CHANNEL ADJUSTMENTS AND SALMONID HABITAT ALTERATION DUE TO EMERGENCY DREDGING IN CREIGHTON CREEK

by

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Abstract

Creighton Creek, near Lumby, British Columbia, is a small, snow-melt driven, fish-bearing stream that has had its lower reaches confined due to agricultural, residential, and industrial development. Over the past four decades, the channel bed has aggraded and the channel geometry has become tortuous and multi-threaded causing habitat degradation and increased flood frequency. Therefore, in May 2017, emergency orders allowed instream dredging operations to take place without significant planning. The availability of pre-dredge data on channel characteristics provided a unique opportunity to quantify the geomorphic adjustments caused by the emergency dredging operations.

An extensive field data set and hydraulic models were used to quantify the spatial and temporal changes within the study reach across three time periods including: (1) the 2015-2016 pre-treatment period; (2) the 2017 immediate post-treatment period; and (3) the 2018 recovery period, which includes the channel response after one freshet. During the 2018 freshet, large volumes of material infilled the dredged zone, returning the streambed to its initial grade. Study observations suggest that the stream was not supply-limited and that the material deposited in the dredged zone was from upstream sources. A reduction in sediment transport potential within the affected zone immediately after dredging was consistent with general coarsening of the stream bed substrate. After recovery, there was a degradation of salmonid habitat in the dredged zone because of grain-size coarsening.

The research suggests that human modifications to stream channels should only be undertaken with full understanding of the broader (and long-term) geomorphic and hydrologic context of the reach. Emergency dredging operations, as occurred in Creighton Creek, may have relatively minor long-term impacts on stream characteristics as reflected in the longitudinal profile or in various average flow parameters. However, this is only the case if there is ample sediment supply that enables the system to return to its pre-dredging state. Despite the stream re-achieving grade quickly, there may be impacts on fisheries habitat quality, especially as reflected in substrate size distributions. These observations from this study can be used to inform management decisions, emergency response procedures, and improve salmonid habitat in systems like Creighton Creek.

Lay Summary

Small streams have been heavily modified throughout the past century, impacting geomorphic processes and fisheries habitat. Creighton Creek is a small snow-melt driven stream containing critical salmonid habitat near Lumby, BC. Creighton Creek's floodplains have been heavily modified for agricultural use, resulting in several sanctioned and unsanctioned modifications within the study reach to reduce flood frequency and improve habitat. These activities in the creek provide a unique opportunity to assess how geomorphic and hydraulic parameters are impacted by unplanned dredging works, a common practice in BC under states of emergency declarations caused by flooding. The motivation for the research is to provide empirical evidence in support of better outcomes for stream rehabilitation projects and emergency works that may impact salmonid habitat

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Abbreviations

BCEMS	British Columbia Emergency Management System
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
D_{10}	Grain size where 10% of the grains are smaller than in the distribution
D_{50}	Median grain size in a distribution
D_{90}	Grain size where 90% of the grains are smaller than in the distribution
FLNRORD	British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development
IFC	Interior Fraser Coho
LWD	Large Woody Debris
MOT	British Columbia Ministry of Transportation
SARA	Canadian Species at Risk Act
WSA	Water Sustainability Act

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Chapter 1.0 Introduction

1.1 Project Overview

Historically, humans have established permanent settlements near streams and rivers for purposes of water supply and transportation, but the built infrastructure is often negatively impacted by the dynamic nature of fluvial systems. In response, stream corridors have been altered, often with fixed engineering structures that inhibit the natural processes supported by the stream. The gradual realization that human modifications to watersheds have had negative effects on ecosystem health and function, led to the development of stream restoration strategies intended to mitigate or reverse the damage.

Watersheds in British Columbia are critical as they provide essential habitats for five anadromous salmonid species that migrate to and from the Pacific Ocean. The majority of Coho spawning and rearing habitat is found in small streams and in the side channels of large rivers (COSEWIC, 2016). Changes in watershed land-use patterns and climatic conditions have altered the flow regimes of streams in British Columbia, leading to the extirpation of Coho from their historic range (COSEWIC, 2016).

The village of Lumby, B.C., was built on a floodplain near the Bessette-Duteau-Creighton Creek confluence and has been subjected to frequent flooding historically. In 2017, the interior of British Columbia received above–average runoff that led to peak flow levels above bankfull stage in many locations, including the Lumby area. The declaration of a local state of emergency in Lumby triggered unplanned channel modifications, including dredging and the erection of temporary berms in order to protect municipal infrastructure. Due to the nature of the emergency response, best management and regulatory practices were not always adhered to.

Creighton Creek provides an ideal opportunity to study the impacts caused by emergency stream modification as it was one of the systems modified during the 2017 emergency response. In 2015 and 2016, a stream channel reference site was established in Creighton Creek to assess sediment transport and channel adjustment processes that may have led to increased flooding and degradation of salmonid habitat in the lower reaches and provided baseline data to evaluate channel adjustments immediately following the dredging activities in 2017 and after the 2018 spring freshet. The availability of high-quality data prior and subsequent to an unplanned stream modification provided a unique opportunity to understand the nature of channel changes and to test ideas about stream equilibrium. The insights gained should be valuable to future restoration efforts on streams of similar size and character, especially those that are fish bearing.

1.2 Study Site

Creighton Creek is a small, snow-melt driven creek located east of Lumby, British Columbia located in the North Okanagan. Creighton Creek is a tributary of Bessette Creek, which feeds the Shuswap River and is part of the Shuswap-Fraser Basin (Figure 1).

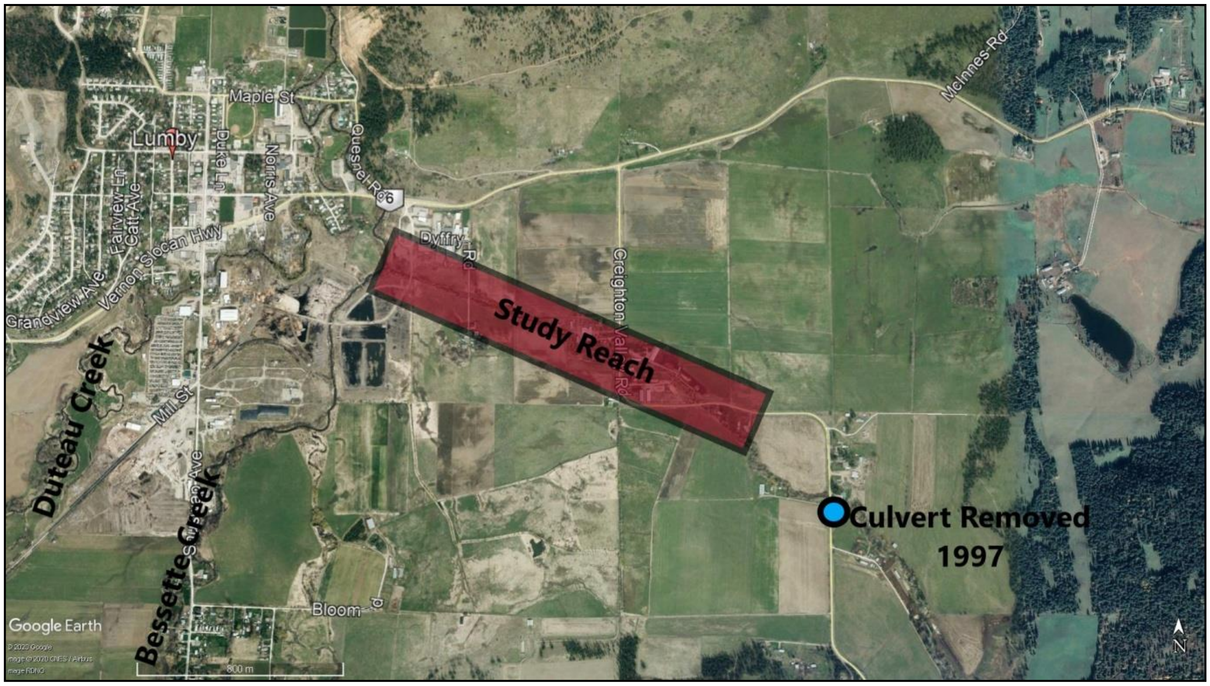


Figure 1. Location of the study site in proximity to the village of Lumby. Image: Google Earth ©, 2020 CNES / Airbus, Regional District of the North Okanagan.

The stream is approximately 16 km long with headwaters located on the Bonneau Plateau. The drainage area is approximately160 km^2 (Nuttall, 1999) and the upper elevations consist primarily of forests. The channel bed comprises mainly boulders and cobbles (with interspersed sand), and has a slope of approximately 4.6% for the upper 10 km, flattening to 1.6% in the lower 6 km. The lower portion of Creighton Creek is surrounded by agricultural areas, and the substrate on the creek bed is finer, containing predominately gravel and sand with some silt. The study reach is the lowest 2 km, immediately upstream of the confluence with Bessette Creek, and has a gradient of 0.78%.

The study site begins at cross-section 1 approximately 40 m upstream of the Bessette-Creighton Creek confluence, where there is an active floodplain and frequent flooding

(Figure 2). The site continues 1650 m upstream to cross-section 19. The dredged zone begins at cross-section 5 at the Dyffryn Road Bridge upstream to cross-section 15 (Figure 2).

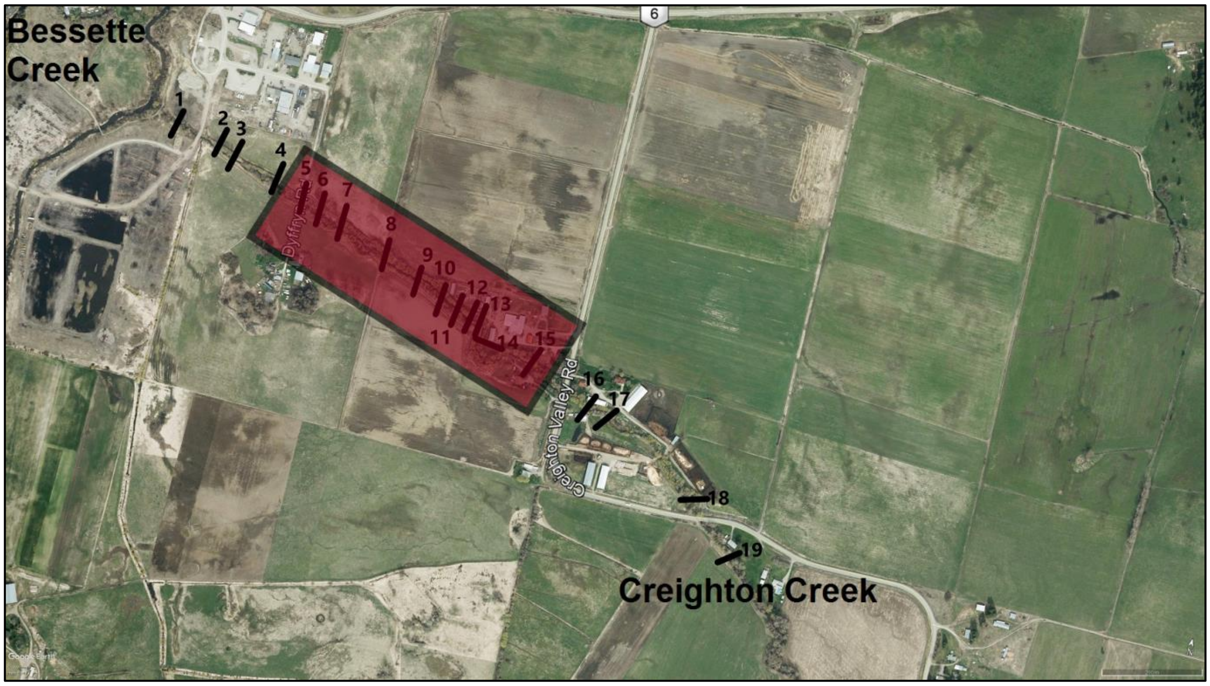


Figure 2. Location of cross-sections and the 2017 dredged zone (red rectangle) within the study reach. Image: Google Earth ©, 2020 CNES / Airbus, Regional District of the North Okanagan.

Depositional processes dominate the lower reaches of streams due to the abundance of alluvial sediment and reduced flow velocities. Natural streams move across their floodplains in sequences of erosion and deposition associated with meander patterns.

However, human modifications often restrict the natural movements of streams in floodplains in order to protect valuable farmland and associated infrastructure (e.g., buildings, irrigation pipes, roadways). The lower portion of Creighton Creek, including the study reach, has occupied its current channel since the 1950s and is now surrounded by mature cottonwoods. However, it previously occupied a different pathway, which was altered because of development of surrounding agricultural land A. Dolman (personal communication, October 2016). The resulting riparian corridor is narrow, confined by artificial levees, and thus largely fixed in place (Minor & Hesketh, 2003).

Historically, Creighton Creek served as habitat for adfluvial rainbow trout [*Oncorhynchus mykiss]* (Mable Lake recruits), Interior Fraser Coho (IFC) [*Oncorhynchus kisutch Walbaum]*, Chinook salmon [*Oncorhynchus tshawytscha]* and Pink salmon [*Oncorhynchus gorbuscha]* (Griffith, 1986; Walsh, 2010). Chinook and Pink salmon populations drastically decreased in the 1970 to 1980s (Jantz,1986). Jantz (1986) reported a decrease in fry densities throughout Creighton Creek, and noted a lack of suitable spawning gravels within the lower portions of the creek due to aggradation and infiltration of fine sediment. The study reach for this project falls within the lower section analyzed by Jantz (1986). Currently, only Coho salmon are found routinely in the lower reaches of Creighton Creek.

There are a number of potential sediment sources that may have contributed to the aggradation problem including a culvert replacement site and an upstream channel avulsion site. In 1997, extensive flooding occurred upstream of an under-sized culvert passing under Creighton Valley Road, located 2200 m upstream (Figure 1) of the Bessette-Creighton Creek confluence (Minor & Hesketh, 2003). The culvert was unable to convey flood waters, resulting in a backwater effect and upstream storage of fine sediment in the channel. In 1997, the culvert was replaced by a bridge, which resulted in the release of stored fine sediment and transport downstream into the study reach.

Fifteen kilometers (15 km) upstream of the study site, a channel avulsion occurred at a private residence in 1998. During the 1990s, the channel in this area had aggraded until the streambed was at a higher elevation than the surrounding land. The aggradation and changes in channel morphology were believed to have caused the avulsion B. Harding (personal communication, December 2019). The avulsion site contained a wide, established riparian corridor despite being close to the headwaters and not within an active floodplain. Throughout the early 2000s, upper Creighton Creek residents reported a drastic change in flow regime within the aggraded area downstream of the avulsion resulting in the creek completely dewatering during the summer months, leading to stranded fish. Residents collectively attempted to salvage fish and transfer them into local lakes. Over a period of two years, residents reported that the pools once containing abundant fish were now dry. No fish were found throughout the upper portions of Creighton Creek from 2000 until 2014 B. Hettrich (personal communication, January 2019).

After the 1998 avulsion, local residents began requesting federal and provincial support to address the issues caused by steam aggradation in Creighton Creek. In large part, the concern was with perennial water shortages in the creek during the late summer, which coincides with the greatest irrigation demands and the beginning of salmonid migration. Resident juvenile salmonids had difficulty finding refuge due to reduced pool volume. In 2002, landowners dredged a section Creighton Creek from 300 m to 700 m upstream from the Creighton-Bessette confluence without authorization. Government officials halted the unauthorized work before it was completed resulting in dredge spill being left on the banks (Minor & Hesketh, 2003). As a response to the concerns from local residents, the Creighton/Bessette Stream Flow Recovery Project was initiated in 2003.

Creighton Creek was prone to greater flooding during the freshet and medium-to-heavy seasonal precipitation events due to a reduction in channel capacity (Minor & Hesketh 2003). Increased frequency of floods had affected surrounding landowners through the loss of 10 hectares of agricultural land (Minor, 2005). At the same time, summer flows were lower than normal, resulting in a reduction of viable salmonid habitat. Specifically, pools were becoming isolated, stream temperatures were increasing, and dissolved oxygen was decreasing (Minor, 2005). Salmonid fry salvages were undertaken in 2002 and 2003 due to the low flow levels in Creighton Creek, which may have been exacerbated by heavy irrigation demands on the remaining water in the creek.

In 2003, landowners and consultants observed an increase instream flow in the dredged areas previously containing only dewatered isolated pools. As a response to landowner concerns, consultants prepared the *Restoration Plan for Lower Creighton Creek* (Minor & Hesketh, 2003) outlining detailed stream restoration practices to remove gravels and implement features that would increase the transport capacity. In 2004, the proposed changes were implemented (Figure 3) T. Minor (personal communication, October 2016).

The 2005 project evaluated and monitored water license usage throughout the summer months. The project concluded that residents were not over-drawing their water licenses, but rather, that available water had been over-allocated by the province (Minor, 2005). The project outlined the need for irrigators to work together to conserve water. Additionally, the project concluded that the drainage ditches adjacent to the channel were dug to a lower elevation than the stream bed, thereby drawing water out of the main channel through the bed and banks via infiltration and percolation.

Figure 3. Location of the 2004 Lower Creighton Creek Restoration Project. Image: Google Earth ©, 2020 CNES / Airbus, Regional District of the North Okanagan.

A second restoration project was undertaken in 2010 using the same methods as in 2004, but farther downstream, approximately 90 m to 530 m upstream of the Bessette-Creighton Creek confluence (Figure 4). This project included the installation of large woody debris and, most notably, side drainage channels on the left and right banks to accommodate flooding.

Figure 4. Location of the 2010 Lower Creighton Creek Restoration Project. Image: Google Earth ©, 2020 CNES / Airbus, Regional District of the North Okanagan.

1.3 Objectives and Hypotheses

The overarching question to be addressed by this thesis is whether the 2017 emergency dredging operations had a significant impact on Creighton Creek, to the extent that natural geomorphic and hydraulic processes were altered substantially with long lasting. The motivation for the research is to provide empirical evidence in support of better outcomes for stream rehabilitation projects that may impact critical salmonid habitat.

Objective 1 is to assess whether the 2017 emergency dredging altered the geomorphic processes influencing sediment transport potential and stream hydraulics by altering the channel configuration in a manner that facilitates an increase in the sediment transport capacity through the study reach. The null hypothesis and alternative hypothesis are:

H_o: The 2017 emergency dredging had no impact on the geomorphic processes influencing stream hydraulics and sediment transport potential.

H_{a1}: The 2017 emergency dredging impacted (either positively or negatively) the geomorphic and hydraulic processes in a substantial way.

Objective 2 is to assess, using standard geomorphic and hydraulic parameters such as particle size, flow velocity, and depth, whether the 2017 emergency dredging operations improved the habitat conditions for Interior Fraser Coho (a threatened species). The null and alternative hypotheses are:

H_o: The 2017 emergency dredging had no noticeable impacts on the habitat conditions for Interior Fraser Coho.

H_{a1}: The 2017 emergency dredging had a noticeable impact (either positive or negative) on habitat conditions in Creighton Creek for Interior Fraser Coho.

Chapter 2.0 Literature Review

To understand how Creighton Creek was impacted by the emergency dredging operations, it is essential to understand how a stream normally functions, especially the relationships between the geomorphic processes influencing channel adjustments and sediment transport dynamics. Stream channels are a morphologic expression of the balance between driving and resisting forces within a watershed, essentially the balance of how much water and sediment needs to move through the channel to maintain an equilibrium form. In this chapter several conceptual ideas on stream equilibrium are summarized, followed by an assessment of critical geomorphic habitat parameters for salmonids and by a summary of stream modification objectives and techniques pertaining to small streams such as Creighton Creek.

2.1 Channel Adjustments

Rivers and streams respond to a range of external driving factors that ultimately lead to changes in water and sediment discharge within the channel network (Darby & Thorne, 1996). These independent variables influence the flow hydraulics in the channel, which affects the potential for erosion and deposition. As a consequence, a channel will adjust its width, depth, velocity, and sediment transport to accommodate the imposed conditions (Darby & Thorne, 1996). Mackin (1948) proposed the concept of a graded stream to express the equilibrium state of a river, which he described in the following classic quote:

"A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in

any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change." (Mackin, 1948. p. 471)

The adjustments envisioned by Mackin (1948) occur over time scales ranging from several years to decades, implying that the channel may be in short-term disequilibrium as a consequence of rapid external influences such as emergency dredging. Part of the purpose of this thesis is to examine whether the dredging activities in Creighton Creek constitute a short-term disruption with a gradual return to a graded state or whether a threshold condition was exceeded leading to more persistent change.

Another useful approach to understanding channel adjustments is Lane's Balance, which relates discharge (Q_w), sediment load (Q_s), sediment grain size (D_s) and channel gradient (S) (Lane 1955) (Figure 5).

$$\mathbf{Qw\ S\ \alpha\ Q_s D_s} \qquad \mathbf{(1)}$$

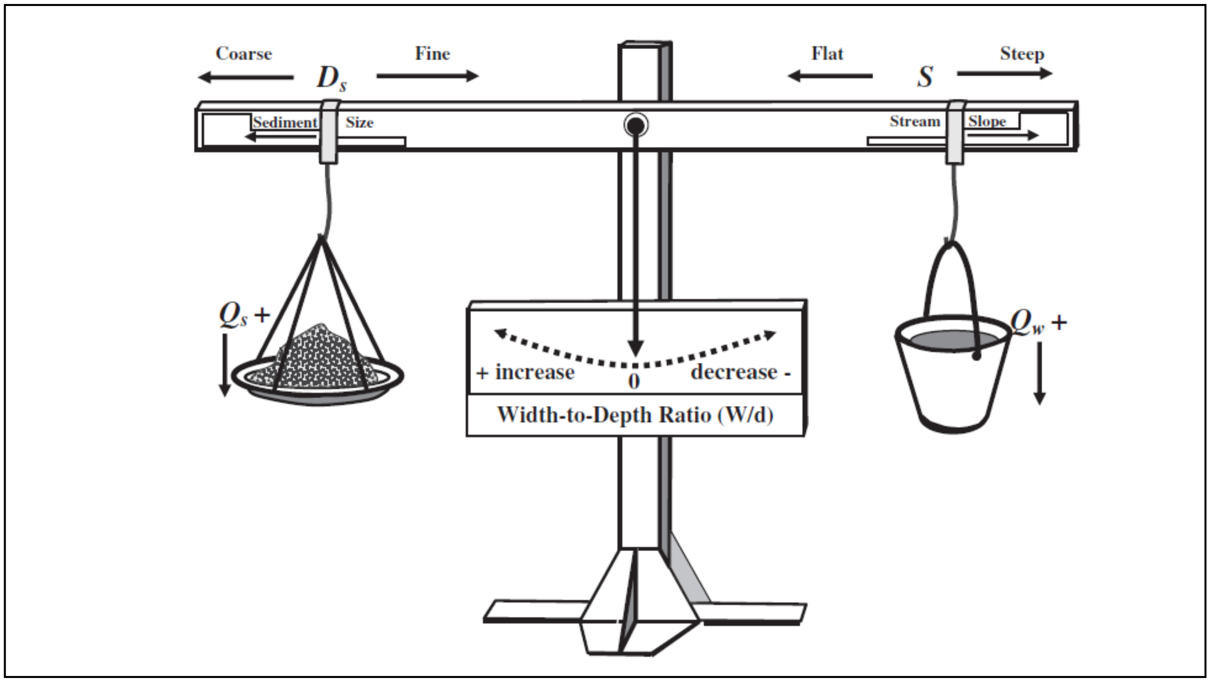


Figure 5. Depiction of Lane's Balance (1955) representing the balance between sediment size, load, channel slope and discharge adapted from Dust & Wohl (2012).

