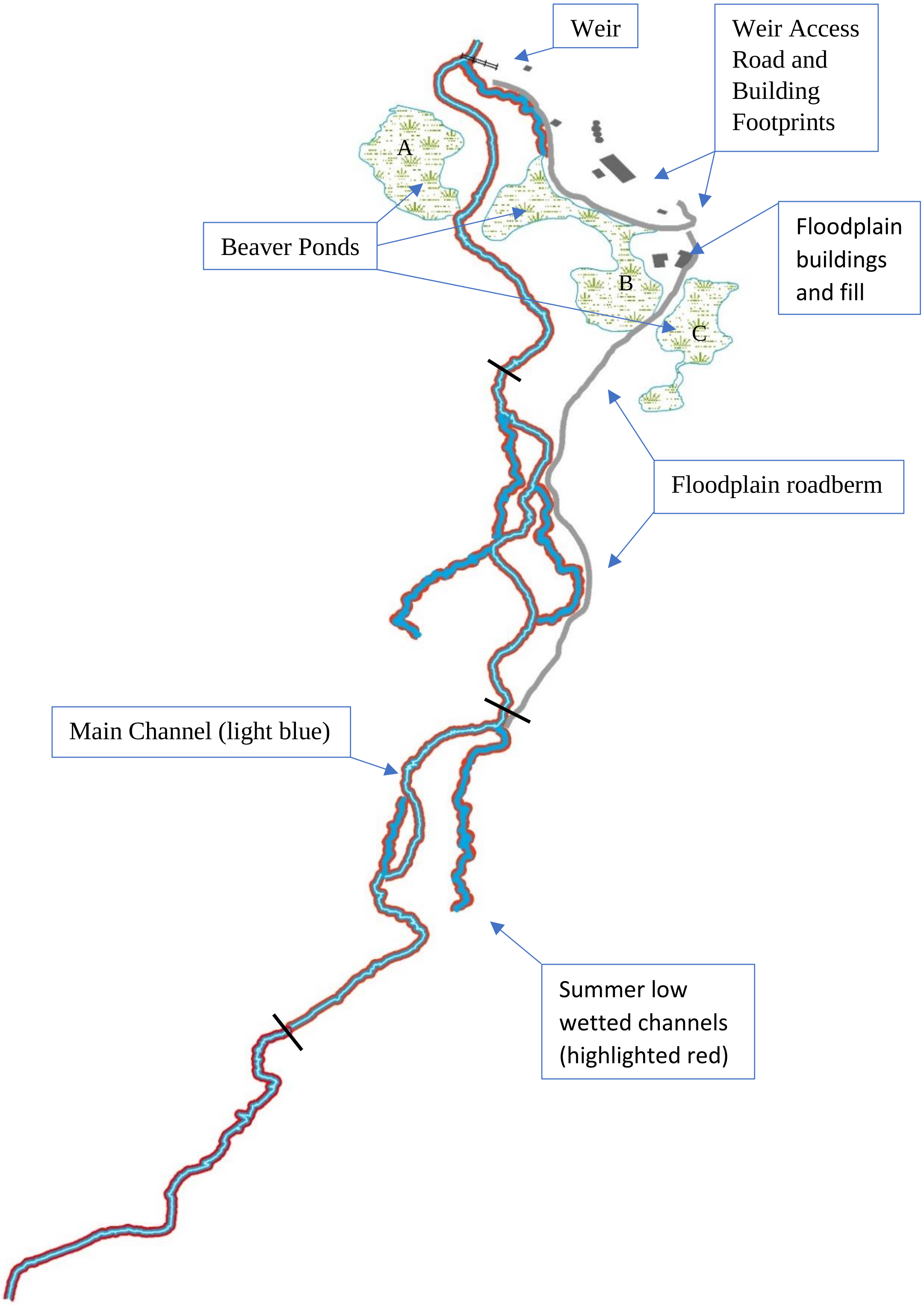


Figure 13A. The lower 2 km of the BBC channel during years 2013-2014. Channel lines that are highlighted in red were wetted during the time of survey. Sub-reaches 1-4 are defined by the three solid block lines set perpendicular to the channel line along with the ends of the depicted channel.

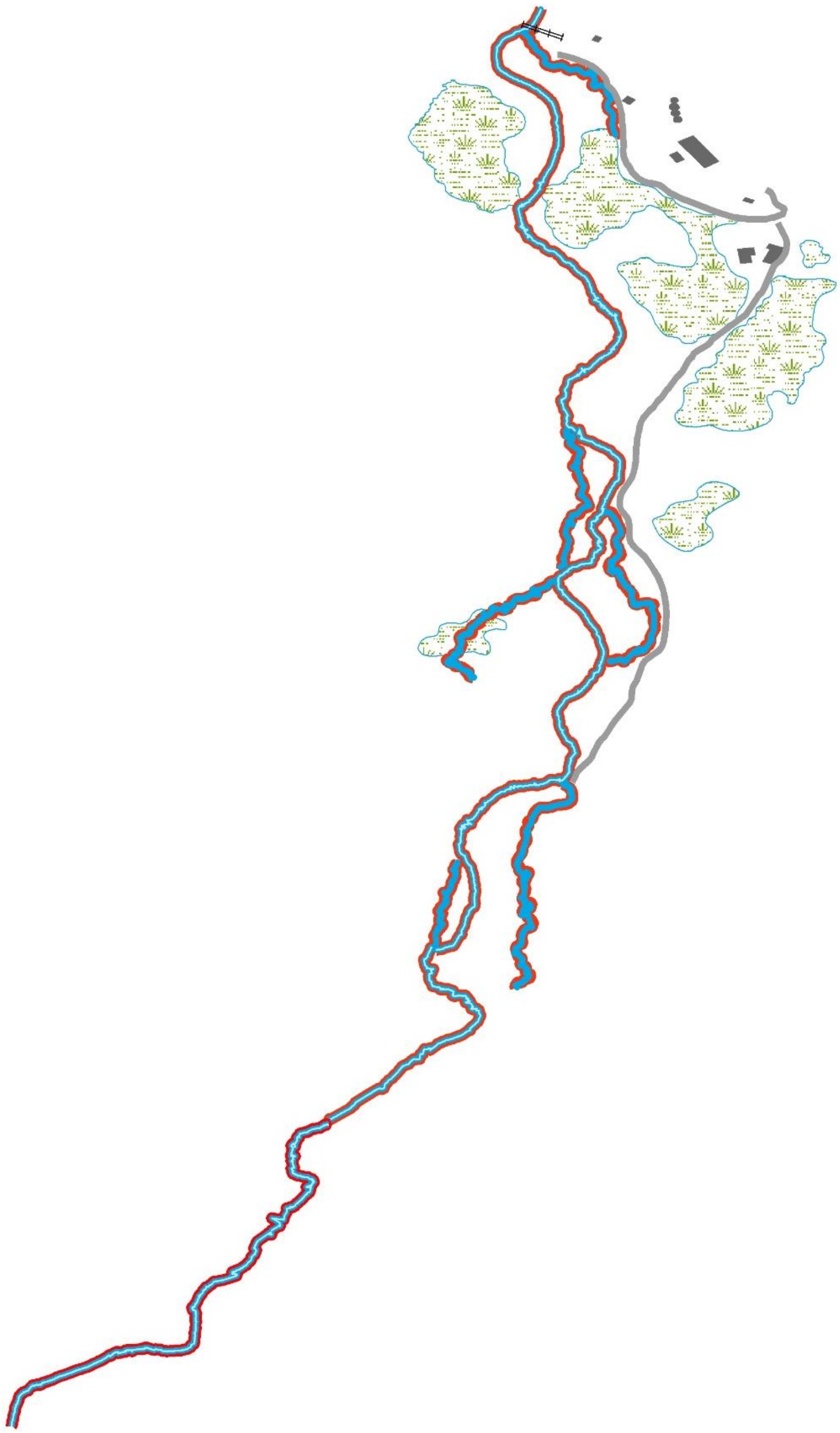


Figure 13B. The lower 2 km of the BBC channel during 2015. Note that while the channel configuration did not change, the surface area of beaver ponds increased since last surveyed in 2013.

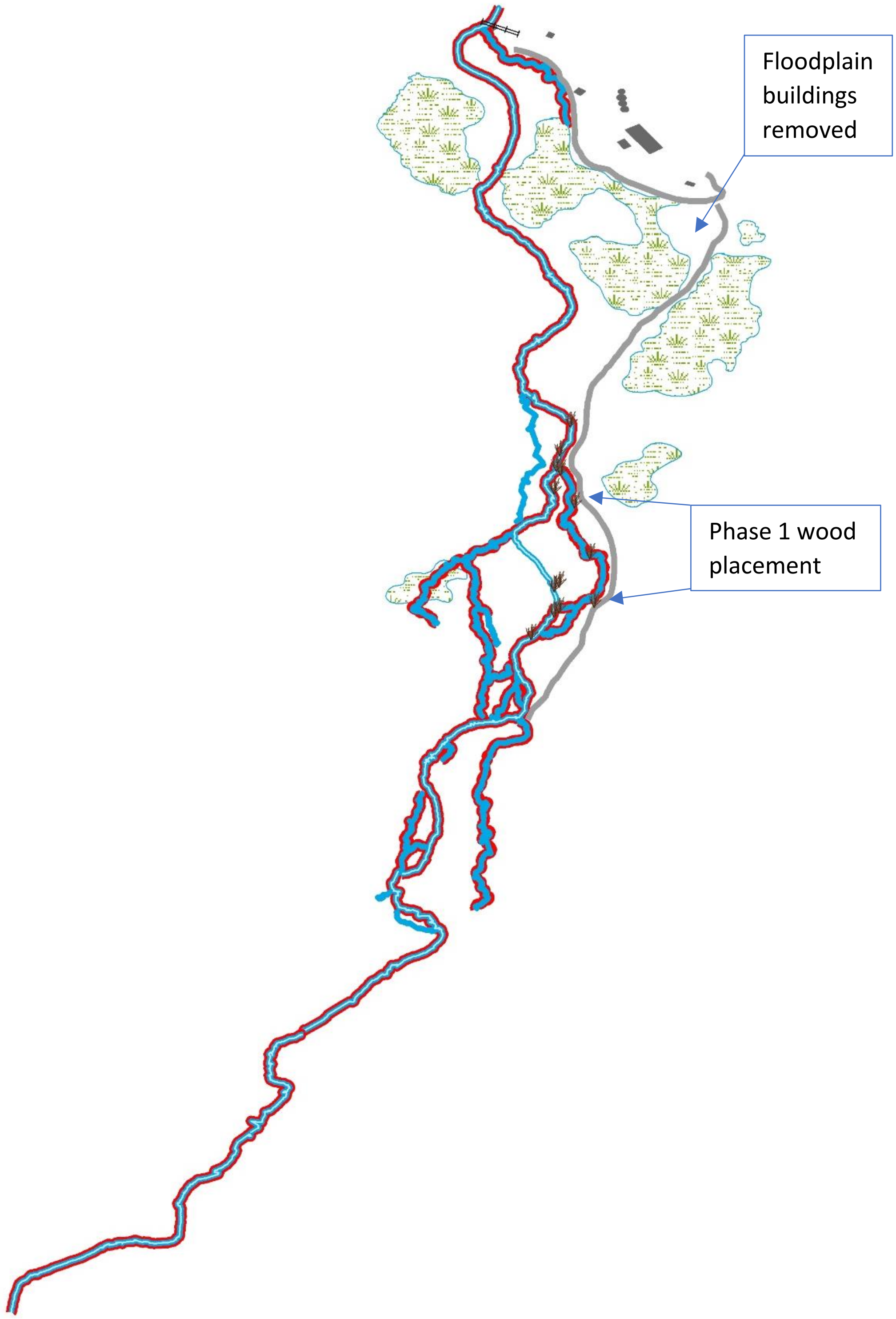


Figure 13C. Plan view of the lower two kilometers of the BBC Channel as mapped in 2016.

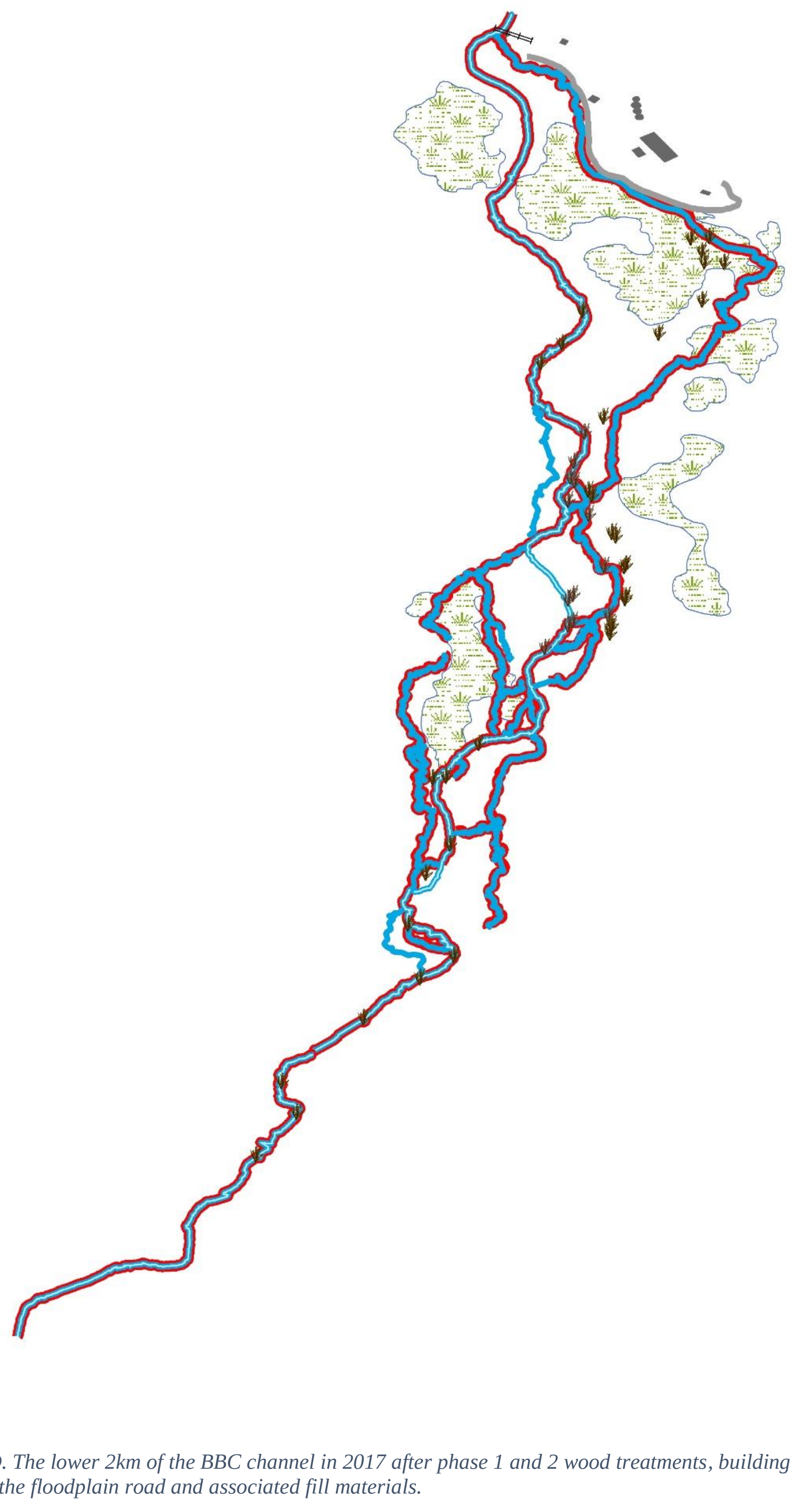


Figure 13D. The lower 2km of the BBC channel in 2017 after phase 1 and 2 wood treatments, building demolition, and the removal of the floodplain road and associated fill materials.

Channel Cross Sections

Stream channel cross-sectional surveys of Big Beef Creek were conducted by previous research in 1969-77 (Cederholm 1972; Madej 1978, 1982)) and in 2014-2017 for this study (Table 9). Sediment sources (bank erosion, streambed degradation, and upstream) are reported along with their percent contribution to the total amount deposited within a given reach. The control reach from previous studies is equal to sub-reach 3. Changes in channel alignment and the lack of a station downstream of the weir prompted me to break out the lowest sub-reach differently than the channelized reach in previous surveys. Therefore, because reach lengths vary, the total amount of sediment deposited within a reach was further expressed as volume/m^{-1} (m^3/m) for comparison (Madej 1978; Table 9). Results within this sub-section will refer back to this table.

Since severe bank erosion or streambed degradation may mask the amount of aggradation at other stations, individual cross sections should be studied as well (see Appendix A; Madej 1978). For all cross sections (2013-2017) the view is looking upstream (also see summary tables of data presented as figures in this section in Appendix C).

Over the entire reach, all variables (bank erosion, streambed degradation, sediment from upstream reach, total sediment deposited during the reach, and volume of sediment per linear meter of stream) peaked in their value during 2016—this observation taking the late addition of sub-reach 4 into consideration. At sub-reach 1, the high value of streambed degradation in WY 2014 is explained by sediment management activities around the weir. Similarly, Madej (1978) reported somewhat anomalous measures at the channelized reach during 1977 under the same circumstances.

Table 9. Sources of sediment deposited by reach (year), sub-reach, and historic observations using the cross sectional survey technique first described by Cederholm (1972) at lower BBC main channel, WY's 1970-71, 1976-77, and 2014-2017 (adapted from Cederholm 1972; Madej 1978). Note that sub-reach 4 is included in the 2017 result.

		Sediment Sources Volume (%)			
Sub-Reach	**Erosion (m^3)**	**Degradation (m^3)**	**Upstream (m^3)**	**Total deposited (m^3)**	**Total m^3/m**
2014	132 (0.05)	2511.3 (0.95)	0.0 (0)	2643.3	1.28
1	62.7 (0.04)	1603.8 (0.96)	0.0 (0)	1666.5	3.37
2	42.9 (0.10)	237.6 (0.55)	148.5 (0.35)	429.0	0.88
3	26.4 (0.04)	669.9 (0.96)	0.0 (0)	696.3	1.32
2015	273.9 (0.13)	1838.4 (0.87)	0.0 (0)	2112.3	1.03
1	72.6 (0.07)	798.6 (0.76)	184.8 (0.18)	1056.0	2.13
2	155.1 (0.22)	548.1 (0.78)	0.0 (0)	703.2	1.44
3	46.2 (0.07)	491.7 (0.79)	85.8 (0.14)	623.7	1.18
2016	1038.0 (0.27)	2730.6 (0.71)	80.1 (0.02)	3848.7	1.87
1	660.0 (0.34)	1257.3 (0.66)	0.0 (0)	1917.3	3.87
2	315.3 (0.24)	767.1 (0.58)	241.8 (0.18)	1324.2	2.71
3	62.7 (0.05)	706.2 (0.57)	468.6 (0.38)	1237.5	2.34
2017	1308.6 (0.29)	3203.7 (0.71)	0.0 (0)	4512.3	2.19
1	293.7 (0.19)	1254 (0.81)	0.0 (0)	1547.7	3.13
2	49.5 (0.06)	738.9 (0.94)	0.0 (0)	788.4	1.61
3	554.4 (0.36)	745.8 (0.49)	221.1 (0.15)	1521.3	2.88
4	411.0 (0.21)	465.0 (0.24)	1047.0 (0.54)	1923.0	3.50
[1]Channelized 1970	920 (0.50)	734 (0.40)	177 (0.10)	1831	3.08
[1]Channelized 1971	1181 (0.32)	152 (0.04)	2398 (0.64)	3731	6.28
[1]Control 1971	210 (0.20)	139 (0.13)	715 (0.67)	1064	[2]1.92
[2]Channelized 1971-76	NA	NA	NA	2438	4.40
[2]Channelized 1977	NA	NA	NA	-36	-0.07
[2]Control 1971-76	NA	NA	NA	864	1.70
[2]Control 1977	NA	NA	NA	-429	-0.86

[1]Reported by (Cederholm 1972).

[2]Reported by (Madej 1978).

Bank erosion contributed more to sediment deposition (aggradation) in the post-project phase (Figure 14), this excepting sub-reach 2 where bank erosion contributed 22% of the deposited sediment during WY2015, before any work had been done. Bank erosion occurred primarily within the main channel at sub-reaches 1, 3, and 4. Overall, bank erosion contributed less to sediment deposited within the study reach than was noted in previous surveys.

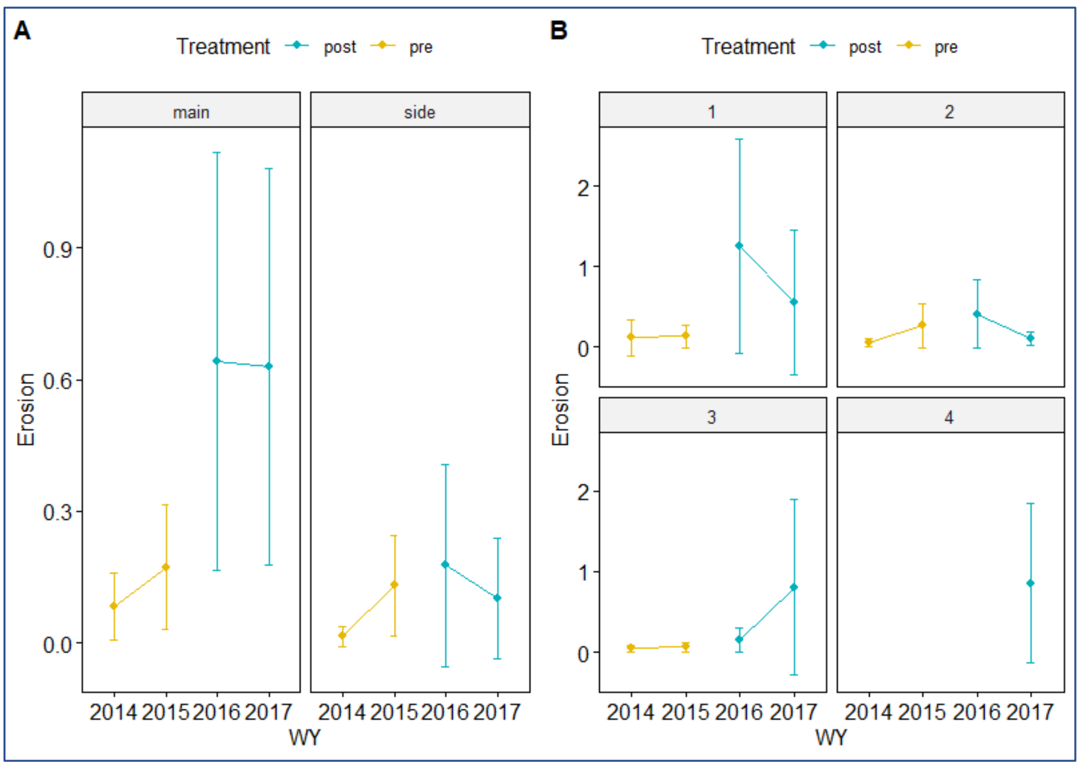


Figure 14. Pre- and post-restoration plots of mean bank erosion (m^2) at lower BBC during WY's 2014-17. Panel A represents the interactions of treatment (wood placement), WY, and channel type on the response variable. Panel B represents the interactions of treatment, WY, and sub-reach on the response variable. Error bars = 0.95 CI.

Streambed degradation contributed less to sediment deposits as time passed (study years) within sub-reach 3 (despite very little change in mean value, Figure 15) but remained variable within the other sub-reaches. Streambed degradation explained 81% of the sediment deposited in that reach in 2017, the highest contribution observed without manipulation (sediment removal around the weir). Overall, streambed degradation contributed more to deposited sediment than observed in previous studies. Mean values of streambed degradation were elevated in side channels (reflected mostly in the RB side channel in sub-reach 2; Figure 15). Mean streambed degradation did not change very much in the main channel after wood placement, however increased variability in this metric is notable in sub-reach 1 post-treatment (Figure 15).

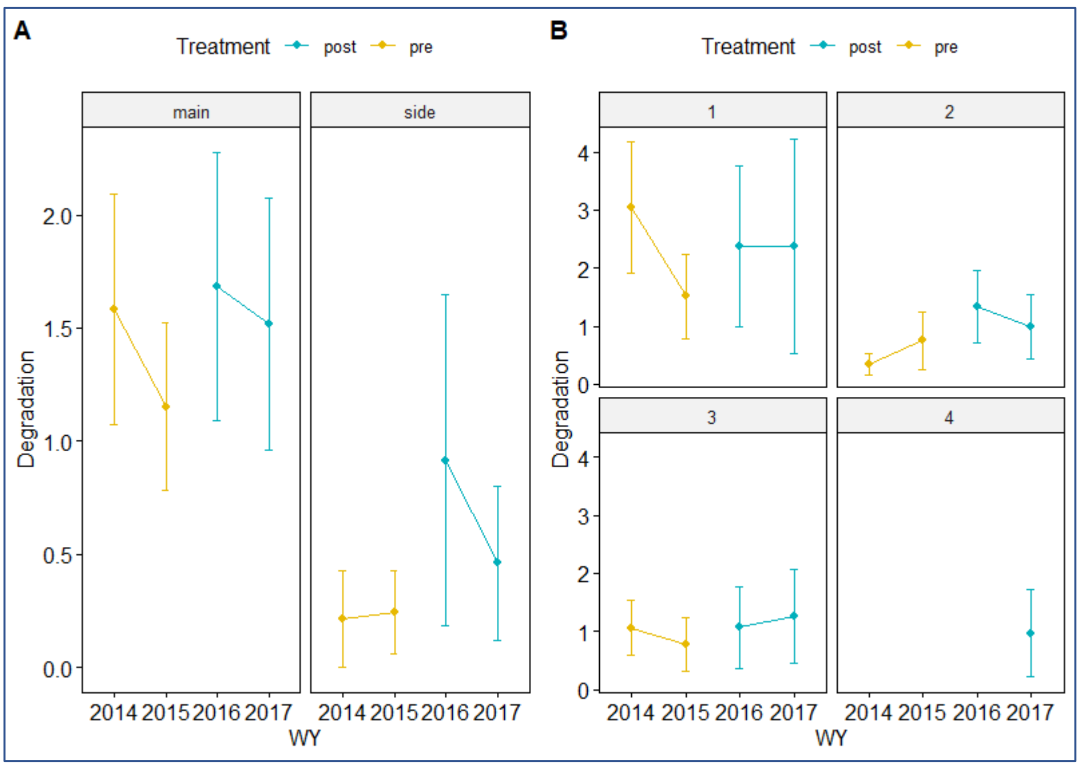


Figure 15. Pre- and post-restoration plots of streambed degradation (m²) at lower BBC during WY's 2014-17. Panel A represents the interactions of treatment (wood placement), WY, and channel type on the response variable. Panel B represents the interactions of treatment, WY, and sub-reach on the response variable. Error bars = 0.95 CI.

Overall, the amount of sediment contributed from upstream sources was not very important at the reach scale, only contributing 0.02% of the total deposits in WY2016. However, at the sub-reach scale upstream sources became more important, contributing to sediment deposited sub-reaches 2, 3 and 4 during WY's 2016-17. Upstream sources contributed 54% of the sediment deposited in sub-reach 4 during WY2017. This value is second only to that recorded at the recently channelized section in 1971.

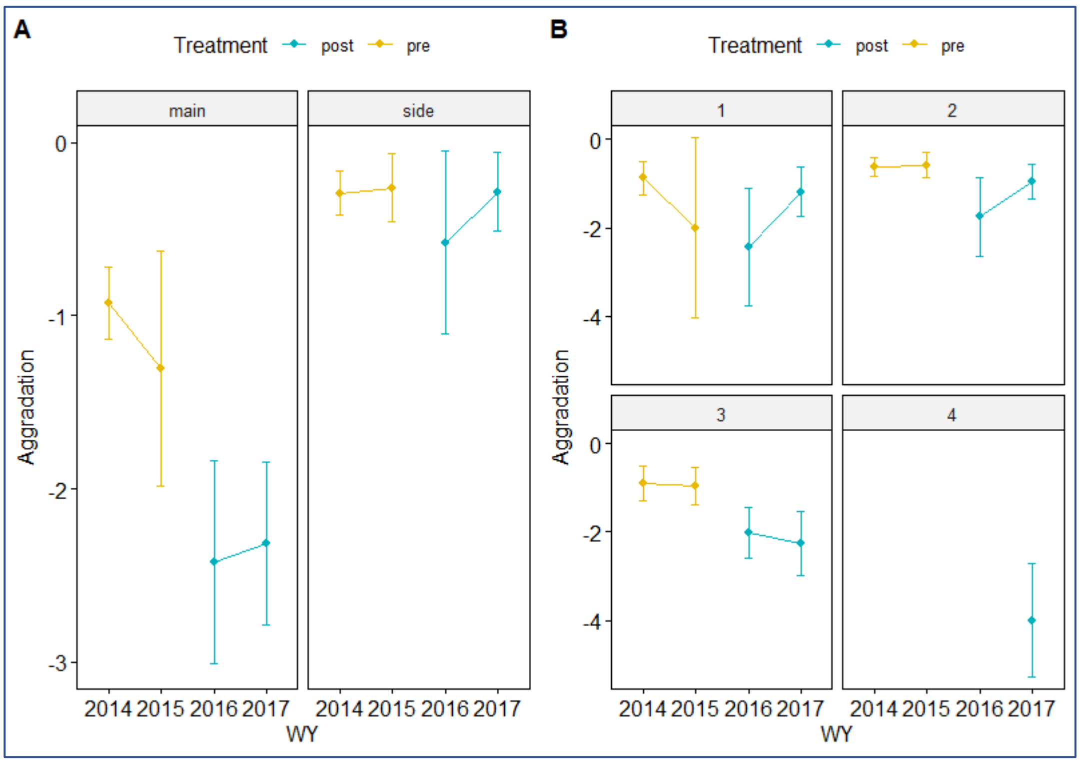


Figure 16. Pre- and post-restoration plots of streambed aggradation (m^2) at lower BBC during WY's 2014-17. Panel A represents the interactions of treatment (wood placement), WY, and channel type on the response variable. Panel B represents the interactions of treatment, WY, and sub-reach on the response variable. Error bars = 0.95 CI.

Within the main channel, mean bank erosion increased 366.7% over the reach with the highest mean values measured within sub-reach 1 (Figure 14). Mean streambed aggradation also increased (87.4%) at the reach scale (Figure 16). Increases in mean streambed aggradation are also notable within sub-reaches 2 and 3 (Figure 16). Mean absolute change to cross section area was nearly doubled in the post-treatment phase (Figure 17). Mean net change to cross section area declined after wood placement, becoming net depositional by WY2017 (Figure 17). The reach scale mean width/depth ratio trended upward after wood placement—this trend also notable in sub-reach 3 (Figure 18). Mean thalweg gradient did not change over the study period, although the variability of these data appeared to respond to wood placement at the sub-reach scale (Figure 19).

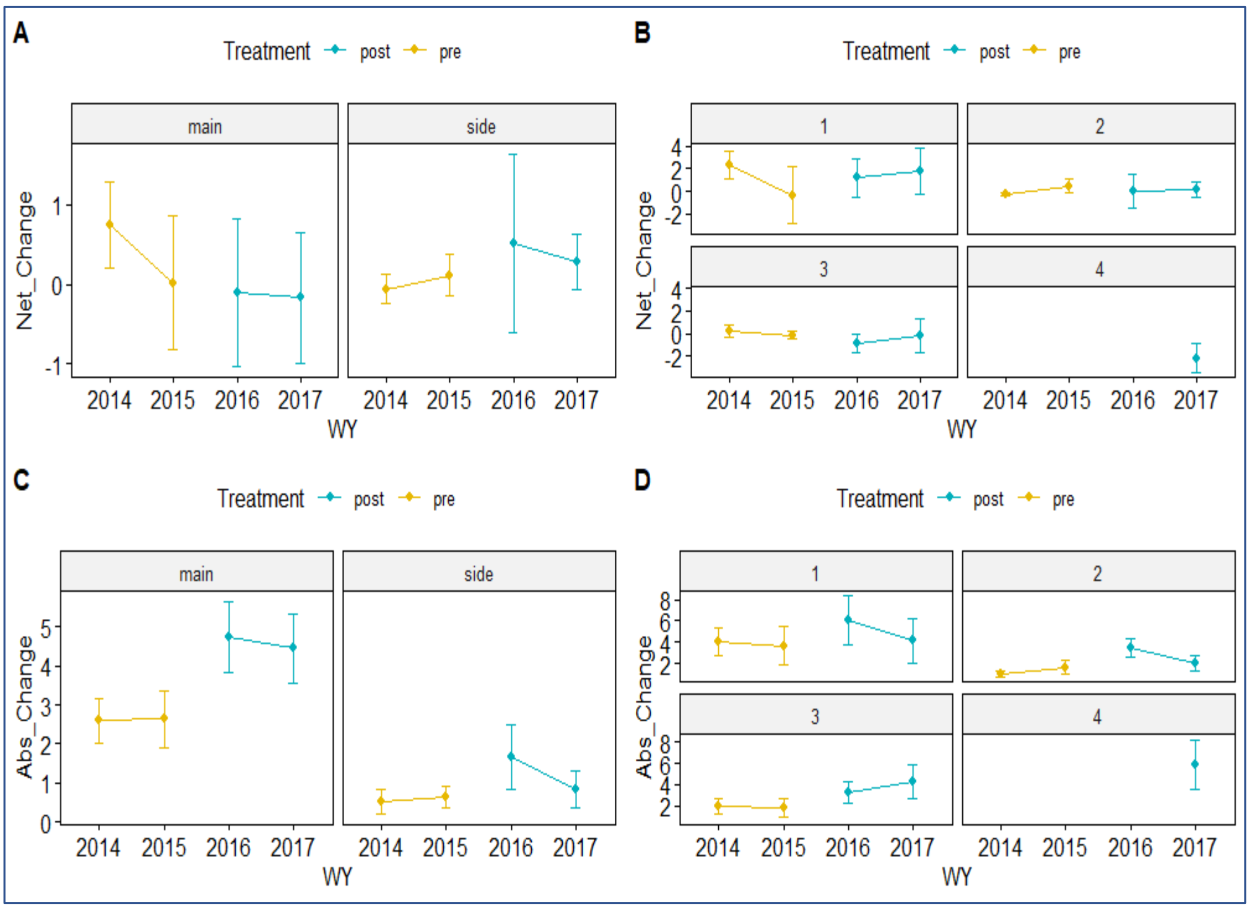


Figure 17. Pre- and post-restoration plots of mean net change (m^2, panels A, B) and mean absolute change (m^2, panels C, D) at lower BBC during WY's 2014-17. Panels A and C represent the interactions of treatment (wood placement), WY, and channel type on the response variables. Panels C and D represent the interactions of treatment, WY, and sub-reach on the response variables. Error bars = 0.95 CI.

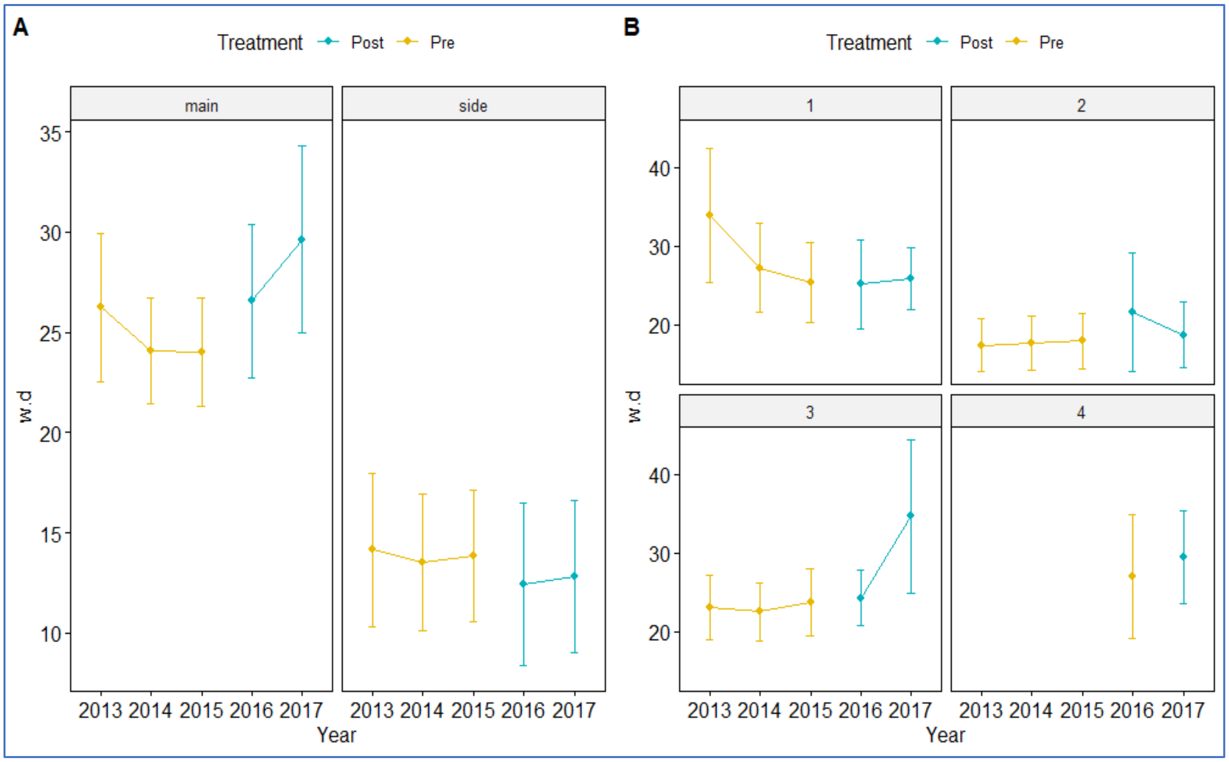


Figure 18. Pre- and post-restoration plots of bankfull width/depth ratio (w.d) at lower BBC during WY's 2014-17. Panel A represents the interactions of treatment (wood placement), WY, and channel type on the response variable. Panel B represents the interactions of treatment, WY, and sub-reach on the response variable. Error bars = 0.95 CI.

Within side channels, mean absolute change to channel cross section area and mean streambed degradation trended upward at the reach scale in the post-treatment phase of the study (Figures 15 and 17). Mean net change to channel cross section area, mean bank erosion, and mean streambed aggradation did not change from the pre-treatment condition (Figures 14, 16, 17). However increased variability in net change measures was detected in sub-reach 2 during WY2016 (Figure 17).

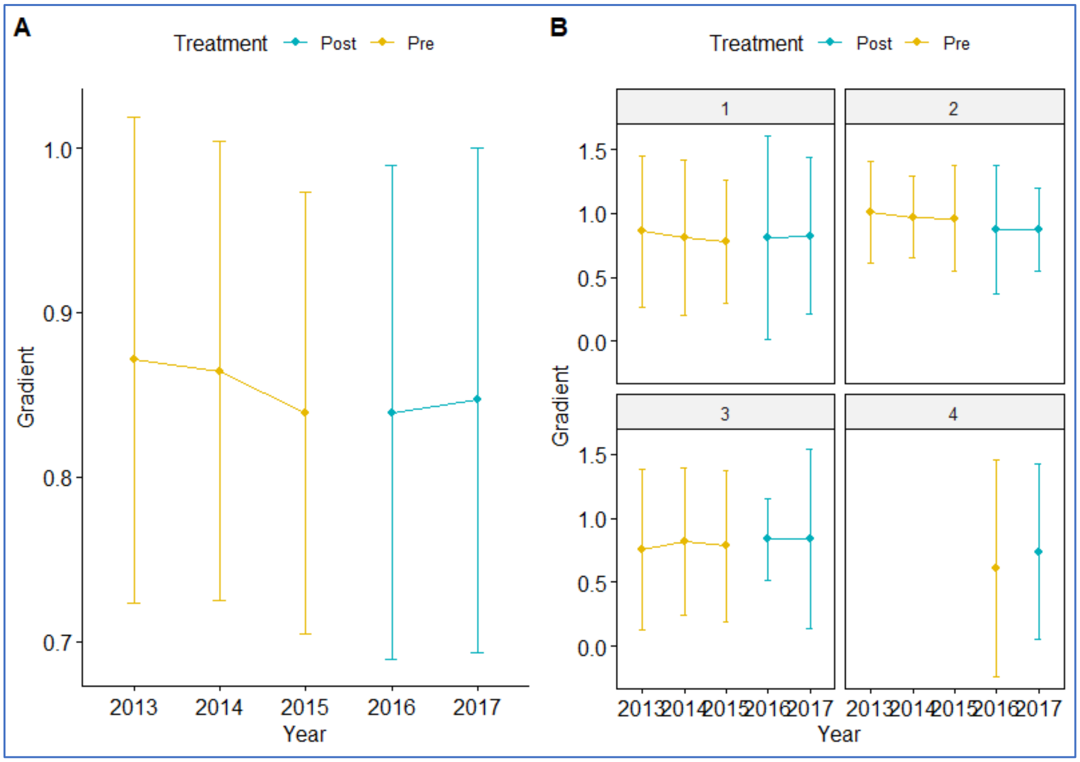


Figure 19. *Pre- and post-restoration plots of thalweg gradient at lower BBC during WY's 2014-17. Panel A represents the interactions of treatment (wood placement), WY, and channel type on the response variable. Panel B represents the interactions of treatment, WY, and sub-reach on the response variable. Error bars = 0.95 CI.*

Change in channel cross section area was affected due to management activities at stations 3 and 4 during water year 2014 when about 535m^3 sediment was excavated from around the weir. The resulting knickpoint in the streambed facilitated positive change in channel cross-section area for some distance upstream of the weir during WY2014-15 (Figures 20-21). As this knickpoint moved upstream, areas above and below the weir (stations 3 and 4) aggraded in response indicating that streambed sediments were freely moving through or over the weir pickets during times of high stream discharge (Figures 20-21).

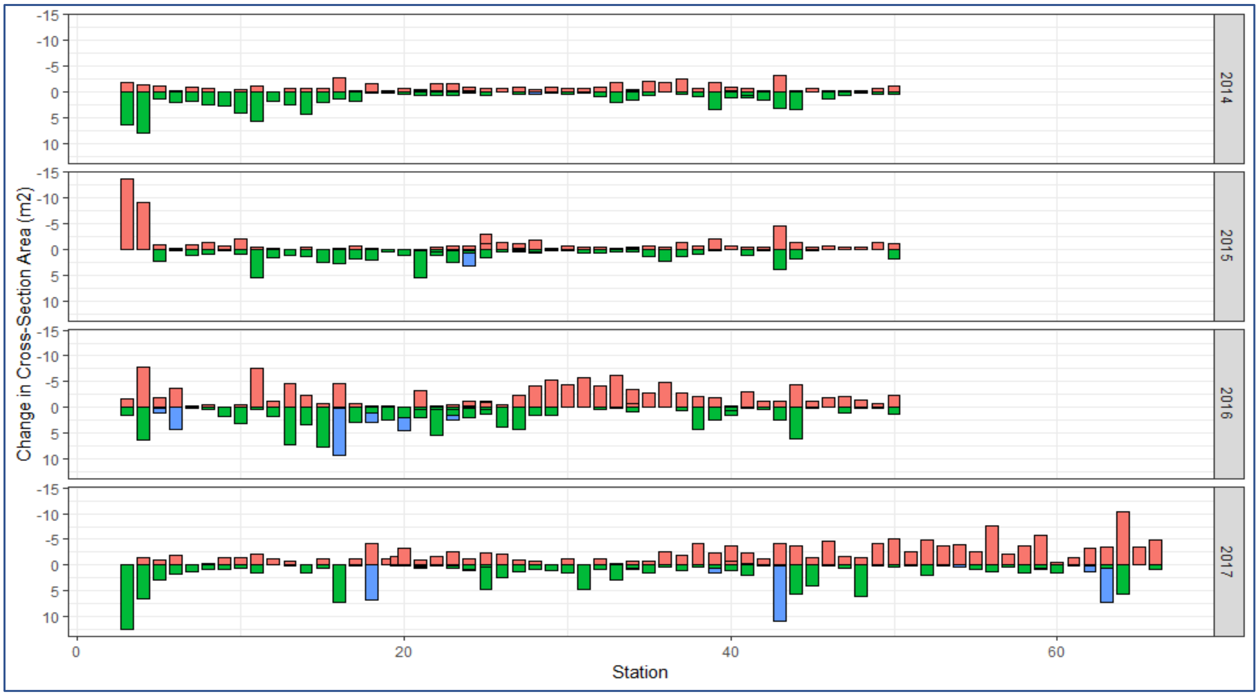


Figure 20. Summary of change to stream channel cross section area via bank erosion (blue), streambed degradation (green,) and streambed aggradation (red) at the lower BBC main channel during WY's 2014-17.

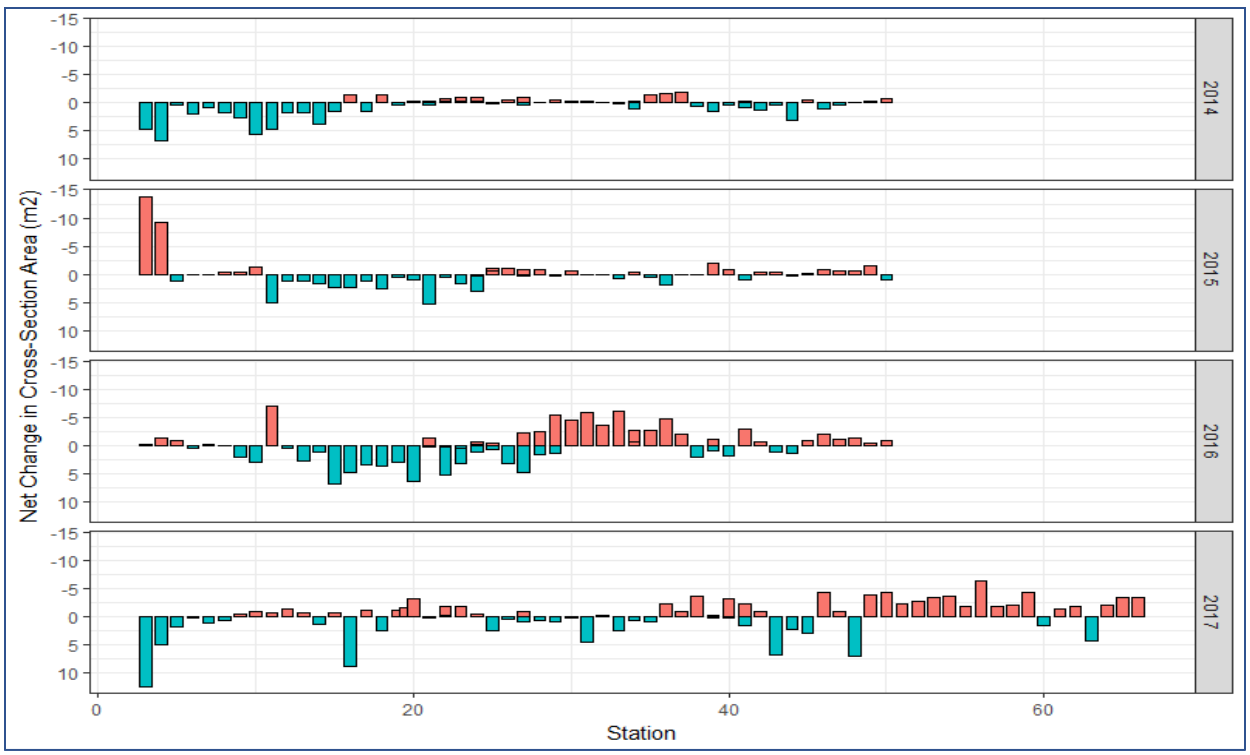


Figure 21. Summary of Net change in cross-sectional area of the main channel (and 3 side channels) at lower BBC, WY's 2014-2017. Red = Net streambed aggradation (negative values), Blue = Net streambed degradation/bank erosion combined (positive values).

Notable channel aggradation occurred at stations 27-40 during WY2016, however most of this reach became net degradational during the following WY (Figures 20-21). Bank erosion at stations 18 and 44 was associated with wood placement at or near these locations (Figure 21). Similarly, streambed degradation (resulting in net change) at stations 16 and 48, was directly associated with wood placement (Figures 20-21).

Thalweg Profile

Mean vertical thalweg profile area (MVTPA) did not change over the reach after wood treatments when measured in terms of either absolute or net values (Figure 22). However, increased variability around these metrics was evident within sub-reach 2 (Figure 22). Furthermore, mean net change to the vertical thalweg profile area appears to be trending downward—the channel becoming more depositional in nature (Figure 22). Notable increases in thalweg profile aggradation appear post-project (Figure 23). Plots of data used to generate these results are provided within Appendix B of this document.

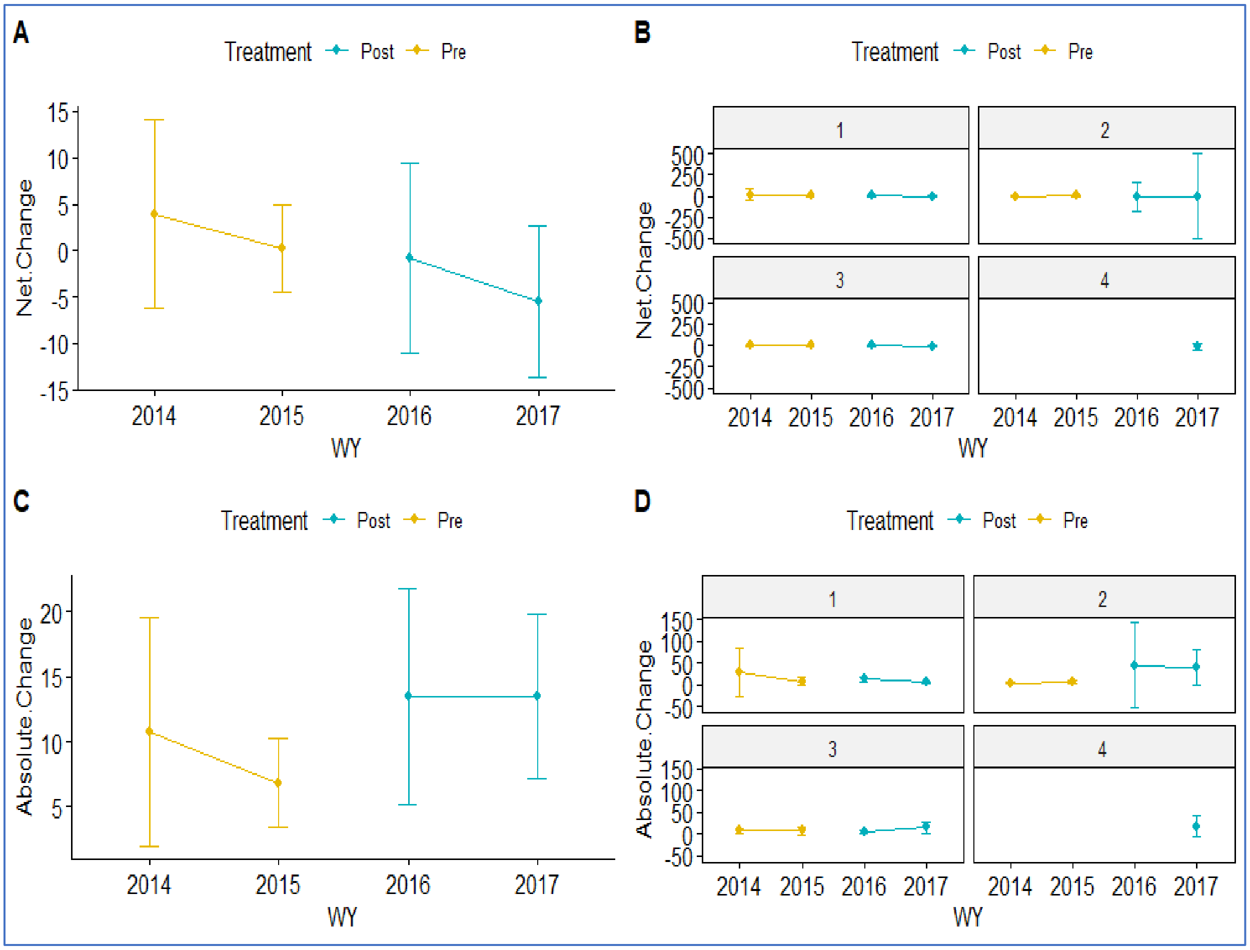


Figure 22. Pre- and post-restoration plots of mean net change (m^2, panels A, B) and mean absolute change (m^2, panels C, D) to the vertical thalweg profile area at lower BBC during WY's 2014-17. Panels A and C represent the interactions of treatment (wood placement), WY, and channel type on the response variables. Panels C and D represent the interactions of treatment, WY, and sub-reach on the response variables. Error bars = 0.95 CI.

Summary plots of changes to the main channel thalweg (by year and sub-reach) is provided in Figure (24 A-D). A general discussion of each, including a general description of wood placement is provided with each.

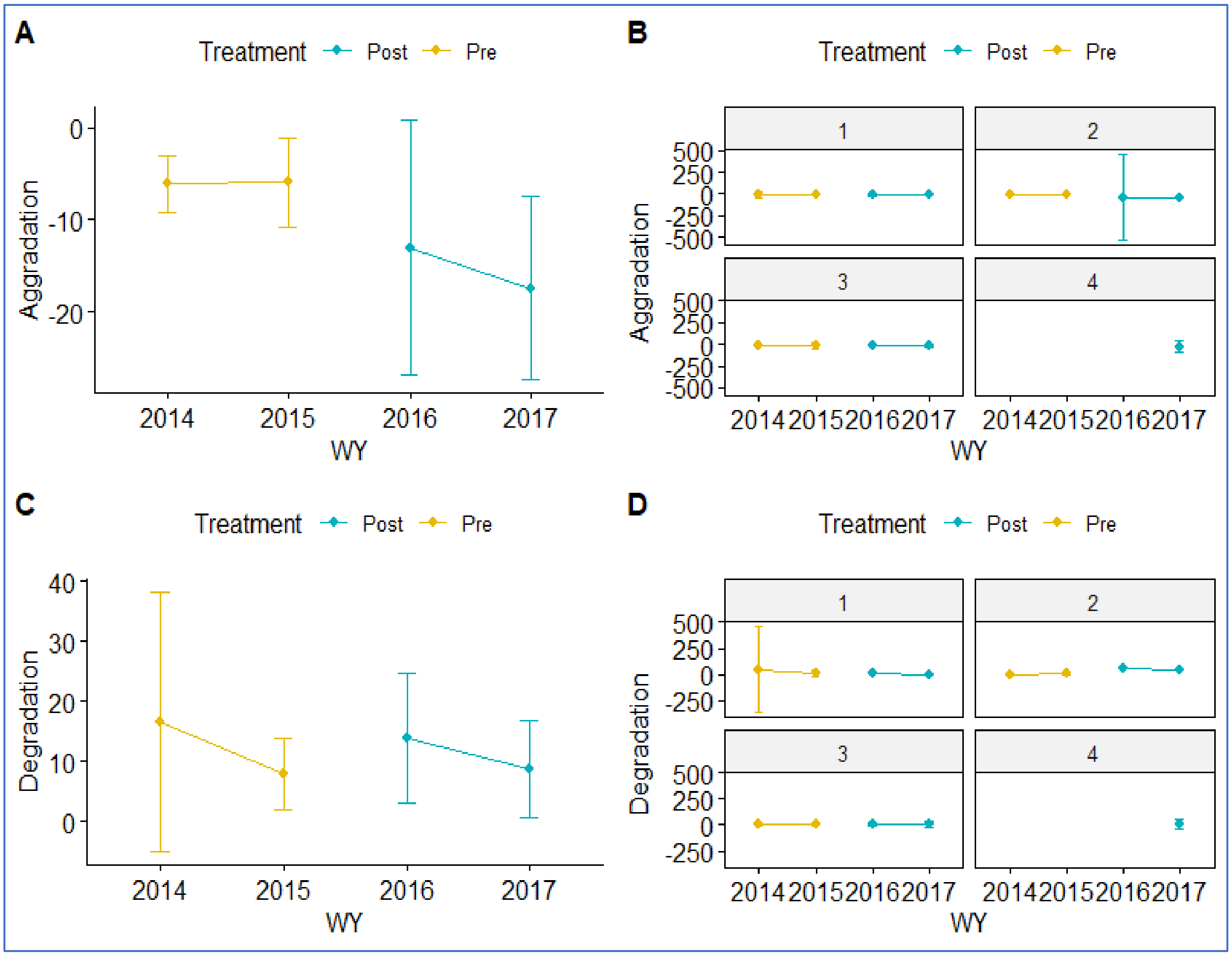


Figure 23. Pre- and post-restoration plots of mean streambed aggradation (m^2, panels A, B) and mean streambed degradation (m^2, panels C, D) to the vertical thalweg profile area at lower BBC during WY's 2014-17. Panels A and C represent the interactions of treatment (wood placement), WY, and channel type on the response variables. Panels C and D represent the interactions of treatment, WY, and sub-reach on the response variables. Error bars = 0.95 CI.

Figure 24A. Changes in the thalweg profile of sub-reach 1 (stations 3-18) at lower BBC, 2013-2017. The location and elevation of the weir is indicated by the vertical dashed line. The observable decrease in thalweg elevation at 330m (station 13) was associated with a large/deep pool created when a buried log re-emerged from the channel bed. Phase 2 wood structures were placed within the uppermost portion of this reach (≥ 429m) in 2016.

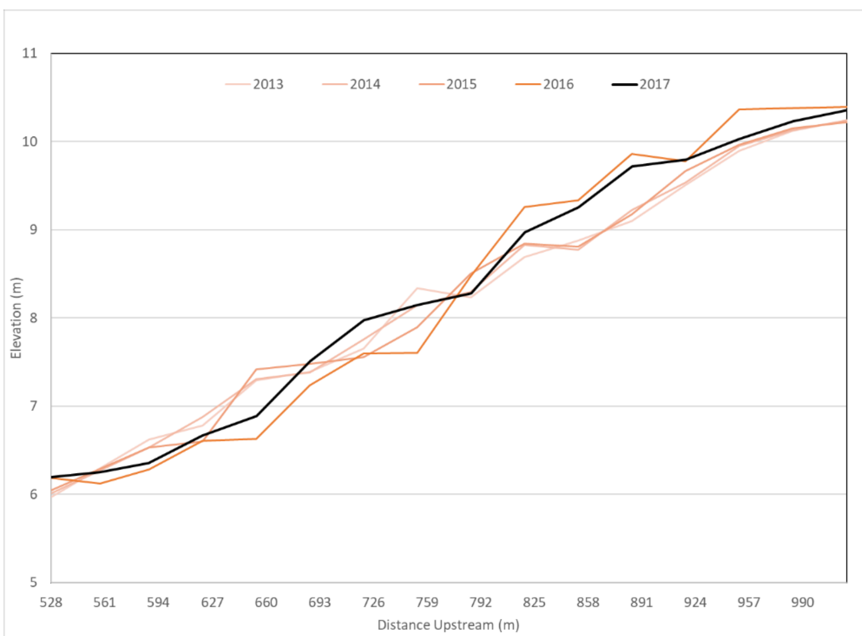


Figure 24B. Changes in the thalweg profile of sub-reach 2 (stations 19-33) at lower BBC, 2013-2017. Phase-one wood structures occurred from 594-924m (stations 21-31) in 2015 and contributed to streambed degradation in the lower half of the sub-reach and aggradation of bed materials in the upper half of the reach during WY2016. Some of the aggraded material was dispersed downstream during WY2017.

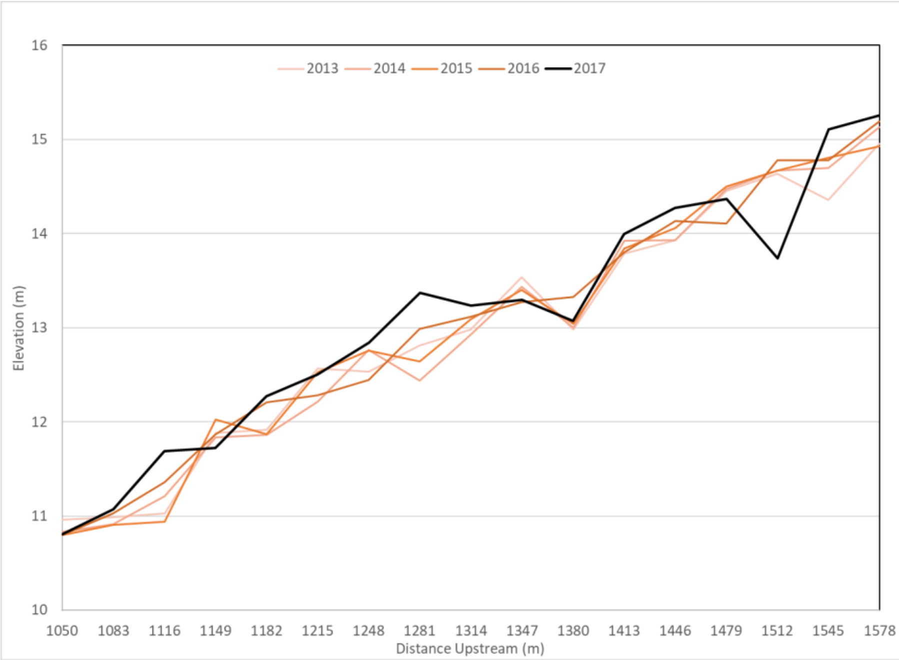


Figure 24C. Changes in thalweg profile of Reach 3 (stations 34-50) at lower BBC, 2013-2017. Phase 2 wood structures were placed throughout this sub-reach in 2016. Noteworthy decrease in thalweg elevation occurred at 1512m (station 48) in response to a structure placed on that cross section.

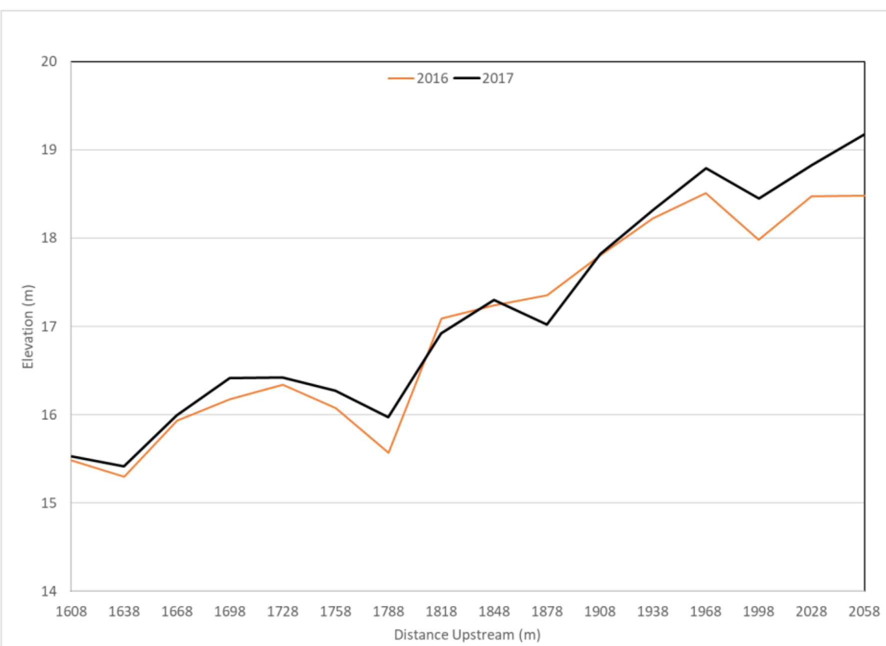


Figure 24D. Changes in the thalweg profile of sub-reach 4 (stations 51-66) at lower BBC, 2016-2017. Phase 2 wood structures were placed within this reach up to 1728m in 2016. Noteworthy within this thalweg profile is the apparent aggradation of the streambed while retaining much of its original shape (as plotted).

Physical Habitat

The total count of channel-type habitat units varied yearly (in part due to changes in survey length in 2016) but ultimately increased to a maximum of 343 measured in 2017 (Table 10). Pool counts increased similarly, except for backwater pools (PB) that declined by 45% over 2015 observations (Table 10). Percent pool increased in 2017 after restoration treatments were complete and a winter had passed (Table 10). Four times as many dry channel units were measured in 2016-17 than were in 2015 (Table 10).

Table 10. Count of physical habitat units by year, treatment and channel type at lower BBC, 2015-17. The 2015 survey extends from the WDFW weir to station 50, 2016-17 surveys were extended further upstream to station 66.

Habitat Units →	# Total	# PL	# PD	# PB	# PI	# PP	# BP	# RI	# GL	# CA	# DR	% pool
2015	320	118	2	20	11	1	4	141	18	0	5	0.49
Pre-Treatment	320	118	2	20	11	1	4	141	18	0	5	0.49
main.channel	200	80	2	17	5	1	0	88	7	0	0	0.53
side.channel	120	38	0	3	6	0	4	53	11	0	5	0.43
2016	294	110	2	10	21	0	1	112	17	0	21	0.49
Pre-Treatment	148	60	2	7	8	0	1	57	6	0	7	0.53
main.channel	104	43	1	7	5	0	1	41	4	0	2	0.55
side.channel	44	17	1		3	0	0	16	2	0	5	0.48
Post-Treatment	146	50	0	3	13	0	0	55	11	0	14	0.45
main.channel	37	17	0	0	0	0	0	17	1	0	2	0.46
side.channel	109	33	0	3	13	0	0	38	10	0	12	0.45
2017	343	137	5	11	21	5	3	132	8	1	20	0.53
Post-Treatment	343	137	5	11	21	5	3	132	8	1	20	0.53
main.channel	178	69	1	6	14	1	3	71	4	0	9	0.53
side.channel	165	68	4	5	7	4	0	61	4	1	11	0.53

The count of habitat units directly associated with placed wood increased sequentially—along with the phases of the project—totaling 51 by the end of observations in 2017 (2.1/structure; Table 11). Pools increased in number and diversity of type at placed wood structures, although the number of pools decreased at phase 1 structures reflecting the loss of wetted habitat (at low flow) around some of these structures in their first year (Table 11). Additionally, 33% of isolated pools observed in 2017 were directly associated with placed wood structures (Tables 10-11). Percent pool increased similarly up to 67% at last observation (Table 11).

Table 11. Count of physical habitat units directly associated with wood treatments by year, treatment and channel type at lower BBC, 2015-17. The 2015 survey extends from the WDFW weir to station 50, 2016-17 surveys were extended further upstream to station 66.