The concept is best represented by a tipping scale (Figure 5). When sediment load decreases or particle size decreases, the channel will degrade because the erosive power of the flow remains large. In contrast, if discharge decreases and all other factors are unchanged, then there will be channel aggradation. One limitation of Lane's conceptual model is the inability to account for changes to cross-sectional geometry (i.e., width), planform geometry (e.g., meandering), and bedform development (Wohl, 2014).

Channel incision occurs when the sediment transport capacity is greater than the sediment supply available for transport within a system (Simon & Rinaldi, 2006). Bed and bank erosion occur as response to excess shear stress or stream power being exerted on the streambed (Lane, 1955). Degradation occurs over a large temporal scale where the stream bed systematically lowers and alters slope at the scale of a river reach or greater (Simon & Rinaldi, 2006).

Lateral connectivity is the inundation of the main channel flow to its flood plains, due to an increase in discharge or reduction of longitudinal connectivity (Wohl & Beckmann, 2014). Longitudinal connectivity is the connection of stream flow and sediment between defined upstream and downstream locations (Wohl, 2014). An inverse relationship is present between the lateral and longitudinal connectivity of a stream. Decreases in longitudinal connectivity, caused by obstructions or periods of high flow, allow the stream to access the flood plain. Lateral connectivity increases through large woody debris (LWD) and instream objects obstructing flow creating a backwater effect upstream of the blockage. Specifically, as the hydrostatic force on the stream obstruction decreases, flow velocity decreases, and flow depth increases resulting in localized upstream flooding. The backwater effect reduces sediment transport capacity creating temporary storage for fine sediment (Burns & McDonnel, 1998), reduces cross-sectional area and increases flooding frequency (John & Klein, 2004; Westbrook et al., 2010).

Large woody debris (LWD), culverts, and other anthropogenic instream objects disturb the longitudinal connectivity of a system. As longitudinal connectivity decreases, lateral connectivity increases (Collins et al., 2001; Pollock et al., 2003; Burchsted et al., 2010). Sediment storage increases when the longitudinal connectivity of a system is disrupted. The resulting impact is stream bed aggradation, and increased overbank flooding from a reduction in cross-section area below the previous bankfull channel elevation (John & Klein 2004; Westbrook et al., 2010).

Restoring longitudinal connectivity by removing instream structures or by installing bridges rather than culverts reduces the lateral complexity of the stream and prevents local sediment storage (Wohl, 2001). The resulting impact is a pulse-like movement of previously stored sediment that will propagate downstream. The spatial and temporal transport of stored sediment is controlled by stream transport capacity, particle size distribution, and seasonal variability of discharge, especially in snow melt driven systems (Burns & McDonnel, 1998) such as Creighton Creek. The spring freshet should therefore restore longitudinal connectivity by breaching and removing instream structures. The stream bed should also coarsen due to an increase in the sediment transport capacity of the stream during high discharge events (Wohl & Beckman, 2014).

Longitudinal connectivity is essential for diadromous salmonid species due to their migratory pathways (Bunn & Arthington, 2002). The disruption of longitudinal connectivity through dams, sedimentation, and instream objects has been a major contributor to the decline of migratory salmonids on the Pacific Northwest (Bonetto et al., 1989; Cadwallader, 1986; Harris, 1984a; Joy & Death, 2001; Welcomme 1985, 1992; Bunn & Arthington, 2002).

Hydrostatic forces on instream obstructions are greater in low gradient channels, located in valleys with wide flood plains in comparison to areas of low lateral connectivity, where channel gradient is high (Wohl & Beckman, 2014). As hydrostatic forces increase, natural and anthropogenic structures cause overbank flooding and the creation of side channels. Inundated side channels alter channel morphology and sediment transport dynamics by storing sediment (Wohl, 2001).

The creation of multiple side channels increases storage of fine sediments by reducing flow velocity and sediment transport capacity. This leads to changes in planform channel morphology, increasing lateral connectivity and changes in cross-sectional geometry leading to a less pronounced thalweg and formation of several shallow channels. Small streams, such as Creighton Creek, become braided due to the formation of bilateral channels caused by overbank flooding (Wohl & Beckman, 2014).

Flow restricting features such as LWD, dams, levees, culverts, and other anthropogenic structures disturb stream dynamics by altering spatial variability and stream bed particle-size distributions, creating patchy and random patterns (Wohl & Beckman, 2014). Instream features (e.g., LWD, dams, levees, and culverts) are often breached or removed during seasonal flood events, the spring freshet, or by dredging processes, re-establishing longitudinal connectivity and causing stored sediment to be pushed downstream in a pulse-like movement (Butler, 1995). LWD and log jams, commonly found in small streams like Creighton Creek, are not permanent instream structures, their residency time and size vary with seasonality (Wohl & Beckman, 2014). Despite not being permanent, these instream structures have the ability to alter the geomorphic processes influencing channel morphology.

2.3 Sediment Transport

Land-use changes within a watershed including mining, building of infrastructure, forestry, and agriculture, have the ability to alter hydrologic and sediment inputs and therefore alter channel adjustments (Kondolf et al., 2002). Reducing tree cover and vegetation within a snow-melt driven watershed increases sediment supply and hydraulic capacity causing erosional processes that influence channel morphology (Yorke & Herb, 1978; Gregory et al., 1992; Kondolf et al., 2002). Channel adjustments, driven by changes in sediment load can take decades to propagate downstream and typically do so in the form of a sediment pulse (Madej & Ozaki, 1996).

The load of a stream is defined by lithologic characteristics, erosion processes, relief, and the grain size of instream sediment (Mackin, 1948). Spatial grain-size distributions vary significantly between systems. Seasonality, variations in transport capacity and sediment supply determine the sediment transport characteristics of a stream. Sediment transport in streams is either capacity or supply-limited. In a supply-limited stream, the amount of sediment available to the stream determines the amount of sediment transport within the system. In a capacity-limited stream sediment supply does not determine the limitations of sediment transport but rather other fluvial properties including gradient, channel morphology, hydraulics, sediment type, and their associated kinetic characteristics (Knighton, 1984). The residency times of sediment in capacity-limited streams tend to be longer in small versus large streams and can span from tens to thousands of years (Knighton, 1984). Sediment characteristics such as grain-size can limit transport. The transport of fine sediments in either dissolved or suspended loads is most often limited by supply, while transport of coarser sediment is limited by stream capacity (Knighton, 1984).

In mountainous streams like Creighton Creek, the spatial variability of grain-size distributions often presents a downstream fining trend, that can occur over a large range in spatial scale (Rice, 1994). The mechanisms that influence downstream fining are local control of stream gradient, sediment supply, and particle weathering (Surian, 2000). Local gradient control is often caused by geographic uplift, river blockages due to mass wasting events, man-made dams, or instream structures. As gradient decreases, so does the sediment carrying capacity and competence of a stream, reducing the potential sediment transport, and altering grain-size distribution (Sambrook Smith & Ferguson, 1995).

Changes in sediment load and disruptions of hydraulics alter the particle-size distribution of the streambed. Strata layers are particle grain-size distribution changes within the vertical profile of a stream bed. The transitions between particle grain-size distribution patterns are typically not gradual nor a function of time, but rather a change in flow dynamics and sediment transport (Bunte & Abt, 2001). A strata unit gives insight to the stream conditions at time of deposition, including sediment transport mode, particle grain-size distribution and flow dynamics. While it may be difficult to determine the exact conditions, strata units give valuable insight as to what the potential temporal hydraulic and spatial sediment interactions or disturbances, such as dredging, were present at the time of deposition.

Armour is a layer of coarse sediments overlying finer sediments found in gravel-bed streams. An armoured surface is static, while a pavement is mobile. This coarsening up sequence of sediment is attributed to three different processes. Selective scour is where fine particles are removed from the streambed through sediment transport processes leaving behind a lag deposit. For this structure to be identified, the lag deposit must be approximately one particle diameter thick, and often found downstream of LWD or instream obstructions (Bunte & Abt, 2001). The deposition of coarser materials overtop of finer streambed materials can be caused by a decrease in competency of stream flow and corresponding decrease in sediment supply (Bunte & Abt, 2001). Lastly, armouring is caused by episodic seasonal fluctuations in flow where the transportation of coarser and larger particles occurs at infrequent intervals. An armoured surface is not considered to be a permanent condition of the streambed and it occurs when the largest particles are immobile during a given flow regime (Sutherland, 1987).

Understanding the type and spatial distribution of armoured surfaces within a stream gives insight to sediment transport capacity and equilibrium. Coarse armouring of the streambed is a prerequisite for a stream to reach equal mobility of fine and coarse sediments. If the stream bed were not armoured, coarse particles would move less frequently than fine particles. Therefore, the bedload would have a finer grain-size distribution than the streambed (Parker et al., 1982; Andrews & Parker, 1987). To observe the relationship between the grain-size distribution of bedload versus the subsurface, the mobilization of coarse particles must increase and inversely the mobility of fine sediments must decrease (Bunte & Abt, 2001). Furthermore, these conditions result in a coarse grain-size distribution within the armoured surface. The entrainment of coarse grains and stream bed mobility increases as fine particles are removed, resulting in a coarse streambed with greater exposed surface area than the underlying fine particles.

In some instances, the purposes of dredging are to remove the surface layer so as to restore channel capacity and promote sediment transport. The removal of coarse sediments, increases sediment transport potential and allows the stream to move towards an equilibrium, where the amount of fine sediment in transport is equal to the amount of coarse sediment in transport (Bunte & Abt ,2001; Parker et al., 1982; Andrews & Parker, 1987).

An armoured streambed is less developed in braided streams where the sediment transport capacity is equal to the amount of sediment supply available. These conditions show a similar distribution of sediment particle-size in both the armour and subsurface layer of streambed (Bunte & Abt, 2001). As the sediment transport capacity of a stream increases, the sediment particle-size increases between the surface and subsurface layers creating an increasingly armoured surface. Snow-melt driven mountain streams have high energy and a low sediment supply leading to the formation of static amour in the streambed that can only be mobilized by large flooding events (Bunte & Abt, 2001; Parker et al., 1982; Andrews & Parker, 1987).

Understanding changes in the grain-size distribution of the streambed is critical to evaluating salmonid habitat values. The viability of habitat is strongly influenced by the infill of fine sediment between spawning size gravels. Two specific mechanisms are responsible for the infiltration of fine sediments. Gravity-based infiltration occurs when sand and fine sediments are mobilized and transported along the stream bed. The mobilized fine sediment becomes entrapped between the larger streambed gravels, causing an infilling of porous spaces. The supply of fine bedload sediment and the amount of porous spaces determines the rate of infiltration (Alonso, 1993). The intrusion of fine sediment between porous gravels can also be caused by down welling flows containing suspended fine sediment (Alonso, 1993). The concentration of suspended sediments within the flow determines the porosity of the streambed and rates of sediment intrusion. As the concentration of suspended sediment, severity of down welling flows, and porosity increase, so do infiltration rates (Lauck et al., 1993). The implications of porosity on salmonid habitat are that the infill of fine sediment between spawning gravels decreases the quality of salmonid spawning habitat. Further, the hyporheic exchange processes decrease, reducing dissolved oxygen levels which are critical for the survival of salmonid eggs during incubation.

2.4 Salmonid Habitat

The assessment of salmonid habitat has evolved from simple patch-level assessments of biological indicators to a broader evaluation of surrounding landscape conditions, including biologic, geomorphic, and hydraulic elements (Lapointe, 2012). Approximately 25% of all Coho in Canada are Interior Fraser Coho (COSEWIC, 2016). The majority of the IFC population is found within the Thompson River watershed and their ocean residences range from Oregon to Alaska. IFC are genetically distinct and have specific evolutionary traits that differ from other North American Coho salmonids, specifically their high homing fidelity (Interior Fraser Coho Recovery Team, 2006). This strongly impacts the ability of IFC to spawn in their natal habitats and success of spawning rates.

Photograph 1. Female Spawning IFC in Creighton Creek November 2016 (Photograph: L. Hettrich).

The IFC was listed as Endangered in 2002 by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) due to a 60% population decline in the 1990s (COSEWIC, 2002). The 2002 endangered designation was given due to a decrease in viable freshwater habitat, poor marine survival rates and overharvesting. While marine survival rates have decreased, a greater threat to IFC populations is the reduction in suitable freshwater habitat. Changes in land-use patterns through urbanization and industrial activities, climate change leading to increased drought periods, and invasive species were the key factors listed by COSEWIC that have contributed to an IFC population decrease exceeding 30% in the last 3 generations (COSEWIC, 2016). In November 2016, the status of the IFC was re-examined and changed to threatened. Like all other fish, IFC and their habitats are protected under the

Canadian Fisheries Act, but have not been listed under the Canadian Species at Risk Act (SARA) and therefore do not have any additional protections (COSEWIC, 2016). The COSEWIC designation was changed from Endangered to Threatened based on an increase in populations from 2005 to 2012, despite a large decrease in 2014 and 2015 escapements.

Table 1. IFC status definitions from © COSEWIC, 2016.

DD	**Data Deficient**	A category that applies when the available information is insufficient (a) to resolve a wildlife species' eligibility for assessment or (b) to permit an assessment of the wildlife species' risk of extinction.
NAR	**Not at Risk**	A wildlife species that has been evaluated and found to be not at risk of extinction given the current circumstances.
SC	**Special Concern**	A wildlife species that may become threatened or endangered because of a combination of biological characteristics and identified threats.
T	**Threatened**	A wildlife species that is likely to become endangered if nothing is done to reverse the factors leading to its extirpation or extinction.
E	**Endangered**	A wildlife species facing imminent extirpation or extinction.
XT	**Extirpated**	A wildlife species that no longer exists in the wild in Canada but exists elsewhere.
X	**Extinct**	A wildlife species that no longer exists.

Interior Fraser Coho spend one year in freshwater systems before migrating to the ocean. Mature and juvenile IFC prefer small streams or side channels of larger rivers containing an abundance of pools and riffles during their rearing and spawning stages (COSEWIC, 2016). Small riffle pool systems tend to have higher levels of dissolved oxygen due the vertical hydraulic gradient created by these instream features.

IFC spawn in October and November. Female spawners prefer to make redds in well oxygenated water at depths less than 0.36 m (Sandercock, 1991; DFG, 2002b). Further the amount of groundwater input plays a critical role in spawning site selection-hyporheic flow improves oxygenation and temperature regulation (McRae et al., 2012). IFC spawning distributions are dependent on groundwater influences on micro and macro scales within the Fraser Basin (Interior Fraser Coho Recovery Team, 2006).

Coho prefer spawning gravels that are less than 0.15 m in diameter (Sandercock, 1991). An empirical relationship developed by Kondolf &Wolman (1993) suggests there is a linear correlation between fish size and sediment grain size of salmon redd site selection, which can be used to evaluate salmonid spawning habitat. The ideal D50 sediment grain size for Coho ranges from 5.4 mm to 35 mm (Chambers et al., 1954; Koski, 1966; Kondolf & Wolman, 1993).

On average, IFC eggs hatch after 137 days, with incubation time varying with water temperature (Sandercock, 1991). The limiting factor to egg survival, in the Fraser Basin, is freezing temperatures and availability of dissolved oxygen during the winter months (Decker & Irvine, 2013). IFC spend approximately one year rearing in freshwater before migrating to the Fraser River estuary (Chittenden et al., 2010). During the spring freshet the limiting factor on juvenile smolting Coho habitat is flow velocity and turbidity (Moyle, 2002). Juvenile Coho seek refuge in pools, side channels and areas with high cover where flow velocity is less than 0.46 ms^{-1} (Moyle, 2002; Bjornn & Reiser, 1991; Tschaplinski & Hartman, 1983). A 2001 to 2011 lower Thompson River study concluded that rearing IFC are mainly found in small streams and side channels, rarely are they found in larger rivers (Decker et al., 2014).

During the summer months juvenile IFC are most threatened by stream temperature fluctuations. Stream temperature can inhibit juvenile development, and Coho are not typically found in streams where stream temperatures exceed 22 °C (Hassler, 1987). While Coho prefer temperatures of 10 °C – 15 °C in summer, the lethal temperature for Coho is 25.1 °C (Roberge et al., 2002). Areas having high groundwater input are preferred habitat due to the temperature and water quality regulation. Flow velocity and stream depth are less critical in summer and reports of ICF juveniles have been found to exist in flow velocities ranging from 0.0 to 0.78 ms^{-1} and depths of 0.13 m – 0.83 m in Kloiya Creek, BC (Bravender & Shirvel, 1990). While the limiting habitat parameters are based on seasonality, stream gradient remains a constant critical habitat parameter for IFC. Most commonly Coho are found in streams with a gradient of 1 – 3% (Decker & Irvine 2013; Montgomery et al., 1999; Reeves et al., 1989).

The limiting factors identified for salmonid spawning habitat in Creighton Creek (Tables 2 to 4) were used as a guideline for model analysis to examine the viability of habitats.

Table 2. Fall IFC Spawning Habitat Parameters.

Limiting Factor	**Parameter**	**Reference**
Surface Grain Size	< 150 mm	Sandercock, 1991
D_{50} Particle Size	5.4 mm – 35 mm	Chambers et al., 1954; Koski, 1966; Kondolf & Wolman, 1993
Flow Depth	0.10 m – 0.36 m	DFG, 2002b; Sandercock, 1991
Flow Velocity	0.3 - 0.9 ms^{-1}	Bjorn & Reiser, 1991
Temperature	4 °C – 9 ^{0}C	Bjorn & Reiser, 1991
Gradient	1 - 3%	Decker & Irvine 2013; Montgomery et al., 1999; Reeves et al., 1989

Table 3. Spring IFC Juvenile Rearing Habitat Parameters.

Limiting Factor	Parameter	Reference
Discharge	< 10 m^3s^{-1}	Reeves et al., 1989
Flow Depth	0.76 m – 1 m	Moyle, 2002; Beecher et al., 2002
Flow Velocity	0.05– 0.46 ms^{-1}	Moyle, 2002; Bjornn & Reiser, 1991
Temperature	12 °C – 14 ° C	Brett, 1952; Welsh et al., 2001; Moyle, 2002
Gradient	1 - 3%	Decker & Irvine, 2013; Montgomery et al., 1999; Reeves et al., 1989

Table 4. Summer IFC Juvenile Rearing Habitat Parameters.

Limiting Factor	Parameter	Reference
Flow Depth	0.13 m – 0.83 m	Bravender & Shirvell, 1990
Flow Velocity	0.00 – 0.78 ms^{-1}	Bravender & Shirvell, 1990
Temperature Preference	10 °C – 15 °C	Reiser & Bjornn, 1979
Maximum Temperature	25.1 °C	Roberge et al., 2002
Gradient	1 - 3%	Decker & Irvine 2013; Montgomery et al., 1999; Reeves et al., 1989

2.5 Stream Modification

Stream modification is considered to be the planned alteration of stream channels and the adjacent floodplains with the goal of restoring or improving hydrologic, geomorphic, and ecologic processes within the stream (Wohl et al., 2015). Stream restoration initiatives range from modification of structural features such as banks to the remediation of riparian areas and ecological functions within a watershed (Warne et al., 2002; Bloesch & Sieber, 2003). Determining the thresholds for restoration and what can be considered improvement of ecological stream function can be highly subjective (Bernhardt & Palmer 2007). Often modification of a system to its former historic condition is not feasible or desired, based on the uncertainty of stream conditions, geomorphic and ecological functions present at a given point in time (Van Diggelen et al., 2001; Ward et al., 1999; McDonald et al., 2004).

Stream modification mainly occurs in small catchments and includes localized modifications to the channel and adjacent flood plains (Bond & Lake 2003; Bernhardt et al., 2005). The objectives of small stream modification projects are often reach-scale activities aimed to improve water quality, aquatic habitat, protection of infrastructure and esthetics (Kenney et al., 2012). Reach-scale projects are often unable to account for the watershed-scale changes that are the root-causes for water quality, habitat and hydraulic factors leading to degradation within the stream (Bernhardt & Palmer, 2011; Doyle & Douglas Shields, 2012).

Streams have been modified for aesthetic, agricultural, and recreational uses focusing on creating single-channel systems (Wohl, 2015). Early stream modification objectives prioritized navigation and protection of infrastructure. Ecologic and geomorphic diversity was reduced as rivers were channelized and straightened and thus became more uniform. (Poff et al., 2007; Rahel, 2007; Liermann et al., 2012; Wohl, 2014). Key legislation such as the *Canada Water Act 1970*, *Clean Water Act 1972,* and initiatives by the European Union led to modification projects prioritizing the development of aquatic habitat, followed by water quality through the modification of channels (Gowan & Fausch, 1996; Bennett et al., 2011; Campana et al., 2014). Stream modification initiatives transitioned to altering channel form as a primary objective to creating aquatic habitat in the late 20th Century (Gowan & Fausch, 1996).

An increase in academic research over the past 30 years has informed the scope of stream modification activities aimed to prioritize the stream function and processes rather than manipulation of stream form (Kondolf, 1998; McDonald et al., 2004; Konrad et al., 2011). Prioritizing stream function includes restoration of floodplains through longitudinal and lateral connectivity, and ecological activity by restoring water and sediment fluxes (Tockner et al., 1999; Shields et al., 2011; Gumiero et al., 2013; Shafroth et al., 2010; Konrad et al., 2011; Lepori et al., 2005; Palmer et al., 2010). The success of these types of modification objectives are evaluated with respect to biotic response and changes to habitat (Helfield et. al., 2007).

The typical guiding principles when developing modification objects, are technical specifications and implementation methods rather than restoring ecosystem response measures (Palmer et al., 2005; Hilderbrand, et al., 2005). The potential impact on geomorphic and ecological functions within a watershed are not always considered by decision makers when determining modification objectives because management actions are implemented over a shorter temporal scale of 1 to 5 years (Kondolf et al., 2002). Therefore, better planning is critical, and it must account for the hydrologic, biological, geomorphic and anthropogenic process present in the system, while evaluating constraints and feasibility (Lake et al., 2007).

Stream modification occurs most prominently in low grade streams surrounded by agricultural areas (Merritts et al. 2013) where bank erosion and upstream land-use changes have led to aggradation within the system (Knox, 2006; Latocha & Migon, 2006; James & Lecce, 2013). Typically, modification of these streams includes reconnecting longitudinal and lateral connectivity to the flood plains by creating artificial meanders, re-stabilization of banks and dredging to remove legacy sediments in order to restore riparian areas (Wade et al., 2007, Lorenz et al., 2009). A common successful practice to improve critical salmonid habitat in British Columbia is the re-connection of off-channel habitats to a main channel, (e. g., Chilliwack River) (Ogston et al., 2015). While ecological function can be improved, the success of these types of modification projects can be limited due to upstream watershed scale stressors affecting stream function (Wohl, 2015).

Determining the success of modification projects is difficult as there is a gap between what the public considers acceptable and what scientists consider to be acceptable in terms of restoring ecosystem function (Cockerill & Anderson, 2014). The success of modification projects is often visible through improvements in habitat, but often has a lag time of ten to fifteen years (Orzetti et al., 2010). Fewer than 10% of projects include post stream modification monitoring, and thus it is difficult to determine the effectiveness of the project and to evaluate long-term impacts (Holl et al., 2003; Palmer et al., 2005). The lack of post project monitoring limits the temporal data available to inform scientific approaches to better conceptualize and develop modification initiatives (Wohl, 2015). The geomorphic processes and associated ecosystem responses are not well documented, and therefore do not contribute to informing stream modification initiatives. Therefore, the examples to determine whether stream modification projects were successful or not are limited (Hobbs & Harris, 2001; Higgs, 1997; Hobbs & Norton, 1996).

2.6 Stream Management in British Columbia

The provincial and federal governments both play a role in providing oversight for stream health. The key federal legislation managing water is the *Canada Water Act* implemented in 1970, laying out the management guidelines for provinces. The Federal *Department of the Environment Act* is responsible for assigning water management objectives to the Federal Minister of Environment. The Federal Department of Fisheries and Oceans ensures compliance and enforcement of the *Fisheries Act.* The goal of the *Fisheries Act* is to avoid causing harm or death to fish and manage activities including infrastructure maintenance where fish habitat may be affected.

The British Columbia Provincial Government manages water through the Ministry of Environment, the Ministry of Forest, Lands, Natural Resources Operations and Rural Development, and the Ministry of Agriculture. The key legislation governing water in British Columbia is the *Water Sustainability Act* (WSA) implemented February 29, 2016 in order to provide BC with a sustainable source of clean fresh water for generations to come. The aim of the *WSA* is to modernize the tools and methods used to manage and protect the use of water resources in BC, such as managing for the environmental flow needs of a system and requiring licences for groundwater extraction.

British Columbia's Water Sustainability Act (WSA) defines a stream as:

> *"(a)a natural watercourse, including a natural glacier course, or a natural body of water, whether or not the stream channel of the stream has been modified, or*

> *(b)a natural source of water supply, including, without limitation, a lake, pond, river, creek, spring, ravine, gulch, wetland or glacier, whether or not usually containing water, including ice, but does not include an aquifer;"*

Stream restoration and stream modifications are regulated by the WSA.

The WSA defines and any changes in and about a stream as:

> *"Any modification to the nature of the stream, including any modification of the land, vegetation and natural environment of a stream or the flow of water in a stream, or*
>
> *Any activity or construction within a stream channel that has or may have an impact on a stream or stream channel."*

Water Sustainability Act Part 1, Section 1 (Water Sustainability Act, 2014).

The provincial *Water Protection Act* serves to protect the removal and diversion of water by stating the provincial ownership of ground and surface water. The provincial *Environmental Protect Act* regulates any activity that has the potential to contaminate water bodies and poses any risk to the environment and public health, through permitting, regulation and provincial codes of practices, and enforcement.

In British Columbia under a declaration of emergency the *British Columbia Emergency Management Response System* (BCEMRS, 2016) response goals indicate habitat and protection of the environment is ranked 7 out of 8 behind the protection of infrastructure and property, and ahead of economic and social losses (BCEMS, 2016). Therefore, protection of the environment during events such as the 2017 emergency dredging was not prioritized. All emergency works installed under a declaration of emergency are considered temporary and shall be removed, and the area needs to be restored to pre-emergency conditions.

Chapter 3: Methods

3.1 Study Site Selection

A reconnaissance assessment of the lower 5 km of Creighton Creek was conducted in October 2015, which consisted of several field visits with supervisory committee members, fisheries biologists, and stream restoration consultants. These assessments determined which areas had flooding challenges, salmonid habitat potential, and apparent channel dynamics of interest.

A 1.6 km study reach was selected, extending from the Creighton Creek-Bessette Creek confluence at 50°14'46.29"N, 118°57'21.53"W to a location at 50°14'16.15"N, 118°55'51.25"W immediately upstream of the second bridge that crosses Creighton Valley Road (Figure 1). The main observations during the reconnaissance visits were sudden changes in planform geometry, abnormal streambed elevations, extensive over bank deposits, and noticeable changes in substrate sediment size, especially in the short section between 400 m and 900 m upstream from the Creighton-Bessette confluence. The study reach (Figure 1) contains two (2) paved bridge crossings maintained and managed by the British Columbia Ministry of Transportation (MOT), three (3) bridges maintained by private landowners, and one (1) bridge maintained by a business owner that provides access to a logging yard.

Table 5. Bridge location upstream of the Bessette-Creighton Creek confluence and associated maintenance responsibility.

Distance Upstream (m)	Maintained by
98	Business Owner
346	Landowner
1043	Landowner
1086	MOT
1395	Landowner
1483	MOT

The study site spans the locations of previous stream restoration projects conducted from 2003 to 2010 and the 2017 emergency dredging.

3.2 Data Collection

3.2.1 Cross-sections

To evaluate channel morphology, 19 permanent cross-sections were established within the reach in November 2015 (Figure 2). There was no set interval for the cross-section locations because ease of access was difficult in many locations. Cross-sections were established in areas of geomorphic or hydraulic significance. Every cross-section was marked by two permanent benchmarks (rebar pins) on either side of the channel in locations high enough on the levees to include the high-water mark, bankfull stage, and any areas of potential overbank flooding. All channel cross-sections are presented in Appendix A.

The following benchmarks were inadvertently removed or buried by heavy machinery operating on the channel margins during the May 2017 emergency dredging (Table 6).

Table 6. Location and identification of pins disturbed during the 2017 emergency dredging. These measurements were taken in Summer 2017 post emergency dredging and used the *NAD 83* datum.

Cross-section	**Benchmark**	**Location**
XS6	Left-bank	360901.532 East 5567699.854 North
XS7	Left-bank	360963.304 East 5567677.058 North
XS10	Left-bank	361181.166 East 5567584.247 North
XS15	Right-bank	361380.085 East 5567516.803 North
XS16	Left-bank	361531.46 East 5567426.825 North

Fortunately, at each of these locations, one of the original pins remained un-disturbed. New pins were re-established using the undisturbed pin and previous horizontal distance at each location for reference. All disturbed cross-sections were re-established and geo-referenced.

3.2.2 Geo-referencing

The rebar pins marking the ends of each cross-section were geo-referenced using a Topcon GR5 Real-Time Kinetic Digital Global Positioning System (RTK-DGPS) consisting of a base station and rover. The base station was positioned over a permanent benchmark (50°14'37.70" N, 118°56'39.80" W) on a concrete slab located on the Dolman farm (Photograph 2). An embedded quartz pebble was used as a marker, and this location was re-occupied with the base station on subsequent surveys to provide a known initial point for the real-time kinetic survey of rebar pins with the rover. All survey data were post-processed using the Natural Resources Canada website via the PPP Direct (v 1.4) application in static processing mode with the NAD83 (CSRS) reference frame. This approach produced values that were accurate to within +/- 0.05 m (Easting), +/- 0.05 m (Northing), and +/- 0.08 m elevation (CGVD28), and often much better

Photograph 2. The Topcon RTK-DGPS base station set up and the quartz pebble benchmark December 12, 2015 (Photograph: B. Bauer).

The base station was occupied for approximately 6 hours at the beginning of the research project to provide for an accurate triangulation of the benchmark. Once established, the coordinates of the benchmark were assessed by using the rover to measure the coordinates of a known provincial benchmark (NTS VERNON 82L.026.3.2) located in a road-side ditch below the cemetery at the base of Creighton Road, approximately one km away. There was a difference in measured versus reported position of approximately 0.2 m. However, since the provincial benchmark was established in 1959, last updated 1998 using manual surveying techniques with a reported accuracy of 0.017 m a decision was made to use the post-processed results from the DGPS directly without further adjustments. Files collected from the base station during later surveys reaffirmed the accurate positioning of the benchmark on the Dolman property.

The rebar pins at each cross-section were surveyed using the rover in real-time kinetic mode in 2015, 2016, 2017, and 2018. Many of the pins were re-occupied within the level of accuracy of the methodology, providing assurance that their coordinates were well known. However, in many instances this proved impossible because of poor signal acquisition due to over-hanging tree canopies, obstructed line-of-site to the base station (e.g., farm buildings, trees), or poor satellite positioning. In other cases, the rebar pins were bent or buried due to human activity on the levee banks. Nevertheless, there was almost always at least one pin on each of the cross-sections (with but a few exceptions) for which the pin position was well established, and this allowed for an accurate geo-referencing of the cross-sections with respect to each other. The engineer's level surveys were then relied upon to provide information on horizontal distance across the channel and for elevation differences between pins. In cases where the pins were never disturbed, this produced results that were repeatable from year to year within an accuracy of +/- 0.02 m or less in the vertical. A DGPS survey of the thalweg along the entire study reach was also conducted, and cross-section positions were measured to check on the geo-referencing accuracy.

3.2.3 Surveying

Topographical surveys were taken at each cross-section using an engineer's level tripod, tape measure, and fibreglass stadia rod, following standard surveying protocols (Photograph 3) (Harrelson et al. 1994). The accuracy of this technique is judged to be within +/- 0.01 m. At each sampling point across the channel, height and distance were recorded along with information on substrate material and geomorphic features (e.g., bars, riffles, woody debris). Sample points were not taken at a set interval, but based on their geomorphic significance and the potential to characterize cross-section geometry accurately.

Photograph 3. Surveying August 30, 2016 using an engineer's level and stadia rod at cross-section 9 (Photograph: L. Hettrich).

Raw data were entered into a spreadsheet for analysis and to plot cross-sectional profiles. Abnormalities or potential data entry errors were identified and rectified. The distances between benchmark pins and their relative elevations from the topographical surveys (using tape measures) were compared to those derived from the DGPS surveys. In most cases, the agreement was quite good, but in some instances, there were uncertainties to address. Often this occurred when the DGPS signals were weak, usually because of thick overhead vegetation, in which case a complicated process was followed that identified the most reliable benchmark location. For example, if a single benchmark pin always had a clear satellite signal on multiple surveys that yielded virtually identical locations, that pin was considered reliable. Also, during surveys different benchmark pins from adjacent cross-sections were tied together, and this served as another means of checking the reliability of benchmark pins. Ultimately, all the cross-section data were geo-referenced within HEC-RAS and plotted using Google Earth, which could then be used to further verify the placement of the cross-section.

3.3 Hydrometric Data

3.3.1 Flow Velocity and Discharge

There are no permanent hydrometric stations on Creighton Creek, therefore discharge needed to be measured manually. Discharge was estimated from flow velocity measurements acquired with a Marsh McBirney Flow Mate electromagnetic current meter. The channel cross-section was divided into small sections, each section being less than 5% of the stream width. Average flow velocity was measured at 60% of the depth from the water surface (or 40% of the depth above the stream bed) as per standard guidelines for shallow conditions. Flow was measured and averaged over a 45-second time interval. The flow velocity (ms^{-1}) and depth (m) were recorded at each location across the channel and the data were entered into spreadsheets.

The discharge equation was applied to the data:

$$\boldsymbol{Q = \sum_{i=1}^{n} w_i * d_i * v_i} \quad \textbf{(2)}$$

Where the stream is divided into a finite number of sections (i) in which

w = flow width (m)

d = flow depth (m)

v = mean velocity perpendicular to the width section (ms^{-1})

Stage was also measured at a staff gauge located at 50°14'45.42" N and 118°57'15.03" W directly upstream of cross-section 2 (Photograph 4). These stage measurements facilitated the development of a discharge-rating curve, relating discharge (**Q**) to stage height.

Photograph 4. FLNRORD staff gauge located at Creighton Creek, identified as CRE2 (Photograph: L. Hettrich).

3.3.2 Staff Gauge Readings

The staff gauge (Photograph 4) was installed by personnel working on behalf of the British Columbia Ministry of Forest, Lands, Natural Resource Operations, and Rural Development (FLNRORD). This location was selected for purposes different from this study and was installed prior to this study. The 1.0 m mark on the staff gauge corresponds to an elevation of 492.935 m (CGVD2013). The staff gauge is a semi-permanent feature bolted to a tree, and therefore shifts slightly as the tree grows. Nevertheless, over the course of the study, these changes were minimal, and stage readings were assumed accurate to within +/- 0.01 m, consistent with the survey methods. Staff gauge readings were taken whenever discharge measurements were made, thereby facilitating the establishment of a discharge-rating curve for this study. Discharge measurements using the electronic current meter had limitations at high and low flows. At high flows, operator safety was the limiting factor due to strong currents, and therefore there are few measurements to verify high stage values on the staff gauge. At low flow, the physical size of the probe posed limitations because the induced electromagnetic field requires flow depths of at least 0.1 m to yield reliable results.

3.4 Sediment Sampling

3.4.1 Wolman Pebble Counts

The Wolman Pebble Count method was used to characterize the stream substrate (Wolman, 1954). This method is an alternative to bulk sampling methods (Kondolf, 1997) that include the surface and subsurface layers. The Woman Pebble Count method yields coarser grain-size distributions because it only samples the surface material, which may display armouring

(Wolman, 1954; Parker & Klingeman, 1982; Kondolf, 1997). However, since this study was primarily concerned with spawning and rearing habitat, the characterization of the surface materials was deemed sufficient.

The Wolman Pebble Count is considered to be a random sampling method (Kondolf, 1997). The standard protocol for the Wolman Pebble Count procedure outlined in Bunte & Abt (2001) was used to collect the data. Samples were taken at each of the 19 cross-sections in every year of the study. The data for all three years were collected at a similar discharge level so there were no major biases in sampling protocols Nevertheless, it is widely appreciated that the Wolman Pebble Count methodology produces operator bias toward larger grain sizes (Leopold, 1970).

3.5 Data Analysis

3.5.1 Longitudinal Profile

The longitudinal profile of Creighton Creek was calculated by taking the average of the geo-referenced survey points that best characterize the thalweg at each cross-section. An average of several survey points was chosen to represent the thalweg elevation instead of a single point, to avoid any potential biases or misrepresentation of the thalweg elevation caused by abnormal instream features or survey errors (Figure 6).

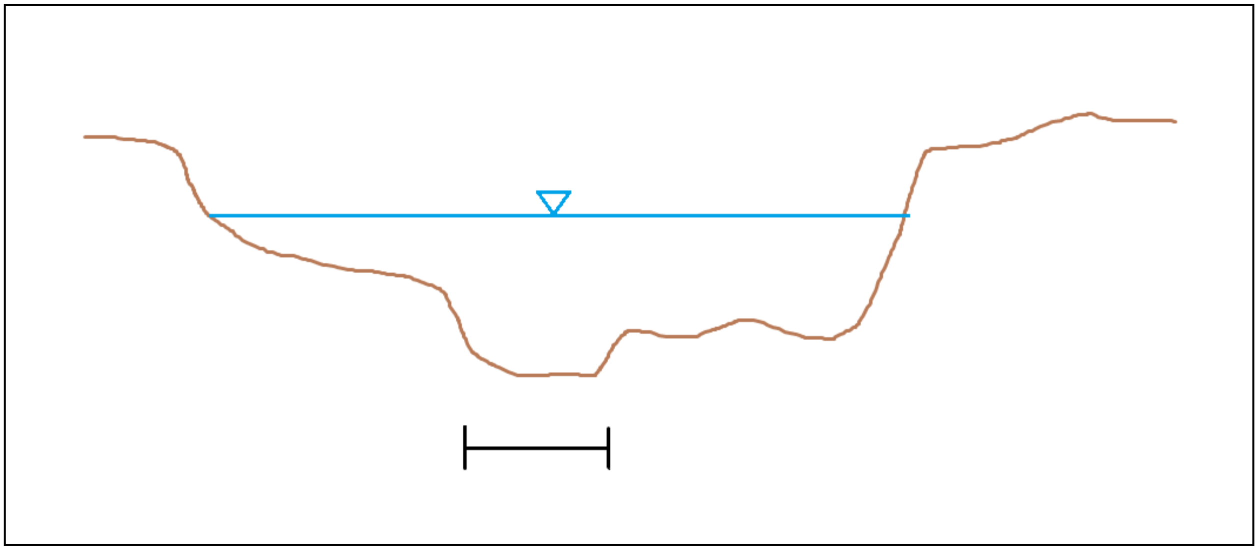


Figure 6. Illustrates the area within a cross-section where the average of the geo-referenced thalweg survey points were taken to represent the elevation of the cross-section.

3.5.2 Cross-section Analysis

Cross-sections were surveyed in every year for the period 2015-2018. To evaluate how much change occurred from year to year, sequential cross-sections were compared using WINXSPro software, developed by the USDA (Hardy et al., 2005). An individual plan file in the *.dat* file format was created for each cross-section for every year and translated into a .sec file format for use in WINSXPro. The *cross-section analyzer* function was used to calculate area changes from one year to the next, which required setting left and right horizontal boundaries to reflect the bankfull width for each cross-section (Figure 7).

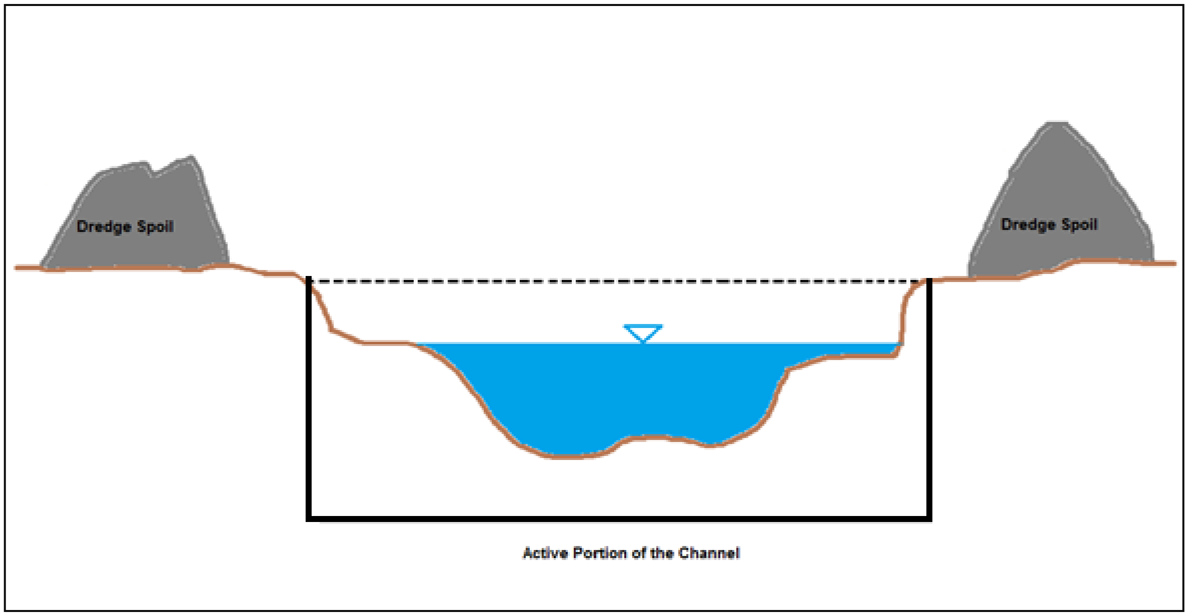
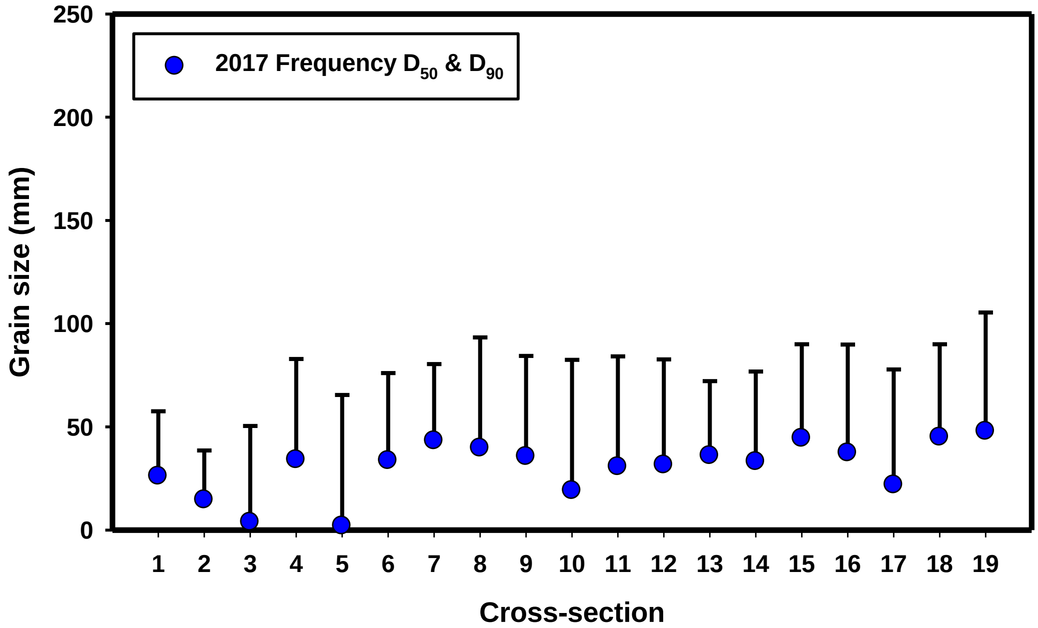


Figure 7. Typical stream levels (solid blue) and peak flood stage (dashed black line) define of the bankfull width for each cross-section, which is used within WINXSPro to define the limits of the area calculations. Areas beyond the bankfull stage, such as dredge spoil and levee-top roads were excluded.