Habitat Units →	# Total	# PL	# PB	# PI	# RI	# DR	% pool
2015	19	11	0	0	8	0	0.58
Pre-treatment	19	11	0	0	8	0	0.58
main.channel	14	9	0	0	5	0	0.64
side.channel	5	2	0	0	3	0	0.40
2016	38	20	3	1	12	2	0.63
Pre-treatment	25	12	3	1	8	1	0.64
main.channel	25	12	3	1	8	1	0.64
Post-treatment	13	8	0	0	4	1	0.62
main.channel	11	6	0	0	4	1	0.55
side.channel	2	2	0	0	0	0	1.00
2017	51	25	2	7	9	8	0.67
Post-treatment	51	25	2	7	9	8	0.67
main.channel	45	20	1	7	9	8	0.62
side.channel	6	5	1	0	0	0	1.00

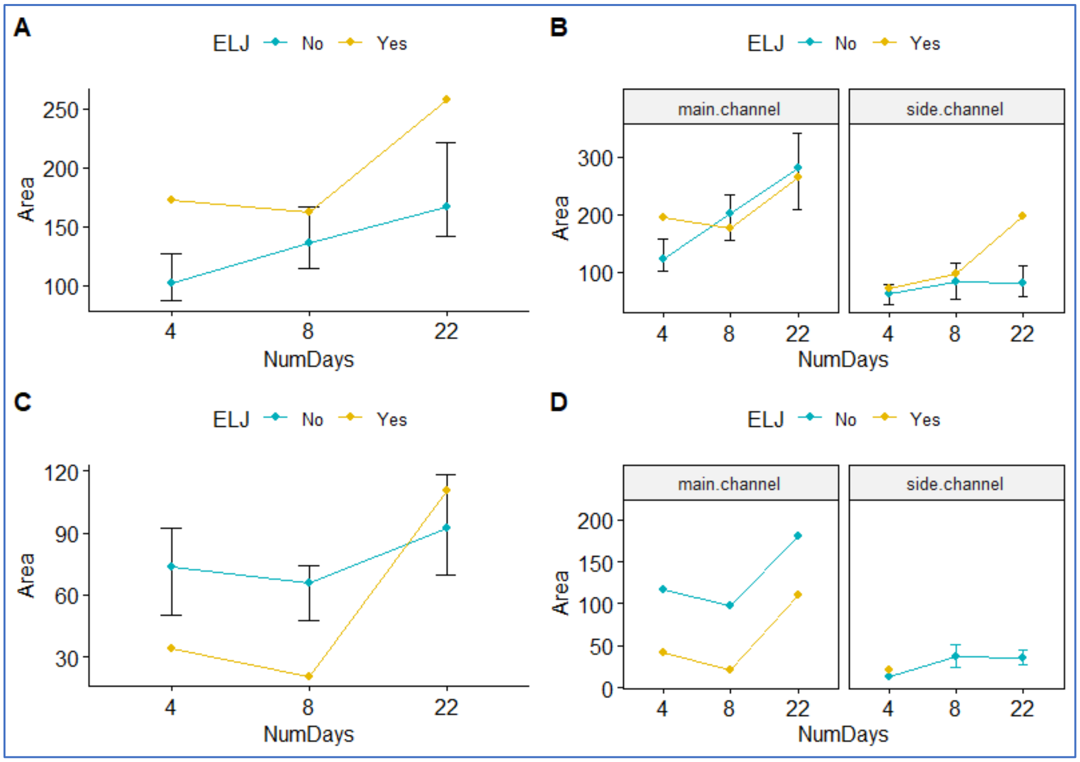


Figure 25. Interaction plots of the effect of the number of bankfull days (NumDays), engineered log jam (ELJ) yes or no, and channel type on habitat unit area at lower BBC, WY's 2015-17. Panels A and B display the interaction of these variables on pool area while panels C and D represent non-pool habitats. Error bars = 0.95 CI.

There was a statistically significant interaction between the effects of channel type and the number of bankfull days on pool area ($Chisq_2 = 6.36$, $p < 0.05$). In the main channel, pool area differed at 4 and 22 days of bankfull flow where no wood was placed (Tukey's *post hoc* test, p < 0.05) but there is no evidence that pool area was different in side channels or at pools that received wood. Pool area was on average 138 m^2 greater at main channels that did not receive wood at 22 days of bankfull flow than those measured after 4 days of bankfull flow (Figure 25). The area of non-pool habitat units responded negatively to the number of bankfull days ($Chisq_1 = 6.36$, $p < 0.05$) and channel type ($Chisq_1 = 9.38$, $p < 0.001$) becoming very small in the main channel by the end of the study (NumDays = 8, Figure 25).

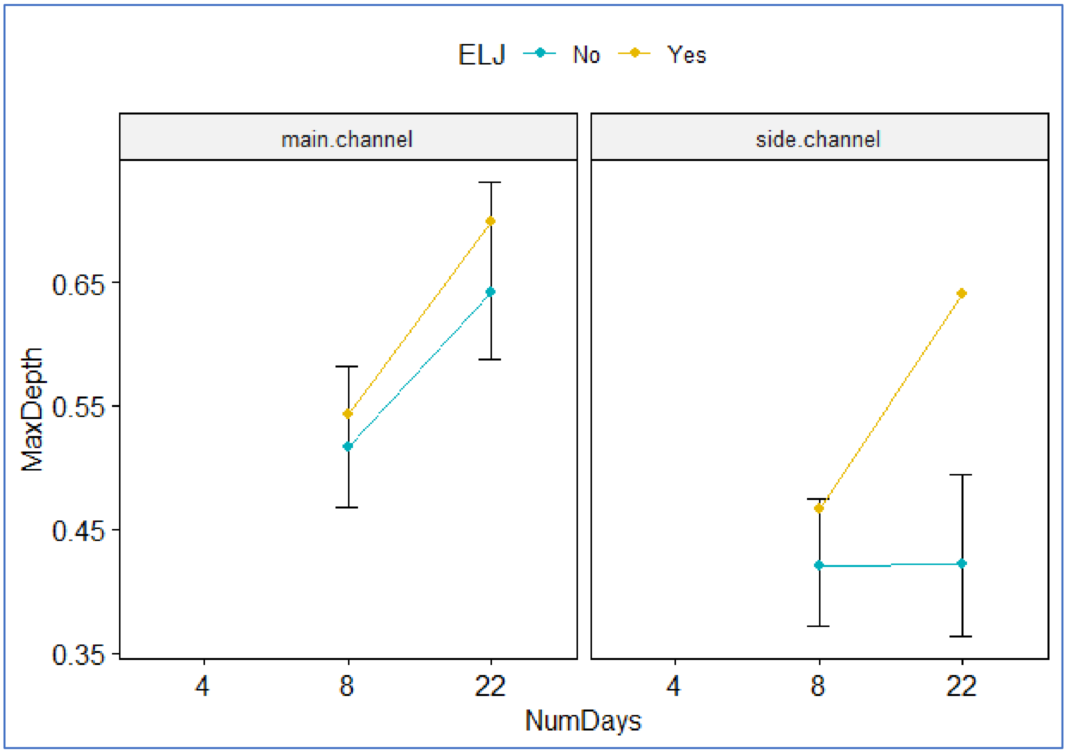


Figure 26. Interaction plots of the effect of channel type, number of bankfull days (Numdays), and engineered log jam (ELJ) yes or no on maximum pool depth at lower BBC, WY's 2016-17. Error bars = 0.95 CI.

There was a statistically significant interaction between the effects of channel type and the number of bankfull days on maximum pool depth ($F_{1, 318} = 2.97$, $p < 0.10$; Figure 26). Maximum pool depth was greater in the main channel (regardless of wood placement) at 22 days of bankfull flow (Tukey's *post hoc* test, $p < 0.05$; Figure 26). In side channels, pools were shallower than main channel pools—and side channel pools that received wood structures ($p < 0.05$; Figure 26). Main channel pools were deeper (regardless of wood placement) after 22 days of bankfull flow than any other grouping observed ($p < 0.05$; Figure 26).

Discussion

The change in the lower BBC channel from what is best described as a forced single thread meander (with minor braiding) to the braided configuration that developed during WY2017 (Figures 13 A-D) is reflective of the conditions documented by Cederholm (1972) prior to channelization (Figure 27). Described as a braided channel that was highly aggraded with bedload sediment, dogs associated with the research station were observed to harass and kill salmon in the small shallow channels (Cederholm 1972). Predation on ESA-listed (threatened) summer Chum Salmon by American River Otter (*Lutra canadensis*) at BBC was noted multiple times in 2017, a lack of available spawning area above the weir caused fish to linger in the pool below it (due to split nature of the 2017 channel) contributing to these observations. At nearby Little Anderson Creek, similar channel conditions to those at lower BBC (current) contributed to heavy losses of Coho Salmon to River Otter predation over several spawning seasons (WDFW, unpublished data).

Suggesting that the recently constructed dam was starving the lower channel of sediment, Cederholm (1972) pointed to erosion of downstream (of the dam) glacial-age terraces as a major source for sediment that was impacting the channel (causing braiding) prior to channelization. Similarly, Madej (1978, 1982) suggested that forestry practices (including roadbuilding/ditching) were affecting the lower creek channel with an increased sediment load leading to a widening/shallowing channel condition. Observations made by these authors remains important in the understanding of how BBC (and other streams with a similar morphology) respond to perturbation.

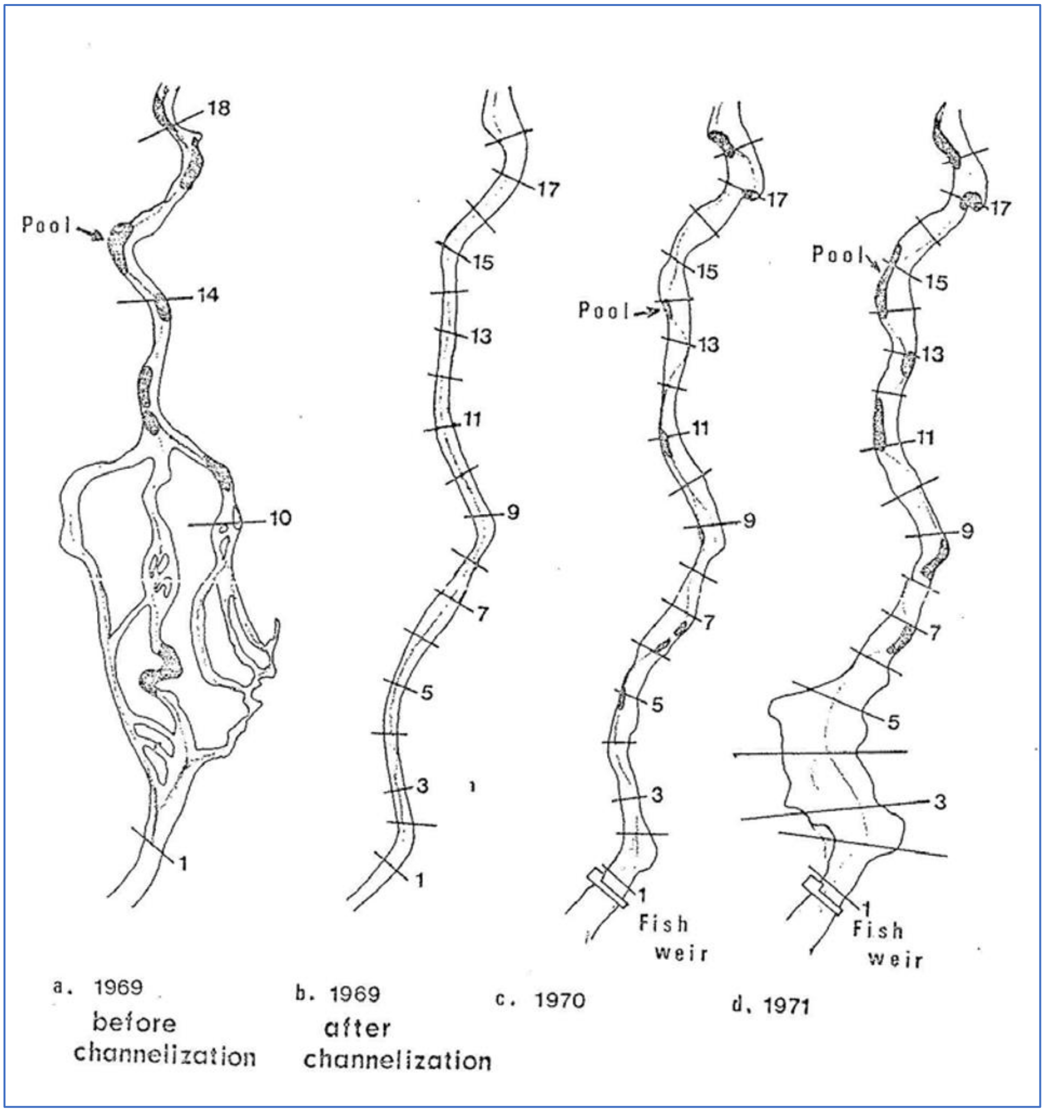


Figure 27. Channel configurations before and after channelization at lower Big Beef Creek, 1969-71 (from Cederholm 1972). Flow direction is from top of image to bottom of image. Stations 4-21 from this study coincide with those (1-18) depicted in this image.

Modern catchment-based thought might also link the channel braiding experienced in 1969 to: (1) the diking of the channel from its historic location, (2) the subsequent capture (by the stream separated from its channel) of blind tidal channels that existed on the landscape, (3) bed de-stabilization from channelization, and (4) additional upstream dam construction/channelization effects on highly erodible adjacent slopes.

While stream channelization is not typically considered a stream/salmon recovery action today (Roni et al. 2002, 2008; Beechie et al. 2008), the observations made by Cederholm (1972) allow for comparison of the historic BBC physical channel (and its function) with that of the pre- and post-restoration channel documented by this study (Table 9). Work done in WY's 1970-71 suggested that bank erosion and streambed aggradation with material from upstream reaches was more important in the lower BBC channel than in modern times. This observation might be best explained by the combination of four factors: (1) additional storage capacity/sediment delivery from side channels, (2) wood removal from the stream channel as part of the channelization process, and the modern recruitment of wood through natural and artificial means, (3) the growth of riparian vegetation along the channel edge (Cederholm 1972), and (4) the presence of North American Beaver (*Castor canadensis*) on the floodplain.

My observations of sediment sources might differ from those of Cederholm (1972) because of additional storage and input capacity that side channels offer to the main channel where my efforts were focused. However, I am unable to make estimates of sediment volume from the relatively few and haphazardly placed side channel cross sections included in my work and cannot adequately answer this question. Measurable amounts of sediment were delivered overbank during WY2017 along the RB side channel in sub-reach 2, while more was deposited in the new 'floodplain avulsion channel' and the upper extent of beaver pond C (Figure 13A). Stream channel cross sections should include all of the streambed and streambank that might be influenced by management actions (Olson-Rutz and Marlow 1992), the valley-wide nature of the results of this restoration project are not completely addressed by my primary effort to study the effect of wood placement on the channel. Since about 87% of the structures were placed within the main channel my efforts were focused there. Floodplain mapping however, did address the addition of newly accessible and created habitats at lower BBC.

Second, the lack of wood encountered by Cederholm (1972) might partly explain the differences in our findings. Much is known about the role of wood in streams and rivers, both naturally (Bilby and Ward 1991; Gurnell et al. 2002; Abbe et al. 2003; Curran 2010) and artificially introduced (Larson 2000; Larson et al. 2001; Kail et al. 2007; Roni et al. 2015) to the system. Sediment retention around logs that have made their way into the stream channel is important to Puget Sound Lowland streams like BBC (Booth et al. 2003; Stillwater Sciences 2008a, 2008b). Large Western Red Cedar stumps still standing within my study area lay testimony to the volume of sediment once retained by wood within these systems. Utilizing the equation for the volume of a wedge;

$$V = bh/6(2a + c)$$

Where:

V = Volume

a = The width at the base side of the wedge = 10

b = The depth of the wedge at the wide end = 0.3 or 0.8

c = The width at the toe of the wedge = 1

h = Length of the wedge = 50

it is easy to imagine a vast change in the sediment retention characteristics of the BBC catchment. Imagining a log laying across the channel, perpendicular to flow, and utilizing the above equation with the hypothetical values listed on the right of the variable definitions; a log with a width value of 0.80 m would store some 140 m^3 of sediment upstream of it. A log with a with value of 0.30 m would only store 52.5 m^3 (62.5%↓) of sediment upstream of it suggesting a large loss of storage capacity catchment-wide with a change in available log size. Unfortunately, the historic/current mean log diameter at BBC remains unknown, so estimates of the loss of sediment storage capacity based on the size of wood in the basin are impossible. These musings on sediment storage ignore the downstream storage capacity of wood in streams/rivers, and thus further limit their value. Both downstream and upstream accumulations of gravel were common at wood structures placed within BBC during 2015-16.

The upstream storage of sediment by wood structures placed in the BBC channel contributed to mid-channel bar development, bank erosion, and channel avulsions. The formation of mid-channel bars act to increase velocity and shear stress thus increasing the erosional attack along the banks of a stream (Madej 1978, 1982; Leopold et al. 1992). Shear stress, an erosional process driven by gravity (Leopold et al. 1992);

$$\tau = \gamma D S w$$

Where:

τ = Shear Stress (N/m^2,)

γ = Weight Density of Water (N/m^3, lb/ft)

D = Average water depth (m, ft)

Sw = Water Surface slope (m/m, ft/ft)

is affected by a localized increase in water surface slope around the mid-channel bar as it begins to back up water (creating head) in the channel, the re-direction of water around the bar contributes to the phenomena. As a result, water depth is increased along the banks as the mid-channel bar forms and causes shallowing in the center channel (a hump shape in a channel cross section). Increases in either variable would likewise increase the value of shear stress along the bank, and thus amplify erosional forces on the streambed flanking the mid-channel bar, the banks, or both (Leopold et al. 1992) and the sediment transport capacity of the channel (Madej 1978, 1982).

Many of the wood structures placed in the BBC channel during phase 2 of the project were channel-spanning, consisting of a sequence of ballast logs placed over a ‘slash bundle’ of smaller diameter logs roped together and situated near-perpendicular to the channel banks (ENTRIX 2010; PRISM 2018). These structures captured sediment effectively while maintaining pools (at wetted locations) 100% of the time in 2017. Despite the obvious sediment retention at/near these structures (increased streambed aggradation and bank erosion post-treatment), streambed degradation continued to explain most of the sediment delivered to reaches throughout the study period. This observation does not agree with the findings of Cederholm (1972), where bank erosion and upstream sources were more important to deposition within the sub-reach.

Wood in the stream channel (both naturally and artificially added) might be influencing coarse sediment movement through streambed scour and transport on high winter flows. Along with its sediment storage capabilities, wood in streams can cause scour of the streambed and contribute to the development of pool habitats (Bilby and Ward 1991; Leopold et al. 1992; Larson et al. 2001; Buffington et al. 2002; Abbe et al. 2003; Roni et al. 2015). The decline of mean non-pool habitat area measured by this study might signal an increase in streambed scour (and coarse sediment mobility via lack of storage in riffle habitats) after wood additions at BBC. Reporting an increased sediment yield, changes to the channel, and a resultant increase in sediment transport due to logging of second-growth forests in the BBC catchment, Madej (1978, 1982) indicates that channel reaches that were adjacent to logging contained 4.8 times more wood jams than those that didn't. Unfortunately, her discussion focused on mineral-type sediment mobility rather than that of wood, citing only the impermanent nature of wood jams as sediment traps for bed material moving downstream (Madej 1978, 1982).

Observations of changes in channel morphology due to the direct felling of trees into eight West Virginia streams noted greater instability of streambed features after wood addition (Studinski et al. 2012). While wood additions increased habitat complexity, these authors reported no increase in net pool area with wood addition as pools were both created and destroyed at a higher rate due to bed instability attributed to the wood placement (Studinski et al. 2012). Increased bed instability due to the addition of wood at BBC might—in part—explain differences in bedload movement between this and historic studies at BBC. These observations further suggest that early assessment of stream channel restoration projects might be biased toward the study of ecological disturbance, rather the intended goals of the project. However, trapped sediment, resulting in bank erosion and channel avulsions coupled with increasing dry and isolated habitats associated with structures placed within BBC suggest that future measures of the wetted channel will be well away from the locations of wood placement.

Moreover, an investigation into the changes in the size and quantity of wood in Olympic Peninsula streams due to logging activities found that: (1) the initial depletion of old-growth wood from streams where old-growth riparian forest was removed was very rapid, (2) a secondary stage of slower depletion of wood associated with catchment destabilization followed, and that (3) wood inputs from second-growth forests up to 73 years old were characterized by small diameter, high mobility, and a high decay rate (McHenry et al. 1998). The high mobility of second-growth wood is an important observation relative to channel bed dynamics at BBC where large quantities of sediment and second growth timber were delivered during the 2007 'channel re-setting' storm event (Stillwater Sciences 2008b; WDFW, unpublished data). My observations of channel change at lower BBC match well with observations made higher in the watershed and among neighboring IMW watersheds. These observations include: (1) complete filling of the channel with sediment accompanied by lateral channel migration, (2) the exchange of coarse bed sediment for finer (more erodible) sediments from the banks, (3) substantial recruitment of wood through direct addition by the storm and later addition through channel migration and avulsion.

The third reason that my observation of sediment delivery to the channel might differ from those of Cederholm (1972), is that the early development condition of the lower BBC floodplain was less forested. Channelization of the creek and associated berm building furthered this condition along the lower one kilometer of the channel (Cederholm 1972). Since then, the construction of the fish-trap weir and other dikes near the mouth of the channel have elevated the base-level of the stream and blocked tide water from reaching its historic upstream extent. A forest of Alder (*Alnus rubra*) and sparsely located coniferous trees grew on site to be largely drowned/felled by beaver by present time. However, trees remain along the banks at BBC, with large beaver ponds covering the majority of the lower floodplain. As bank stability is known to be strongly correlated with the roots of riparian vegetation (Beechie et al. 2006), the growth of trees along the previously channelized reach at BBC probably accounts for the difference in erosion volumes noted between this and previous studies. Even one-year-old alder saplings might have contributed to bank stability in the second winter after channelization (Cederholm 1972). A considerable number of the streamside trees have begun entering the stream channel (notably in sub-reach 1) where lateral migration of the channel is underway.

Finally, the damming of streams by beaver to increase suitability for their occupation can cause modification of the landscape, giving them great significance as a geomorphic agent and the title ‘ecosystem engineer’ (Pollock et al. 1995; Gurney and Lawton 1996; Gurnell 1998). Consequently, their direct and significant control on ecosystem structure and dynamics has also led to their consideration as a ‘keystone species’ (Naiman et al. 1988; Gurnell 1998). At least five separate beaver lodges are located along the lower two km of BBC. Taking advantage of valley-wall seeps, large beaver ponds were created in off channel areas protected from floodwaters by berms and channelization (the first appearing on the left bank near the mouth of the stream around 1990). Similarly, at neighboring IMW stream Little Anderson Creek, pond creation through beaver damming has been commonplace over the past 15 years. However, lack of protection from high stream discharge and bedload movement, has led to a relatively quicker rate of construction and destruction of these habitats. Large ponds—like those at BBC—filled entirely with sediment in less than 24 hours during the 2007 storm event, moving the creek channel about 200 m from one valley wall to the other (WDFW, unpublished data). This potential for rapid change of the stream channel complicates any prediction of future conditions at lower BBC.

Bedload sediment is being delivered to the right bank series of beaver ponds and eventually to the new wetland habitat that was created as part of this restoration project. While the project goal of ‘reconnecting wetland habitat’ was met, the circumstance by which it was met was twofold: (1) the removal of buildings and fill allowed connection of beaver ponds B and C increasing upstream access to important pond habitats, and (2) the partial avulsion of the stream into the ponds from sub-reach 2. Geomorphic assessment and early-phase design of this project warned of the consequences (i.e., loss of habitat, damage to infrastructure) from this predictable avulsion path, suggesting that restoration at this site should be a stop-gap measure while a more long-term plan for the floodplain is put in place (ENTRIX 2010). Some floodplain restoration projects set goals to increase channel migration and erosion (Abbe et al. 2002) suggesting that evaluation of these results remain context dependent, and thus may be negative or positive depending on the context and project goals (Roni et al. 2015). However, materials associated with the lower BBC restoration—along with relatively general project goals—do not make clear the goals of wood placement that were part of the project (PRISM 2018). My experience agrees well with the published literature that calls for the setting of clear project goals (Jähnig et al. 2011; Morandi et al. 2014) and a continued need for direct, collaborative involvement between scientists, managers, and practitioners to conduct meaningful project evaluations to forward progress in the science and application of stream restoration (Bernhardt et al. 2007).

In examination of 787 restoration projects implemented within California's Russian River catchment since the1980's, researchers revealed that stream restoration was primarily limited to the 'repair' of streams and the re-routing of sediment at specific sites (Christian-Smith and Merenlender 2010). The perceived importance of these pond habitats to salmon may be short-lived at lower BBC. The presence of beaver, however, makes the prediction of outcomes at this site difficult. During summer 2017, dam building activities caused a short-term avulsion of nearly all available stream discharge into the experimental spawning channel. Within 10 days another dam had been built that re-directed the flow once again. Additionally, saturation of the weir road (a dike) by the increased pond levels led to low-flow bank erosion over about an 80 m reach. Filling of the ponds at lower BBC with sediment would likely re-direct stream discharge into the pre-existing channel as water levels over much of the floodplain are higher in elevation that those in the channel at low summer flow. Channel degradation within sub-reach 1 (particularly downstream of the weir) suggests a decline in sediment delivery to the mouth of the stream. For the first time in the 48 years since a weir has been in place at BBC, management concerns have shifted to undercutting of the structure rather than burial.

The mixed results of my assessment of channel condition associated with the restoration of lower BBC might illuminate the difficulty in evaluating such projects. A large increase in accessible beaver pond habitat might be considered an improvement from existing conditions as the importance of these habitats to Coho Salmon production is well known (Pollock et al. 2004). However, the filling of those ponds with sediment via channel avulsion may lead to a lack of those habitats as a future condition. Apparent instability of the channel associated with wood placement and sediment delivery from upstream complicates any prediction of future outcomes. A large influx of sediment from upstream sources was documented within sub-reach 4 over WY2017 that will likely test the permanency of the existing pond habitats at lower BBC.

Throughout the literature an increase in pool area, frequency, or depth is largely considered an improvement to salmon habitat in streams (Cederholm et al. 1997; Roni and Quinn 2001; Roni et al. 2015; O'Neal et al. 2016; Jones et al. 2017). Results from this study might be important in that they demonstrate the number of bankfull flow days within a given WY might be more important than wood placement in creating large, deep, slow moving summer habitat types in low gradient gravel bedded stream reaches like the one at BBC. Even though pool-count and frequency improved with this project, pool 'quality' (in terms of area and depth) decreased. My results might also lend weight to the observation made by Roni et al. (2015)—that lack of response at stream restoration sites might be indicative that the existing habitat wasn't necessarily degraded. The placement of wood at pools that are greater in area and depth than the reach average at the beginning of a project might not lead to an increase in these metrics that is detectible.

In conclusion, a short-term physical assessment of restoration actions at BBC might not answer longer-term and biological questions posed by the HCIMW (Anderson et al. 2015;

Bennett et al. 2016), but it may begin to answer the question posed by Roni et al. (2015); "In what stream channel types or geomorphic settings can wood placement result in minimal or even detrimental physical change (i.e., increased erosion and habitat degradation)?" The short-term results of the project monitoring presented here help answer this question. Observations made by this study at lower BBC (along with those at similarly executed restoration projects at other IMW streams; WDFW, unpublished data) suggest that placement of wood structures at or near the mouth of streams without first understanding/addressing catchment wide water/sediment delivery to the restoration reach may result in burial of, the complete reorganization of, or loss of the structures. This might be first reflected in the literature 26 years ago as frequent damage (to structures) in low-gradient stream segments (Frissell and Nawa 1992), the typical geomorphic setting associated with the mouth of Puget Sound stream/river catchments (Collins et al. 2002) commonly associated with the built environment where they are subject to active channel and catchment management (Curran 2010).

Although damage was only noted at three of the 23 structures added to the lower BBC channel, sediment accumulation at the structures and resulting bank erosion and channel avulsions/abandonment might signal some failure of these structures to meet project goals—assuming that increases in pool habitat (area, frequency, depth) associated with placed wood, signal 'improvement' in salmon habitat—and understanding that the physical success of instream structures is influenced by many factors, including structure type, materials, and design; stream power; and the investigators' definition of failure or success (Roni et al. 2008).

Literature Cited

Abbe, T. B., D. R. Montgomery, B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic effects of wood in rivers.

Abbe, T. B., G. R. Pess, D. R. Montgomery, and K. Featherson. 2002. Integrating engineered log jam technology into reach-scale river restoration. Pages 443–482 *in* D. R. Montgomery, S. Bolton, and D. B. Booth, editors. Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA.

Anderson, J., K. Krueger, B. Ehinger, S. Heerhartz, C. Kinsel, T. Quinn, R. Bilby, and G. Volkhardt. 2015. Hood Canal Intensively Monitored Watershed Study Plan. Olympia, Washington.

Beechie, T. J., M. Liermann, M. M. Pollock, S. Baker, and J. Davies. 2006. Channel pattern and river-floodplain dynamics in forested mountain river systems. Geomorphology 78(1–2):124–141.

Beechie, T. J., D. A. Sear, J. D. Olden, G. R. Pess, J. M. Buffington, H. Moir, P. Roni, and M. M. Pollock. 2010. Process-based Principles for Restoring River Ecosystems. BioScience 60(3):209–222. Oxford University Press.

Beechie, T., G. Pess, P. Roni, and G. Giannico. 2008. Setting River Restoration Priorities: A Review of Approaches and a General Protocol for Identifying and Prioritizing Actions. North American Journal of Fisheries Management 28(3):891–905.

Bellmore, J. R., C. V. Baxter, K. Martens, and P. J. Connolly. 2013. The floodplain food web mosaic: a study of its importance to salmon and steelhead with implications for their recovery. Ecological Applications 23(1):189–207. Wiley-Blackwell.

Bennett, S., G. Pess, N. Bouwes, P. Roni, R. E. Bilby, S. Gallagher, J. Ruzycki, T. Buehrens, K. Krueger, W. Ehinger, J. Anderson, C. Jordan, B. Bowersox, and C. Greene. 2016a. Progress and Challenges of Testing the Effectiveness of Stream Restoration in the Pacific Northwest Using Intensively Monitored Watersheds. Fisheries 41(2):92–103.

Bernhardt, E. S., E. B. Sudduth, M. A. Palmer, J. D. Allan, J. L. Meyer, G. Alexander, J. Follastad-Shah, B. Hassett, R. Jenkinson, R. Lave, J. Rumps, and L. Pagano. 2007. Restoring Rivers One Reach at a Time: Results from a Survey of U.S. River Restoration Practitioners. Restoration Ecology 15(3):482–493. Wiley/Blackwell (10.1111).

Bilby, R. E., and J. W. Ward. 1991. Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48(12):2499–2508.

Bisson, P. A., J. L. Nielsen, R. A. Palmason, and L. E. Grove. 1982. System of Naming Habitat Types in Small Streams, With Examples of Habitat Utilization by Salmonids During Low Streamflow. Pages 62–73 *in* N. B. Armantrout, editor. Aquisition and Utilization of Aquatic Habitat Information. American Fisheries Society, Western Division, Portland Oregon.

Bisson, P. A., S. M. Wondzell, and G. H. Reeves. 2003. Trends in using wood to restore aquatic habitats and fish communities in western North Amaerican rivers. American Fisheries Society Sympsium 37:391–406.

Booth, D. B., R. A. Haugerud, and K. G. Troost. 2003. Geology, Watersheds, and Puget Lowland Rivers. Page 505 *in* D. R. Montgomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Pugets Sound Rivers. Center for Water and Watershed Studies in association with University of Washington Press, Seattle.

Buffington, J. M., T. E. Lisle, R. D. Woodsmith, and S. Hilton. 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18(6):507–531.

Carah, J. K., C. C. Blencowe, D. W. Wright, and L. A. Bolton. 2014. Low-Cost Restoration Techniques for Rapidly Increasing Wood Cover in Coastal Coho Salmon Streams. North American Journal of Fisheries Management 34(5):1003–1013. Wiley-Blackwell.

Cederholm, C., R. Bilby, P. Bisson, T. Bumstead, B. Fransen, W. Scarlett, and J. Ward. 1997a. Response of juvenile coho salmon and steelhead to placement of large woody debris in a coastal Washington stream. North American Journal of Fisheries Management 17(4):947–963.

Cederholm, C. J. 1972. The short-term physical and biological effects of stream channelization at Big Beef Creek, Kitsap County, Washington. University of Washington, Seattle.

Christian-Smith, J., and A. M. Merenlender. 2010. The disconnect between restoration goals and practices: A case study of watershed restoration in the Russian River basin, California. Restoration Ecology 18(1):95–102.

Collins, B. D., D. R. Montgomery, and A. D. Haas. 2002. Historical changes in the distribution and functions of large wood in Puget Lowland rivers. Canadian Journal of Fisheries and Aquatic Sciences 59(1):66–76. NRC Research Press Ottawa, Canada .

Crawford, B. 2011a. Protocol for monitoring effectiveness of floodplain enhancement projects (Dike Removal/Setback, Riprap Removal, Road Removal/Setback, and Landfill Removal, Off- Channel Habitat Creation, Side Channel Creation) Washington Salmon Recovery Funding Board.

Crawford, B. A. 2011b. Protocol for monitoring effectiveness of instream habitat projects MC-2 Washington Salmon Recovery Funding Board.

Curran, J. C. 2010. Mobility of large woody debris (LWD) jams in a low gradient channel.

ENTRIX. 2010. Geomprphic assessment technical memorandum. Seattle, WA.

Frissell, C. a., and R. K. Nawa. 1992. Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington. North American Journal of Fisheries Management 12(1):182–197.

Gregory, K. J. 2006. The human role in changing river channels. Geomorphology 79(3–4):172–191. Elsevier.

Gurnell, A. M. 1998. The hydrogeomorphological effects of beaver dam-building activity. Progress in Physical Geography 22(2):167–189.

Gurnell, A. M., H. Pié Gay, F. J. Swanson, and S. V Gregory. 2002. Large wood and fluvial processes. Freshwater Biology 47:601–619.

Gurney, W. S. C., and J. H. Lawton. 1996. The Population Dynamics of Ecosystem Engineers. Oikos 76(2):273. WileyNordic Society Oikos.

Hardy, T., P. Panja, D. Mathias, D. M. Winxspro, and a C. C. Section. 2005. WinXSPRO , A Channel Cross Section Analyzer , User ' s Manual , Version 3.0. Gen Tech Rep RMRSGTR147 Fort Collins CO US Department of Agriculture Forest Service Rocky Mountain Research Station 95 p (January):94.

Haugerud, R. A. 2009. Preliminary Geomorphic Map of the Kitsap Peninsula, Washington. U.S. Geological Survey, Open-File Report 2009-1033, 2 sheets, scale 1:36,000 [https://pubs.usgs.gov/of/2009/1033/].

Haugerud, R. A., and R. W. Tabor. 2008. Geomorphic Evidence for Multiple Large Post-glacial Earthquakes on the Western Seattle Fault. Page American Geophysical Union, Fall Meeting 2008, abstract id. T23E-05.

Henning, J. A., R. E. Gresswell, and I. A. Fleming. 2007. Use of seasonal freshwater wetlands by fishes in a temperate river floodplain. Journal of Fish Biology 71(2):476–492.

Hoffman, D. F., and E. J. Gabet. 2007. Effects of sediment pulses on channel morphology in a gravel-bed river. Geological Society of America Bulletin 119(1–2):116–125. GeoScienceWorld.

Jähnig, S. C. J., A. W. Lorenz, D. Hering, C. Antons, A. Sundermann, E. Jedicke, and A. P. Haase. 2011. River restoration success: a question of perception. Ecological Applications 21(6):2007–2015.

Jones, K. K., K. Anlauf-Dunn, P. S. Jacobsen, M. Strickland, L. Tennant, and S. E. Tippery. 2017. Effectiveness of Instream Wood Treatments to Restore Stream Complexity and Winter Rearing Habitat for Juvenile Coho Salmon.

Kail, J., D. Hering, S. Muhar, M. Gerhard, and S. Preis. 2007. The use of large wood in stream restoration: Experiences from 50 projects in Germany and Austria. Journal of Applied Ecology 44(6):1145–1155. Blackwell Publishing Ltd.

Katz, S. L., K. Barnas, R. Hicks, J. Cowen, and R. Jenkinson. 2007. Freshwater Habitat

Restoration Actions in the Pacific Northwest: A Decade's Investment in Habitat Improvement. Restoration Ecology 15(3):494–505.

Kitsap Public Utility District, Economic, Engineering Services Inc, Pacific Groundwater Group Inc, Robinson and Noble Inc, and KCM Inc. 1997. Kitsap County Initial Basin Assessment. Retrieved from http://www.kpud.org/downloads/kc_init-basin-assmnt.pdf.

Kondolf, G. M., and E. R. Micheli. 1995. Evaluating stream restoration projects. Environmental Management 19(1):1–15. Springer-Verlag.

KPUDhydro (n.d.) Kitsap Public Utility District hydrological data. http://kpudhydrodata.kpud.org/

Krueger, K., K. Pierce, N. Pittman, K. Samson, R. Nauer, D. Price, and T. Quinn. 2010. Intensively Monitored Watersheds: Habitat Monitoring Report 2010. Washington Department of Fish and Wildlife Habitat Science Team. Olympia, WA.

Lane, S. N., and K. S. Richards. 1997. Linking river channel form and process: time, space and casuality revisited. Earth Surface Processes and Landforms 22(3):249–260.

Larson, M. 2000. Effectiveness of Large Woody Debris in Stream Rehabilitation Projects in Urban Basins.

Larson, M. G., D. B. Booth, and S. A. Morley. 2001. Effectiveness of large woody debris in stream rehabilitation projects in urban basins. Ecological Engineering 18(2):211–226. Elsevier.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1992. Fluvial Processes in Geomorphology. Dover Publications, Mineola, NY.

Madej, M. 1978. Response of a stream channel to an increase in sediment load. University of

Washington, Seattle.

Madej, M. 1982. Sediment transport and channel changes in an aggrading stream in the Puget Lowland, Washington. Pages 97-18 in, GTRPNW 141, Sediment Budgets and Routing in Forested Drainage Basins. USFS.

Mangiafico, S. S. 2016. Summary and Analysis of Extension Program Evaluation in R, version 1.15.0. http://rcompanion.org/handbook/.

McCullough, P. H. 2015. Hood Canal Salmon Enhancement Group Lower Big Beef Creek Restoration - Phase 1 SRFB Project No. 11-1351 - Revised Design. Engineering Services Associates, Belfair, WA.

McDonald, J. H. 2014. Handbook of Biological Statistics, 3rd edition. Sparky House Publishing.

McHenry, M. L., E. Shott, R. H. Conrad, and G. B. Grette. 1998. Changes in the quantity and characteristics of large woody debris in streams of the Olympic Peninsula, Washington, U.S.A. (1982-1993). Canadian Journal of Fisheries and Aquatic Sciences 55(6):1395–1407. NRC Research Press Ottawa, Canada .

Michael McHenry, George Pess, Tim Abbe, Holly Coe, Jennifer Goldsmith, Martin Liermann, Randall McCoy, Sarah Morley, R. P. 2007. The Physical and Biological Effects of Engineered Logjams (ELJs) in the Elwha River, Washington. Elwha River Engineered Logjam Monitoring Report:90.

Morandi, B., H. Piégay, N. Lamouroux, and L. Vaudor. 2014. How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. Journal of Environmental Management 137:178–188. Academic Press.

Naiman, R. J., C. A. Johnston, and J. C. Kelley. 1988. Alteration of North American Streams by Beaver. BioScience 38(11):753–762. Oxford University PressAmerican Institute of Biological Sciences.

Nichols, R. A., and G. L. Ketcheson. 2013. A Two-Decade Watershed Approach to Stream Restoration Log Jam Design and Stream Recovery Monitoring: Finney Creek, Washington. JAWRA Journal of the American Water Resources Association 49(6):1367–1384. Wiley/Blackwell (10.1111).

O'Neal, J. S., P. Roni, B. Crawford, A. Ritchie, and A. Shelly. 2016. Comparing stream restoration project effectiveness using a programmatic evaluation of salmonid habitat and fish response. North American Journal of Fisheries Management 36(3):681–703.

Olson-Rutz, K. M., and C. B. Marlow. 1992. Analysis and Interpretation of Stream Channel Cross-Sectional Data. North American Journal of Fisheries Management 12:55–61.

Palmer, M. A., E. S. Bernhardt, J. D. Allan, P. S. Lake, G. Alexander, S. Brooks, J. Carr, S. Clayton, C. N. Dahm, J. Follstad Shah, D. L. Galat, S. G. Loss, P. Goodwin, D. D. Hart, B. Hassett, R. Jenkinson, G. M. Kondolf, R. Lave, J. L. Meyer, T. K. O'Donnell, L. Pagano, and E. Sudduth. 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology 42(2):208–217. Blackwell Science Ltd.

Palmer, M. A., H. L. Menninger, and E. Bernhardt. 2009. River restoration, habitat heterogeneity and biodiversity: A failure of theory or practice? Freshwater Biology 55(SUPPL. 1):205–222.

Pollock, M. M., R. J. Naiman, H. E. Erickson, C. A. Johnston, J. Pastor, and G. Pinay. 1995. Beaver as Engineers: Influences on Biotic and Abiotic Characteristics of Drainage Basins.

Pages 117–126 Linking Species & Ecosystems. Springer US, Boston, MA.

Pollock, M. M., G. R. Pess, T. J. Beechie, and D. R. Montgomery. 2004. The Importance of Beaver Ponds to Coho Salmon Production in the Stillaguamish River Basin, Washington, USA. North American Journal of Fisheries Management 24(3):749–760. Taylor & Francis Group .

PRISM. 2018. PRISM Project Search - Washington State Recreation and Conservation Office. https://secure.rco.wa.gov/prism/search/projectsearch.aspx.

Quinn, T. P., and N. P. Peterson. 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. Canadian Journal of Fisheries and Aquatic Sciences 53(7):1555–1564.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna Austria. https://www.r-project.org/.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A Review of Stream Restoration Techniques and a Hierarchical Strategy for Prioritizing Restoration in Pacific Northwest Watersheds. North American Journal of Fisheries Management 22(1):1–20.

Roni, P., T. Beechie, G. Pess, and K. Hanson. 2015. Wood placement in river restoration: fact, fiction, and future direction. Canadian Journal of Fisheries and Aquatic Sciences 72(3):466–478. NRC Research Press.

Roni, P., K. Hanson, and T. Beechie. 2008a. Global Review of the Physical and Biological

Effectiveness of Stream Habitat Rehabilitation Techniques. North American Journal of Fisheries Management 28(3):856–890.

Roni, P., and T. P. Quinn. 2001. Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58(2):282–292. NRC Research Press Ottawa, Canada .

Stillwater Sciences. 2008a. Seabeck Creek Channel and Sediment Assessment: Technical Memorandum. Prepared for the Intensively Monitored Watershed Project, Seattle, WA.

Stillwater Sciences. 2008b. Phase II Little Anderson Creek Habitat Large Woody Debris Enhancement Designs. Page Prepared for the Hood Canal Salmon Enhancement Group. Seattle, WA.

Studinski, J. M., K. J. Hartman, J. M. Niles, and P. Keyser. 2012. The effects of riparian forest disturbance on stream temperature, sedimentation, and morphology. Hydrobiologia 686(1):107–117. Springer Netherlands.

USGS. 2018. USGS Surface Water for USA: Peak Streamflow. https://nwis.waterdata.usgs.gov/usa/nwis/peak/?site_no=12069550.

Vogel, R. M. 2011. Hydromorphology. Journal of Water Resources Planning and Management 137(2):147–149.

White, J. Q., G. B. Pasternack, and H. J. Moir. 2010. Valley width variation influences riffle-pool location and persistence on a rapidly incising gravel-bed river. Geomorphology 121(3–4):206–221. Elsevier B.V.

Williams, K. R. 1970. Some ecological investigations of Big Beef Creek, 1966-67. University of

Washington, Seattle.

Woolsey, S., F. C. Apelli, T. O. Gonser, E. Hoehn, S. Hos, T. Man N, B. Junker, A. P. Aetzold, C. I. Roulier, S. Schweizer, S. D. T. Iegs, # Klement Tockner, C. W. Eber, A. Nd, and A. Peter. 2007. A strategy to assess river restoration success. Freshwater Biology 52:752–769.

Appendices

Appendix A. Channel cross section plots analyzed within WinXSPRO for WY2014-17 (stations 3-50) and WY2017 only (stations 51-66).

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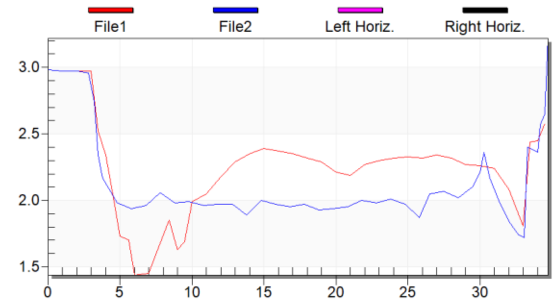

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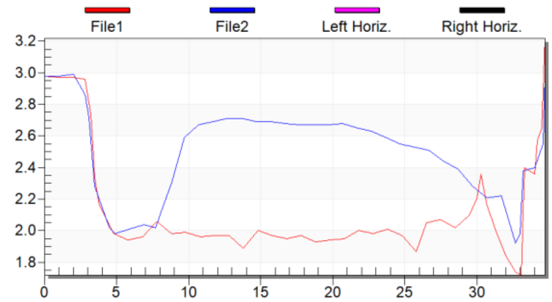

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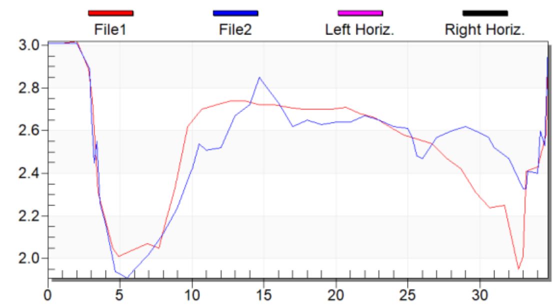

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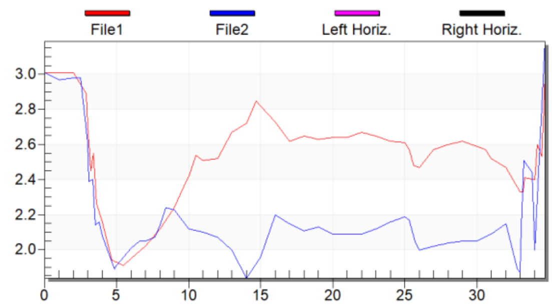

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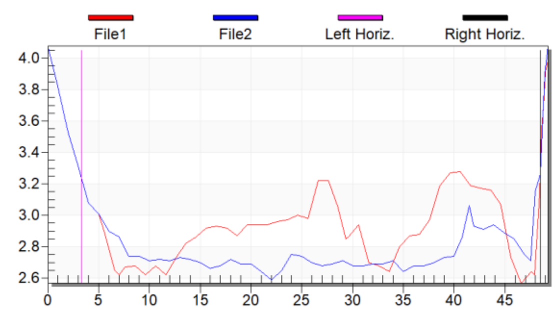

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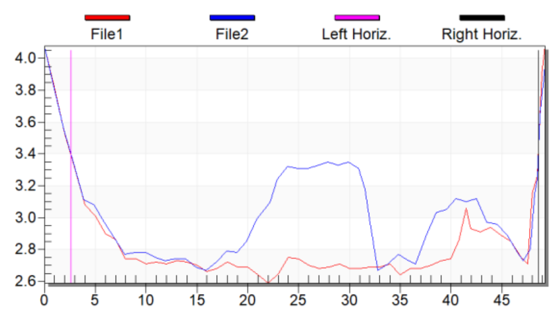

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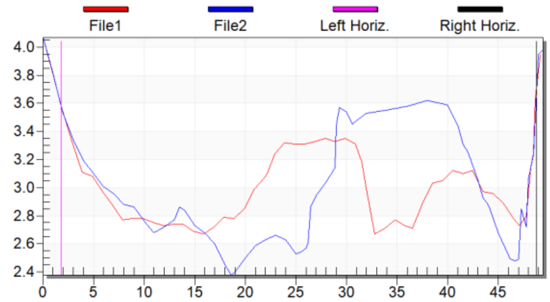

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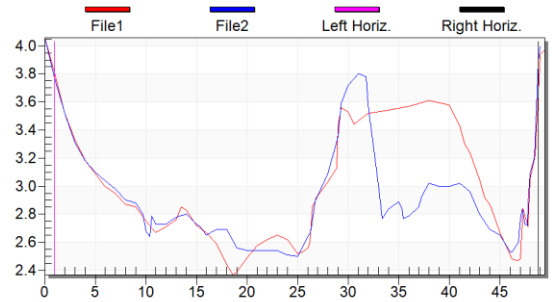

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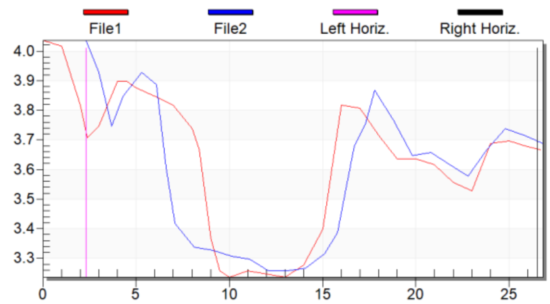

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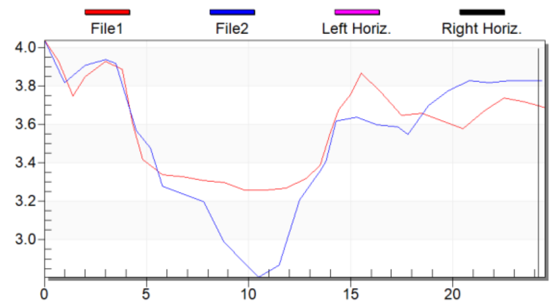

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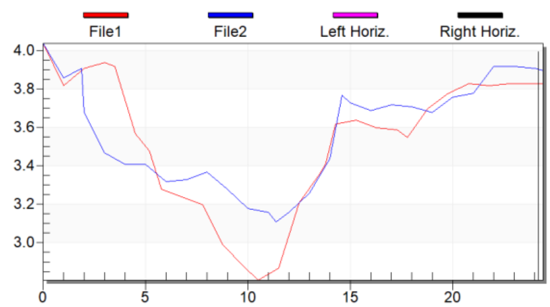

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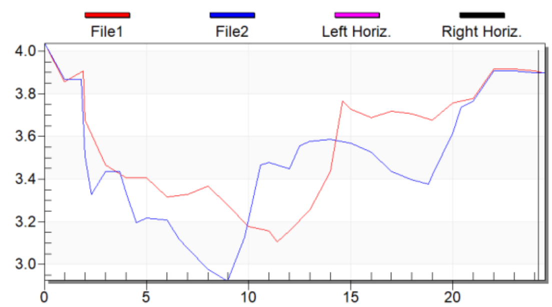

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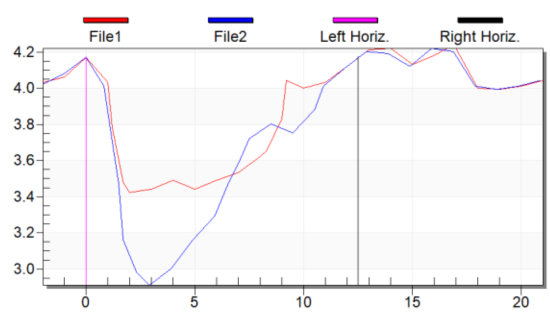

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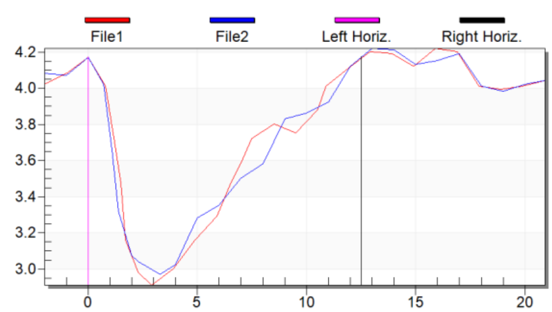

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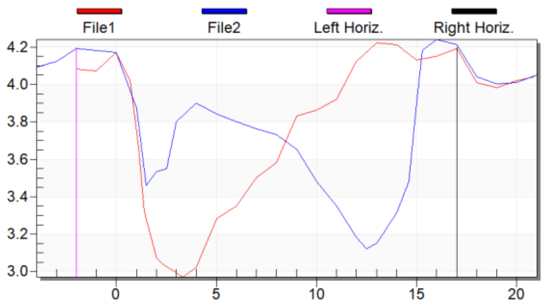

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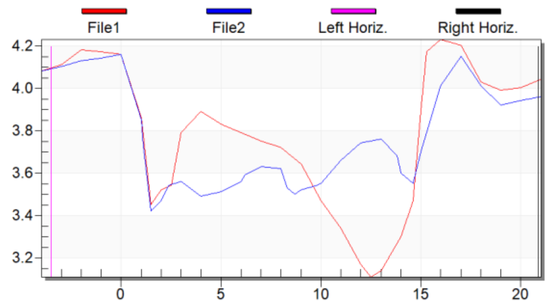

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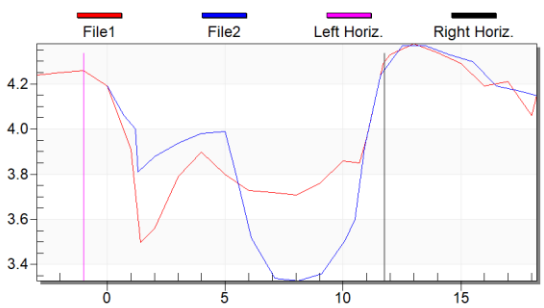

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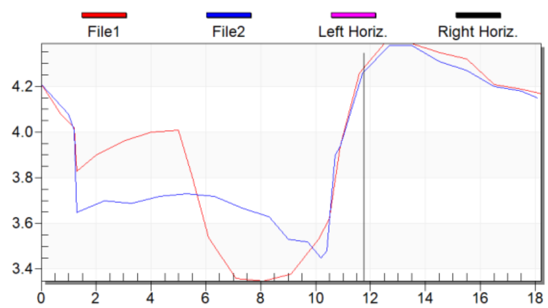

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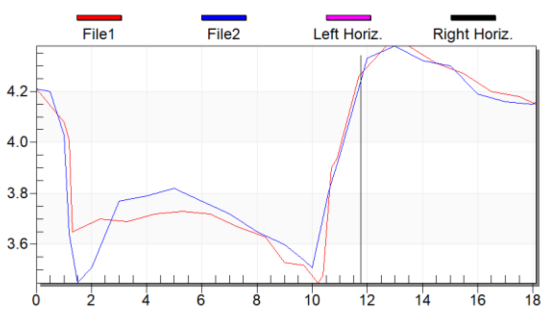

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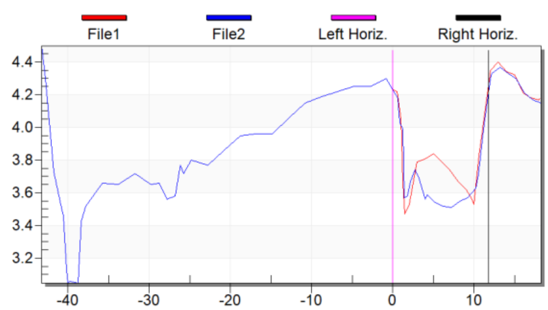

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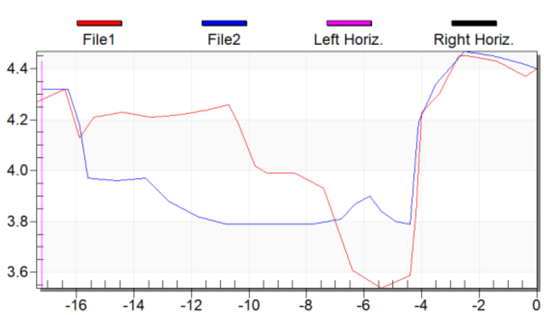

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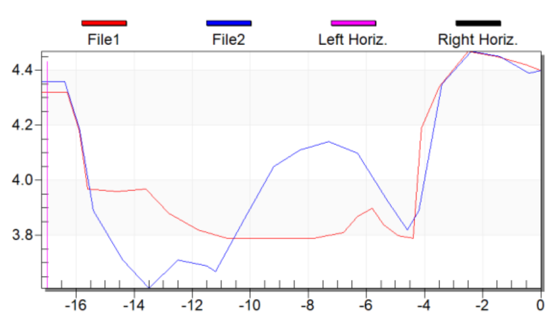

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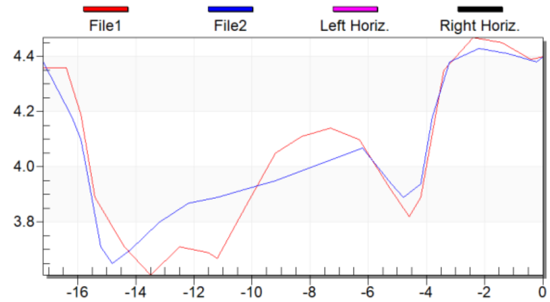

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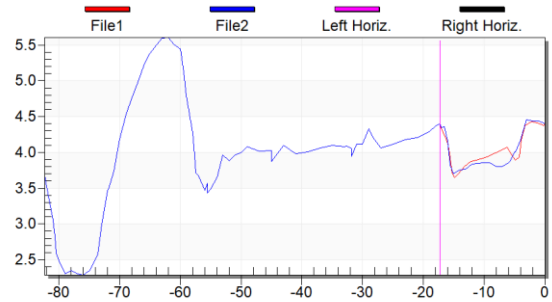

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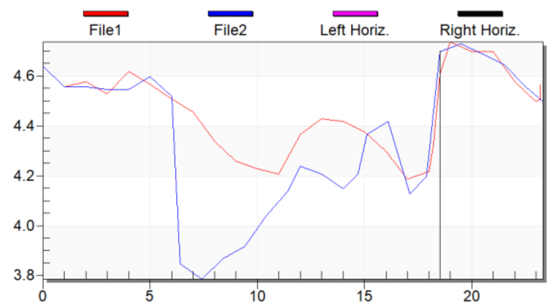

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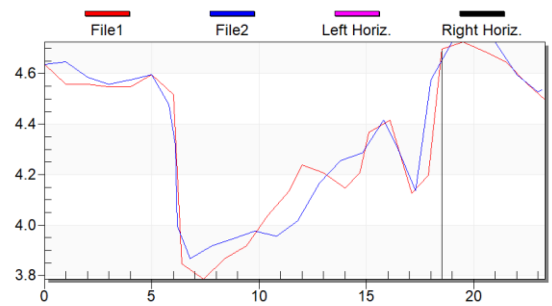

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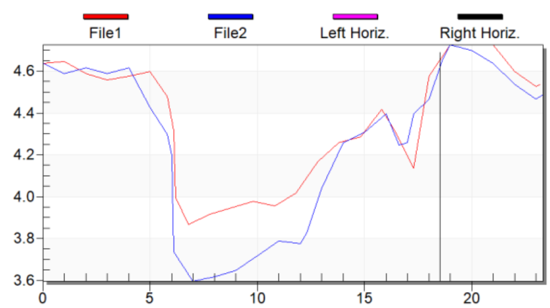

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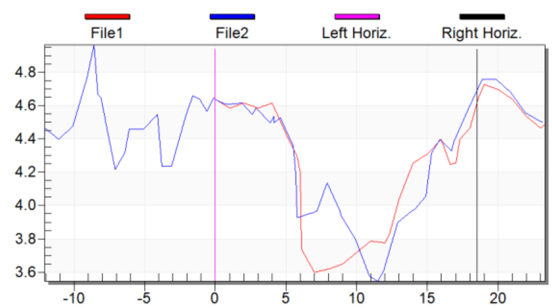

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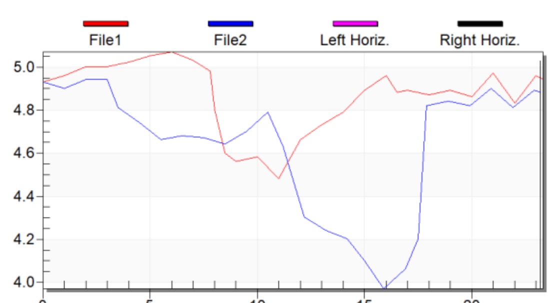

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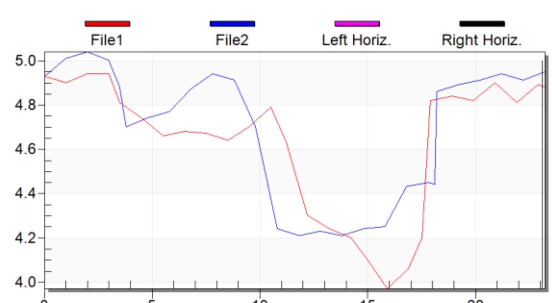

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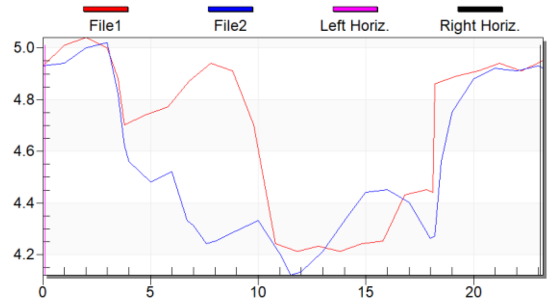

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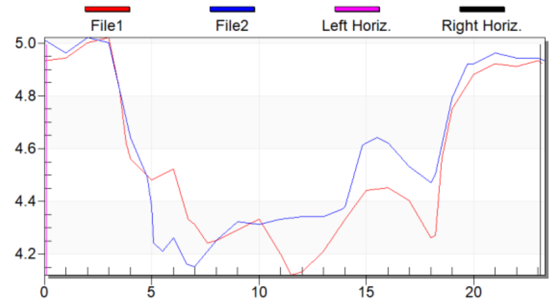

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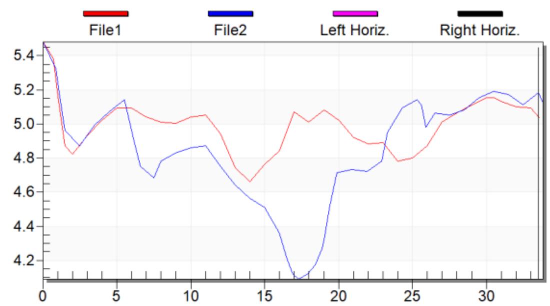

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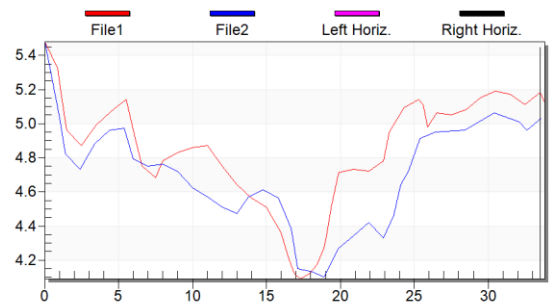

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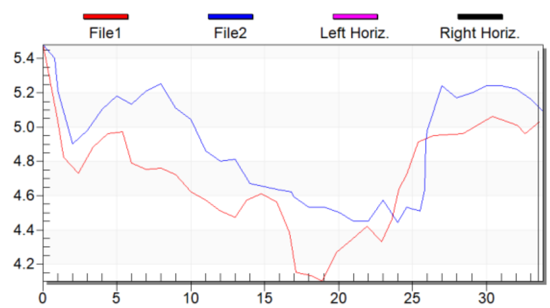

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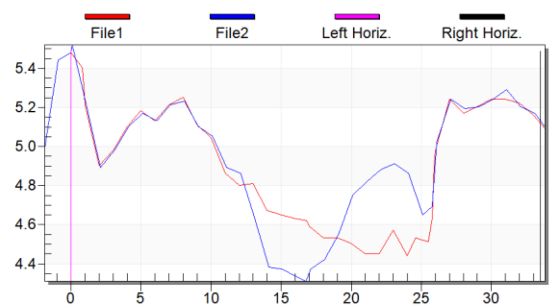

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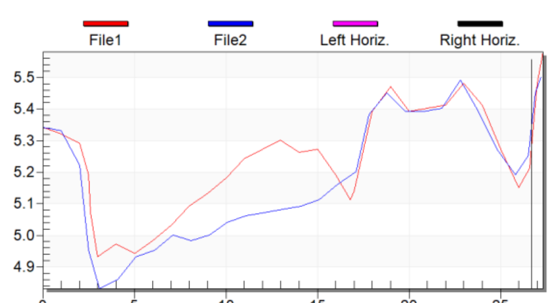

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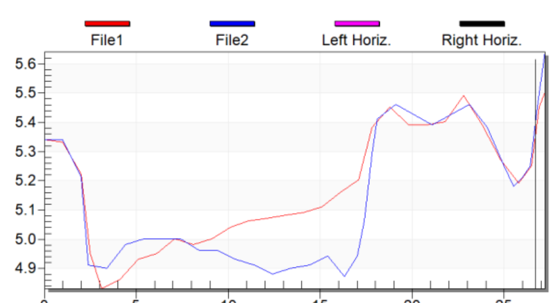

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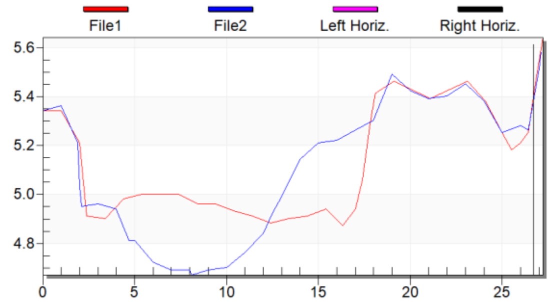

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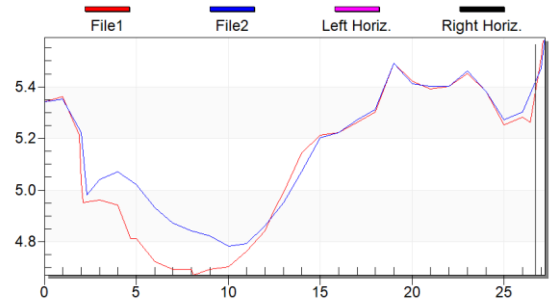

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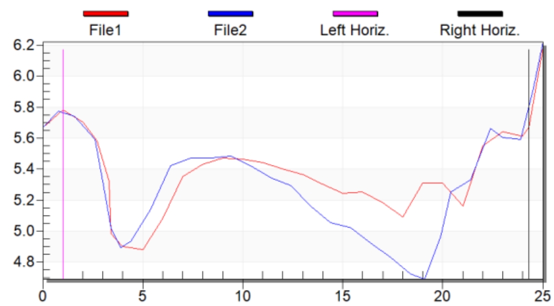

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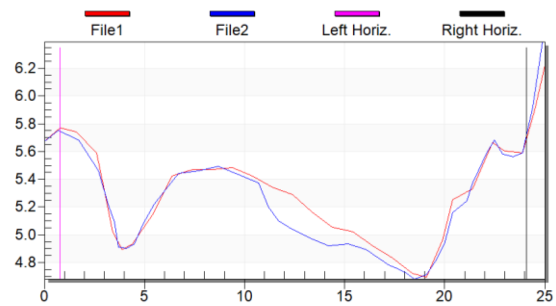

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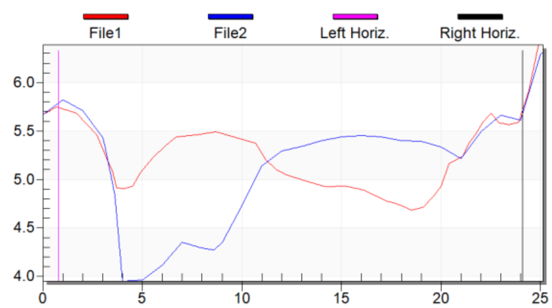

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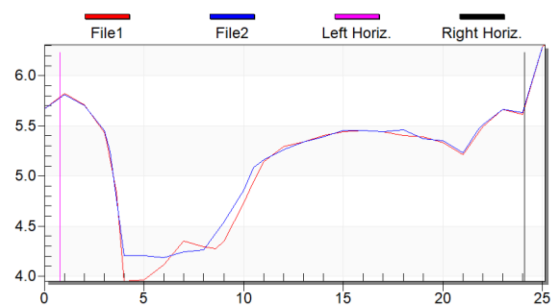

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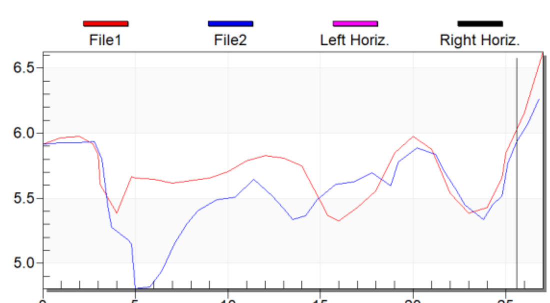