Conditional boundaries were set to identify channel adjustments occurring over a specified time period, to analyze the streambed volume change, reflecting channel adjustments caused by the freshet. It was important to exclude anthropogenic features, i.e. dredge spoil, as volume calculations would not accurately represent channel adjustments. The procedure of isolating natural channel adjustments, was an important data interpretation processes used in the assessment of volume changes throughout the reach to determine the magnitude of channel adjustments. The calculated cross-section area changes were used to portray volume changes within the reach by using the distances between cross-sections to find the volume change per cross-section.

3.5.3 Sediment Data Analysis

The substrate sediments ranged from fine sands to cobbles, therefore two methods were compared to determine which method best represented the grain size distribution in Creighton Creek. The first involved a cumulative frequency distribution, which was based on the number of particles in each size class (Figure 8a). The second was a cumulative mass distribution, which involved converting the frequency data into mass equivalents assuming spherical grains of uniform density (quartz) (Figure 8b). The mass method, traditionally based on sieving and weighing, is optimal for sand-sized distributions, whereas the frequency method is typically used to evaluate gravel and cobble-sized distributions based on counting the number of particles on the bed using the Wolman sampling method (Bunte & Abt, 2001). The distribution data were then entered into Gradistat, an Excel-based, particle-size analysis routine (Blott & Pye, 2001). Statistics are reported according to graphical measures as well as the method of moments.



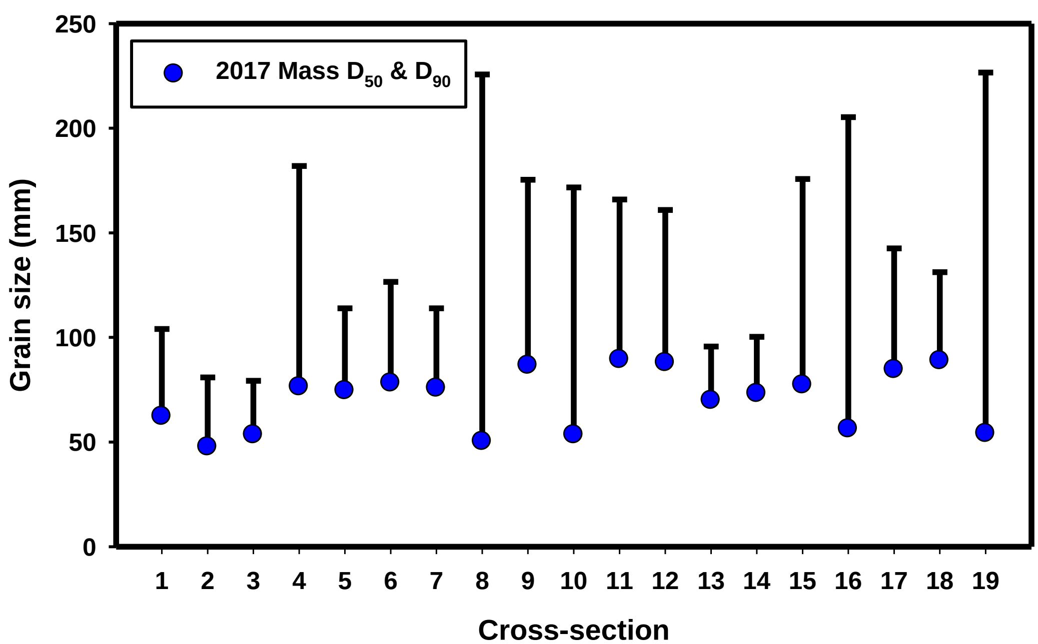


Figure 8. Frequency (a) and mass (b). The 2017 D_{50} and D_{90} per cross-section using the frequency and mass processing methods. The D_{50} is represented by the blue marker and the D_{90} with the upper marker.

Both methods used the same raw data and Gradistat analysis processes. The variation in results using the same sample was attributed to the data processing methods. Figure 8b showed the mass method had an average D_{50} of 89.4 mm, minimum D_{50} of 47.6 mm and maximum D_{50} of 70.5 mm within the reach. In comparison the frequency method (Figure 8a) yielded an average D_{50} of 30.5 mm, minimum D_{50} of 1.93 mm and maximum D_{50} of 47.8 mm within the reach. By comparing the mass and frequency analysis of the D_{50}, the mass method showed a significantly coarser distribution, where the frequency maximum is 0.2 mm greater than the mass minimum D_{50}. Using the D_{90} to evaluate the processing methods, the mass method resulted in a D_{90} average of 146.2 mm, minimum D_{90} of 79.3 mm, and maximum D_{90} of 226.6 mm within the reach. In comparison the frequency method calculated an average D_{90} of 50.4 mm, minimum D_{90} of 38.6 mm, and max D_{90} of 105.4 mm. The mass method showed a significantly coarser distribution where the D_{90} average is 50.4 mm coarser and the D_{90} maximum is 105.4 mm coarser than the frequency method. The raw data were analyzed, and it was concluded that one observation within a coarse grain size class had the ability to significantly skew the distribution of a sample towards a coarser trend using the mass method. Therefore, it was determined that the frequency method more accurately represented the surface grain size distribution of Creighton Creek, and was used for all sediment analysis.

3.6 Hydraulic Modelling

3.6.1 HEC-RAS

The Hydraulic Engineering Center River Analysis System (HEC-RAS) is a river analysis modelling package developed by the US Army Corps of Engineers. Early versions allowed steady and unsteady flow simulations in the streamwise direction (i.e., one dimensional or

1D). A range of modules have been added that allow for simulation of sediment transport, engineering design, and water quality. Recently, limited 2D capacities were integrated to simulate flooding potential on overbank areas although this requires accurate digital elevation data. All geo-referenced cross-sections from the Creighton Creek surveys were entered into HEC-RAS 5.0.7, and these served as the basis for geometry data that underpins the hydraulic model.

Separate models were created for each of 2016, 2017, and 2018, and each model was calibrated separately using surveyed water surface levels and corresponding discharges (usually estimated from the stage-discharge relationship created for the staff gauge). Gauge in and gauge out levels were taken each day before and after surveying the cross-sections to ensure no significant water level changes had occurred during the surveying period. This was necessary because discharge can vary significantly during low flows due to irrigation pumps being switched on and off. Due to disturbances to the staff gauge during the 2017 dredging, the rating curve required external analysis. For all HEC-RAS work completed after the staff gauge was disturbed, the external rating equation accounting for the shift in staff gauge height was:

$$\mathbf{Q} = -0.908198\ (\text{m}) + 1.123903 * \mathbf{Ht}\ (\text{m}) + 2.849132 * \mathbf{Ht}\ (\text{m})^2 \qquad \textbf{(3)}$$

Where:

Q = Discharge (m^3s^{-1})

Ht = Staff Height (m)

The model calibration process involved adjusting the Manning's N-coefficient (Chow, 1959) for every cross-section so that the modeled water surface intersected the survey water level points on the left and right banks at the given discharge. The steady flow analysis routine was used with initial bankfull boundary conditions, and Manning's N were adjusted iteratively over several runs until convergence was achieved. In addition to comparing simulated and surveyed water-surface elevations, output parameters including Froude number, flow velocity, channel area, and shear were evaluated to ensure model outputs were in compliance with observed conditions.

In general, good results were achieved except at one location (cross-section 5) where a small, private bridge influenced the flow and where there was significant dredging activity. In addition, there was poor control on the survey points, so this cross-section was removed from the model and others were interpolated from cross-sections upstream and downstream to maintain model stability (Table 7 & Table 8).

Table 7. Describes each of the cross-sections removed from the corresponding model.

Model	**Location**	**Comments**
2016	Cross-section 5	Removed due to irregular geometry and model was unable to balance energy equations.
2017	Cross-section 5	Removed due to irregular geometry and model was unable to balance energy equations.
2018	Cross-section 5	Removed due to irregular geometry and model was unable to balance energy equations.

Table 8. The HEC-RAS models and corresponding cross-sections that required interpolation. These cross-sections reflect modelled cross-sectional geometry and not survey data.

Model	Location	Comments
2016	Cross-section 3.5	Cross-section was interpolated due to significant changes in geometry between cross-sections 3 and 4.
2016	Cross-section 5.8347	Cross-section was interpolated due to distance between cross-sections 4 and 6.
2017	Cross-section 3.5	Cross-section was interpolated due to significant changes in geometry between cross-sections 3 and 4.
2017	Cross-section 12.5	Cross-section was interpolated due to significant changes in geometry between cross-sections 12 and 13.
2018	Cross-section 3.5	Cross-section was interpolated due to significant changes in geometry between cross-sections 3 and 4.
2018	Cross-section 12.5	Cross-section was interpolated due to significant changes in geometry between cross-sections 12 and 13.

A reach boundary condition of normal depth where $S = 0.0076$ was chosen for all models based on the known water surface levels and energy equations.

3.6.2 Sediment Transport Potential

Although some sediment transport data were collected for this study using a Helley-Smith bedload sampler, most of these data were of no direct relevance. At low flows, there is no measurable sediment transport in this system. At high flows, such as during the freshet, there is a great deal of sediment transport, but it was too dangerous to take measurements. Thus, a modeling approach was adopted to evaluate sediment transport potential.

The 2016, 2017, and 2018 HEC-RAS models were simulated using an average freshet discharge of 2.7 m^3s^{-1} to determine the average shear stress (Nm^{-2}) at each cross-section. The Boundary Reynolds number was calculated using the modelled shear stress output from HEC-RAS and D_{50} for each cross-section. Dimensionless critical shear was calculated using the modelled shear stress applied to:

$$\boldsymbol{\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)gD}} \quad \textbf{(4)}$$

Where:

$\boldsymbol{\tau_c^*}$ = dimensionless critical shear stress

$\boldsymbol{\tau_c}$ = shear stress

$\boldsymbol{\rho_s}$ = sediment density

$\boldsymbol{\rho}$ = water density (kgm^{-3})

g = gravitational acceleration (ms^{-2})

D = grain diameter (i.e., D_{50})

The results for each model were plotted on a Shields Diagram to determine the potential for sediment transport at each cross-section for an average freshet discharge of 2.7 m^3s^{-1}.

Chapter 4.0 Results

4.1 Longitudinal Profile Changes

The 2015, 2016, 2017 and 2018 thalweg survey data were plotted to represent the longitudinal profile and compared to analyze the year-to-year changes. The 2015 and 2016 thalweg profiles indicate that there were no significant changes caused by the 2016 freshet (Figure 9). Minimal degradation occurred at cross-section 3, which is located within a large pool. Thus, the trends better reflect the changes in pool elevation rather than the longitudinal profile. Minimal aggradation occurred in the reach between cross-sections 7 and 13. No significant changes occurred from cross-sections 14 to 19.

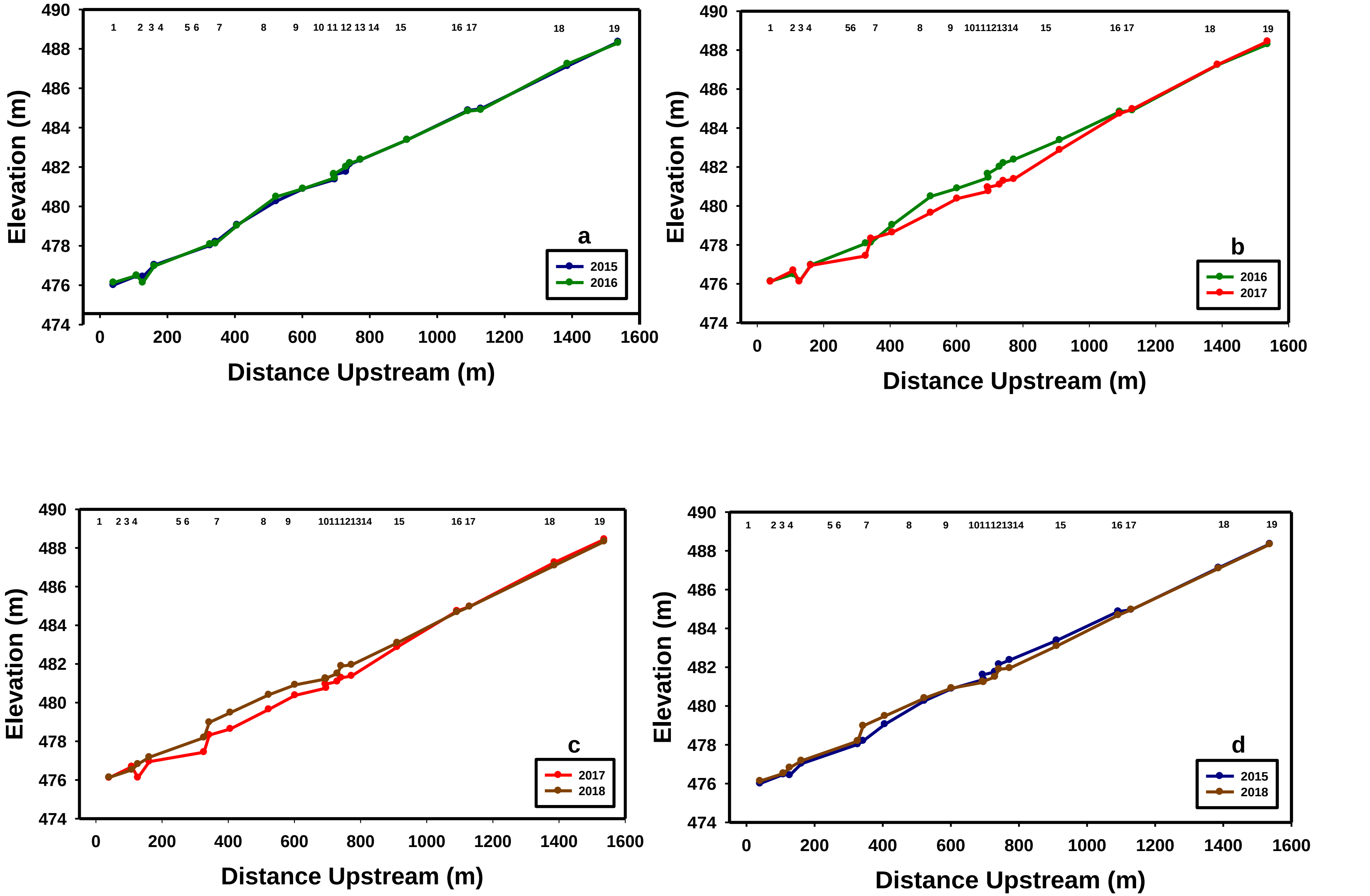


Figure 9. Longitudinal profiles of Creighton Creek from 2015 to 2016 (a), 2016 to 2017 (b), 2017 to 2018 (c), and 2015 to 2018 (d).

Comparing the 2016 and 2017 thalweg profiles highlights the changes from the May 2017 emergency dredging activities as well as the subsequent 2017 freshet flows (Figure 9b). No substantial changes in the longitudinal profile were observed in the downstream section (between cross-sections 1 and 4) or in the upstream section (between cross-sections 16 and 19). Dredging did not occur in these sections. In contrast, there were significant changes to the longitudinal profile between cross-sections 5 and 15, where the bed elevation was lowered substantially. These changes are attributed to the May 2017 emergency dredging activities.

The 2017 and 2018 thalweg profiles also show significant changes. Once again, the downstream and upstream sections remained largely unchanged, whereas the section between cross-sections 5 and 15 experienced significant aggradation. The section subjected to dredging during May 2017 was infilled, and the longitudinal profile returned to a configuration similar to that of 2016 prior to dredging.

A comparison of the 2015 profile to the 2018 profile indicates that there were no significant changes in the upstream section (cross-sections 16 to 19). Similarly, the downstream section (cross-sections 1 to 4) saw relatively small changes. Surprisingly, despite major disruption due to dredging in 2017, the section between cross-sections 2 to 16 returned to a pre-disturbance state. The upper cross-sections appear to have experienced some degradation whereas the lower cross-sections experienced minor aggradation, but overall, these changes are small in comparison to those following dredging.

4.2 Cross-section Changes

To evaluate the changes in cross-sectional geometry and corresponding channel adjustments throughout the reach, the year to year changes were compared. Cross-sections representative of sub reach trends from 2015 to 2018 are presented in Figures 10, 11, 12 and 13. Cross-sectional profiles for each individual cross-section for the duration of the study are located in Appendix A.

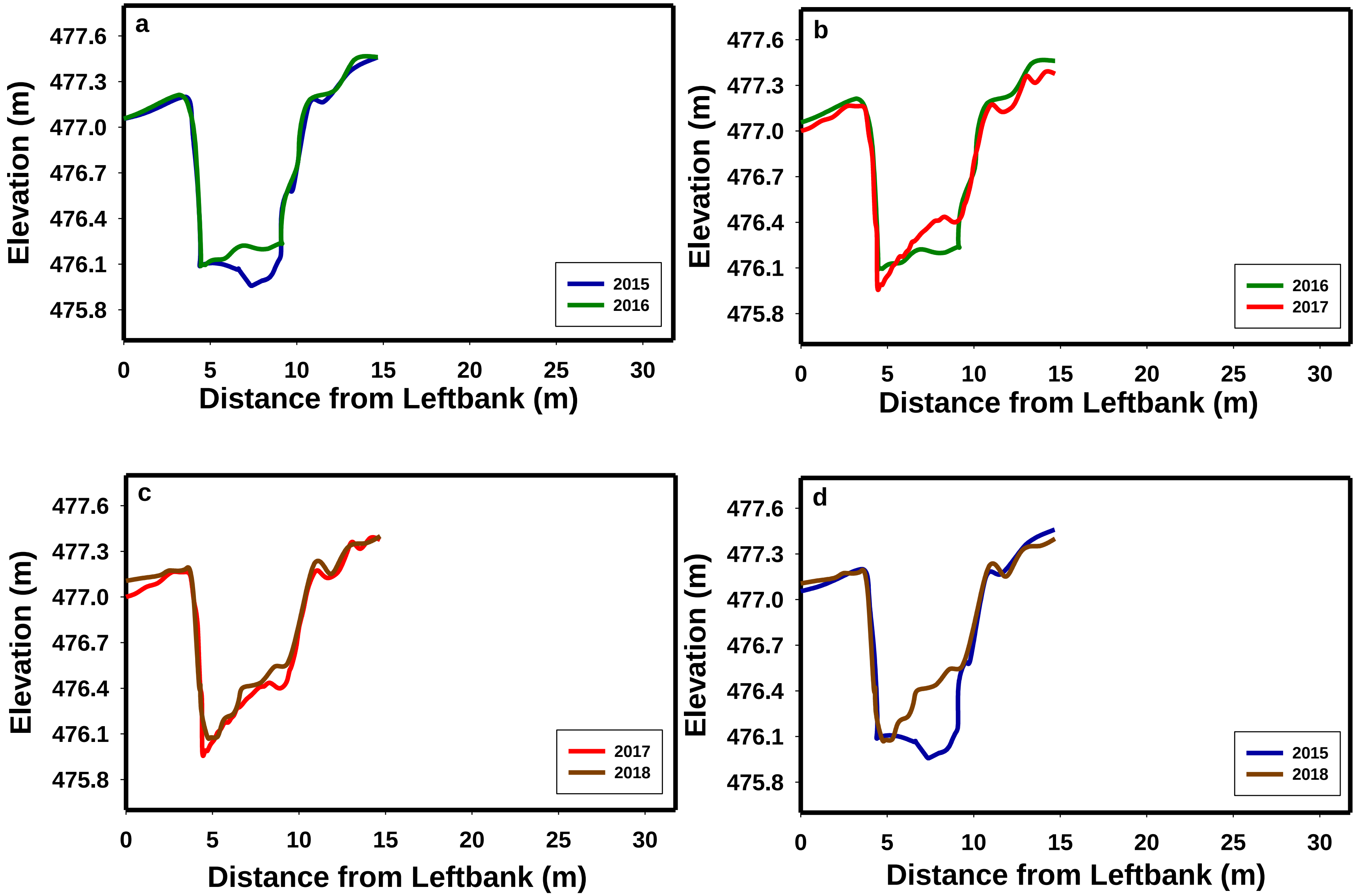


Figure 10. Channel geometry changes at cross-section 1 from 2015 to 2016 (a), 2016 to 2017 (b), 2017 to 2018 (c), and 2015 to 2018 (d).

Cross-section 1 is representative of the downstream section immediately above the Bessette-Creighton Creek confluence and shows slight aggradation on the bed between 2015 and 2016, which was sustained through 2017 (Figure 10). Then the channel appeared to stabilize, leaving a long-term trend of net aggradation between 2015 and 2018 associated with in-filling of a pool and development of channel margin bar on the right bank. Although the details differ for cross-sections 2, 3 and 4, overall there were only minor changes attributed to minimal aggradation in this lower section.