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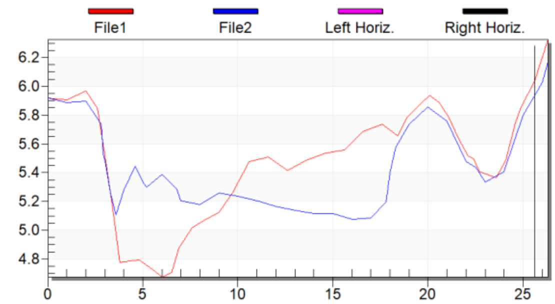

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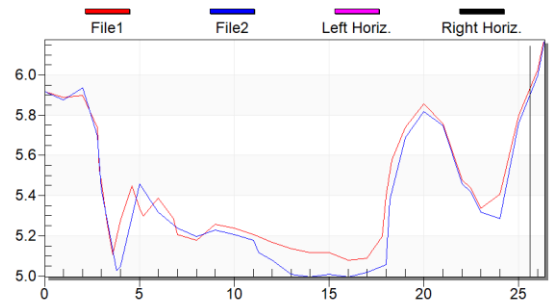

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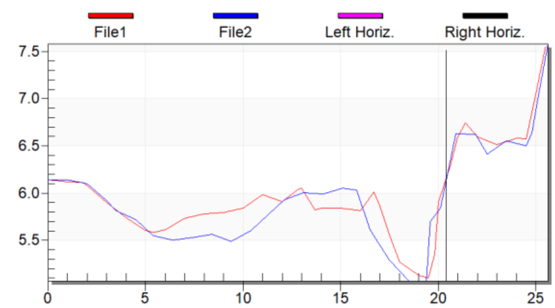

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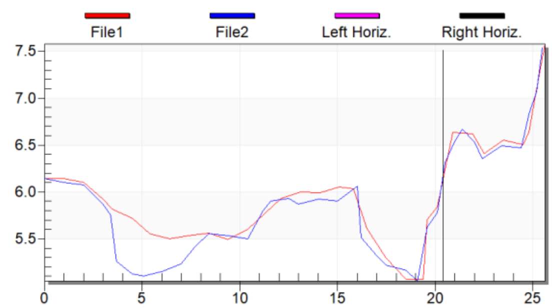

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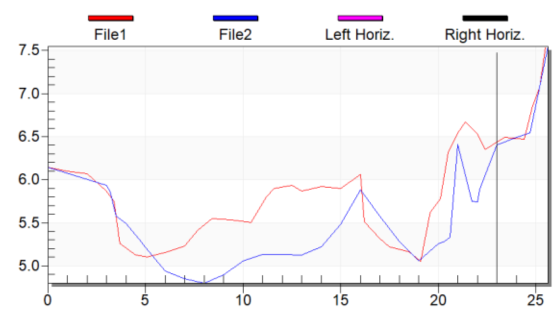

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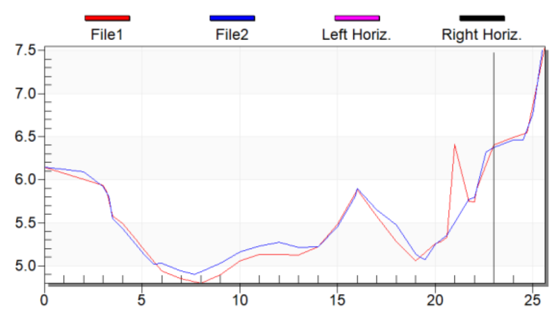

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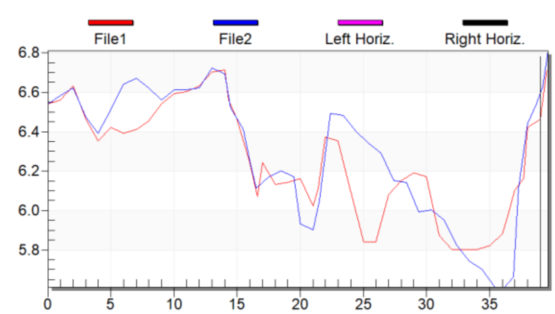

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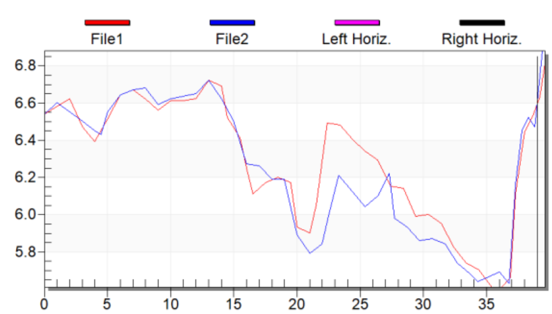

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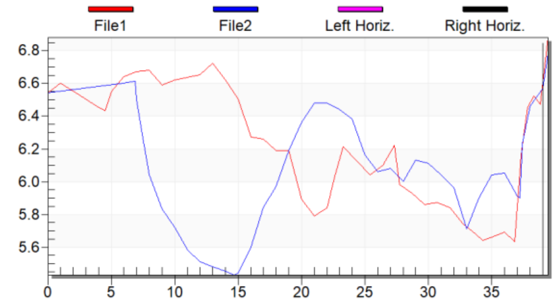

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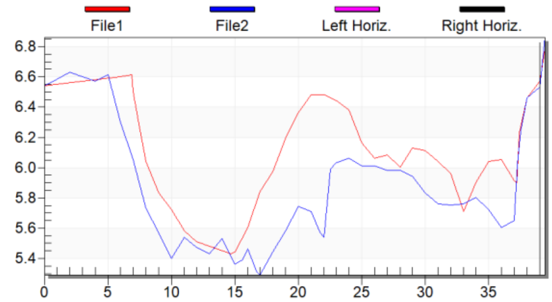

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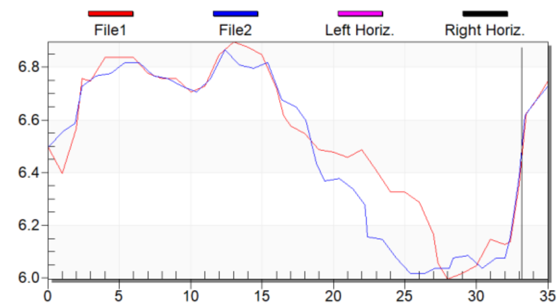

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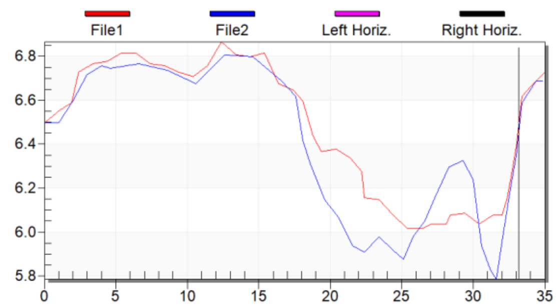

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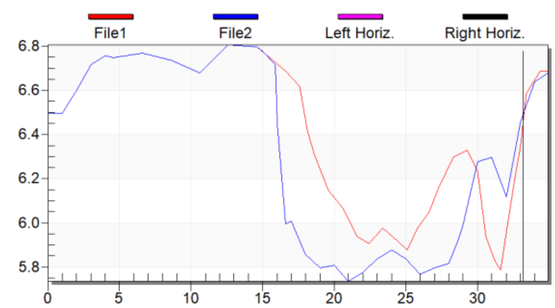

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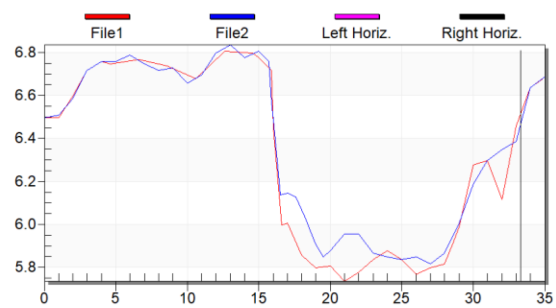

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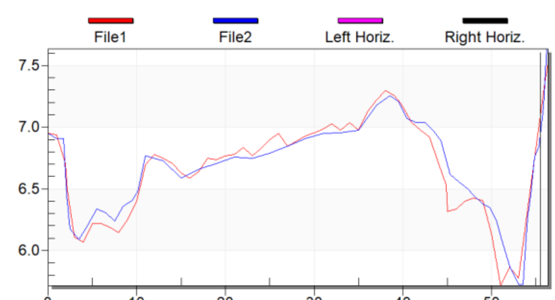
Station 18



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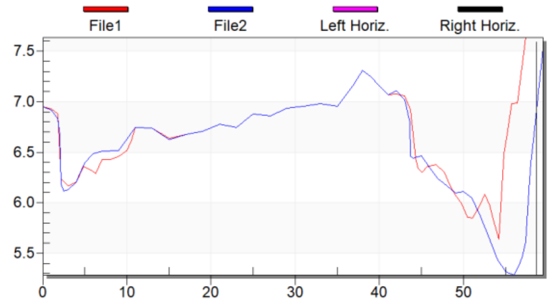

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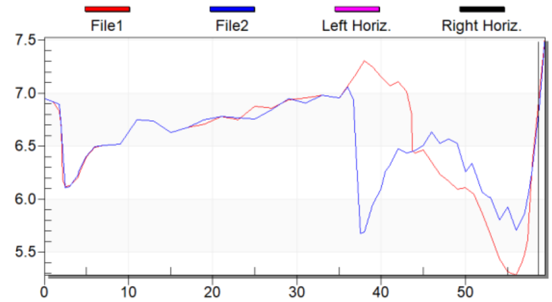

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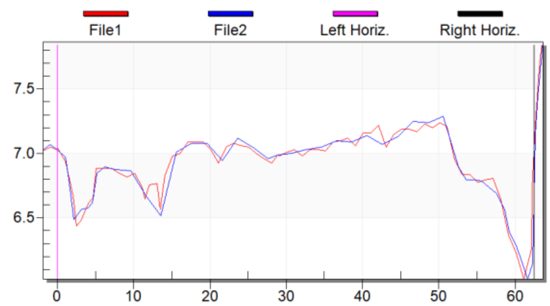
Station 19



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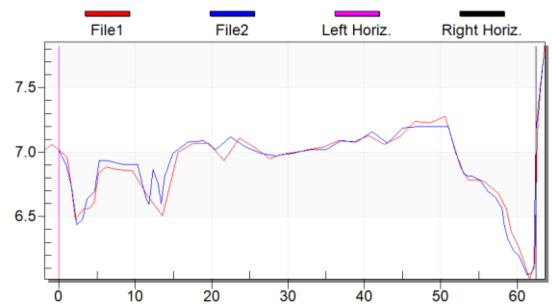

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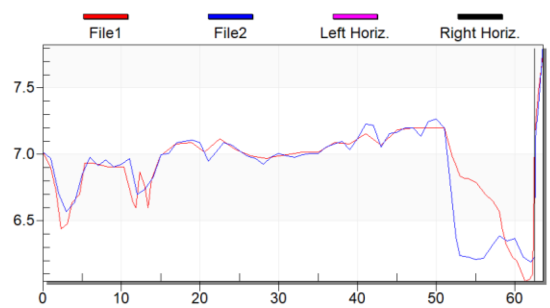

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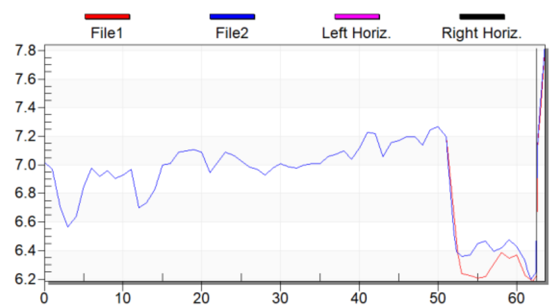

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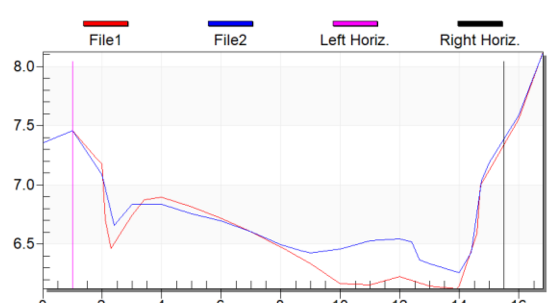
Station 19.5



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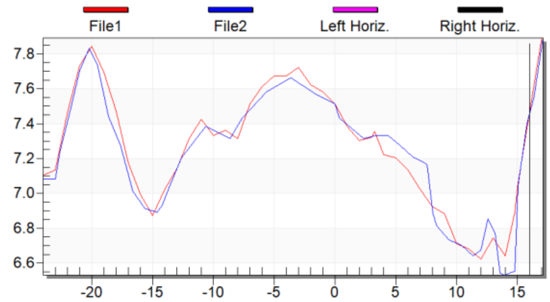
Station 20



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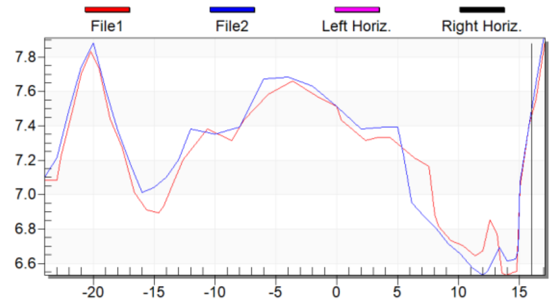

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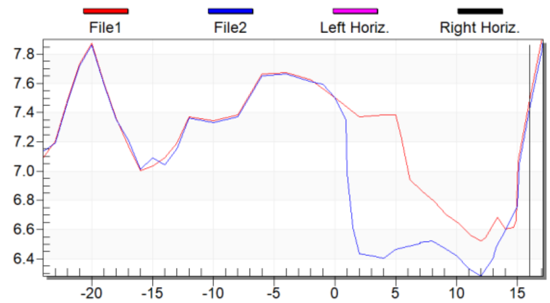

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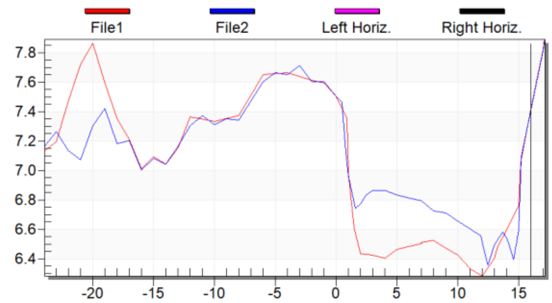

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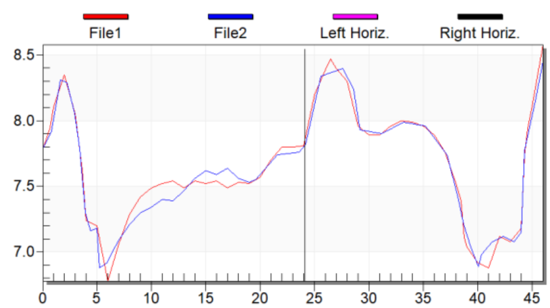
Station 21 – main channel



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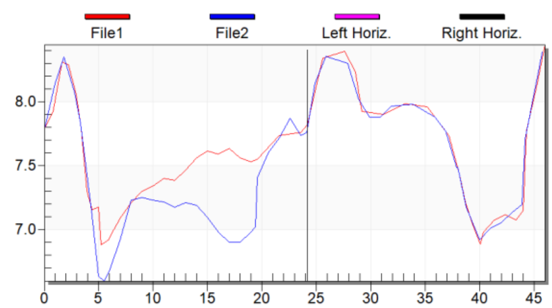

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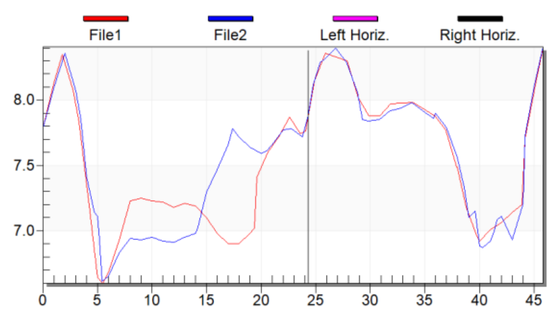

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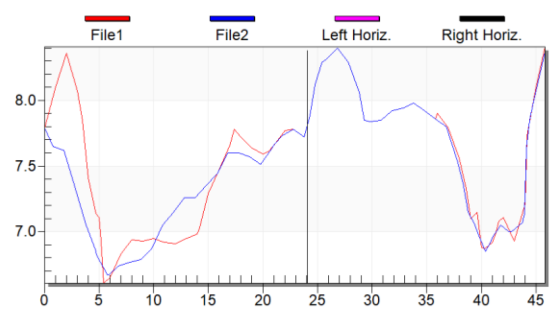

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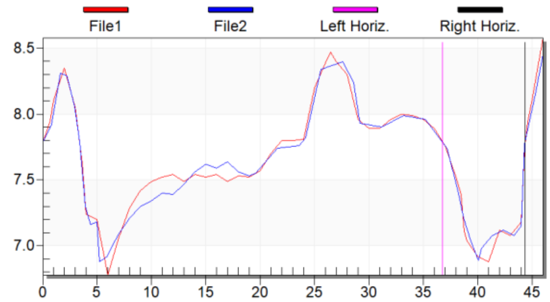
Station 21 – left bank side channel



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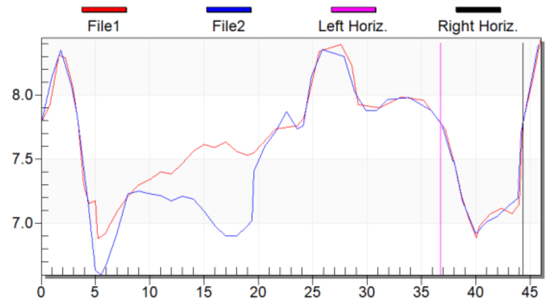

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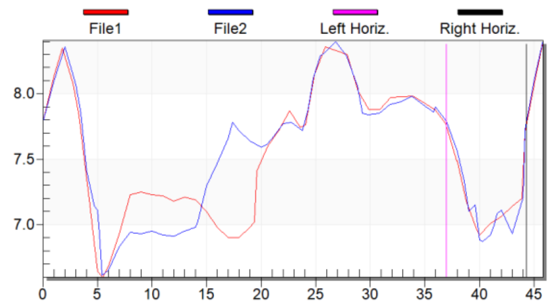

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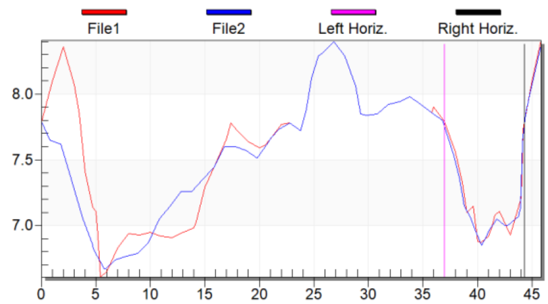

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Station 22 – main channel

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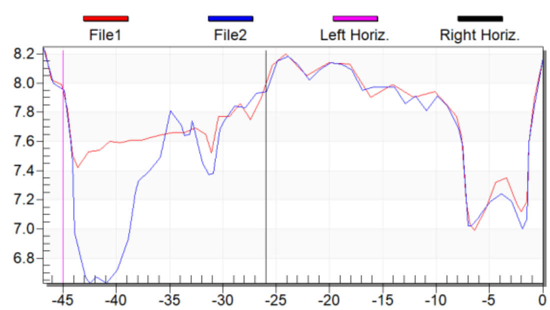
15



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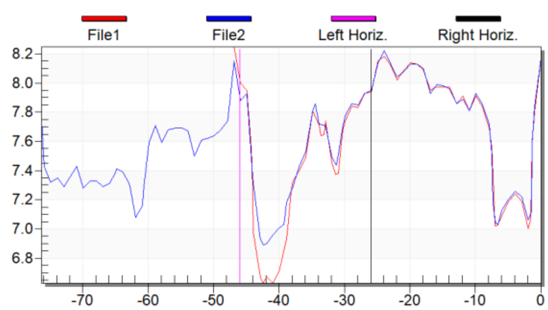

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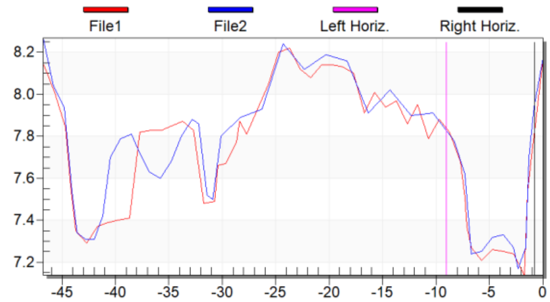
Station 22 – left bank side channel



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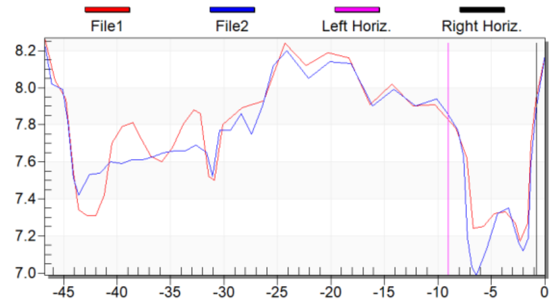

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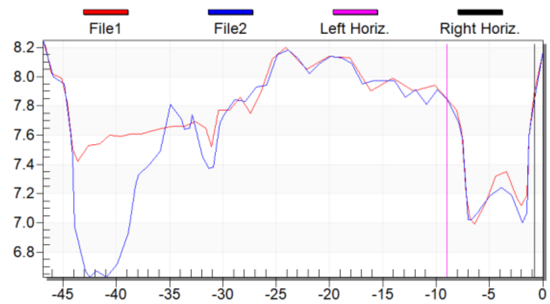

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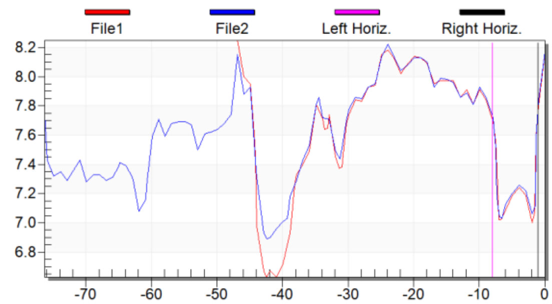

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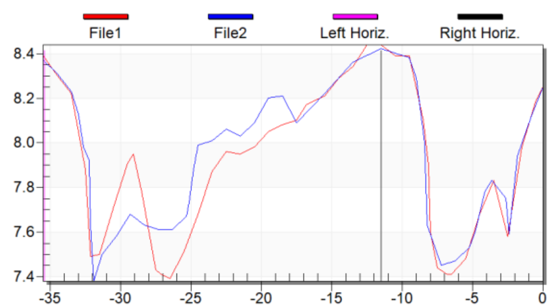
Station 23 – main channel



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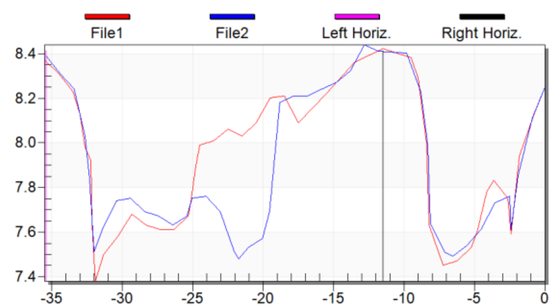

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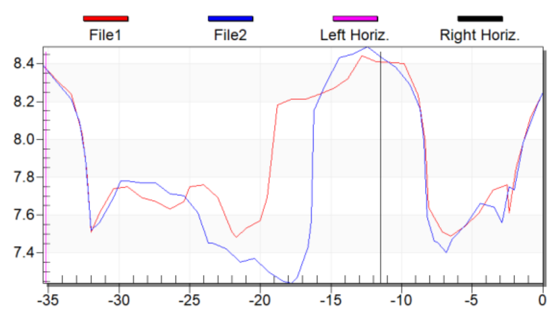

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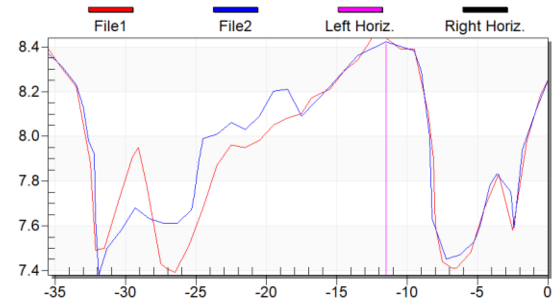
17

Station 23 – left bank side channel



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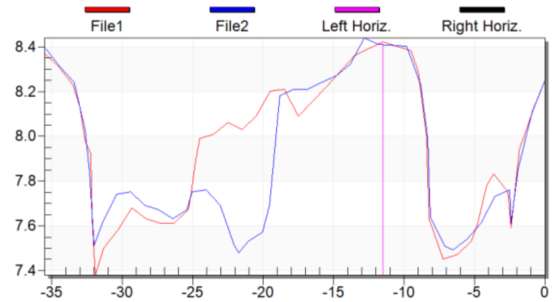

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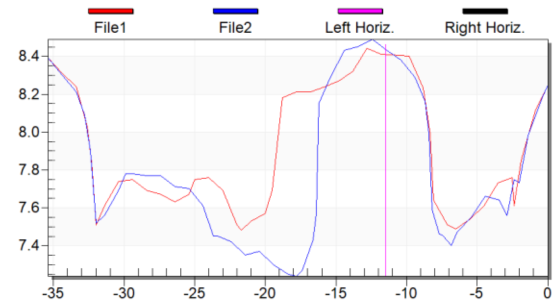

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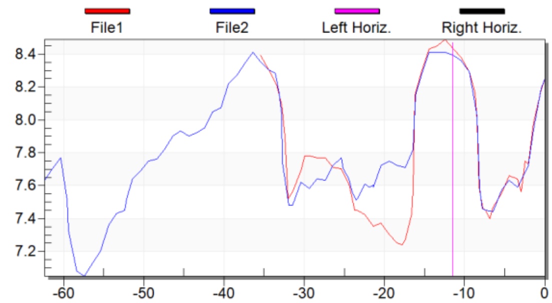

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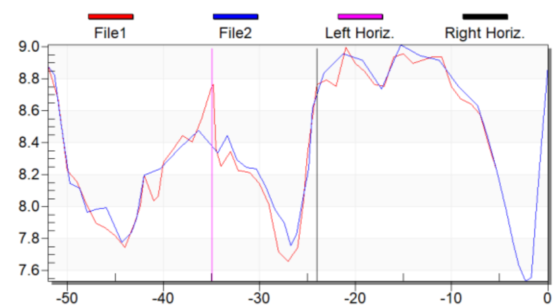
Station 24 – main channel



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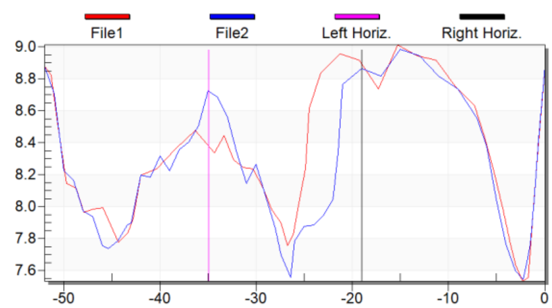

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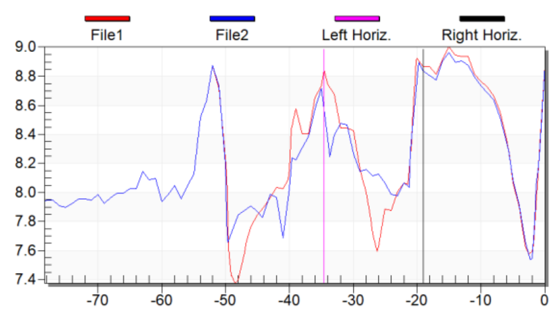
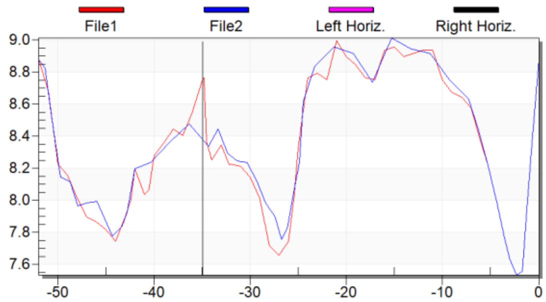


17

Station 24 – right bank side channel



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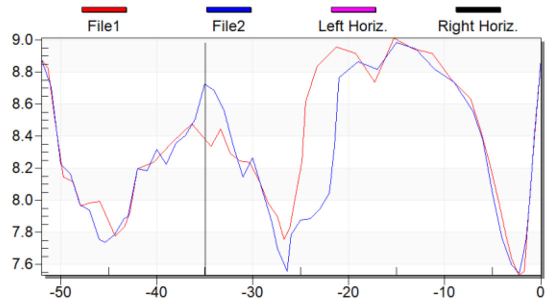

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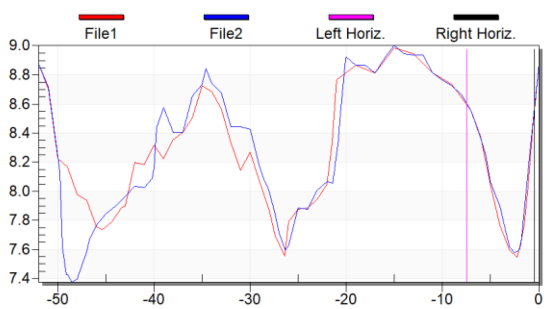
16

17

Station 24 – left bank side channel

14

15



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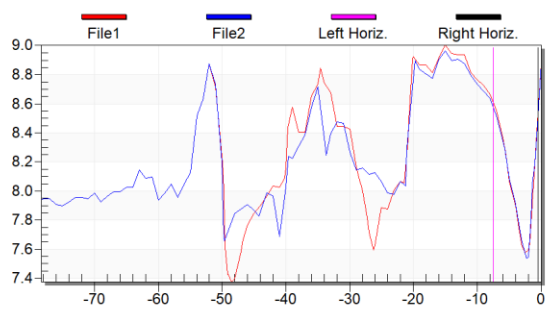

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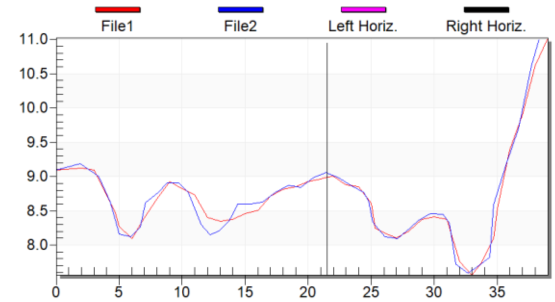
Station 25 – main channel



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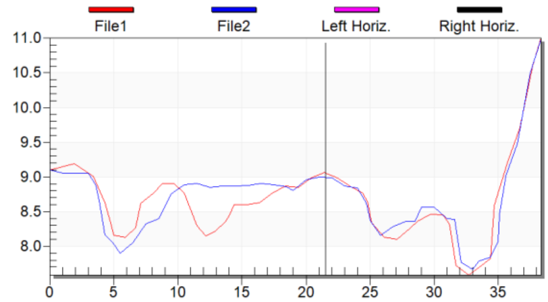

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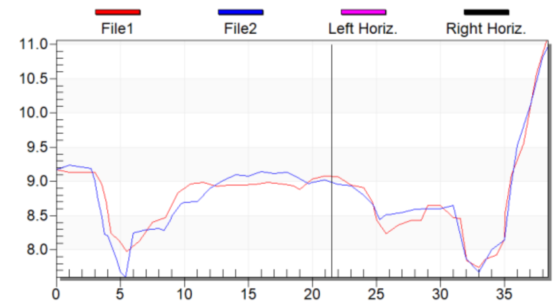

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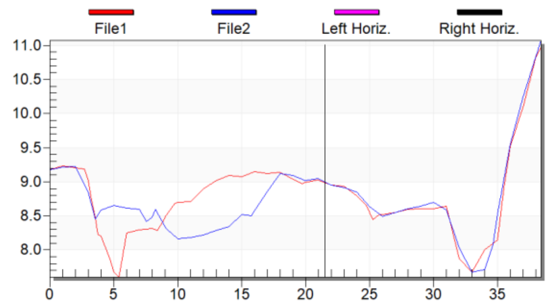

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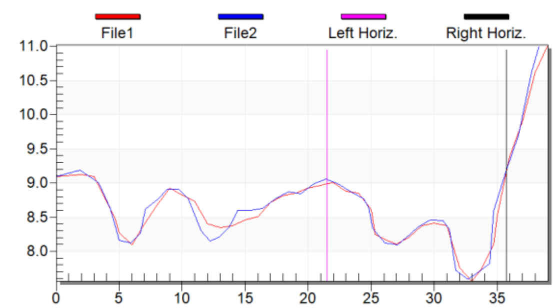
Station 25 – left bank side channel



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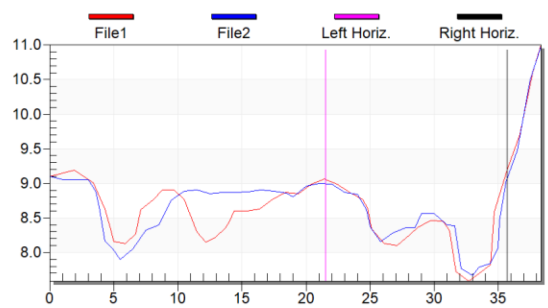

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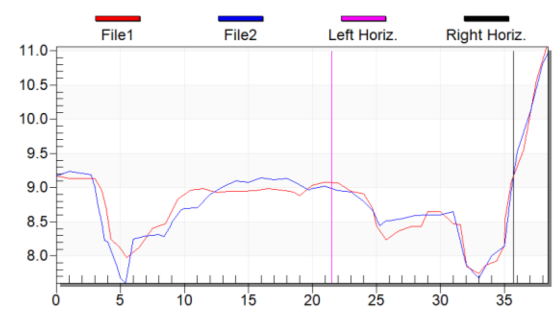

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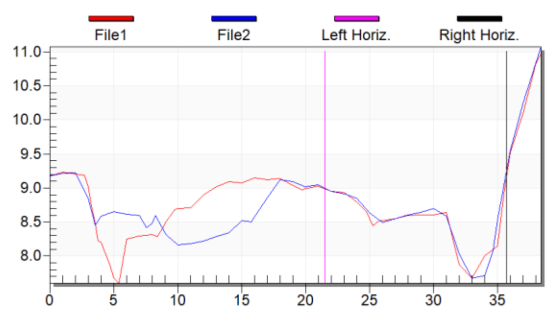

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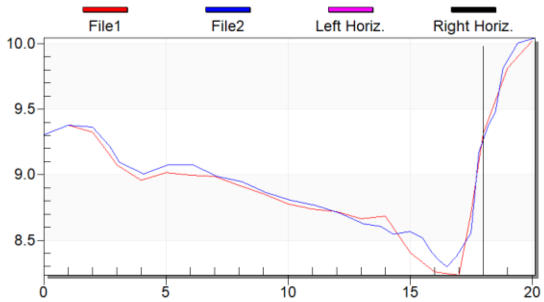
Station 26



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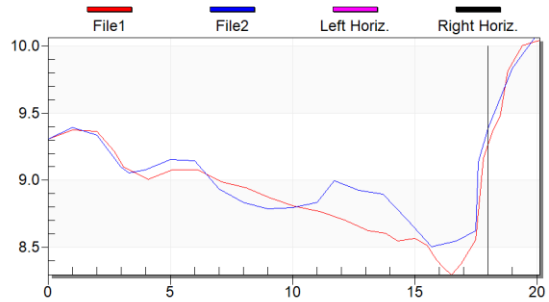

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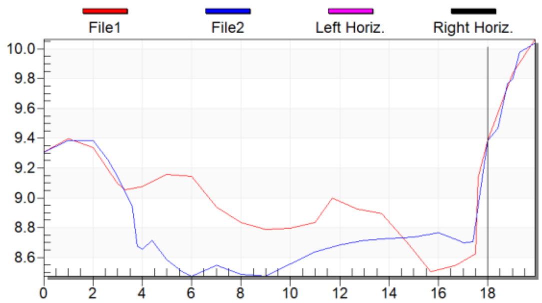

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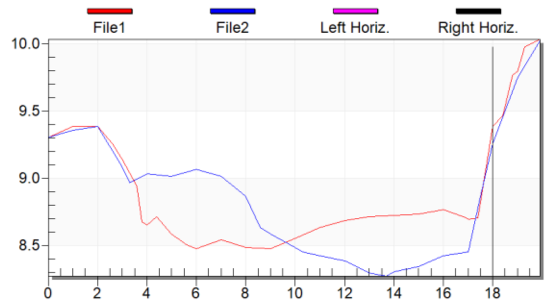
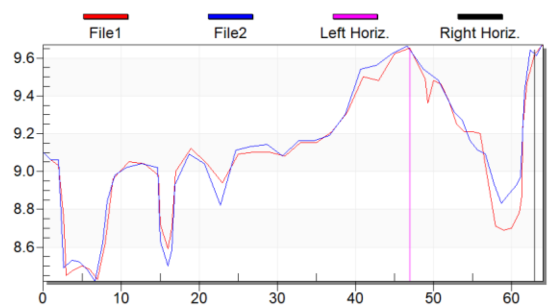


17

Station 27 – main channel



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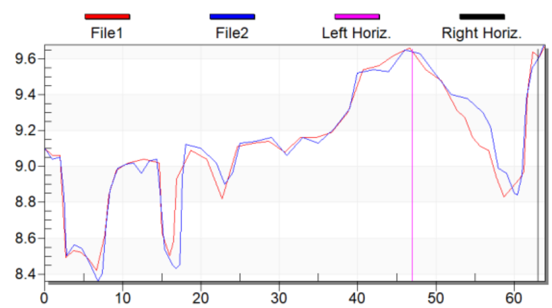

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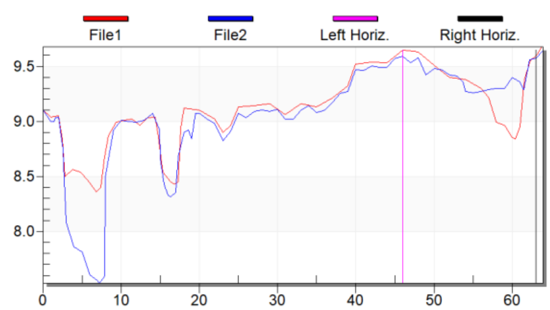

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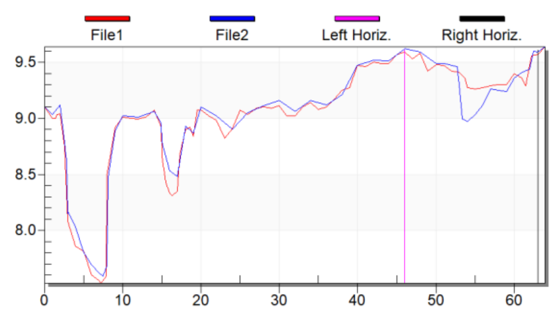
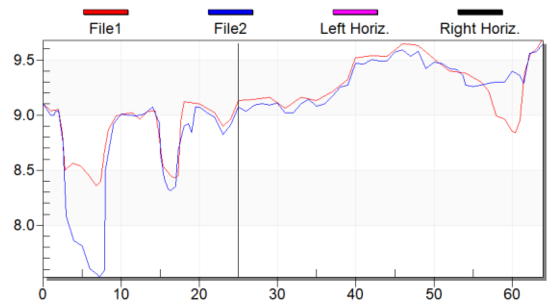


17

Station 27 – right bank side channel

14

15



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17

Station 28 – main channel

14

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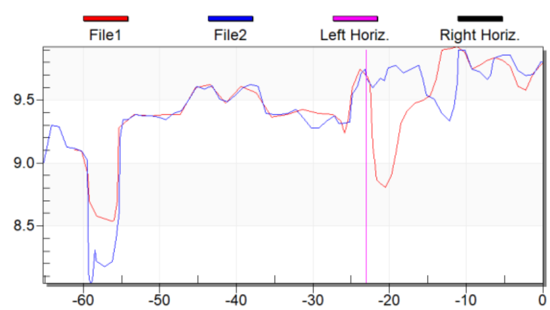

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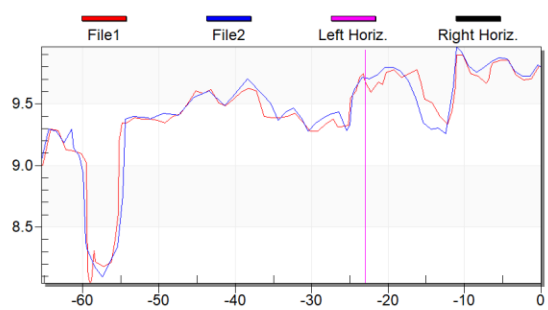

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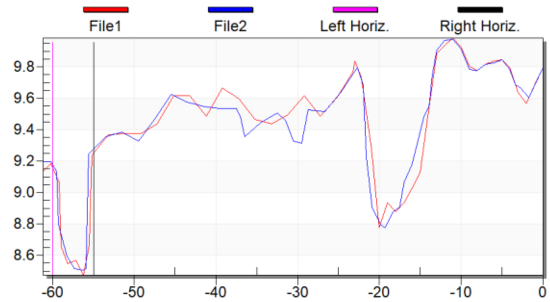
Station 28 – right bank side channel



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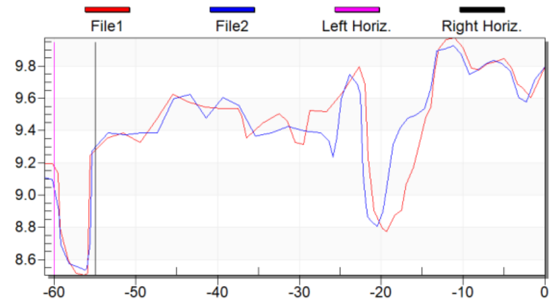

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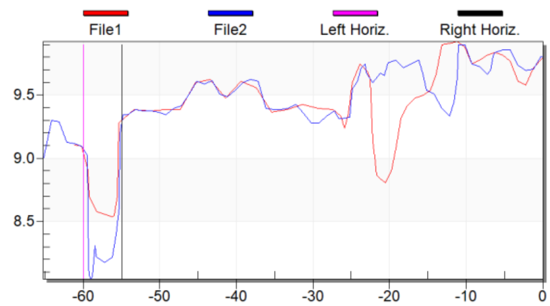

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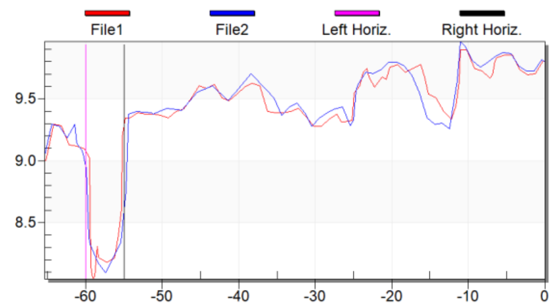
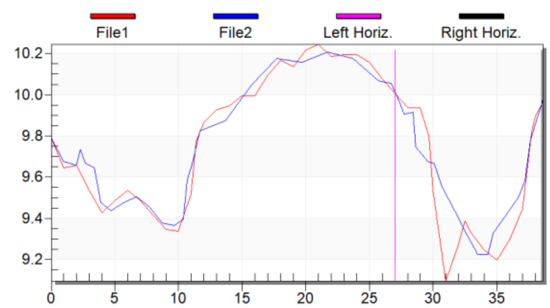


17

Station 29 – main channel



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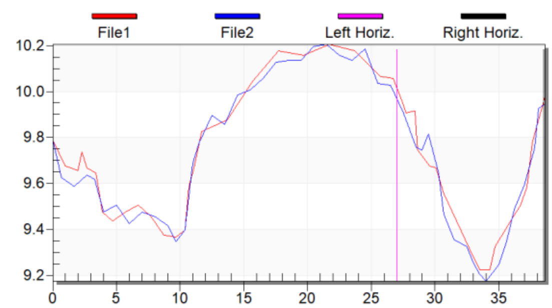

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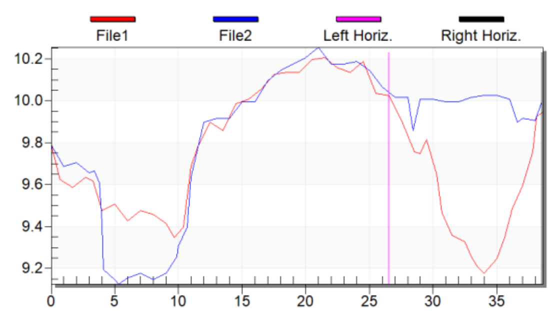

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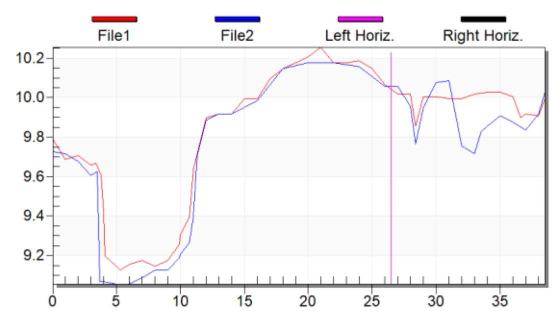
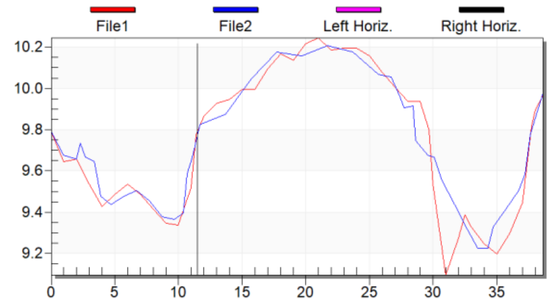


17

Station 29 – right bank side channel



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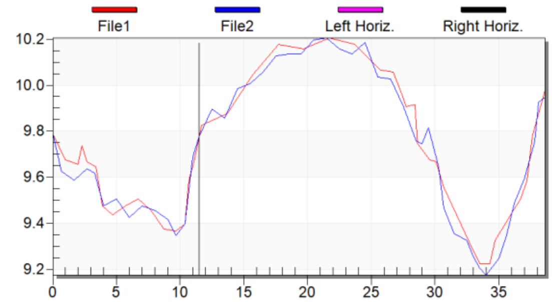

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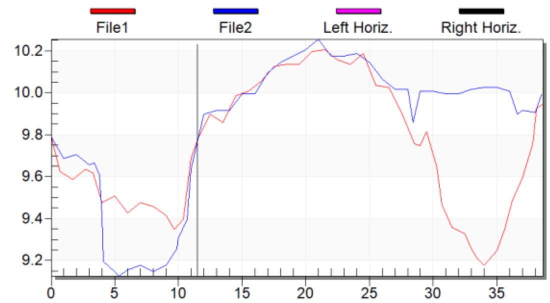

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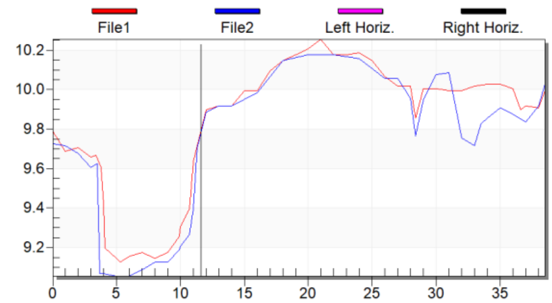
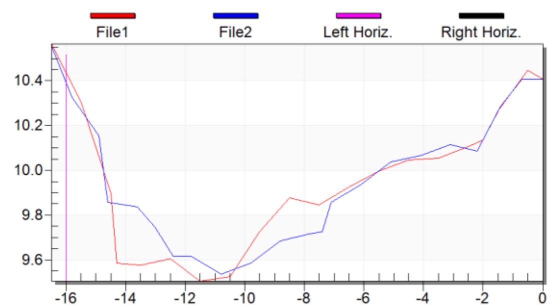


17

Station 30



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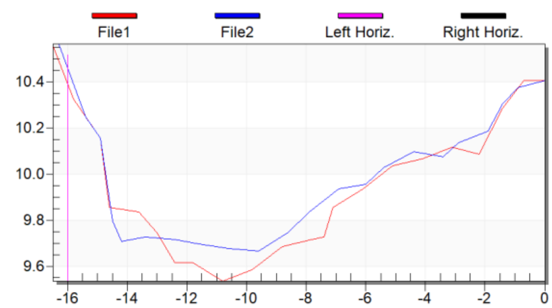

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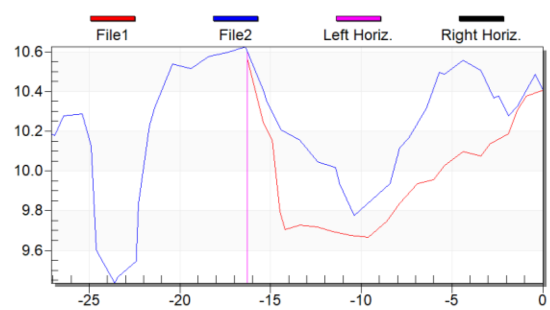

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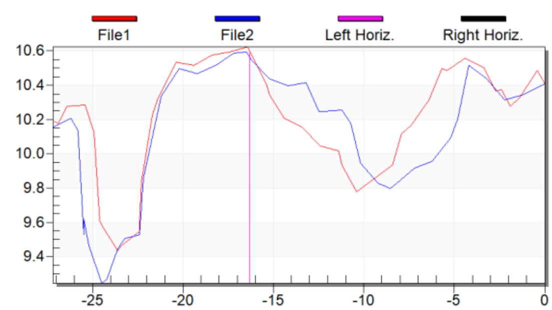

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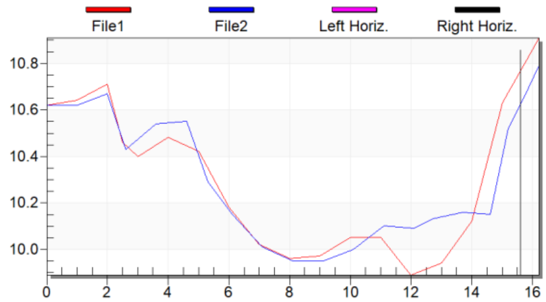
Station 31



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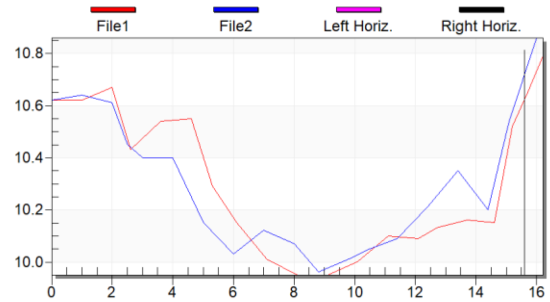

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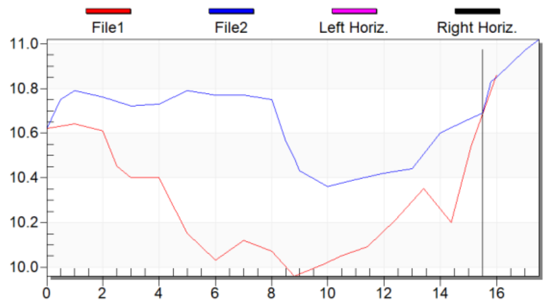

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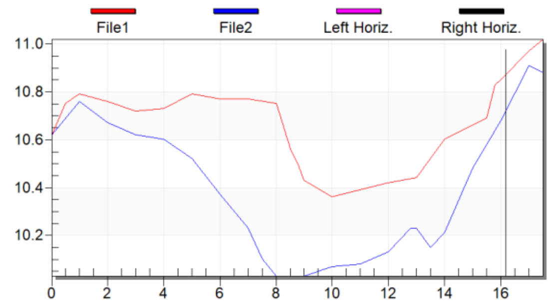

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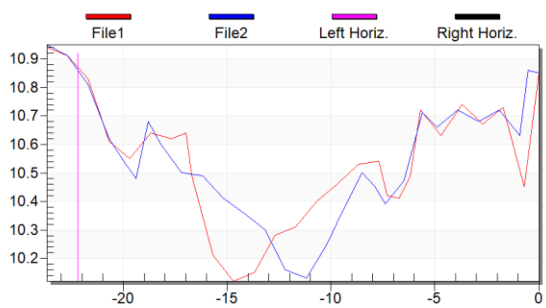
Station 32



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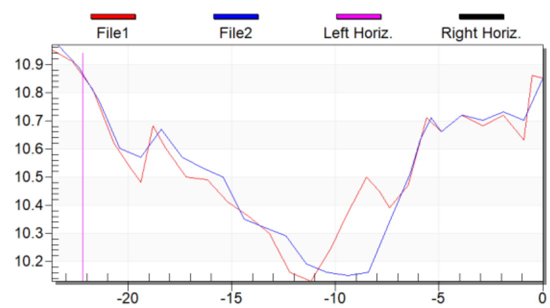

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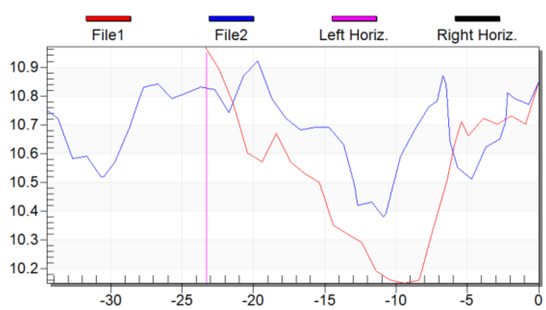

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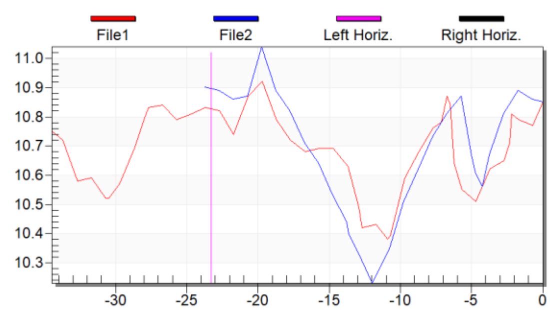

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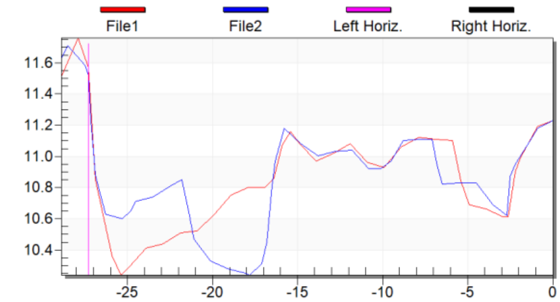
Station 33



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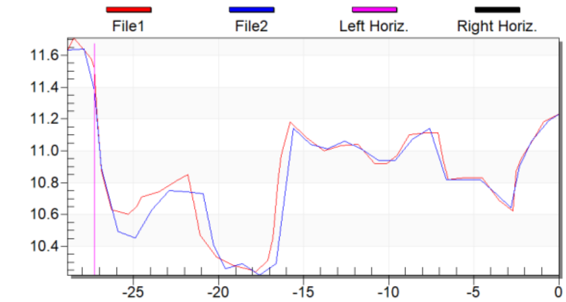

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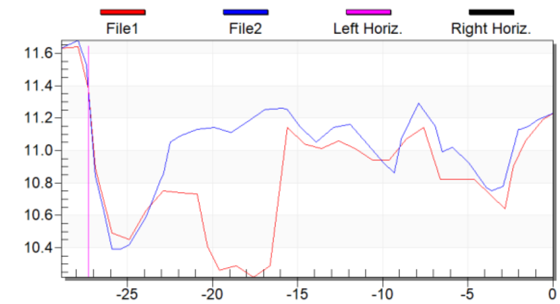

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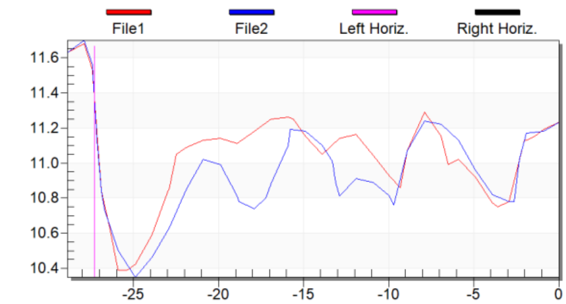

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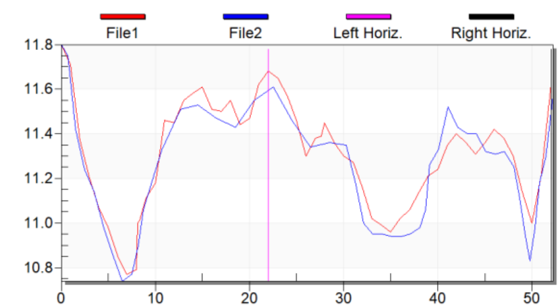
Station 34 – main channel



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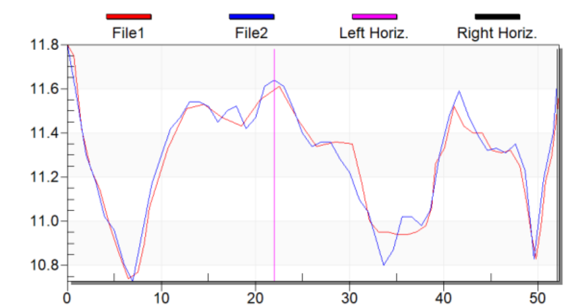

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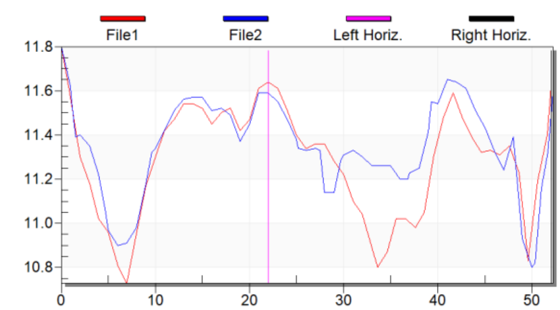

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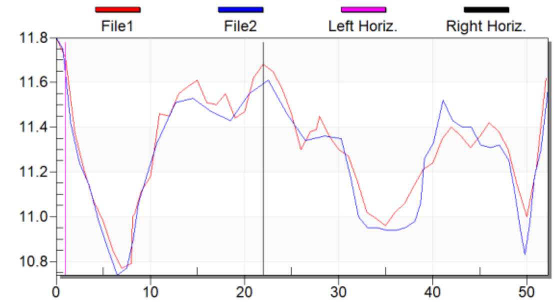
17

Station 34 - right bank side channel



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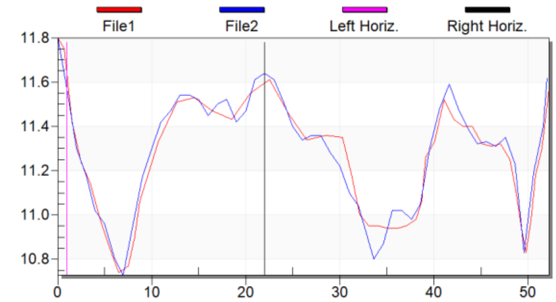

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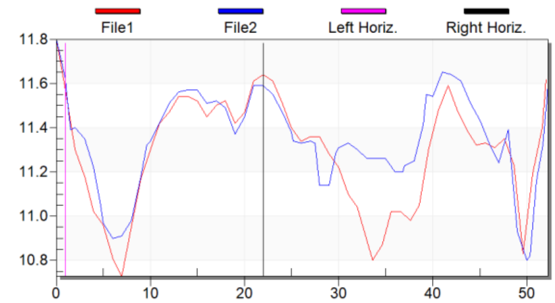

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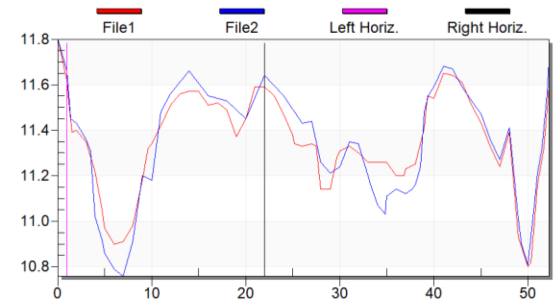

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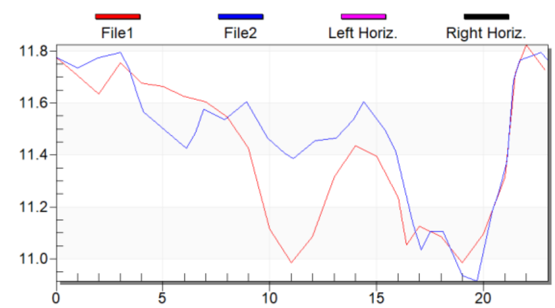
Station 35



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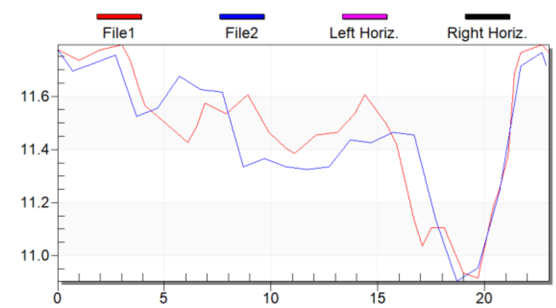

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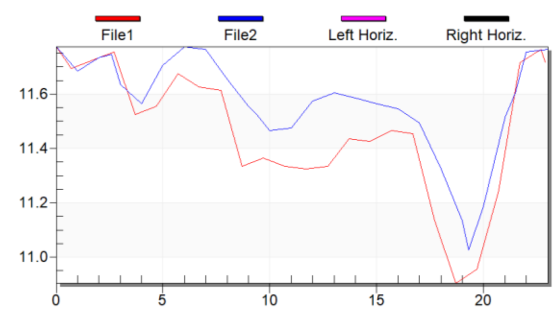

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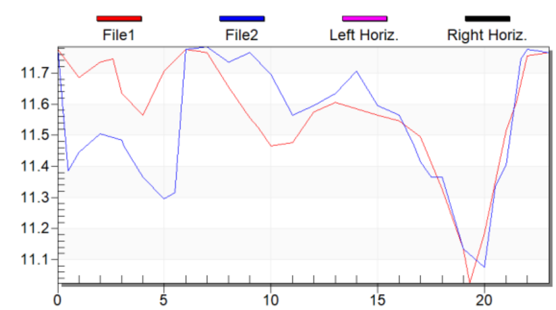

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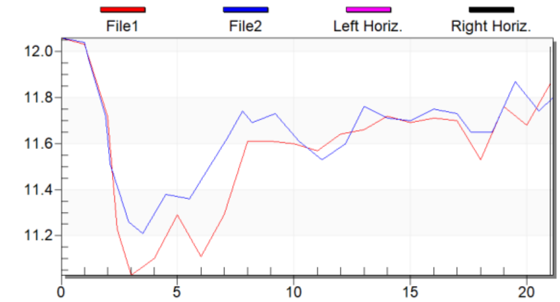
Station 36



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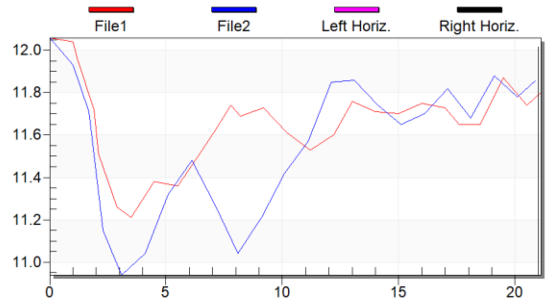

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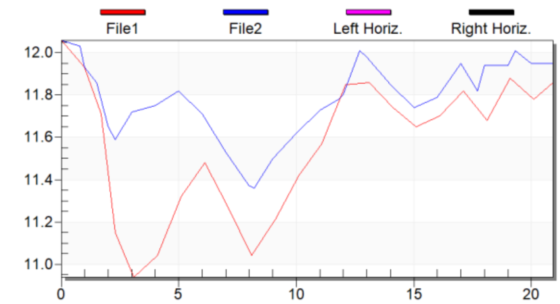

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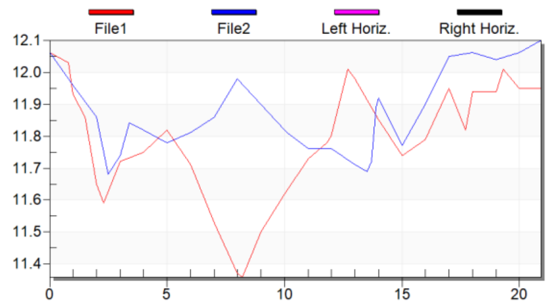

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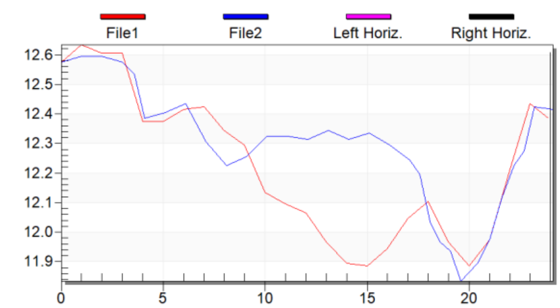
Station 37



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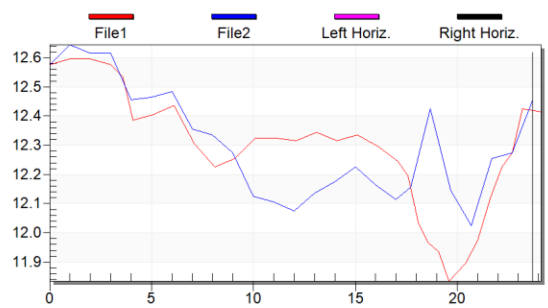

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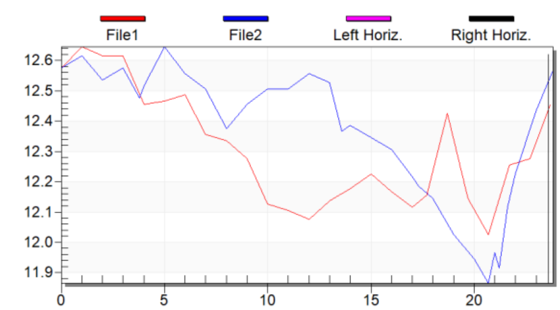

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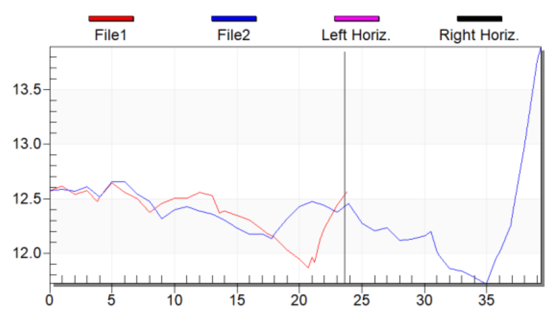

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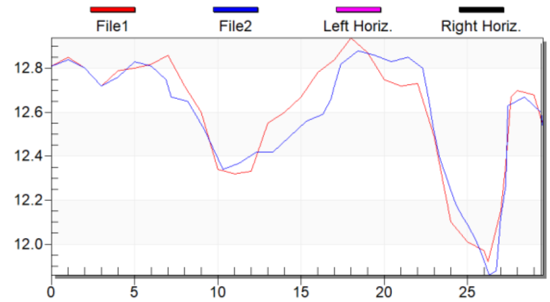
Station 38



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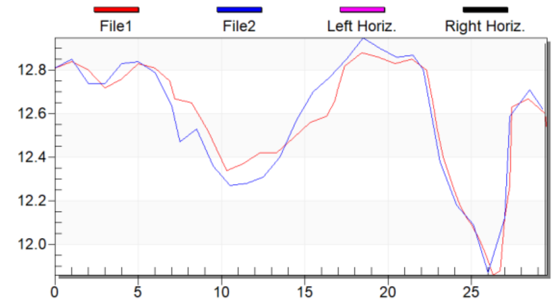