Cross-sections 5 to 15 were located in the zone where channel dredging was conducted May 2017. Figures 11 and 12 show two representative cross-sections (8 and 12), and in both cases, the impact of the emergency dredging is readily apparent. The middle section of the stream had a distinctive channel geometry that was wide and braided due to long-term sediment accumulation. Progressive aggradation is apparent in the changes between 2015 and 2018, as is the multi-channel nature of the cross-section.

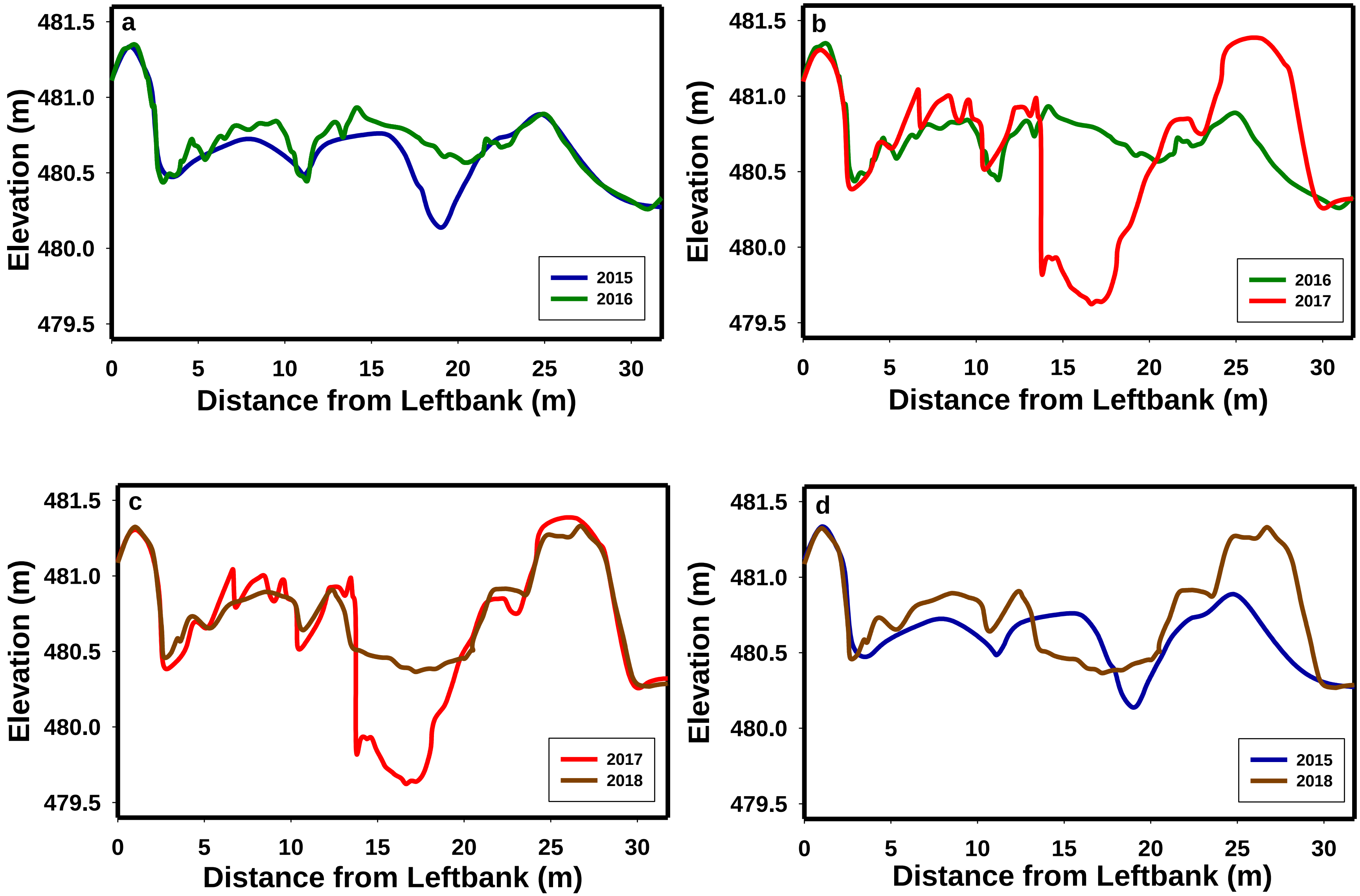


Figure 11. Channel geometry changes at cross-section 8 from 2015 to 2016 (a), 2016 to 2017 (b), 2017 to 2018 (c), and 2015 to 2018 (d).

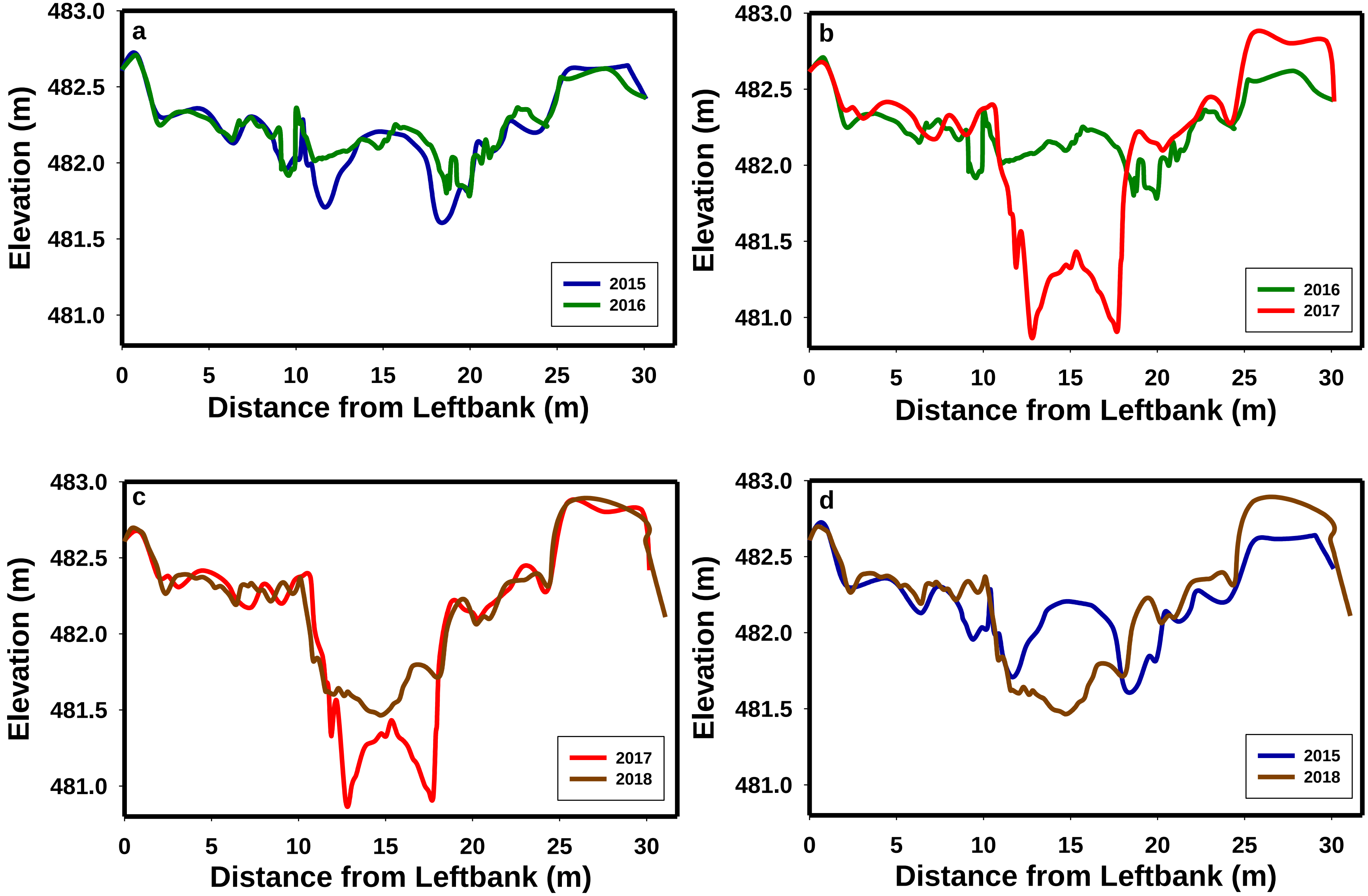


Figure 12. Channel geometry changes at cross-section 12 from 2015 to 2016 (a), 2016 to 2017 (b), 2017 to 2018 (c), and 2015 to 2018 (d).

Cross-sections 8 and 12 are representative of the dredging zone channel geometries, extending from cross-section 6 to 15. The 2015 to 2016 cross-sections show minor aggradation, whereas the 2016 to 2017 cross-sections show the impact of the 2017 emergency dredging, followed by the freshet. A narrow and deep channel was created, lowering the channel bottom by approximately one meter throughout the dredged zone. The right overbank aggradation was due to placement of dredge spoil in the form of a wide berm. The 2017 to 2018 cross-sections indicate that the excavated reach transitioned from a single, deep channel back to a braided system due to sediment infill. The net change from 2015 to 2018 resulted in considerable aggradation on the channel levees due to artificial placement and only minor degradation in the main channel where the dredging occurred.

The upstream section of the study reach, (cross-sections 16 to 19) contains a single meandering stream that was not directly affected by emergency dredging. A small berm was built on the right bank between cross-section 16 and 17 to prevent overbank flooding from damaging nearby infrastructure, but field observations confirm it had no impact on in-channel adjustments. Cross-section 19 (Figure 13) best represented the changes observed in this zone throughout the study period.

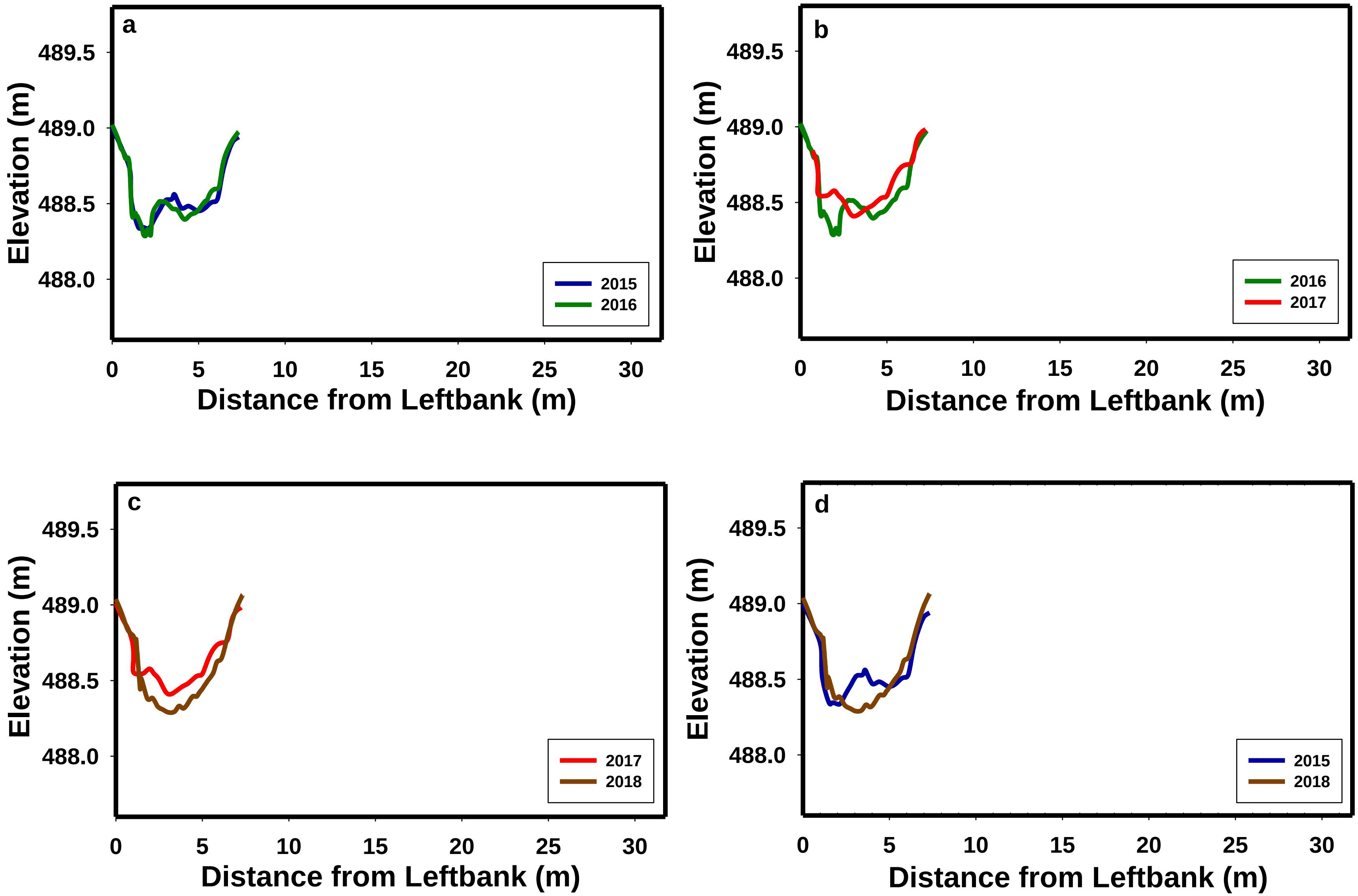


Figure 13. Channel geometry changes at cross-section 19 from 2015 to 2016 (a), 2016 to 2017 (b), 2017 to 2018 (b), and 2015 to 2018 (d).

Unlike the dredged section, there were no significant changes to the channel geometry in this upstream section between 2015 and 2016. Minor streambed aggradation occurred from 2016 to 2017 due to sediment transport during the freshet. The 2017 to 2018 cross-sections indicate minor erosion of the stream bed. This may be an upstream impact due to lowering of base level in the dredged reach downstream or it may simply be the scale of annual fluctuations in the stream bed. Over the entire study period from 2015 to 2018 there was minor erosion of the stream bed that is not considered a significant channel adjustment.

Channel adjustments were further assessed by quantifying the change in cross-sectional area at every cross-section from year to year. To exclude those zones in the cross-section that were not influenced by flowing water (e.g., dredge spoil placed on the levee), the bankfull width was used to define the left and right boundary conditions in WINXSPro. A positive change in area indicated aggradation, while a negative change in area indicated degradation (Figure 14).

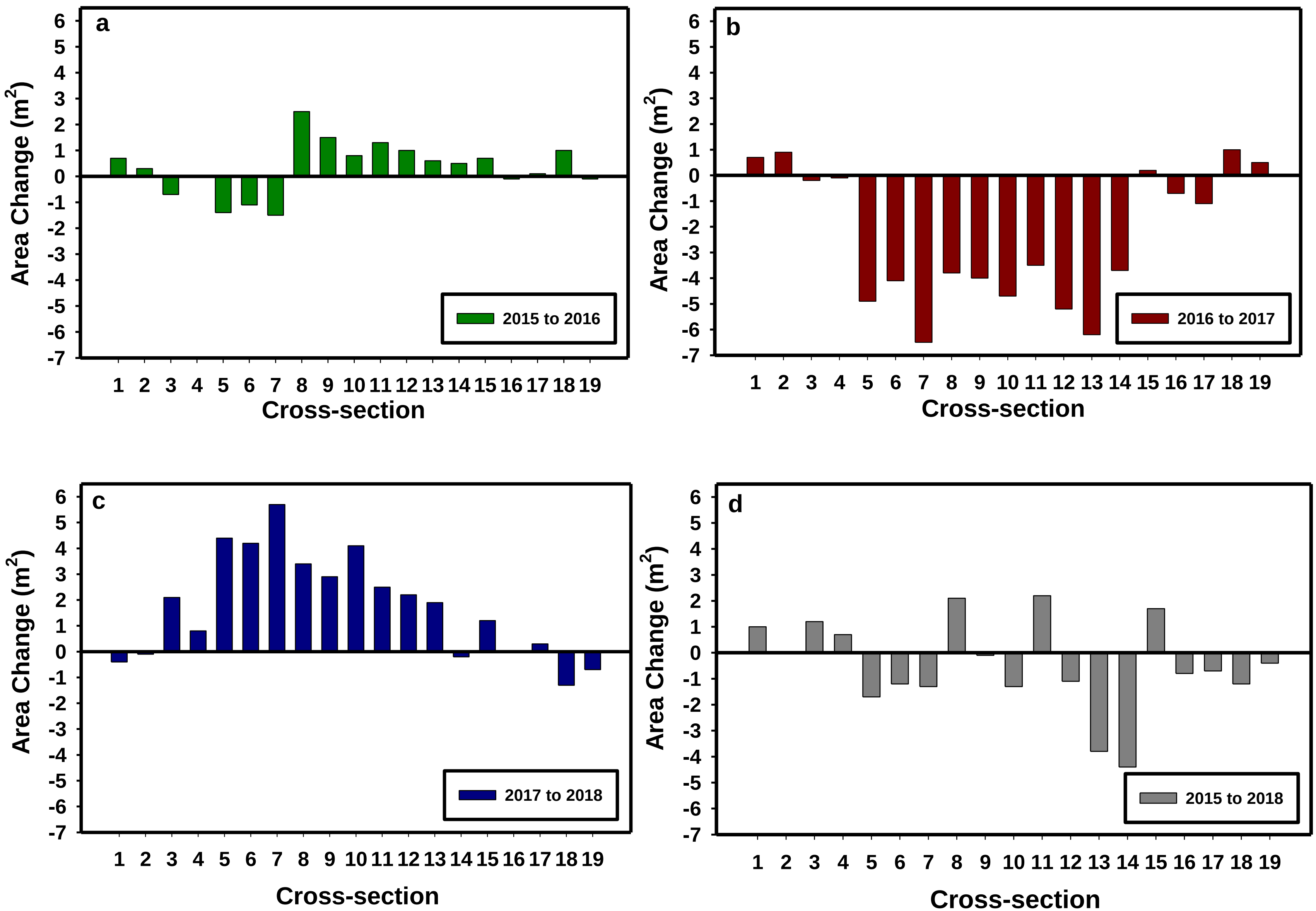


Figure 14. Change in cross-section area (m^2), calculated using WINXSPRO, within the bankfull width per cross-section 2015 to 2016 (a), 2016 to 2017 (b), 2017-2018 (c), and 2015 to 2018 (d).

Figure 14 shows the annual changes in cross-sectional area for all cross-sections in the study reach from downstream (cross-section 1) to upstream (cross-section 19). The 2015 to 2016 observations show that there was relatively little change in the upstream section (cross-sections 16 to 19) except for approximately 1 m^2 squared of aggradation at cross-section 18. Aggradation increased gradually from cross-section 15 through to cross-section 8, where there was about 2.8 m^2 of aggradation. Immediately, downstream of cross-section 8, there was bed degradation of approximately -1 to -1.5 m^2, which transition to bed aggradation at cross-sections 1 and 2. These trends are consistent with a 'wedge' of sediment moving from upstream to downstream, with the advancing front of the wedge located at cross-section 8.

The 2016 to 2017 area changes clearly show the impact of dredging between cross-sections 5 through 14, where bed degradation of between -4 to -6 m^2 was measured. Cross-sections 1 to 4 showed minor aggradation and degradation that are not considered significant. Cross-sections 15 through 19 displayed minor aggradation and degradation consistent with natural variations.

The 2017 to 2018 analysis indicates no significant changes in the downstream section between cross-sections 1 and 4. In the middle section (cross-sections 5 to 13), however, there was significant bed aggradation due to infilling of the dredged cross-sections. Cross-section 14 seems abnormal, however field observations confirm that a large pool formed during the 2018 freshet, perhaps because this location is situated between two sharp meander bends. No significant changes were observed upstream of the dredged area, between cross-sections 15 and 19.

The 2015 to 2018 net changes in cross-sectional area show a highly variable pattern of adjustments throughout the reach. The downstream cross-sections 1 to 4 show only minor aggradation, and year-to-year there were only minor changes. The middle section, including cross-sections 5 through 15 displayed both increases and decreases in area, with the most extreme degradation occurring at cross-sections 13 and 14. The middle section was subjected to emergency dredging in 2017, and experienced a rapid return to pre-disturbance elevations in 2018. Cross-sections 16 to 19 remained relatively stable but displayed a small net decrease in cross-sectional area. The volume of sediment is not sufficient to account for the aggradation documented in the downstream cross-sections, which suggests that the upstream section served only as a corridor through which sediment from farther upstream was transported with little net change to the channel geometry. Most of the channel change activity occurred at the cross-sections where dredging was conducted.

4.3 Sediment Analysis

The substrate sediments ranged from fine sands to cobbles, therefore two methods were compared to determine which method best represented the grain size distribution in Creighton Creek. The mass method, based on sieving and weighing, is optimal for sand sized distributions, whereas the volume (frequency) method is used to evaluate gravel and cobble sized distributions based on counting the number of particles on the bed using the Wolman sampling method (Bunte & Abt, 2001). The 2016, 2017, and 2018 grain size mean, D_{50} (median), D_{10} and D_{90} for each cross-section were plotted to represent the spatial grain-size distribution within the study reach (Figure 15).