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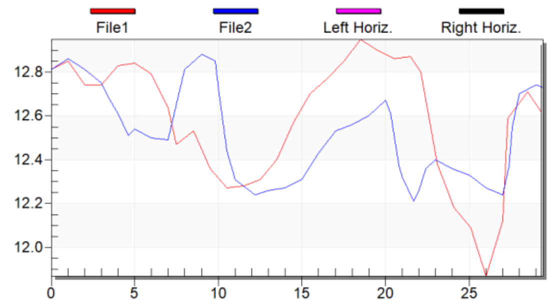

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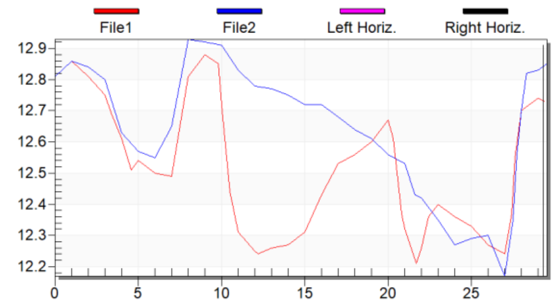
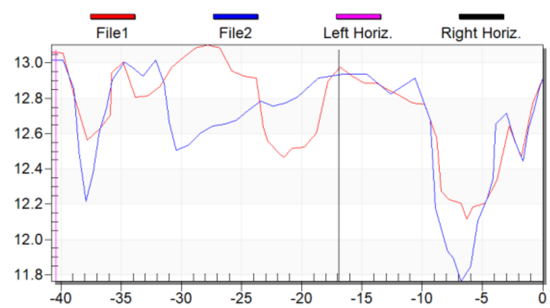


17

Station 39 – main channel



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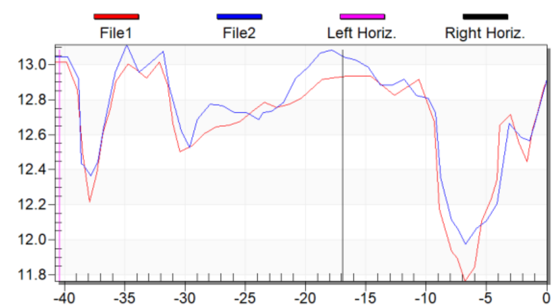

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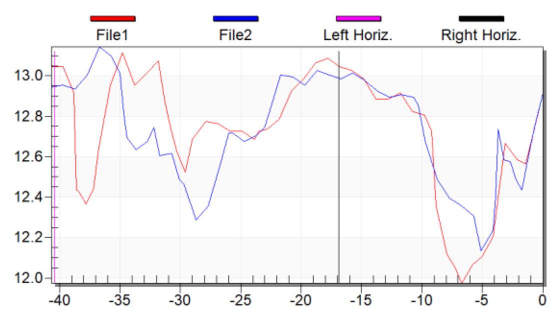

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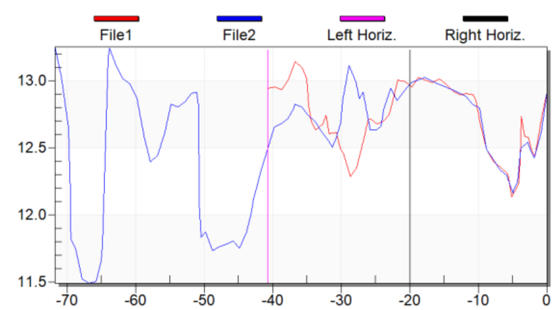
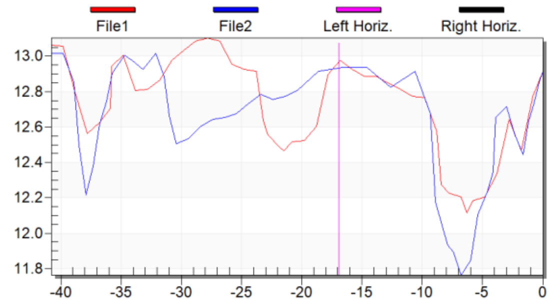


17

Station 39 – left bank side channel



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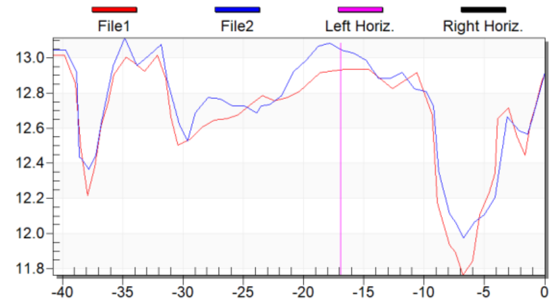

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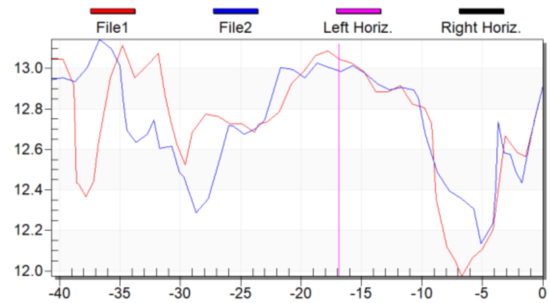

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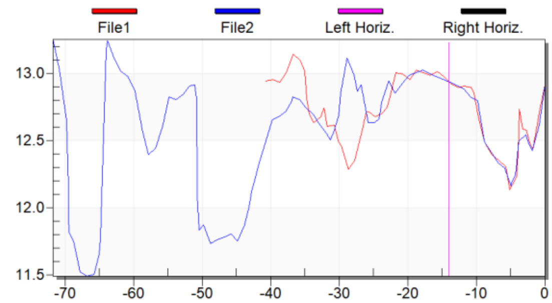

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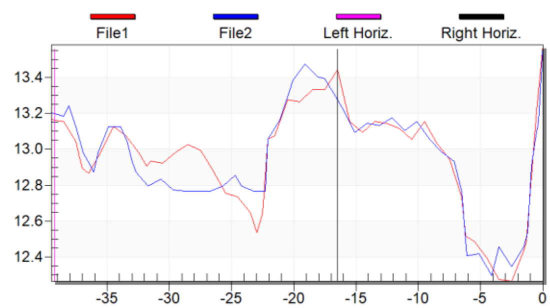
Station 40 – main channel



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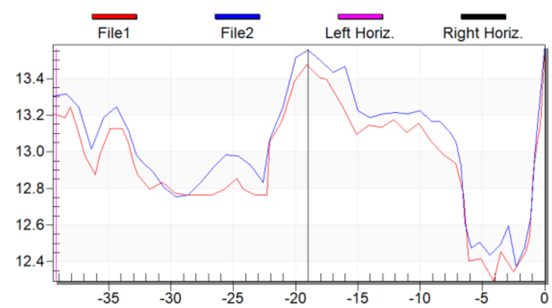

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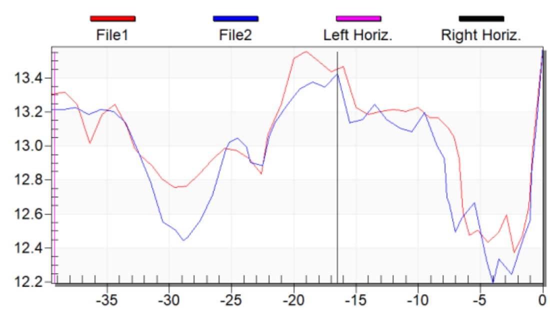

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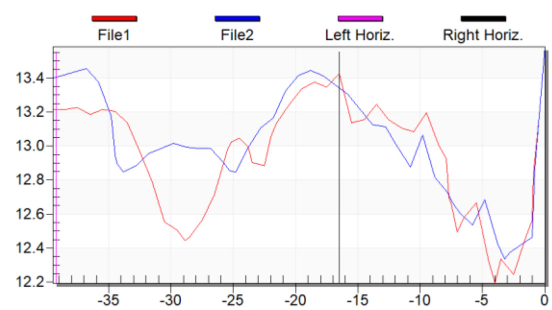

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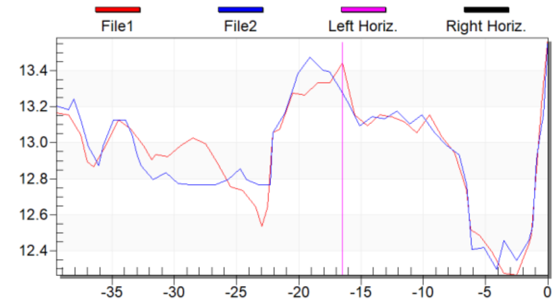
Station 40 – left bank side channel



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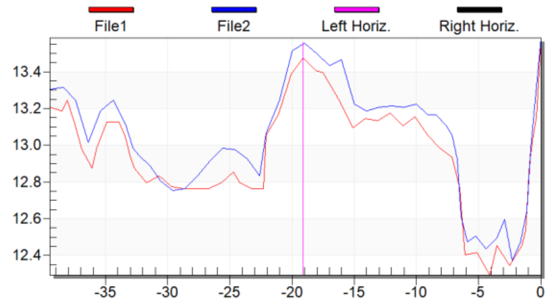

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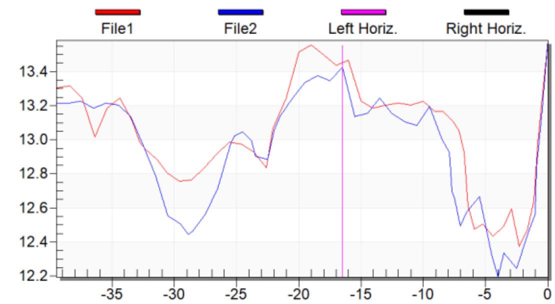

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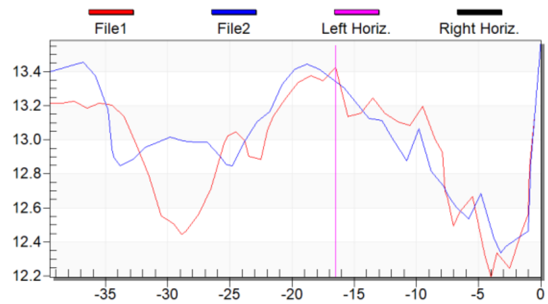

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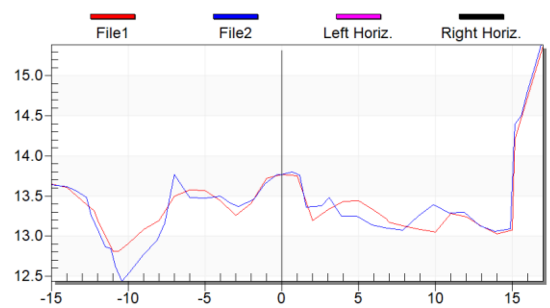
Station 41 – main channel



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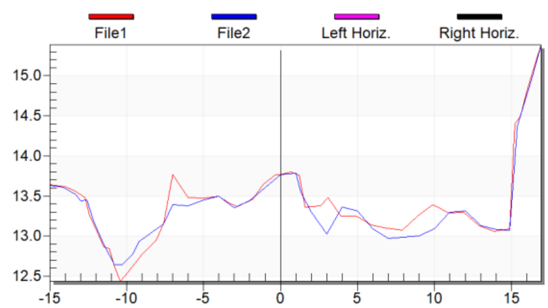

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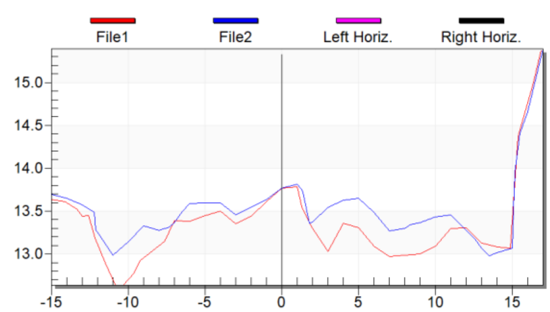

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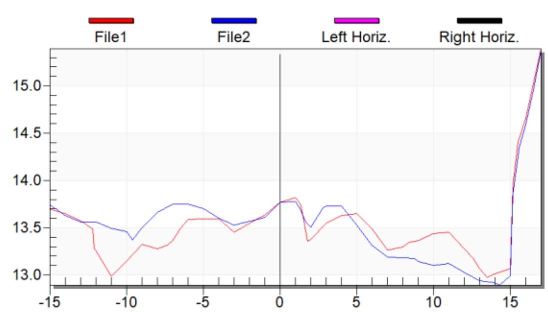

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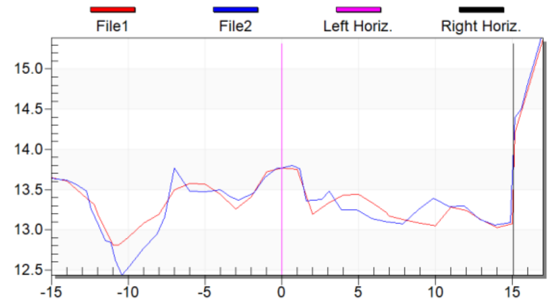
Station 41 – left bank side channel



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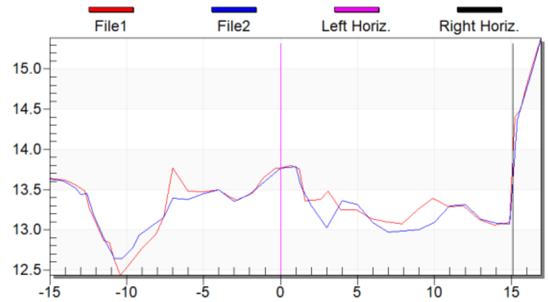

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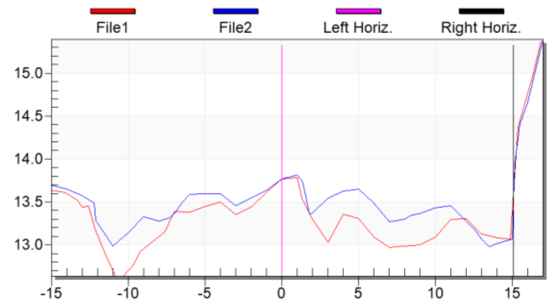

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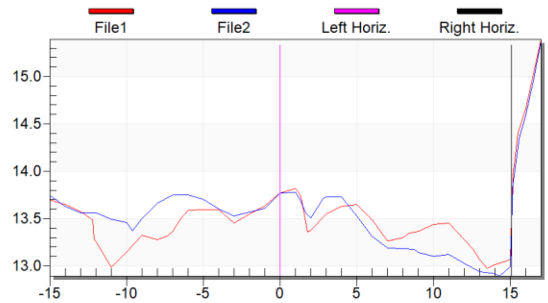

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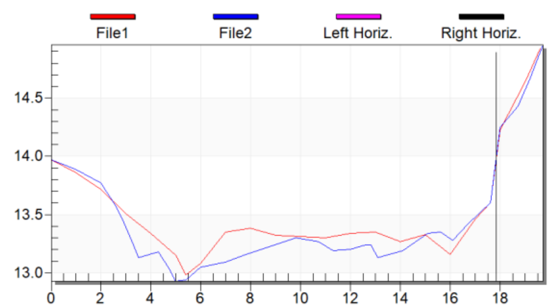
Station 42



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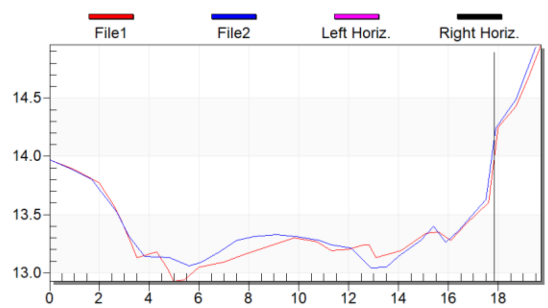

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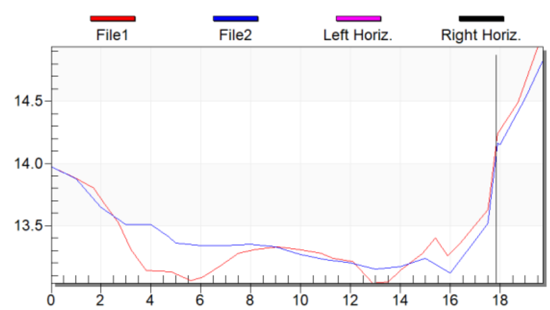

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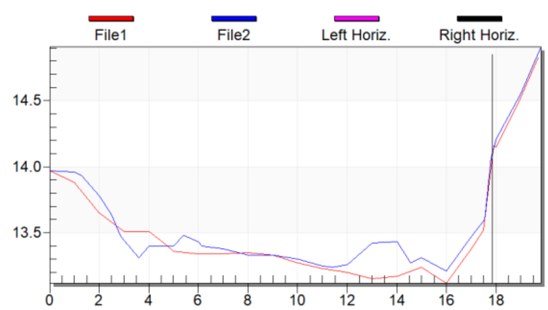

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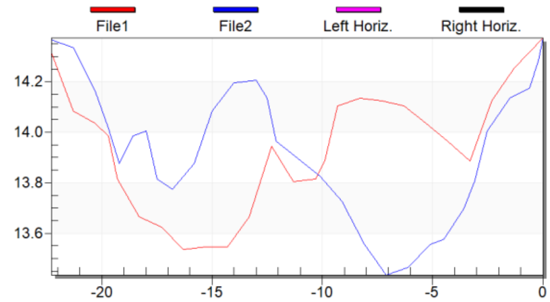
Station 43



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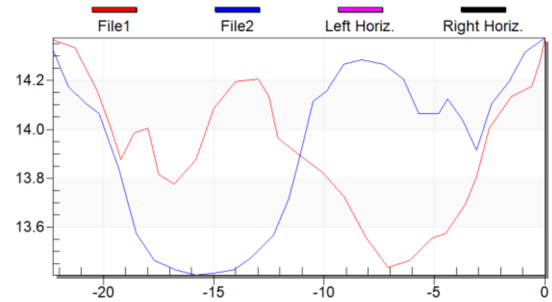

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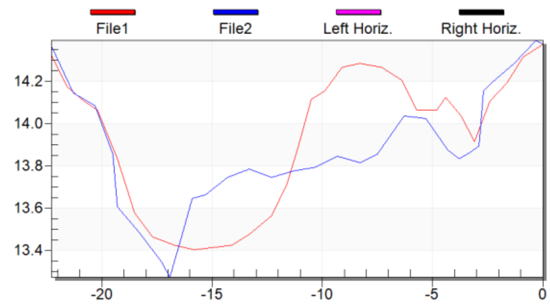

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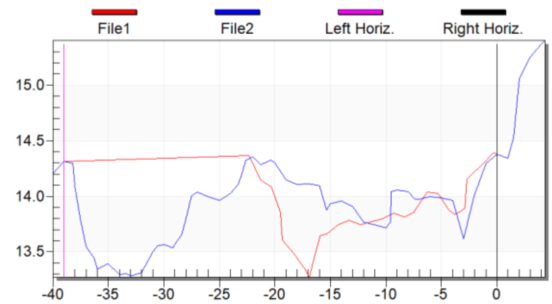

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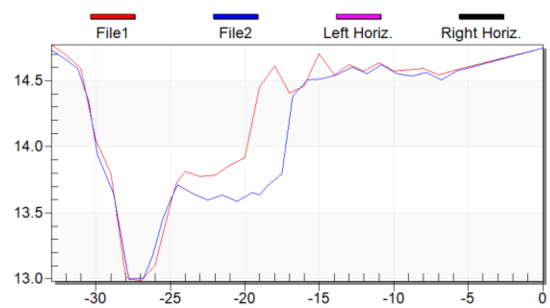
Station 44



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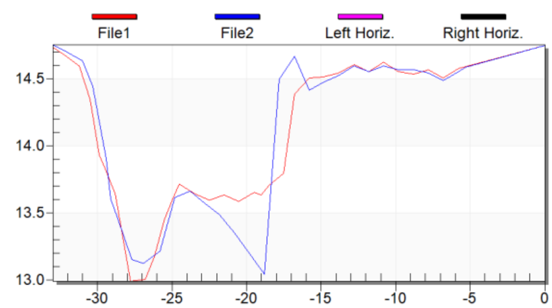

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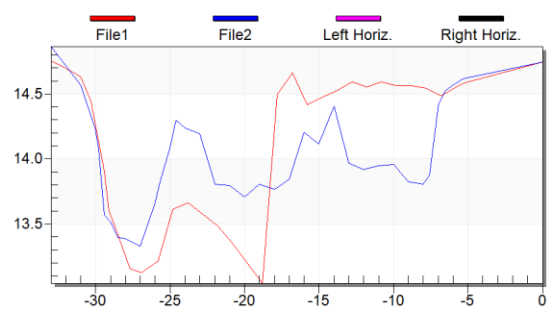

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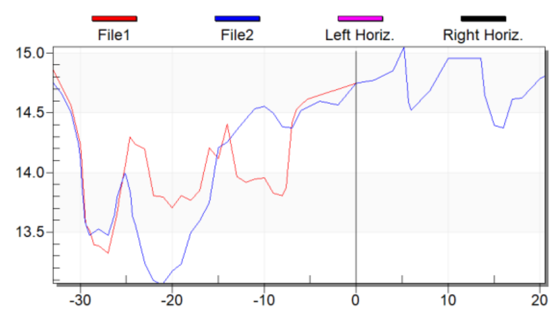

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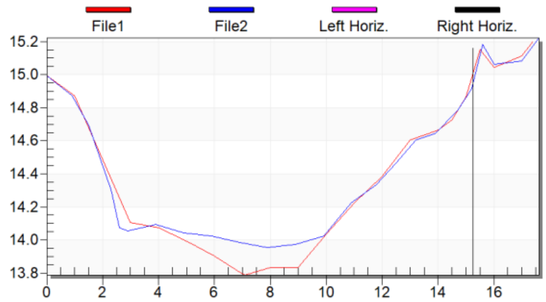
Station 45



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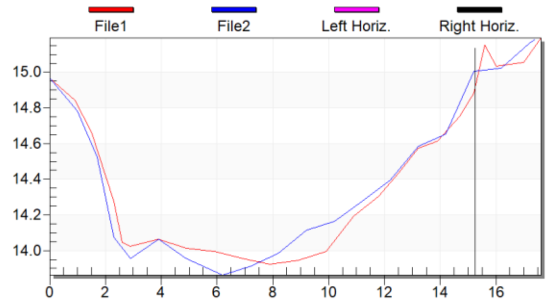

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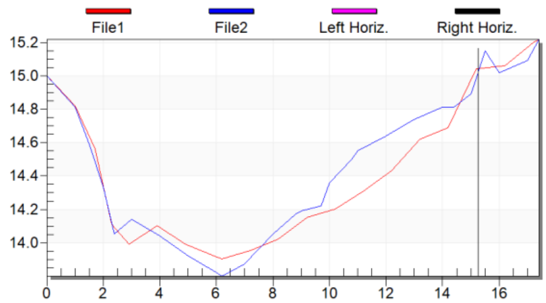

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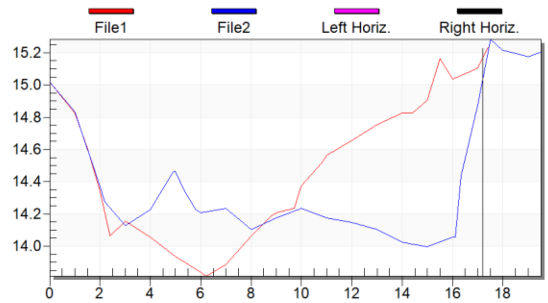

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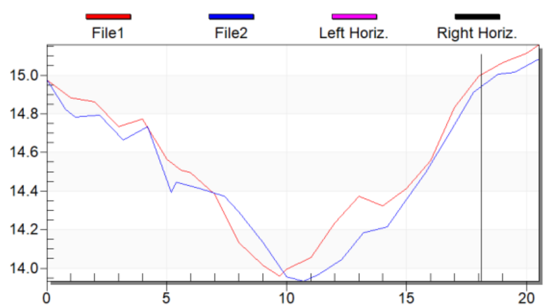
Station 46



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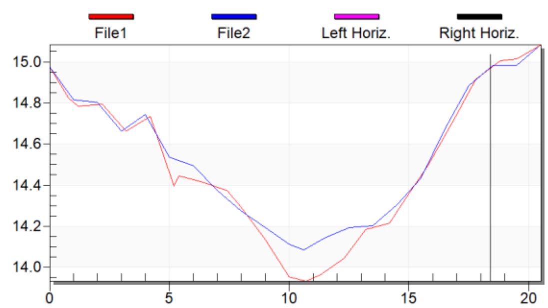

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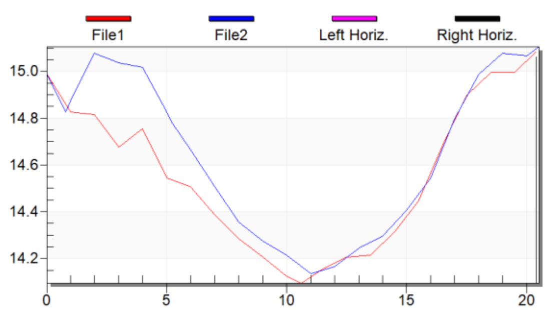

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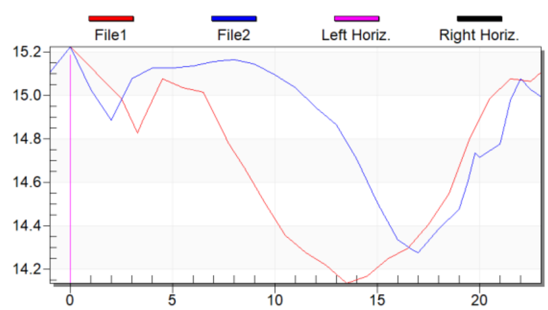

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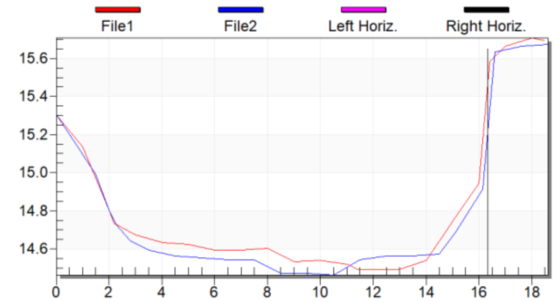

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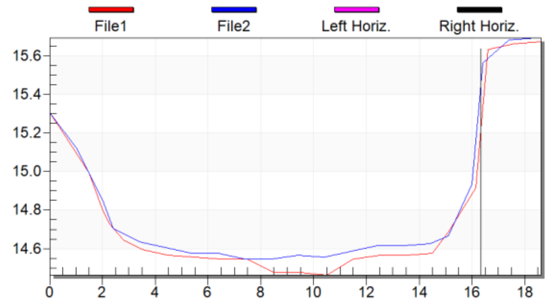

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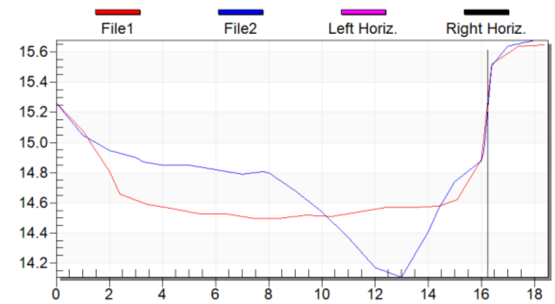

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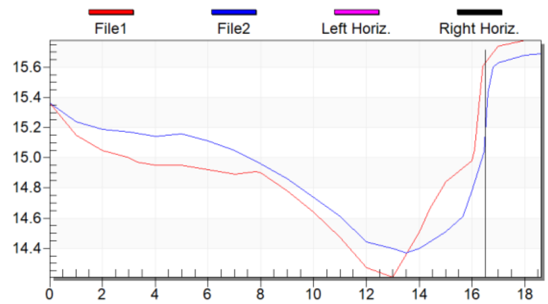

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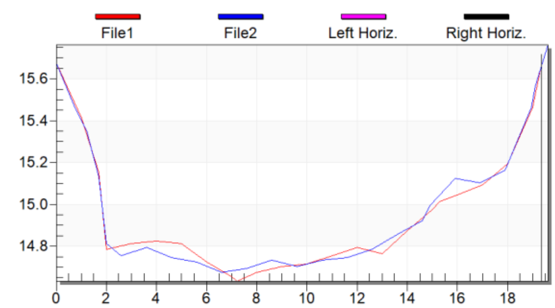

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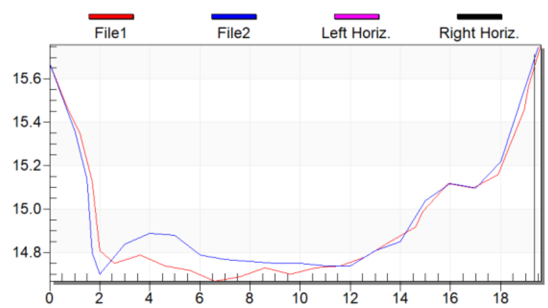

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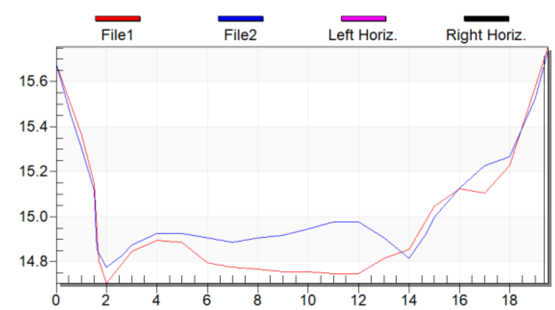

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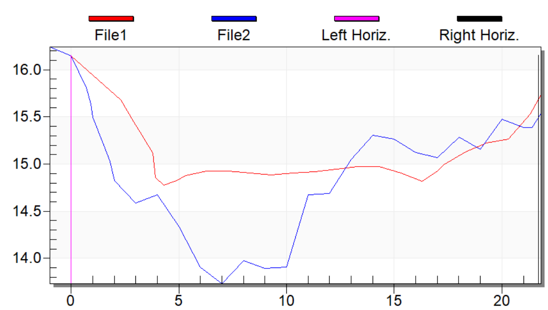

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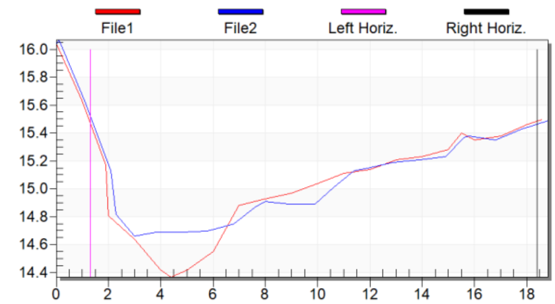

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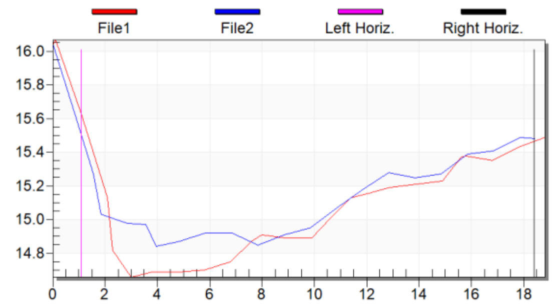

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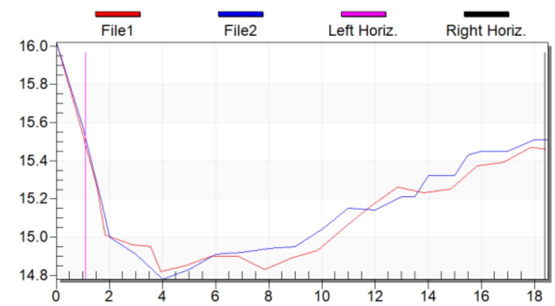

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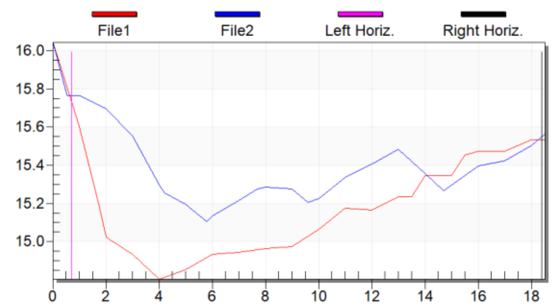

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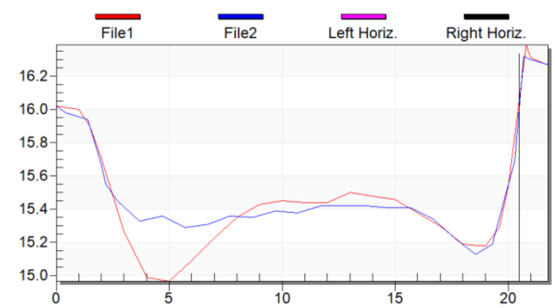

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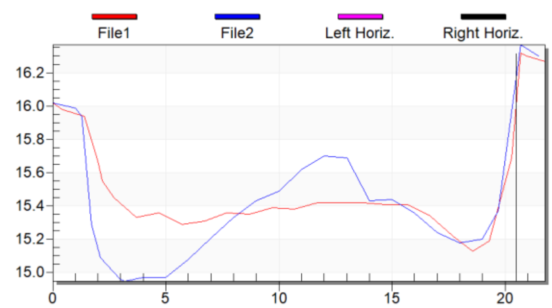

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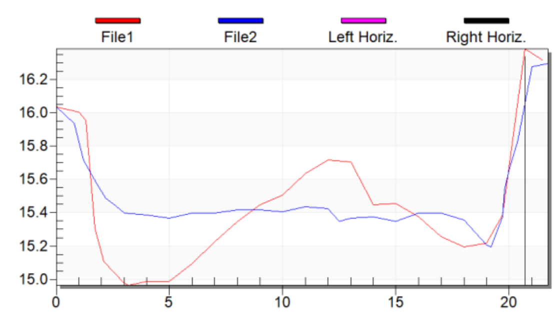