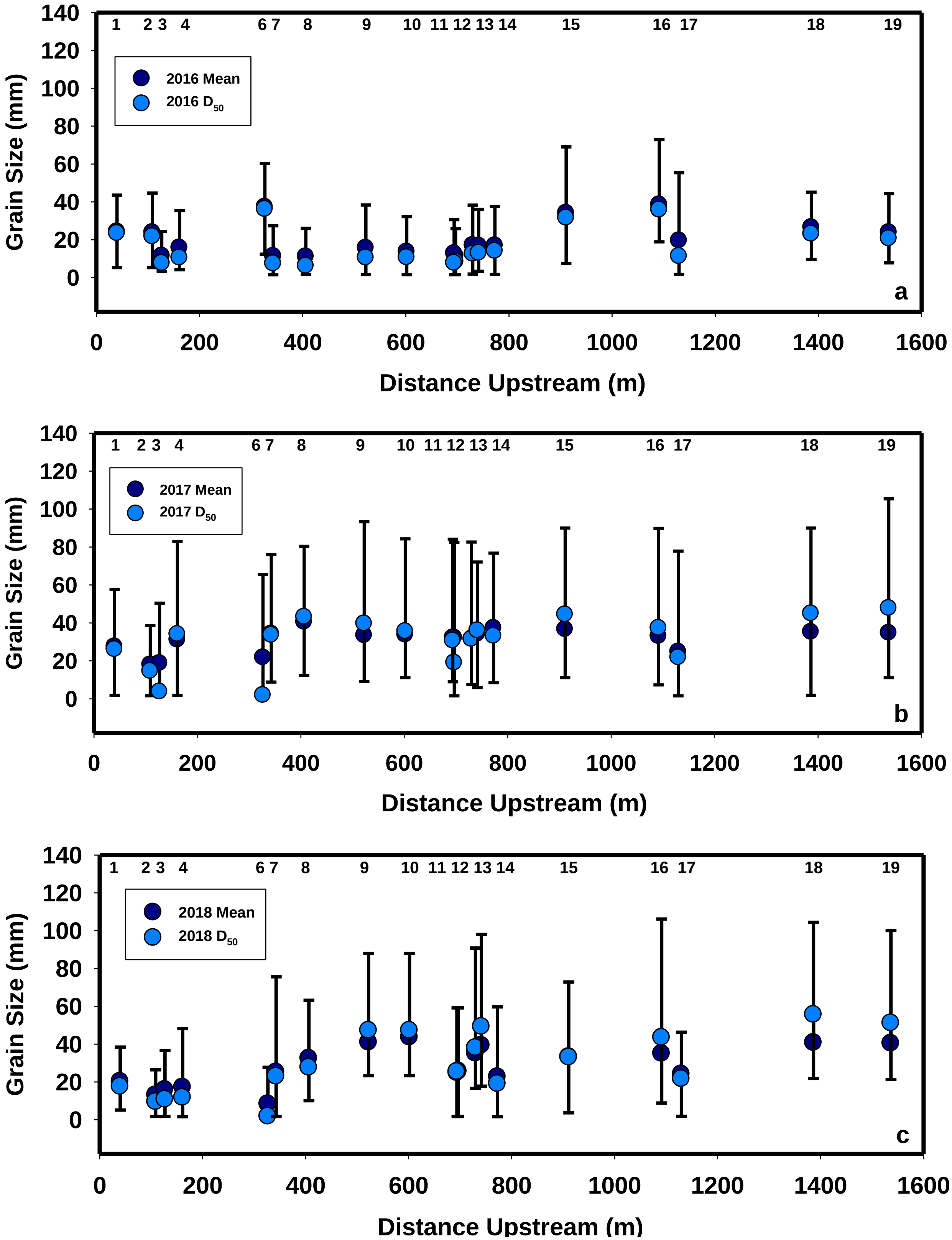


Figure 15. 2016 (a), 2017 (b), and 2018 (c) D_{50} and mean per cross-section. The upper whisker presents the D_{90} and the lower represents the D_{10} per cross-section.

The sediment data (Appendix B) are summarized in Table 9 to present the 2016 to 2018 changes in mean, D_{10}, D_{50}, and D_{90}.

Table 9. 2016 to 2018 surface sediment statistics calculated in Gradistat using the Wolman Pebble Count field data.

		Mean (mm)	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)
2016	Minimum	11.11	1.53	6.21	24.39
	Average	20.12	4.86	16.46	41.45
	Maximum	38.54	18.88	36.14	72.92
2017	Minimum	18.01	1.49	1.93	38.58
	Average	31.14	6.10	30.50	77.90
	Maximum	40.57	12.35	47.80	105.36
2018	Minimum	8.34	1.47	1.79	26.42
	Average	28.32	8.79	29.38	67.83
	Maximum	43.59	23.31	55.63	106.12

Cross-sections 1 to 4 are predominantly fines (i.e., sand size) (Appendix B). The fine, well sorted distribution present at cross-section 3 is due a large pool and does not reflect the sediment distribution upstream or downstream of this feature. The spread between the D_{10} and D_{90} from cross-sections 6 to 14 show that in 2016, the substrate in this sub-reach was well sorted. Based on three indicators, this zone was a sediment sink where depositional processes were dominant. First, channel geometry transitioned from a single channel to multiple braided channels. Second, overbank deposits of fine materials were more frequently found in the most downstream cross-sections. A downstream fining trend was present from cross-sections 14 to 6. The coarsest grain-size distributions were observed at cross-sections 5, and 16 to 18. Cross-section 5 was considered an anomaly as it was the upstream side of a bridge, where excavation of the streambed occurred during the 2018 freshet while the bridged was replaced. The greatest spread between the D_{50} and D_{90} was observed at cross-sections 15 to 17, suggesting the presence of larger substrate within this sub-reach.

The 2017 data showed a significant coarsening trend, except for cross-sections 3 and 5 displaying a fining trend in the lower section. Table 9 summarizes the 2017 sediment data from Appendix B. In comparison to the 2016 data the 2017 data show a reach scale increase in average and maximum grain size. Thus, the changes in 2017, the year of the emergency dredging, was a coarsening of the streambed within the entire reach. The observed coarsening trend was most evident between cross-section 5 and 15, which is the zone where dredging took place. However, the greatest observed change in 2017 occurred at cross-section 19, where the surface sediment significantly coarsened. Cross-section 19 was not impacted by the emergency dredging. The least amount of change occurred between cross-sections 1 and 3, where no dredging occurred. The 2017 distribution showed a significant increase in spread between the D_{50} and D_{90} distributions, suggesting greater variance in within the population due to the disturbance within the dredged zone.

In comparison to the 2017 data, in 2018, the averages for the mean, D_{50}, and D_{90} slightly decreased while the D_{10} slightly increased (Table 9). These changes from 2017 to 2018 were minor in comparison to the major changes between 2016 and 2017. The general pattern of substrate coarsening between 2016 and 2017, held through the 2018 freshet (Table 9). From cross-sections 18 to 14 and again from cross-sections 13 to 2, the 2018 data showed a downstream fining trend within the reach (Figure 15). From 2017 to 2018 there was a small decrease in mean sediment size and minor increase in sorting. Cross-sections displaying no significant changes in mean showed no significant changes in sorting (Appendix C). The 2018 data showed cross-sections 1 to 4 return to similar mean and sorting distributions as the 2016 data. The dredged cross-sections remained coarser and showed less sorting than the 2016 distribution, despite the infill of the dredged zone and cross-sectional geometry adjustments similar to the 2016 trends. Within the dredged zone, a downstream fining trend was present in comparison to the 2017 distribution. Cross-section 5 showed no substantial change in the D_{50} distribution likely due to unauthorized dredging during the 2018 freshet while replacing the bridge at this cross-section (Figure 15). The formation of pools during the 2018 freshet at cross-sections 14 and 17 contributed to the observed fining. Thus, the grain size distribution is representative of the instream feature at the specified location and not the general trend surrounding the cross-section. With the exclusion of cross-section 17, cross-sections 16 to 19 show the coarsest distributions. From cross-sections 16 to 19 the spread between the D_{50} and D_{90} remained greater than the 2016 and was comparable to the 2017 distribution.

4.4 HEC-RAS Hydraulic Modelling

Three hydraulic models using survey data from 2016, 2017 and 2018 were created to simulate the hydraulic conditions present in Creighton Creek for the duration of the study. To test the accuracy of the calibrated models, the surveyed water surface elevation and simulated water surface elevation were compared (Table 10). While water-surface elevation was the primary parameter used for calibration, other modelled hydraulic parameters such as flow velocity, energy grade-line elevation, shear, and the Froude number for each cross-section were evaluated. In an ideal scenario there would be no elevation difference between the model simulated and surveyed water-surface elevation. However, model capabilities and accuracy are limited by the inability of the model to account for changes in hydraulics caused by spatial variation in geomorphic features present between cross-sections and flow fluctuations caused by surface-groundwater interactions. Model simulation accuracy increases with discharge as the impact of these features on hydraulics is reduced.

Table 10. Channel Manning's N per cross-section used to calibrate the 2016 HEC-RAS model and the elevation difference between the surveyed and simulated water surface elevations at a specified discharge.

Cross-section	Manning's N	0.090 m^3s^{-1} Surveyed Water Surface (m)	2.05 m^3s^{-1} Surveyed Water Surface (m)	2.67 m^3s^{-1} Surveyed Water Surface (m)	0.090 m^3s^{-1} Simulated Water Surface (m)	2.05 m^3s^{-1} Simulated Water Surface (m)	2.67 m^3s^{-1} Simulated Water Surface (m)	0.090 m^3s^{-1} Difference (m)	2.05 m^3s^{-1} Difference (m)	2.67 m^3s^{-1} Difference (m)
1	0.055		476.639	476.726		476.640	476.720		**-0.001**	**0.006**
2	0.065		477.166			477.160	477.250		**0.006**	
3	0.100	476.744			476.700			**0.044**		
4	0.075		477.562	477.673		477.560	477.680		**0.002**	**-0.007**
6	0.040		478.875	478.997		478.900	478.990		**-0.025**	**0.007**
7	0.060		479.339	479.372		479.320	479.370		**0.019**	**0.002**
8	0.170		481.042	481.042		481.010	481.060		**0.032**	**-0.018**
9	0.150		481.574	481.602		481.550	481.610		**0.024**	**-0.008**
10	0.150		481.989	481.989		481.960	482.030		**0.029**	**-0.041**
11	0.075		482.102	482.137		482.090	482.160		**0.012**	**-0.023**
12	0.070	482.002			481.930			**0.072**		
13	0.065		482.558	482.587		482.540	482.570		**0.018**	**0.017**
14	0.030		482.784	482.825		482.740	482.770		**0.044**	**0.055**
15	0.020		483.365	483.377		483.660	483.700		**-0.295**	**-0.323**
16	0.075	484.963			484.960			**0.003**		
17	0.150	485.193			485.190			**0.003**		
18	0.200	487.401			487.390			**0.011**		
19	0.020	488.430			488.480			**-0.050**		

The 2016 HEC-RAS model was calibrated using three different discharges. The 0.090 m^3s^{-1} survey data was obtained in 2016 during low flows while surveying the cross-sections and represents low flow conditions. The survey data representing the water surface elevation at 2.05 m^3s^{-1} and 2.67 m^3s^{-1} discharge was obtained by installing temporary markers during flood conditions, that were later surveyed. Due to safety concerns it was not possible to obtain flood level data at cross-sections 3 and 16 to 19. Table 10 showed 17 out of 19 cross-sections were able to be calibrated within 0.05 m and 11 out of 19 cross-sections were able to be calibrated within 0.02 m. Cross-section 15 was unable to be accurately calibrated based on water-surface survey data. The Manning's N for cross-section 15 was chosen based on the simulated energy grade-line elevation, flow velocity, Froude number and shear stress. The data simulated at cross-section 15 were compared to the upstream and downstream cross-section simulations and to field data ,including measured flow velocity and empirical observations, in order to ensure that no abnormalities were present and that model outputs accurately represented the condition of Creighton Creek. Accurate calibration of the 2016 model to three different discharges with the same Manning's N and boundary conditions gives confidence in the results obtained from the model simulations. The same method to analyze model calibration accuracy was used for the 2017 (Table 11) and 2018 (Table 12) models.

Table 11. Channel Manning's N per cross-section used to calibrate the 2017 HEC-RAS model and the elevation difference between the surveyed and simulated water surface elevations at a specified discharge.

Cross-section	Manning's N	0.225 m^3s^{-1} Surveyed Water Surface (m)	0.225 m^3s^{-1} Simulated Water Surface (m)	Difference (m)
1	0.045	476.291	476.3	**-0.009**
2	0.100	476.925	476.91	**0.015**
3	0.100	476.881	476.92	**-0.039**
4	0.080	477.235	477.17	**0.065**
6	0.045	478.480	478.55	**-0.070**
7	0.055	478.942	478.85	**0.092**
8	0.055	479.861	479.85	**0.011**
9	0.055	480.603	480.58	**0.023**
10	0.055	480.905	480.920	**-0.015**
11	0.055	481.138	481.130	**0.008**
12	0.050	481.327	481.300	**0.027**
13	0.070	481.550	481.550	**0.000**
14	0.075	481.755	481.760	**-0.005**
15	0.100	483.077	483.040	**0.037**
16	0.045	484.901	484.890	**0.011**
17	0.085	485.212	485.150	**0.062**
18	0.045	487.479	487.450	**0.029**
19	0.045	488.636	488.630	**0.006**

The 2017 HEC-RAS model was calibrated using water-surface elevation data at 0.225 m^3s^{-1} discharge and represents stream conditions after the emergency dredging (Table 11). Flood level data was not obtained due to dredging disturbances burying and removing the cross-section benchmarks. For safety reasons, cross-section benchmarks were re-established at lower flows. The 2017 model had similar Manning's N values in comparison to 2016 at cross-sections 1 to 4. A decrease in Manning's N values for the channel, especially in the dredged zone, cross-section 6 to 15 were required to calibrate the model. During the dredging, willows, LWD and large boulders were removed within the bankfull width of the channel. Further there was significant change in channel morphology supporting a reduction in Manning's N values. A decrease in Manning's N was observed at cross-sections16 to 19 where no dredging occurred. Table 11 showed 15 out of 19 cross-sections were able to be calibrated within 0.05 m and 9 out of 19 cross-sections were able to be calibrated within 0.02 m. The 2017 model results accurately simulated the post dredging conditions of Creighton Creek (Table 11).

Table 12. Channel Manning's N per cross-section used to calibrate the 2018 HEC-RAS model and the elevation difference between the surveyed and simulated water surface elevations at a specified discharge.

Cross-section	Manning's N	0.181 m^3s^{-1} Surveyed Water Surface (m)	0.181 m^3s^{-1} Simulated Water Surface (m)	Difference (m)
1	0.055	476.338	476.340	**-0.002**
2	0.200	476.880	476.830	**0.050**
3	0.200	477.094	477.010	**0.084**
4	0.180	477.324	477.270	**0.054**
6	0.030	479.080	479.100	**-0.020**
7	0.040	479.525	479.560	**-0.035**
8	0.030	480.505	480.510	**-0.005**
9	0.030	480.924	480.970	**-0.046**
10	0.050	481.346	481.350	**-0.004**
11	0.030	481.422	481.450	**-0.028**
12	0.040	481.599	481.600	**-0.001**
13	0.070	482.040	481.970	**0.070**
14	0.130	482.310	482.310	**0.000**
15	0.040	483.268	483.160	**0.108**
16	0.080	484.899	484.900	**-0.001**
17	0.150	485.156	485.150	**0.006**
18	0.040	487.248	487.248	**-0.000**
19	0.085	488.500	488.500	**0.000**

The 2018 HEC-RAS model was calibrated using water-surface elevation data at 0.181 m^3s^{-1} discharge (Table 12). Due to the limitation of flood water-surface data the model was not able to be tested for accuracy at flood level flows. The 2018 model shows an increase in

Manning's N at cross-sections 1 to 4 despite no significant observed channel adjustments and changes in cross-section morphology. A decrease in Manning's N was observed in the dredged zone (cross-sections 5 to 15). Despite channel adjustments and infill of the dredged zone cross-sections, the Manning's N values for this sub-reach did not return to conditions similar to pre-dredging values used to calibrate the 2016 model (Table 10). Cross-section 15 was calibrated using the same method used for the 2016 model, due to abnormal model outputs for hydraulic parameters observed at this cross-section when simulated and measured water-surfaces were calibrated within 0.05 m. With the exclusion of cross-section 17, cross-sections 16 to 19 showed an increase in Manning's N values required to calibrate the model, however these cross-sections were able to be calibrated within 0.01 m supporting model accuracy. Table 12 showed 15 out of 19 cross-sections were able to be calibrated within 0.05 m and 10 out of 19 cross-sections were able to be calibrated within 0.02 m. The Table 12 results show, while no flood data was available, the model still accurately represents the hydraulic conditions of Creighton Creek in 2018.

The water surface and minimum ground elevation profile for each model was plotted in HEC-RAS to examine the water profile trends of Creighton Creek within the study reach (Figure 16). A discharge of 2.7 $m^3s^{-1}$was used to simulate the models at high flows, as it was the maximum discharge where flow was contained within the bankfull boundaries and no overbank flooding occurred. Model accuracy is reduced when flow exceeds the bankfull due to limitations caused by the survey data used to build the geometry files, because the data do not include all the overbank features such as, drainage ditches and flood plain features at each cross-section. The HEC-RAS water surface profile gave insight to channel morphology characteristics that affect hydraulic parameters like water surface elevation. Where the channel is narrow and deep, the profile is predicted to show a higher surface elevation. Where channel geometry is wide and shallow, the profile is predicted to have a lower elevation. Abrupt changes in the water surface elevation profile can indicate the presence of instream features such as pools, riffles, or log jams. The water surface elevation is impacted by slope, channel geometry, streambed features and channel roughness.

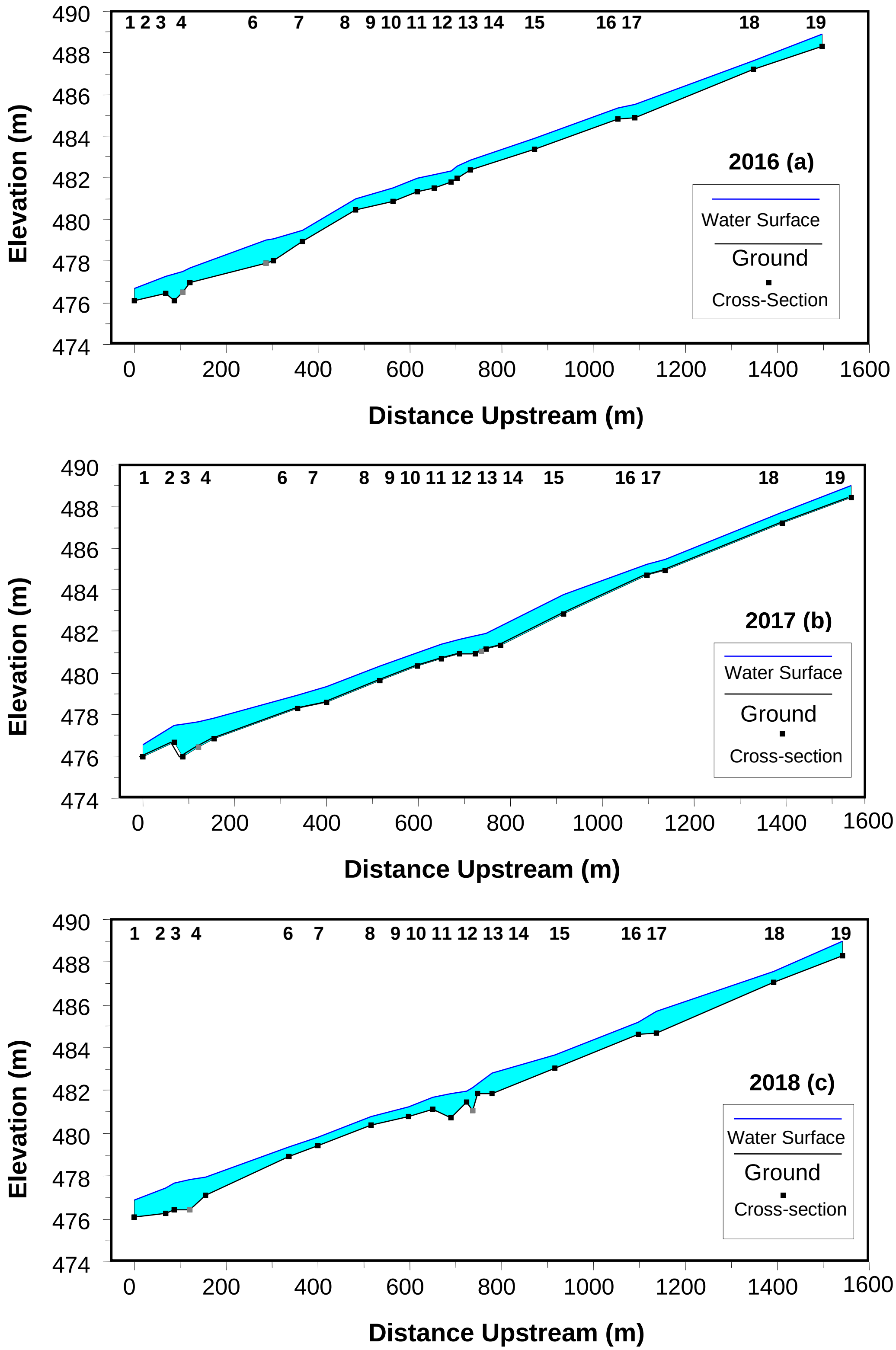


Figure 16. HEC-RAS modelled surface water elevation and minimum channel elevation per cross-section simulated at 2.7m^3s^{-1} discharge for 2016 (a), 2017 (b), and 2018 (c).

The 2016 HEC-RAS profile shows a uniform water surface elevation within the study reach (Figure 16a). The lower reach of the profile between cross-sections 1 to 6 show a higher water surface elevation in comparison to the rest of reach, this is likely due to the channel being narrow and confined at these locations. Cross-sections 7 to 15 show a relatively low water surface elevation profile, likely due to the channel morphology transitioning to a wide cross-section profile with several braided channels. The abnormalities present at cross-section 3 are caused by the geometry of a pool at this location. The 2017 HEC-RAS profile shows a distinct increase in modelled surface elevation in the dredged zone at cross-sections 6 to 15 (Figure 16b). Changes in channel morphology and channel roughness caused by the dredging have led to an increase in the water surface profile. A small increase in profile elevation was observed at cross-section 3, caused by channel adjustments (Appendix A). No changes were observed upstream of the dredging. The 2018 HEC-RAS profile shows an increase in water surface profile at cross-section 2 (Figure 16c), attributed to the channel adjustments at this cross-section (Appendix A). The dredged zone cross-sections 6 to 9 returned to a similar profile to the 2016 model output, however the changes at cross-section 11 and 17 are due to channel adjustments and the formation of pools (Appendix A).

Chapter 5.0 Discussion

5.1 Channel Adjustments

Channel adjustments yielding alterations to the longitudinal profile and local cross-section geometry of a fluvial system are driven by changes in flow and sediment supply (Darby & Thorne, 1996) as mediated by anthropogenic influences such as land-use changes, flow control structures, and in-channel works (e.g., aggregate mining, levee construction). Creighton Creek has been subjected to numerous modifications historically, and most recently an emergency dredging operation in the lower reaches.

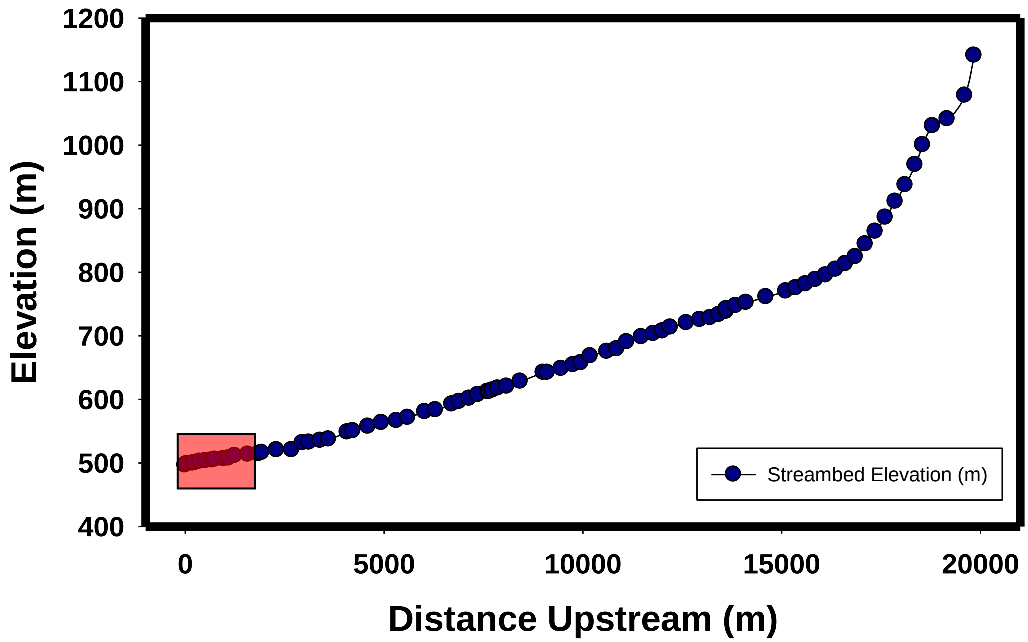


Figure 17. Longitudinal profile of Creighton Creek beginning at the junction with Bessette Creek at 0 m. Study site in lower reach is indicated by red shaded rectangle. Data source: Google Earth.

The channel gradient of Creighton Creek decreases in the downstream direction and the study reach is in the flattest section, immediately upstream of the confluence with Bessette

Creek (Figure 17). Potential base level adjustments in Bessette Creek may cause backwater effects to propagate upstream into the study reach, which need to be considered in the hydraulic model. Such backwater effects may have an influence on sediment transport capacity leading to aggradation in the lower reach. Given the connection between Creighton and Bessette Creeks at their confluence, a base level increase or decrease in Bessette Creek would be expected to trigger a corresponding increase or decrease in the thalweg elevation at cross-sections 1 and 2. However, no substantial changes in elevation at cross-section 1 and cross-section 2 were observed through the duration of the study (Figure 18) suggesting that there were no significant changes in channel gradient. Therefore, the drivers of change in the study reach were likely not forced by base-level changes in Bessette Creek, but rather from upstream sources.

Vertical changes in the longitudinal profile were determined by comparing the thalweg elevations between the 2015, 2016, 2017 and 2018 surveys (Figure 18). The least amount of thalweg elevation change occurred between 2015 and 2016, suggesting that the channel was neither aggrading nor degrading and sediment inputs were balanced with sediment outputs. Minor changes in elevation at some cross-sections were likely due to semi-mobile bedform features such as riffles and pools. Between 2016 and 2017, a significant decrease in bed elevation occurred in consequence of the emergency dredging between cross-sections 5 to 15. The downstream zones from cross-sections 1 to 4 and upstream zone from cross-sections 16 to 19, where no dredging occurred, displayed thalweg elevation change of similar magnitude to the 2015 to 2016 elevation changes.

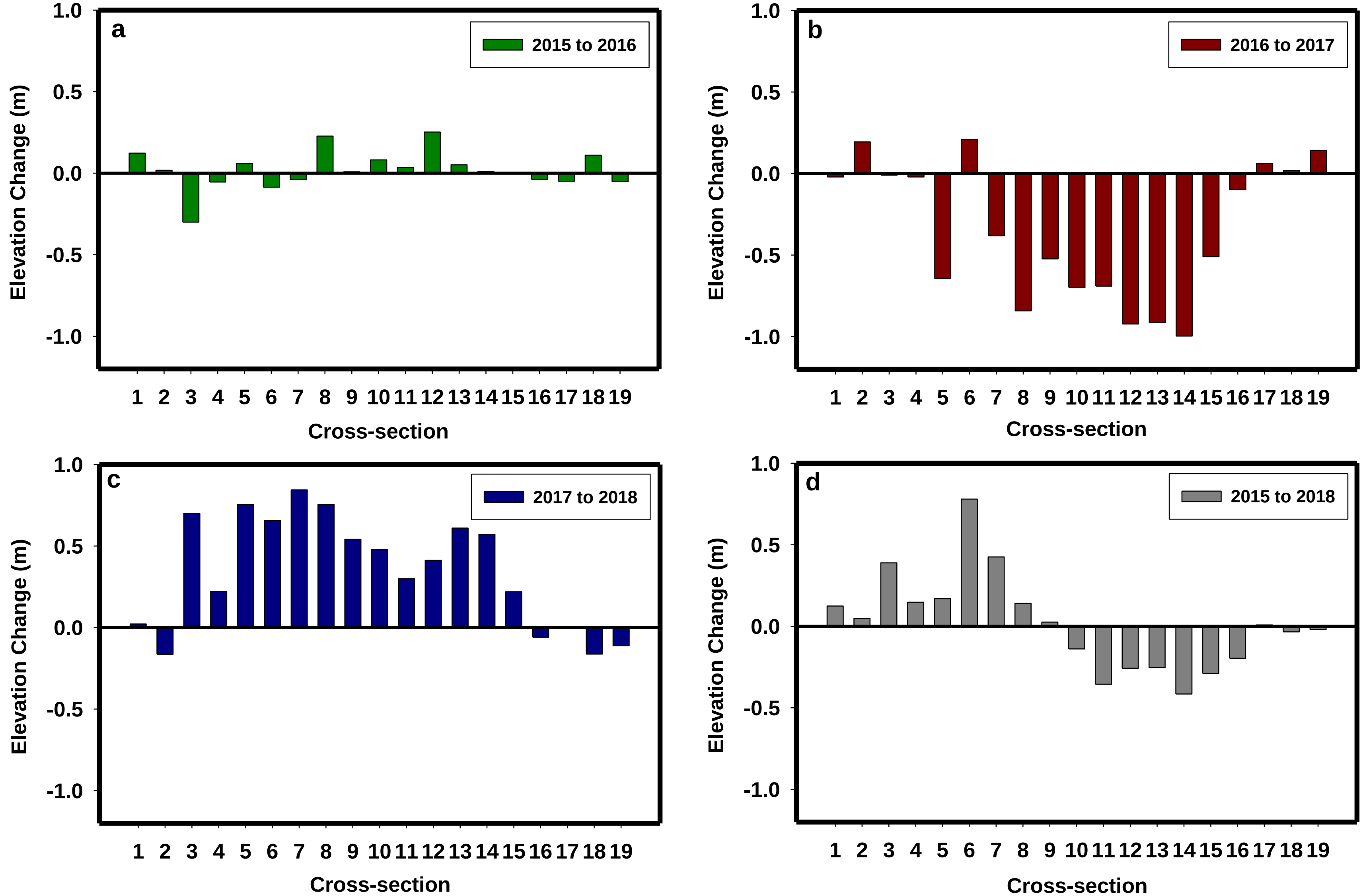


Figure 18. Thalweg elevation change per cross-section 2015 to 2016 (a), 2016 to 2017 (b), 2017 to 2018 (c), and 2015 to 2018 (d).

The 2017 to 2018 observations indicate the main driver of change was sediment transport during the spring freshet. A significant increase in elevation between cross-sections 5 and 15 was evident within the dredged zone. The magnitude of aggradation was similar to losses caused by the dredging. The upstream and downstream zones, not subject to emergency dredging, showed a similar magnitude of elevation change to the 2015 to 2016 and 2017 to 2018 changes. Thus, the data reveal that only minor elevation changes were present at cross-sections where no in-stream dredging occurred. The cross-sections impacted by the 2017 emergency dredging showed the greatest elevation change, followed by the subsequent 2018 aggradation as the system responded to the dredging. Mackin (1948) describes these types and scale of adjustment processes, which are typical of a graded stream as occurring over a long temporal scale, typically tens of years. However, Creighton Creek returned to the pre-dredging equilibrium within one year of disturbance suggesting a substantially shorter temporal scale than would be expected.

The sediment aggradation trends at cross-section 3 and cross-section 6 for the duration of the study, were not representative of the channel adjustments within the reach but rather were due to localized infilling of pools. Creighton Creek's ability to re-achieve its pre-dredging grade within one year of the disturbance, implied the ineffectiveness of the emergency dredging to alter channel morphology for the purpose of increasing sediment transport capacity.

The magnitude of channel adjustments characterizing the impact of the dredging and stream response was determined by calculating the volume change of the active portions of the streambed. The volume of adjustments for the duration of the study from 2015 to 2018 were analyzed by calculating the cross-sectional area change over a specified distance. The change in volume (Figure 19) characterized the type of channel adjustments within the reach driven by the freshet and dredging.

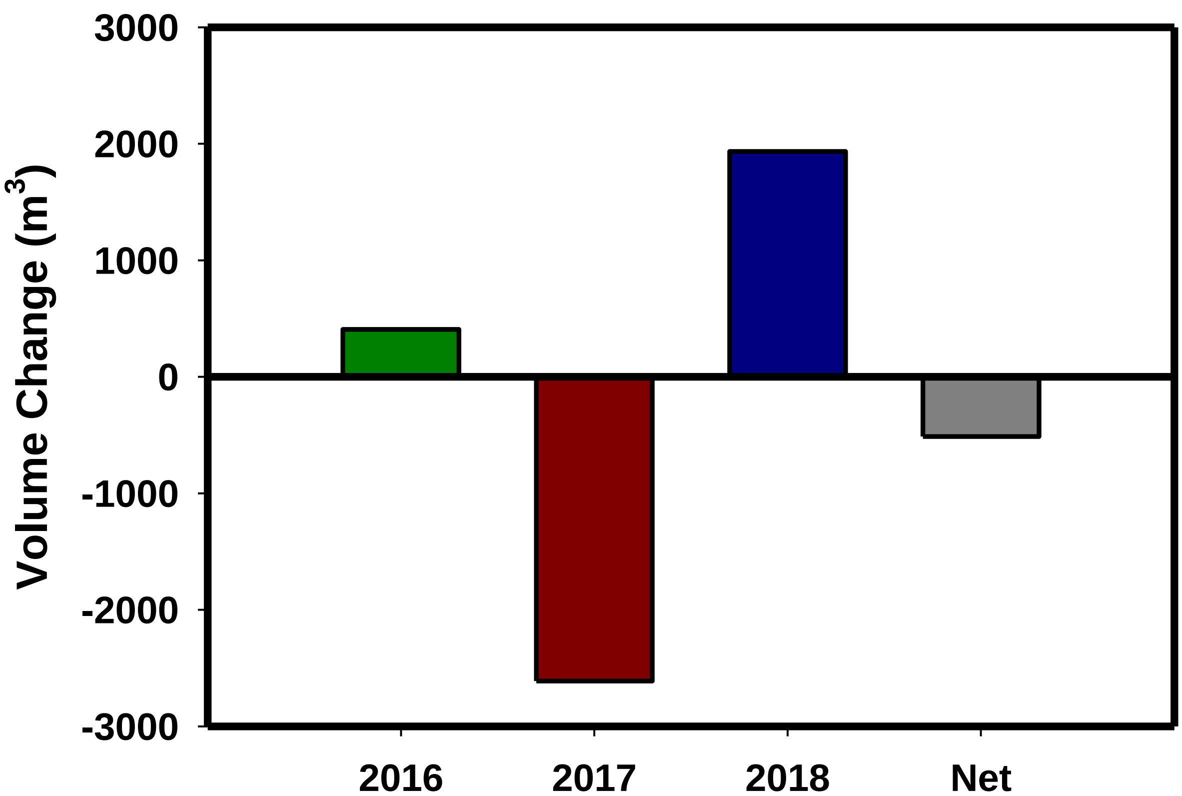


Figure 19. 2016 to 2018 volume change of the active portions of the channel per year.

Channel adjustments resulting from the 2016 freshet led to an aggradation of 406 m^3 of sediment within the entire study reach. The positive change in volume indicated an aggrading trend is present within the study reach. The 2016 geomorphic changes presented in Section 4 and field observations suggested most of the change occurred in areas affected by previous restoration projects. The volume of change within the reach, and minimal channel adjustments in zones where no previous restoration projects occurred, suggests the system was aggrading.

Local landowners estimated that 300 truckloads (approximately 3000 m^3) of sediment was hauled away from the site during the dredging A. Dolman & L. Hesketh (personal communication, June 2017). The 2017 emergency dredging and freshet yielded a degradation of -2611 m^3 within the study reach. The increase in magnitude of channel change was directly attributed to the dredging processes and was considered significantly greater than natural occurring disturbances within the stream. The 2018 volume change of 1935 m^3 indicates a very high rate of bed transport. The geomorphic changes within the reach presented suggest that the dredged zone had the greater propensity towards aggradation than other parts of the stream (Figure 20).

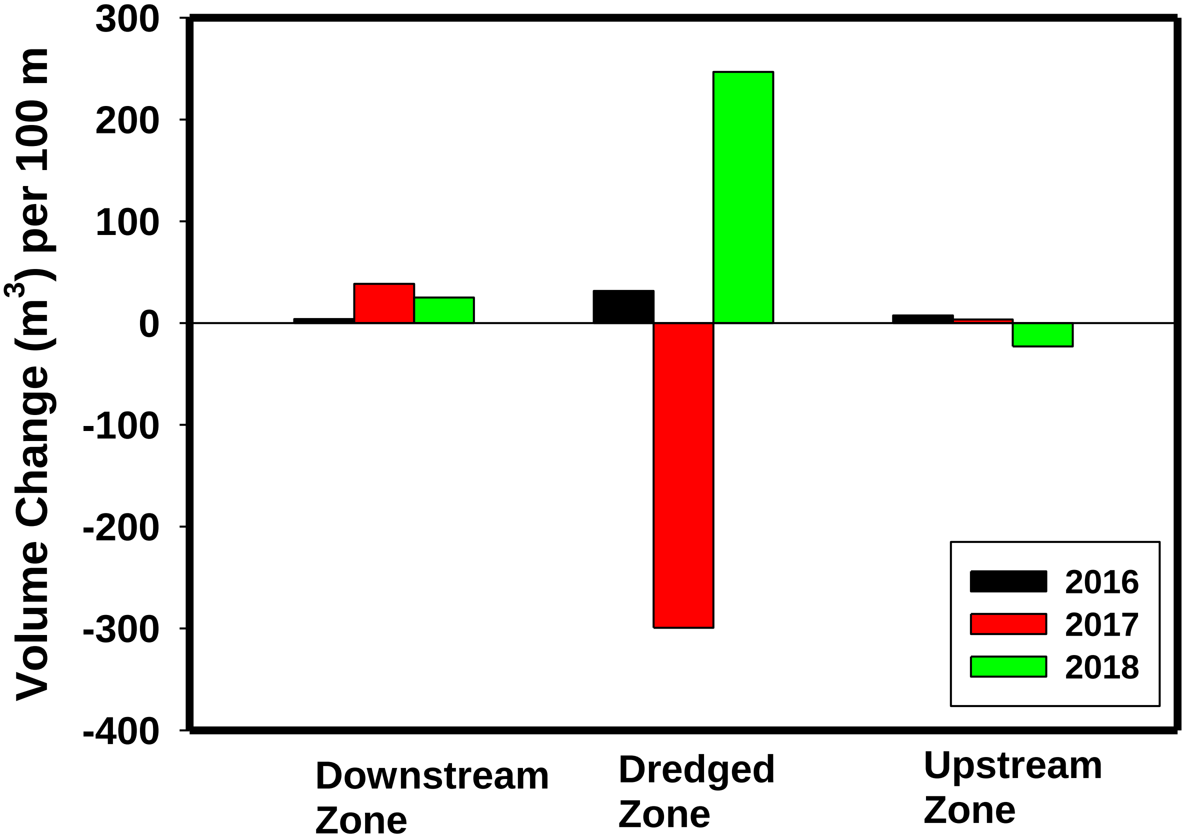


Figure 20. Compares the rate of volume change (m^3) of the active portions of the channel per 100 m reach length in each zone. The downstream zone represents cross-sections 1 to 4. The dredged zone represents cross-sections 5 to 15 and the upstream zone cross-sections 16 to 19.

From 2016 to 2018, the downstream zone, cross-sections 1 to 4, displayed a minor increase in volume per 100 m. The greatest observed increase in streambed volume per 100 m reach length was observed in 2017 (-299 m^3/100 m) (Figure 20). The dredging processes removed the equivalent of 273, 10 m^3 sized dump trucks worth of sediment from cross-sections 5 to 15. The dredged zone observations indicate that Creighton Creek was stable with minor aggradation in 2016, supporting the observed changes in longitudinal profile. The rates of streambed volume change from 2017 to 2018 further indicate Creighton Creek was able to re-achieve grade within one year of the dredging disturbance. The upstream zone, cross-sections 16 to 19 remained stable from 2016 to 2018 with no significant changes. Thus, the mechanism driving the dominant channel adjustment processes was the 2017 dredging.

While the net impact of the dredging on channel adjustments from 2016 to 2018 was limited, substantial changes in grain-size distribution were observed throughout the entire study reach (Figure 21)

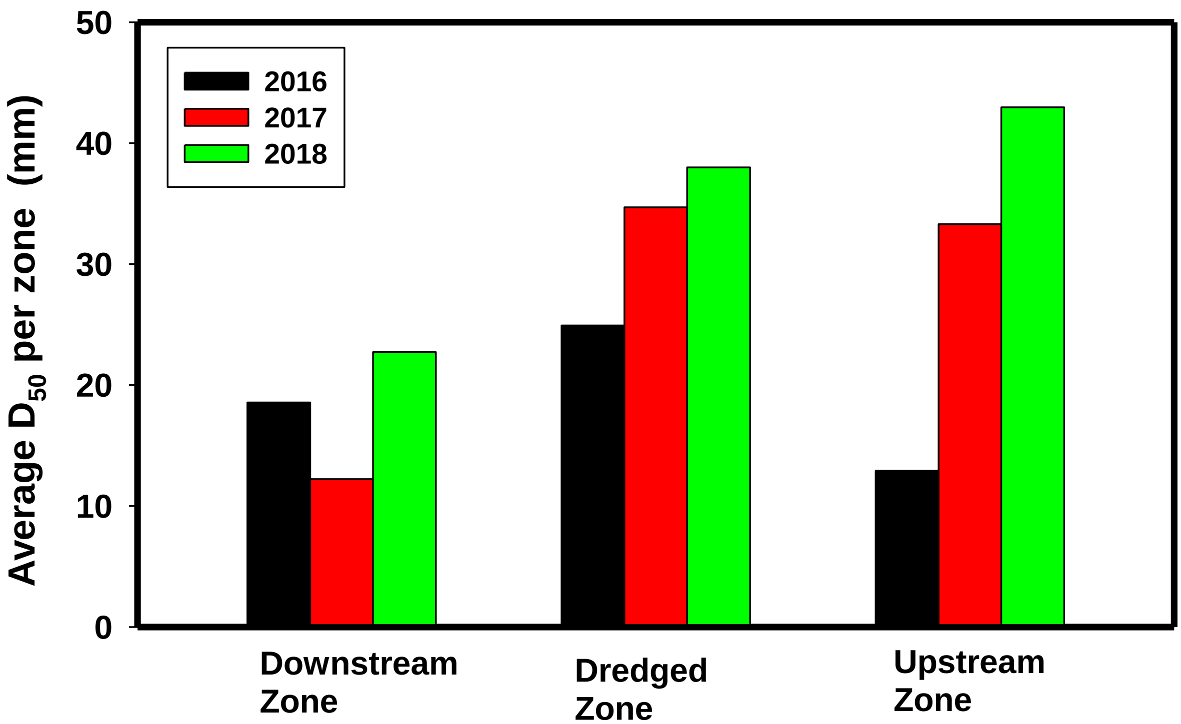
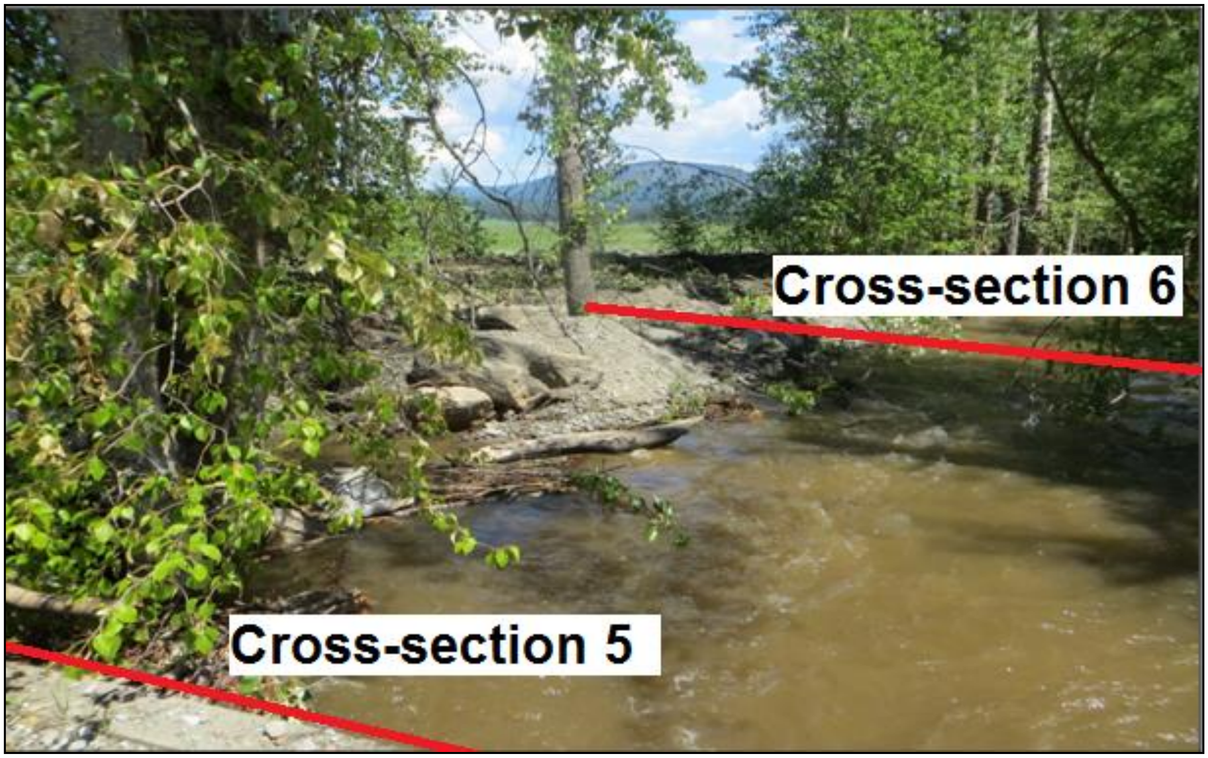


Figure 21. Compares the average D_{50} (mm) in the downstream zone (cross-sections 1, 2, 4) to the dredged zone (cross-section 6-15) and the upstream zone (cross-sections 16-19).