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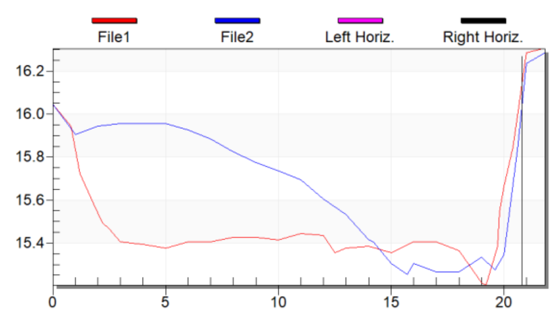
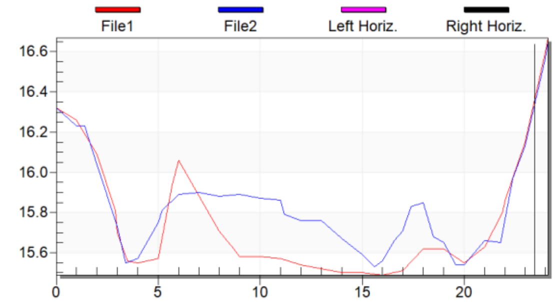


17

Stations 51-66 – water year 2017 only



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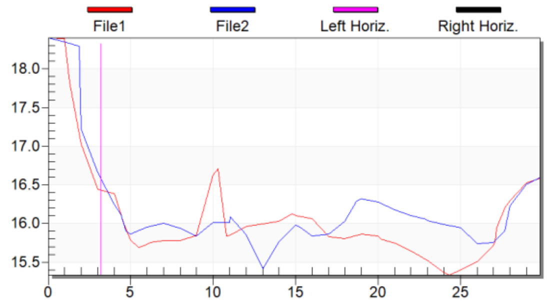

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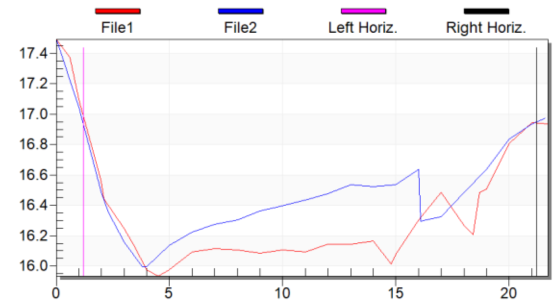

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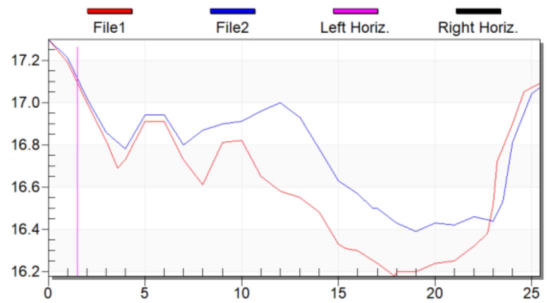

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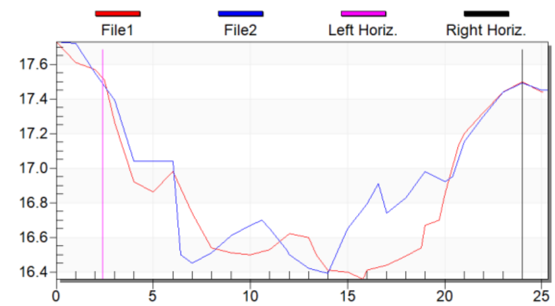

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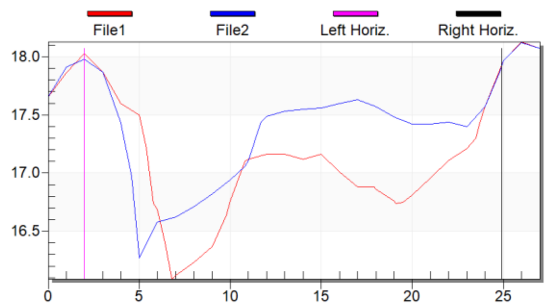

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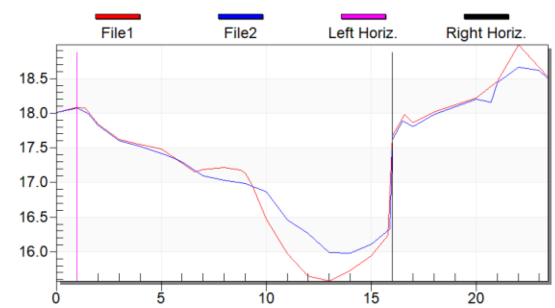

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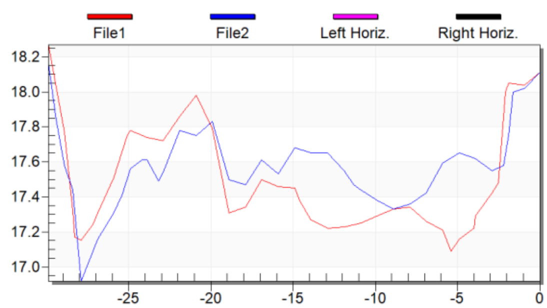

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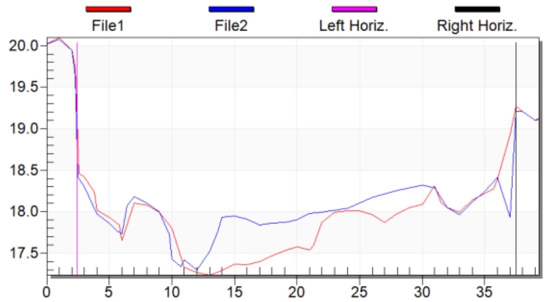

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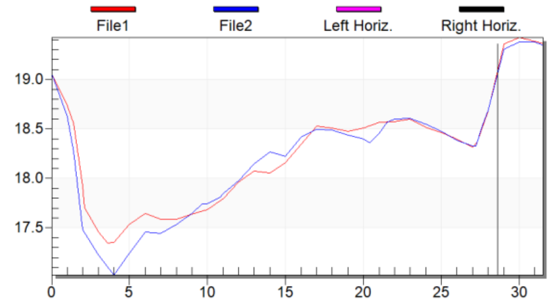

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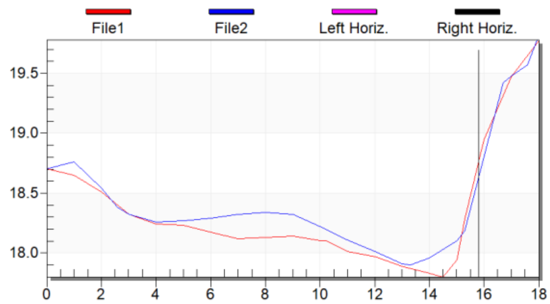

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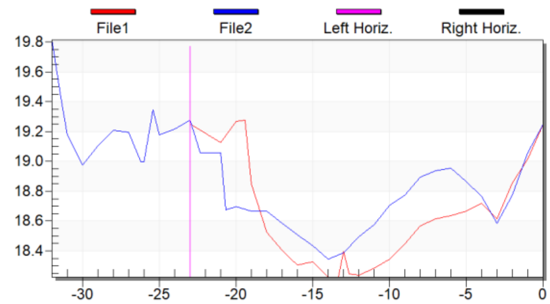

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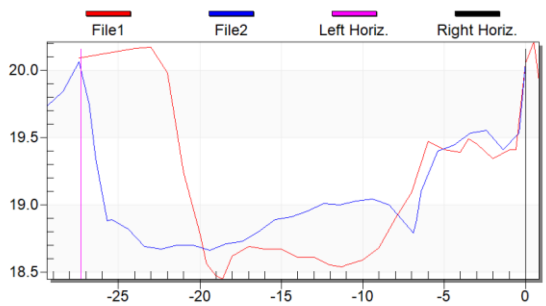

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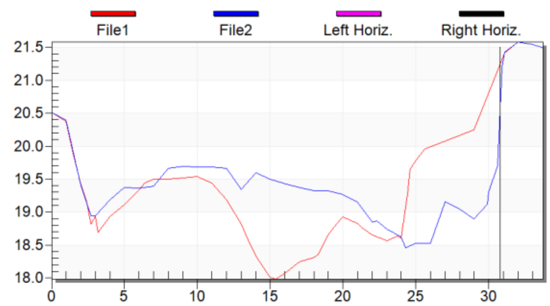

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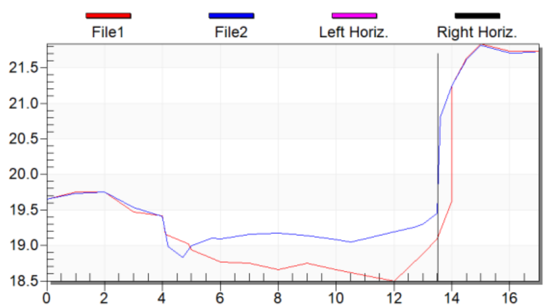

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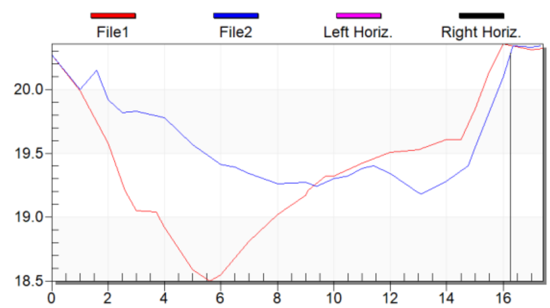
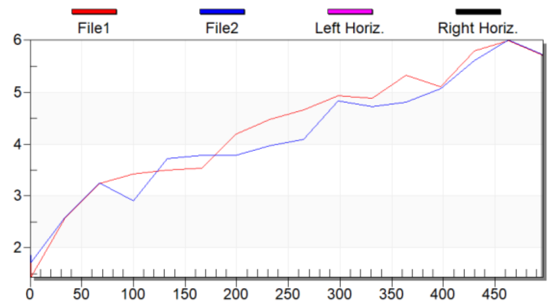


66

Appendix B. Data plots analyzed within WinXSPRO for changes in vertical thalweg profile, WY2014-17 (sub-reaches 1-3) and WY2017 only (sub-reach 4).

Sub-Reach 1



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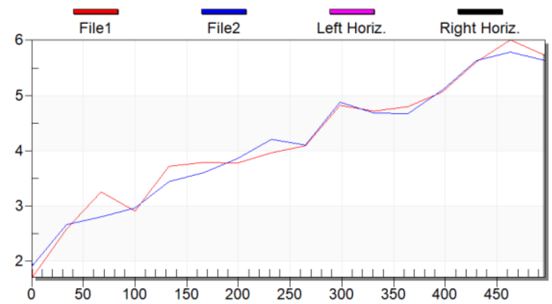

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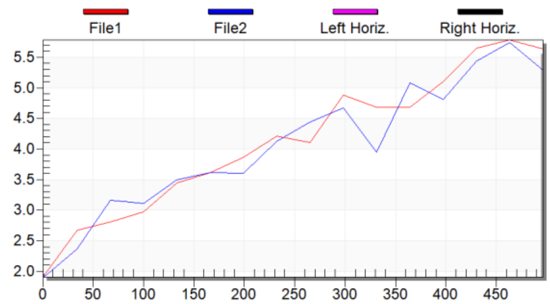

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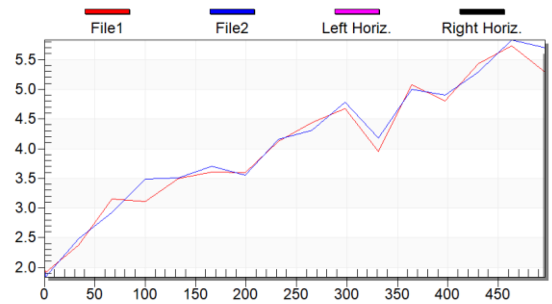
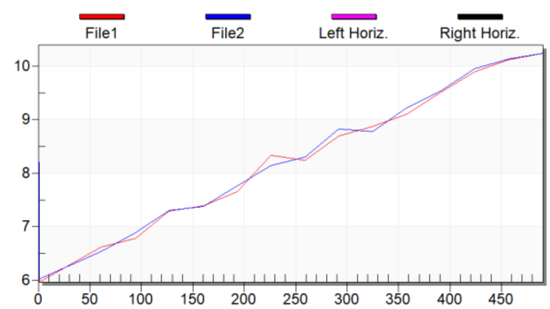


17

Sub-Reach 2



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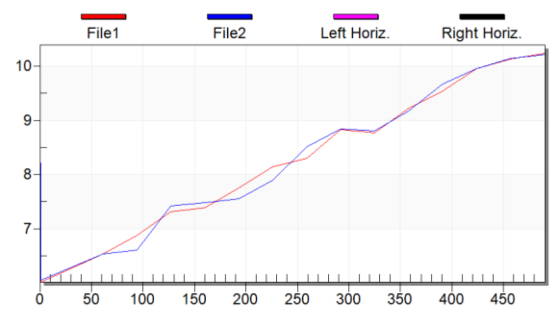

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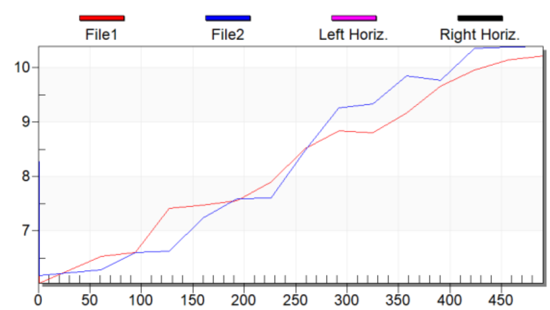

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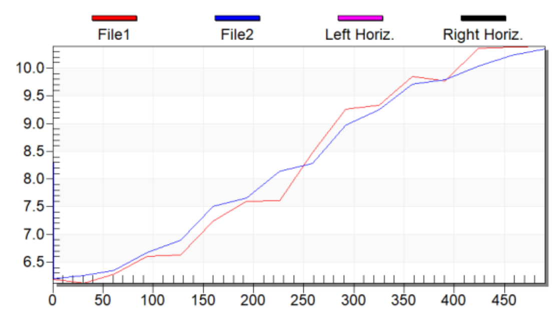
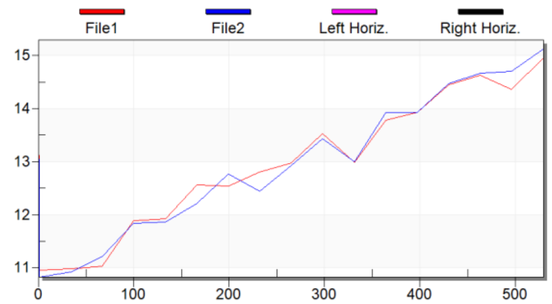


17

Sub-Reach 3



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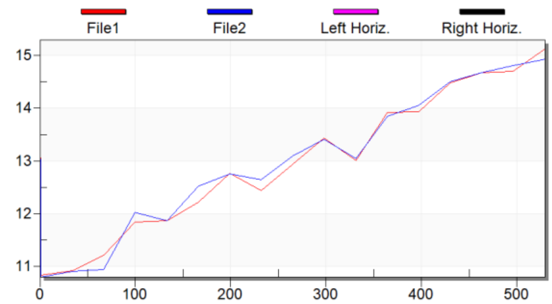

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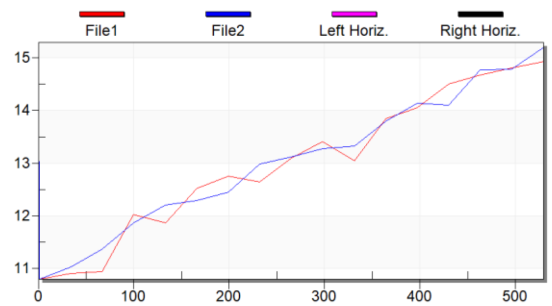

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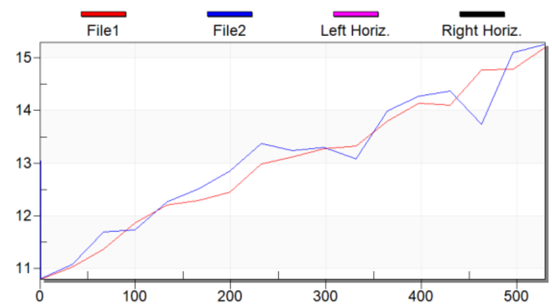
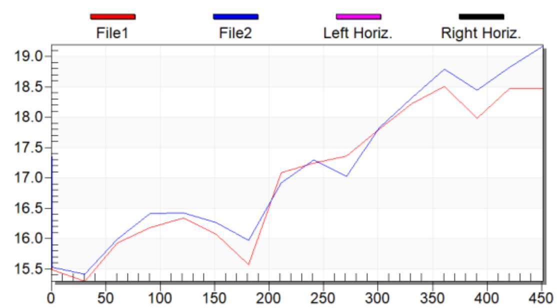


17

Sub-Reach 4



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Appendix C. Summary data tables.

Summary of absolute and net changes in vertical thalweg profile area (m^2) at lower Big Beef Creek mainstem, water years 2014-2017. The results for sub-reach 4 are shown as reference but not included in pre/post treatment analysis.

Sub-Reach	Water Year	Number of Samples	Sum of Absolute Change	Mean Absolute Change (CV)	Sum of Net Change	Mean of Net Change (CV)
Pre-Treatment		38	329.0	8.66 (1.53)	75.2	1.98 (7.95)
1		11	165.2	15.02 (1.48)	98.6	8.96 (2.86)
	2014	4	109.0	27.25 (1.27)	76.8	19.20 (2.15)
	2015	7	56.2	8.03 (1.05)	21.8	3.11 (3.73)
2		14	61.3	4.38 (0.72)	-3.9	-0.28 (19.85)
	2014	7	25.1	3.59 (0.61)	-8.7	-1.24 (3.41)
	2015	7	36.2	5.17 (0.76)	4.8	0.69 (9.90)
3		13	102.5	7.88 (0.94)	-19.5	-1.50 (7.29)
	2014	7	58.6	8.37 (0.67)	2.0	0.29 (37.26)
	2015	6	43.9	7.32 (1.32)	-21.5	-3.58 (3.32)
Post-Treatment		41	528.8	12.90 (1.27)	-83.2	-2.03 (10.26)
1		17	134.8	7.93 (0.83)	8.4	0.49 (21.19)
	2016	7	89.4	12.77 (0.50)	31.2	4.46 (3.24)
	2017	10	45.4	4.54 (0.94)	-22.8	-2.28 (2.61)
2		5	213.5	42.70 (0.67)	-36.9	-7.38 (7.44)
	2016	3	133.5	44.50 (0.90)	-30.7	-10.23 (6.49)
	2017	2	80.0	40.00 (0.11)	-6.2	-3.10 (18.25)
3		19	180.5	9.50 (1.02)	-54.7	-2.88 (4.66)
	2016	12	73.5	6.13 (0.85)	-18.3	-1.53 (5.32)
	2017	7	107.0	15.29 (0.85)	-36.4	-5.20 (3.89)
4	2017	5	60.0	18.0 (0.89)	-66.8	-13.4 (0.55)

Mean values and coefficient of variation (CV) for channel metrics (1) gradient (% slope), (2) bank height (m), (3) bank width (m), and (4) channel width to depth ratio (w/d) at lower Big Beef Creek main channel, 2013-2017.

Sub-Reach	Year	Number of Samples	Mean Gradient (CV)	Mean Bank Height (CV)	Mean Bank Width (CV)	Mean Width/Depth Ratio (CV)
Pre-Treatment		160	0.83 (1.22)	0.90 (0.29)	20.85 (0.33)	25 (0.44)
1		48	0.82 (1.27)	0.88 (0.34)	23.46 (0.41)	29 (0.44)
	2013	16	0.86 (1.29)	0.78 (0.42)	23.40 (0.42)	34 (0.47)
	2014	16	0.81 (1.40)	0.92 (0.33)	23.49 (0.42)	27 (0.39)
	2015	16	0.78 (1.15)	0.95 (0.25)	23.49 (0.42)	25 (0.38)
2		45	0.98 (0.68)	0.87 (0.19)	17.36 (0.27)	21 (0.37)
	2013	15	1.01 (0.72)	0.88 (0.19)	17.15 (0.29)	20 (0.38)
	2014	15	0.97 (0.59)	0.86 (0.17)	17.48 (0.27)	21 (0.35)
	2015	15	0.96 (0.78)	0.87 (0.23)	17.45 (0.27)	21 (0.39)
3		51	0.78 (1.40)	0.93 (0.27)	20.99 (0.21)	24 (0.37)
	2013	17	0.76 (1.56)	0.94 (0.27)	20.99 (0.21)	24 (0.39)
	2014	17	0.81 (1.33)	0.94 (0.25)	20.99 (0.21)	24 (0.35)
	2015	17	0.78 (1.42)	0.91 (0.29)	20.99 (0.21)	25 (0.39)
4	2016	16	0.61 (2.52)	0.97 (0.38)	22.43 (0.26)	27 (0.55)
Post-Treatment		114	0.83 (1.30)	0.88 (0.37)	21.72 (0.33)	28 (0.50)
1		32	0.82 (1.60)	1.00 (0.33)	24.25 (0.38)	25 (0.35)
	2016	16	0.81 (1.84)	1.03 (0.36)	24.00 (0.39)	25 (0.42)
	2017	16	0.83 (1.39)	0.98 (0.31)	24.50 (0.37)	26 (0.29)
2		30	0.84 (0.95)	0.83 (0.38)	16.85 (0.22)	24 (0.57)
	2016	15	0.85 (1.15)	0.85 (0.46)	16.71 (0.23)	26 (0.70)
	2017	15	0.84 (0.73)	0.82 (0.29)	16.99 (0.21)	22 (0.34)
3		36	0.86 (1.18)	0.82 (0.40)	22.85 (0.27)	33 (0.54)
	2016	18	0.86 (0.70)	0.85 (0.25)	21.47 (0.21)	27 (0.38)
	2017	18	0.87 (1.53)	0.80 (0.53)	24.24 (0.30)	38 (0.57)
4	2017	16	0.74 (1.69)	0.86 (0.31)	23.23 (0.26)	29 (0.38)

Changes in mean absolute and mean net cross-sectional area (m^2) and 3 sub-categories: mean erosion (m^2), mean aggradation (m^2), mean degradation (m^2) at lower Big Beef Creek main channel, WY's 2014-2017. Sub-reach 4 is shown as reference but not included within the pre/post-treatment analysis.

Sub-Reach	Water Year	Number of Samples	Mean Absolute change (CV)	Mean net change area (CV)	Mean Erosion (CV)	Mean Aggradation (CV)	Mean Degradation (CV)
Pre-Treatment		96	2.61 (0.87)	0.38 (6.41)	0.13 (3.07)	-1.12 (1.55)	1.37 (1.13)
1		32	3.84 (0.75)	0.96 (4.00)	0.13 (2.73)	-1.44 (1.92)	2.28 (0.84)
	2014	16	4.04 (0.59)	2.28 (1.01)	0.12 (3.58)	-0.88 (0.80)	3.04 (0.70)
	2015	16	3.65 (0.93)	-0.35 (13.29)	0.14 (1.95)	-2.00 (1.91)	1.51 (0.90)
2		30	1.81 (0.74)	0.15 (8.71)	0.20 (2.96)	-0.83 (0.77)	0.78 (1.36)
	2014	15	1.43 (0.55)	-0.30 (1.46)	0.09 (1.62)	-0.87 (0.51)	0.48 (1.05)
	2015	15	2.18 (0.76)	0.61 (2.89)	0.31 (2.63)	-0.79 (1.01)	1.08 (1.27)
3		34	2.16 (0.82)	0.04 (31.49)	0.06 (1.86)	-1.06 (0.88)	1.04 (1.24)
	2014	17	2.26 (0.70)	0.22 (5.79)	0.05 (2.14)	-1.02 (0.91)	1.19 (0.91)
	2015	17	2.07 (0.95)	-0.15 (5.84)	0.08 (1.68)	-1.11 (0.88)	0.88 (1.24)
Post -Treatment		97	4.37 (0.72)	0.19 (16.67)	0.60 (2.89)	-2.09 (0.82)	1.69 (1.33)
1		32	5.09 (0.81)	1.47 (2.37)	0.90 (2.36)	-1.81 (1.10)	2.38 (1.27)
	2016	16	6.07 (0.72)	1.19 (2.63)	1.25 (2.00)	-2.44 (1.03)	2.38 (1.10)
	2017	16	4.12 (0.93)	1.74 (2.23)	0.56 (3.05)	-1.19 (0.88)	2.38 (1.46)
2		31	3.72 (0.47)	-0.23 (13.60)	0.34 (2.64)	-1.97 (0.91)	1.41 (1.09)
	2016	15	4.66 (0.31)	-0.65 (6.38)	0.59 (2.07)	-2.65 (0.84)	1.41 (1.14)
	2017	16	2.83 (0.57)	0.16 (12.37)	0.09 (1.93)	-1.34 (0.70)	1.40 (1.08)
3		34	4.30 (0.71)	-0.61 (4.54)	0.55 (3.44)	-2.46 (0.54)	1.29 (1.38)
	2016	17	3.58 (0.64)	-0.84 (2.25)	0.11 (1.70)	-2.21 (0.56)	1.26 (1.33)
	2017	17	5.03 (0.71)	-0.39 (8.93)	0.99 (2.67)	-2.71 (0.52)	1.33 (1.47)
4	2017	16	5.83 (0.74)	-2.18 (1.10)	0.86 (2.15)	-4.01 (0.60)	0.97 (1.45)

Mean values and coefficient of variation (CV) for channel metrics (1) bank height (m), (2) bank width (m), and (3) channel width to depth ratio at lower Big Beef Creek side channels, 2013-2017.

Sub-Reach	Year	Number of Samples	Mean Bank Height (CV)	Mean Bank Width (CV)	Mean Width/Depth Ratio (CV)
Pre-Treatment		39	0.82 (0.28)	10.68 (0.34)	14 (0.41)
2		27	0.85 (0.31)	9.67 (0.35)	12 (0.44)
	2013	9	0.85 (0.29)	9.67 (0.36)	12 (0.44)
	2014	9	0.88 (0.37)	9.67 (0.36)	12 (0.48)
	2015	9	0.83 (0.31)	9.67 (0.36)	12 (0.44)
3		12	0.75 (0.14)	12.98 (0.25)	18 (0.27)
	2013	4	0.72 (0.16)	12.98 (0.28)	19 (0.36)
	2014	4	0.78 (0.20)	12.98 (0.28)	17 (0.24)
	2015	4	0.76 (0.32)	12.98 (0.34)	17 (0.44)
Post-Treatment		26	0.98 (0.33)	11.15 (0.35)	13 (0.50)
2		18	1.10 (0.28)	10.06 (0.38)	9 (0.34)
	2016	9	1.11 (0.31)	10.00 (0.40)	9 (0.37)
	2017	9	1.08 (0.27)	10.11 (0.38)	10 (0.33)
3		8	0.72 (0.21)	13.63 (0.22)	20 (0.30)
	2016	4	0.72 (0.28)	12.98 (0.28)	19 (0.38)
	2017	4	0.73 (0.17)	14.28 (0.17)	20 (0.27)

Changes in mean absolute and mean net cross-sectional area (m^2) and 3 sub-categories: mean erosion (m^2), mean aggradation (m^2), mean degradation (m^2) at lower Big Beef Creek side channels, WY's 2014-2017. Sub-reach 4 is shown as reference but not included within the pre/post-treatment analysis.

Sub-Reach	Water Year	Number of Samples	Mean Absolute Change Area (CV)	Mean Net Change Area (CV)	Mean Erosion (CV)	Mean Aggradation (CV)	Mean Degradation (CV)
Pre-Treatment		26	0.58 (0.85)	0.03 (13.84)	0.07 (1.99)	-0.28 (0.97)	0.23 (1.40)
2		18	0.47 (0.83)	0.02 (17.00)	0.09 (1.80)	-0.23 (1.09)	0.15 (1.10)
	2014	9	0.31 (0.73)	-0.11 (1.71)	0.00 (0)	-0.21 (0.69)	0.10 (1.50)
	2015	9	0.63 (0.73)	0.14 (2.16)	0.19 (1.07)	-0.24 (1.36)	0.20 (0.87)
3		8	0.83 (0.77)	0.05 (10.95)	0.03 (1.85)	-0.39 (0.76)	0.41 (1.21)
	2014	4	1.00 (0.72)	0.05 (10.13)	0.05 (1.15)	-0.48 (0.50)	0.48 (1.16)
	2015	4	0.65 (0.91)	0.05 (13.32)	0.00 (0)	-0.30 (1.19)	0.35 (1.48)
Post-Treatment		26	1.26 (0.94)	0.40 (3.39)	0.14 (2.24)	-0.43 (1.56)	0.69 (1.38)
2		18	1.12 (1.12)	0.58 (2.17)	0.12 (1.91)	-0.27 (1.41)	0.73 (1.49)
	2016	9	1.57 (0.99)	1.06 (1.54)	0.11 (1.88)	-0.26 (1.39)	1.20 (1.14)
	2017	9	0.67 (1.00)	0.11 (4.60)	0.13 (2.02)	-0.28 (1.51)	0.26 (1.33)
3		8	1.58 (0.63)	-0.03 (60.24)	0.18 (2.61)	-0.80 (1.28)	0.60 (1.04)
	2016	4	1.90 (0.57)	-0.70 (2.76)	0.33 (2.00)	-1.30 (1.00)	0.28 (0.91)
	2017	4	1.25 (0.75)	0.65 (0.91)	0.03 (2.00)	-0.30 (1.05)	0.93 (0.81)

: Whole Area, all habtypes, pools only, non-pool, avulsion channel at bottom.

	Number of Samples	Total Area (m^2)	Mean Unit Area (CV)	Mean Maximum Pool Depth (CV)
Wetted Channel				
Pre-Treatment	468	56712.9	121.2 (1.50)	0.62 (0.52)
main.channel	304	50230.8	165.2 (1.26)	0.66 (0.49)
side.channel	164	6482.1	39.5 (1.56)	0.49 (0.52)
Post-Treatment	489	47380.1	96.8 (1.47)	0.47 (0.57)
main.channel	215	30701.3	142.8 (1.19)	0.54 (0.50)
side.channel	274	16678.8	60.9 (1.72)	0.42 (0.61)
Pools				
Pre-Treatment	234	34619.70	147.95 (1.34)	0.62 (0.52)
main.channel	162	29787.53	183.87 (1.21)	0.66 (0.49)
side.channel	72	4832.17	67.11 (1.20)	0.49 (0.52)
Post-Treatment	248	33894.75	136.67 (1.30)	0.47 (0.57)
main.channel	111	22395.86	201.76 (1.00)	0.54 (0.50)
side.channel	137	11498.89	83.93 (1.60)	0.42 (0.61)
Non-Pool				
Pre-Treatment	234	22093.22	94.42 (1.71)	NA
main.channel	142	20443.25	143.97 (1.33)	NA
side.channel	92	1649.97	17.93 (1.39)	NA
Post-Treatment	241	13485.32	55.96 (1.35)	NA
main.channel	104	8305.41	79.86 (1.16)	NA
side.channel	137	5179.91	37.81 (1.41)	NA
Avulsion Channel				
Post-Treatment	48	3593.22	74.86 (2.29)	0.37 (0.54)

Summary of habitat metrics total area (m²), mean habitat unit area (m²), and mean maximum pool depth (m) including the coefficient of variation (CV) for mean values. ELJNo whole survey, pools, non pool top, ELJYes whole survey, pools, non pool bottom

Row Labels	Number of Samples	Total Area (m^2)	Mean Unit Area (CV)	Mean Maximum Pool Depth (CV)
Wet Channel Habitat				
Pre-Treatment	424	48191.2	113.7 (1.54)	NA
main.channel	265	41910.1	158.2 (1.28)	NA
side.channel	159	6281.1	39.5 (1.58)	NA
Post-Treatment	425	40125.3	94.4 (1.53)	NA
main.channel	159	24418.3	153.6 (1.16)	NA
side.channel	266	15707.0	59.1 (1.76)	NA
Pools				
Pre-Treatment	207	27630.43	133.48 (1.36)	0.59 (0.53)
main.channel	137	22938.60	167.44 (1.24)	0.64 (0.51)
side.channel	70	4691.83	67.03 (1.22)	0.49 (0.52)
Post-Treatment	206	27277.25	132.41 (1.39)	0.46 (0.60)
main.channel	77	16750.18	217.53 (1.01)	0.53 (0.53)
side.channel	129	10527.07	81.61 (1.66)	0.41 (0.64)
Non-Pool				
Pre-Treatment	217	20560.74	94.75 (1.75)	NA
main.channel	128	18971.47	148.21 (1.34)	NA
side.channel	89	1589.27	17.86 (1.42)	NA
Post-Treatment	219	12848.03	58.67 (1.32)	NA
main.channel	82	7668.12	93.51 (1.04)	NA
side.channel	137	5179.91	37.81 (1.41)	NA
Wet Channel Habitat				
Pre-Treatment	44	8521.7	193.7 (1.21)	0.71 (0.46)
main.channel	39	8320.7	213.35 (1.13)	0.71 (0.46)
side.channel	5	201.0	40.21 (0.75)	NA
Post-Treatment	64	7254.8	113.36 (1.19)	0.55 (0.43)
main.channel	56	6283.0	112.20 (1.24)	0.56 (0.46)
side.channel	8	971.8	121.48 (0.87)	0.51 (0.22)
Pools				
Pre-Treatment	27	6989.26	258.86 (1.05)	0.71 (0.46)
main.channel	25	6848.92	273.96 (1.02)	0.71 (0.46)
side.channel	2	140.34	70.17 (0.33)	
Post-Treatment	42	6617.50	157.56 (0.92)	0.55 (0.43)
main.channel	34	5645.68	166.05 (0.92)	0.56 (0.46)
side.channel	8	971.82	121.48 (0.87)	0.51 (0.22)
Non-Pool				
Pre-Treatment	17	1532.48	90.15 (1.72)	NA
main.channel	14	1471.78	105.13 (1.50)	NA
side.channel	3	60.70	20.23 (1.26)	NA
Post-Treatment	22	637.29	28.97 (1.47)	NA
main.channel	22	637.29	28.97 (1.19)	NA
side.channel	0	NA	NA	NA