From 2016 to 2017 there was a slight fining trend in the downstream zone (Figure 21), which is the only period and location where such fining occurred anywhere during the study. From 2017 to 2018 the increase in average D_{50} was of similar magnitude in all three zones, suggesting that overall coarsening of the substrate was not a local phenomenon induced directly by dredging. With the exception of the downstream zone from 2016 to 2017, the average D_{50} increased and the streambed coarsened for the duration of the study. The dredging did not significantly impact the average D_{50} as a similar coarsening trend was observed throughout the entire reach for the duration of the study. The greatest coarsening was observed in the upstream zone, however Section 4.2 shows no significant channel changes were observed in this zone, and thus the spatial and scale differences between the dredged and upstream zones were likely due to the activation of bed armour from the above average freshets in both 2017 and 2018 causing high bedload transport.

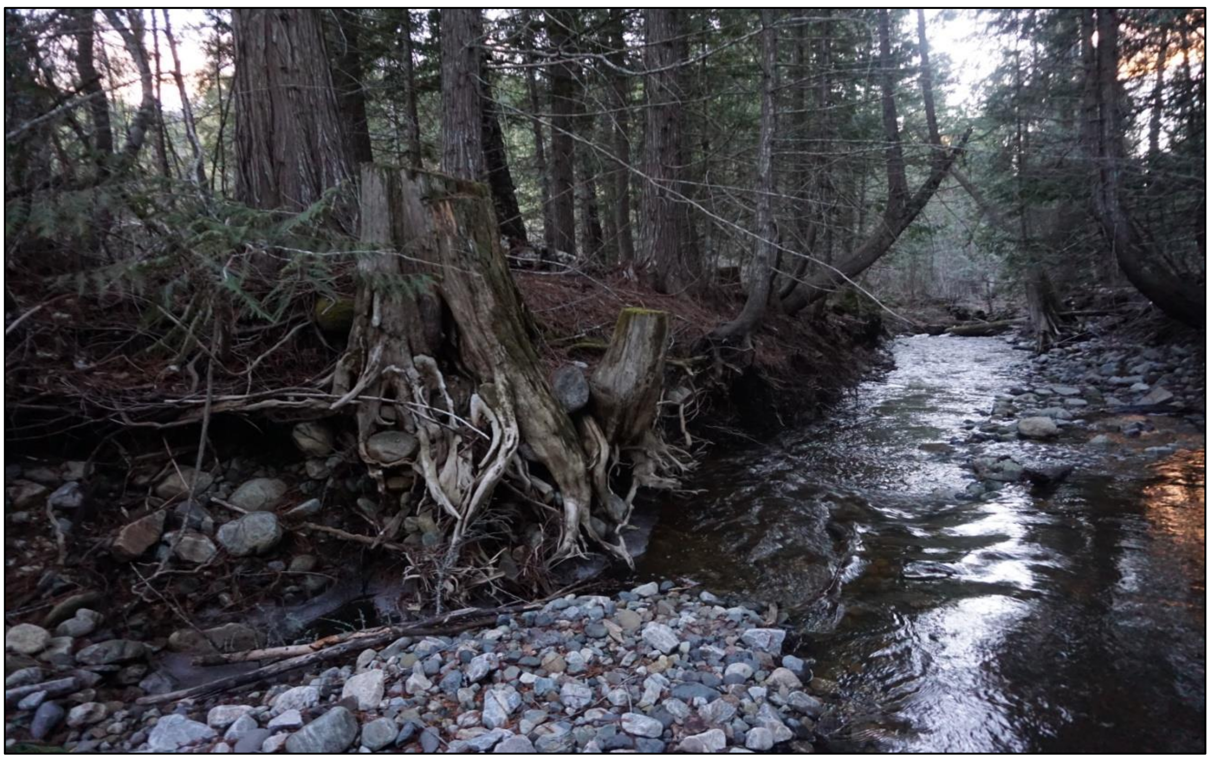
The short time frame in which Creighton Creek was able to re-achieve pre-dredging grade indicates that sediment supply is plentiful within the system. The changes in longitudinal profile and geomorphic processes throughout the reach from 2015 to 2018, presented in Section 4, suggested Creighton Creek was capacity-limited not supply-limited during the spring freshet. The dredging processes were intended to completely remove sediment from the creek, but were unsuccessful in doing so. Sediment was removed from the streambed and excess dredge spoil was deposited on the banks in large non-cohesive piles.



Photograph 5. Cross-section 5 looking upstream to Cross-section 6 post emergency dredging May 28, 2017 showing the right bank dredge spoil (Photograph: L. Hettrich).

The excess dredge spoil was left adjacent to the stream (Photograph 5). During the 2018 freshet the unconsolidated dredge spoil along the bank was easily eroded and transported downstream. The 2017 to 2018 changes in cross-sectional geometry and empirical field observations confirmed the transfer of some of the dredged sediment from the stream banks into the channel. However, the changes in cross-section geometry from 2017 to 2018 indicate that the dredge spoil was not a substantial source of available sediment for transport. Another source of sediment must have been active during the freshet.

It is likely that the main source of sediment was from upstream locations, perhaps due to erosion at the watershed level because of changes in land-use patterns and climate change. In British Columbia, the sustainable management of watersheds and land-use activities are integral for managing and protecting salmonid habitat (Chen & Wei, 2008). The predominant watershed-level change, affecting Creighton Creek was an increase in clear-cut logging practices within the headwaters since the late 1990s. Extensive clear-cut logging within a watershed can potentially alter the annual hydrograph of a watershed, resulting in earlier peak flows that are often of greater magnitude (Winkler et al., 2010). Changes in climate affecting seasonality also greatly impact the flow regime of a snow-melt driven system like Creighton Creek (Pike et al., 2010). Changes in flow regime alter the sediment transport capacity of a stream by increasing the sediment supply through erosional processes driven by greater hydraulic capacity.



Photograph 6. Creighton Creek bank erosion below the 1998 avulsion site and 12000 m upstream of the Creighton-Bessette Creek confluence April 08, 2019 (Photograph: L. Hettrich).

Photograph 6 shows erosion upstream of the study reach that has potentially increased the sediment supply to Creighton Creek.

Landscape level erosion provides a potential source of sediment responsible for the channel adjustments occurring in Creighton Creek from 2015 to 2018. The zone immediately upstream of the dredging site shows no substantial longitudinal or lateral changes in cross-sectional geometry throughout the study duration. The absence of changes in cross-section geometry suggests the channel acts as a sediment transport corridor. The changes within the dredged zone also suggest the sediment source is upstream of the reach. The results show no substantial changes in lateral cross-section geometry and erosion occurring on the banks of the dredged channel. Further, the lack of significant changes in cross-section geometry observed in the zone downstream of the dredging for the duration of the study, support the reach acting as sediment transport corridor, and therefore the sediment source for infilling of the dredged zone must have been from upstream.

5.2 Hydraulic Modeling

5.2.1 Flow Velocity

The hydraulic parameters of a stream are controlled by natural characteristics including grain-size distribution, bed roughness and flow resistance from instream objects (Wohl, 2014). HEC- RAS was used to simulate hydraulic conditions during the spring freshet using a discharge of 2.7 $m^3 s^{-1}$ discharge. While the field data show that maximum discharge levels exceeded 2.7 $m^3 s^{-1}$ during the height of the freshet, model performance and accuracy decreased at greater discharge because overbank flooding led to loss of flow in the main channel. Flow velocities at all cross-sections from HEC-RAS simulations were used to assess spatial changes in velocity within the study reach (Figure 22).

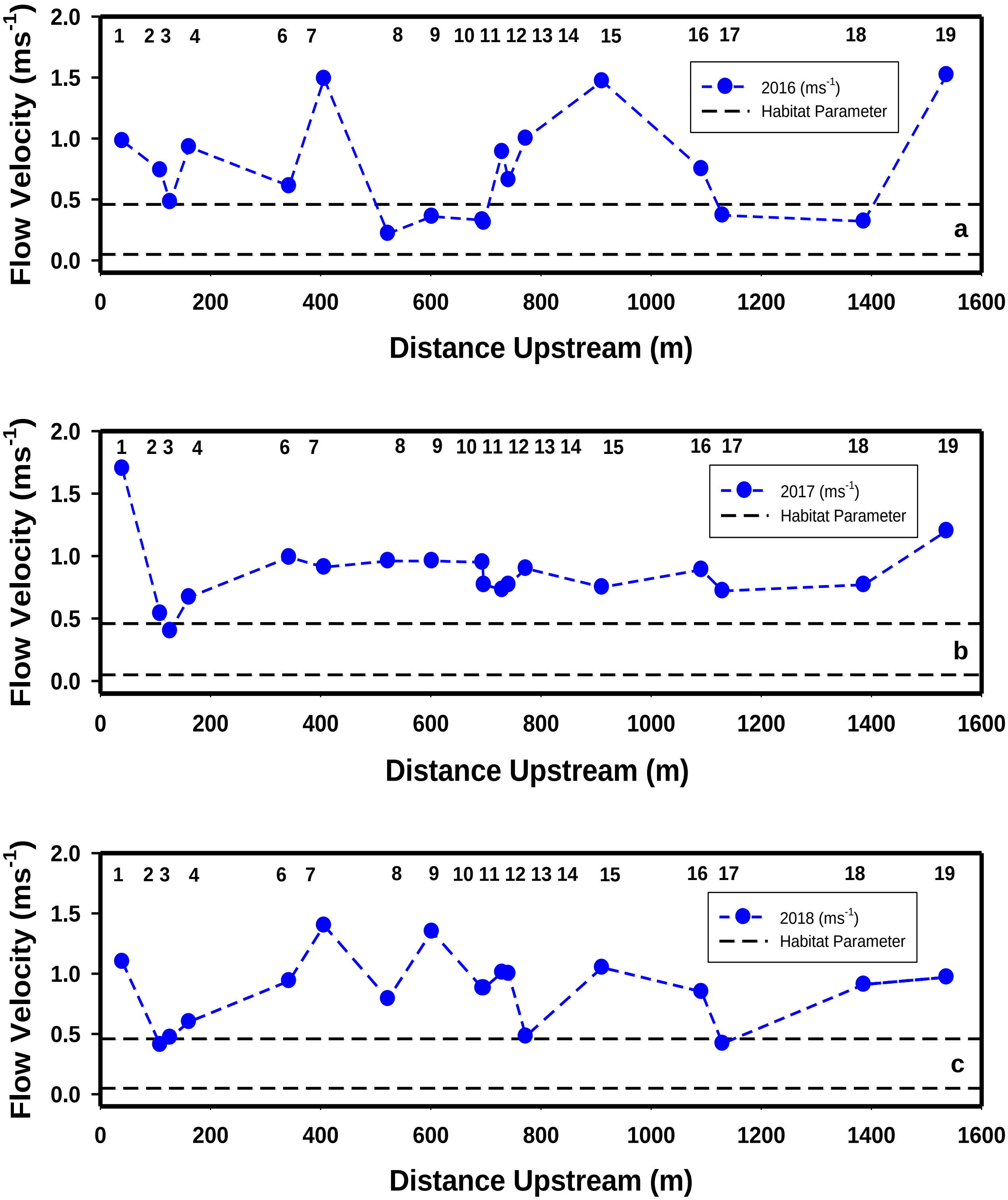


Figure 22. 2016 (a), 2017 (b), and 2018 (c) HEC-RAS 2.7 m^3s^{-1} simulated average flow velocity (ms^{-1}) at each cross-section. The dotted lines represent the critical velocity habitat requirements (0.05 - 0.46 ms^{-1}) (Bjornn & Reiser, 1991; Moyle, 2002) for juvenile Coho Salmon.

The 2016 model showed highly variable flow velocities throughout the reach ranging from a minimum of 0.22 ms^{-1} at cross-section 8 to 1.52 ms^{-1} at cross-section 19 (Figure 22a). The observed changes in flow velocity within the 2016 study reach are strongly correlated with the changes in channel morphology presented in Section 4.2, specifically straightening and deepening the channel into a single thread. Based on the morphological changes, there was a direct correlation between changes in flow velocity and channel morphology. The model simulations and cross-section surveys suggested where the channel is narrow and confined flow velocity was greatest, and where the channel is wide and shallow flow velocity was the lowest. Assuming discharge remains constant, it can be presumed that changes in natural variables such as instream objects and sediment characteristics within the reach do not significantly alter flow velocity, but instead channel morphology impacted the energy of stream flow. In 2016 at the flood flow of 2.7 m^3s^{-1} viable rearing IFC habitat was only found at cross-sections 3, 8 to 10 and 17 to 18 where the channel is widest within the study reach (Figure 22a). In contrast the 2017 model showed less variability of flow velocity between cross-sections. Modelled velocity ranging from 0.4 ms^{-1} (cross-section 3) to 1.7 ms^{-1} (cross-section 1) (Figure 22b). The flow velocity trend from cross-sections 2 to 1 was similar to the 2016 model, but of greater magnitude. As an aside, the increase in flow velocity was caused by the emergency dredging significantly expanding capacity of the adjacent irrigation ditch allowing greater discharge to enter the stream between cross-sections 2 and 3. Although these expected flow changes are not captured in the model results, they may be important considerations when comparing the model predictions to actual high flow conditions. Cross-section 3 displayed the lowest flow velocity and was shown to be the only viable IFC rearing habitat, due to being located within a large pool. Modelled flow velocity was constant from cross-sections 4 to 19, suggesting the changes in channel morphology, from the emergency dredging at cross-sections 6 to 15 (Section 4), reduced the channel form roughness including the sinuosity and longitudinal profile variability in natural pool-riffle sequences, thereby increasing the velocity in locations that previously provided suitable refuge areas for juvenile IFC. The lower dredged zone, cross-sections 8 to 10 increased in velocity, cross-section 11 and 12 remained constant, while cross-section 13 to15 significantly decreased. The change in hydraulics effecting flow velocity were caused by the reduction of channel complexity, where the previously shallow and wide channel transition to a narrow-confined channel. Creighton Creek was a fairly uniform confined channel in 2017 throughout the study reach (Appendix A), the reduction in flow velocity variability between cross-sections throughout the reach (Figure 22b) further supports the uniformity of the channel caused by the dredging.

The 2018 model displayed a similar reach trend to the 2016 model in terms of the fluctuations in flow velocity between cross-sections, and general increase in flow velocity with the exclusion of cross-section 12 and 17 in comparison to 2017. The change in flow velocity was directly related to the channel adjustments that occurred during the 2018 freshet, as a response to the geomorphic changes caused by the 2017 emergency dredging presented in Section 4. The results and model simulations showed Creighton Creek adjusted to the emergency dredging by decreasing the slope and sinuosity of dredged section as the channel transitions from a narrow and deep channel to complex wide and shallow channel. As channel complexity increased, the variability of flow velocity within the dredged zone increased. The channel maintained flow capacity from cross-sections 16 to 19 where no dredging had occurred. A small increase in potential IFC habitat was observed in 2018 at cross sections 2, 3, 14, and 17, as the stream adjusted to the 2017 dredging; with some marginal habitat however the quantity remains substantially reduced in comparison to 2016. Figure 22 shows the flow velocity within the study reach was impacted by the 2017 dredging with a loss of velocity variation between cross sections. Changes in width-to-depth ratio from the dredging are the expected cause. The trends from the flow velocity model simulations and cross-section analysis display a relationship where decreases in flow velocity occur in response to widening of the channel which cause subsequent changes in sediment transport rates.

5.2.2. Sediment Transport Potential

The sediment transport capacity of a stream is a function of sediment supply and flow conditions. Transport capacity is considered to be a function of the boundary shear stress that is available after the dissipation of shear stress from hydraulic roughness elements within the system (Montgomery & Buffington, 1997). While transport capacity decreases in the downstream direction due to a decrease in gradient, sediment supply typically increases in direct correlation with an increase in drainage area (Montgomery & Buffington, 1997). Natural and anthropogenic disturbances influence the spatial distribution of channel characteristics by altering the processes and mechanisms that supply sediment to the channel (Rice, 1994).

Although bedload sampling during the freshet was not conducted due to safety concerns, it is possible to estimate transport potential based on theoretical arguments informed by the hydraulic parameters from HEC-RAS. The dimensionless shear stress and Boundary (Grain) Reynolds Number were plotted on a Shields diagram to evaluate the potential for sediment transport within the reach at a discharge of 2.7 m^3s^{-1} for each of the three years (2016, 2017, and 2018). The main quantities are flow strength and substrate size, estimated by cross-section averaged D_{50}.

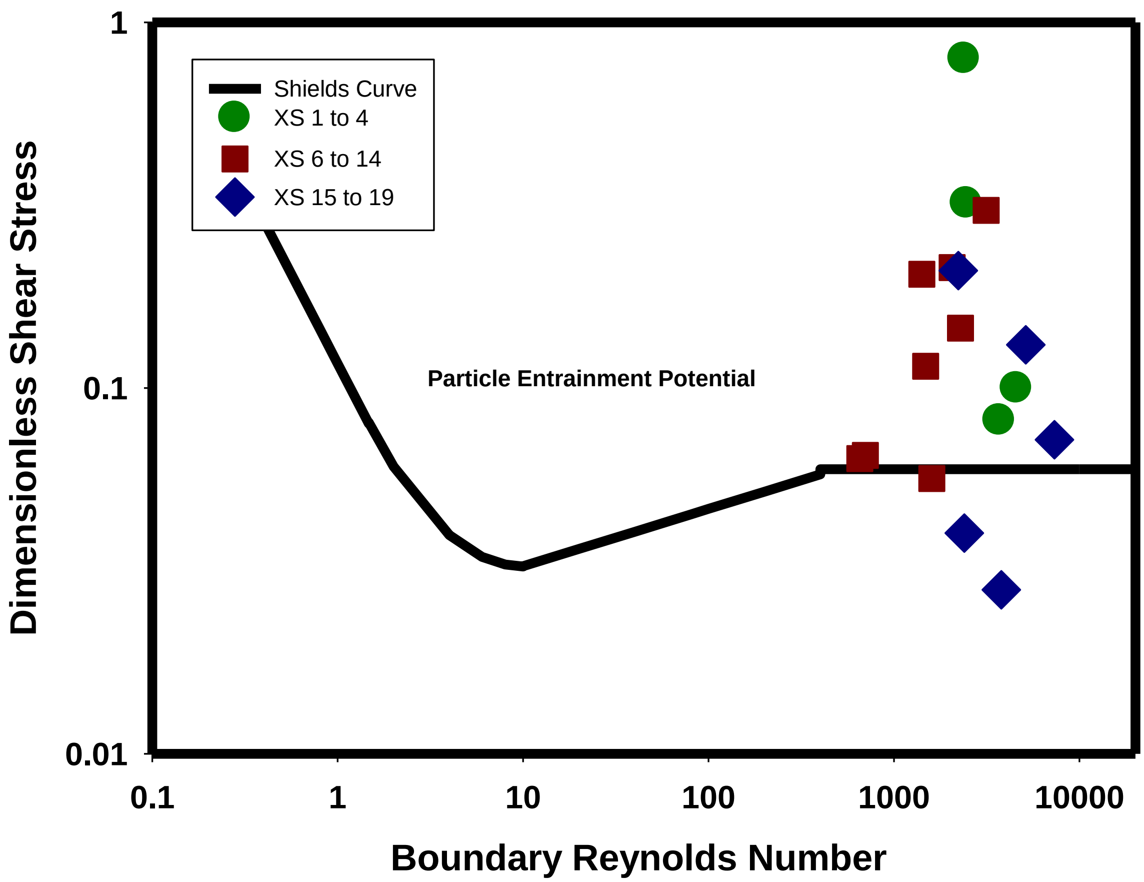


Figure 23. 2016 calculated dimensionless shear stress and Boundary Reynolds number per cross-section plotted against the critical shear stress for particle entrainment curve at 2.7 m^3s^{-1} discharge.

The 2016 Shields diagram (Figure 23) represents the sediment transport dynamics prior to the May 2017 emergency dredging. The data show that at a 2.7 m^3s^{-1} discharge sediment transport was likely to occur at all cross-sections with the exceptions of 14, 15 and 16 where no sediment entrainment was likely. The 2016 cross-sections were very similar to the 2015 cross-sections (Appendix A), indicating that sediment transport may have been generally active during the freshet but with little change to the overall channel configuration. These conditions are consistent with a graded channel state as defined by Mackin (1948).

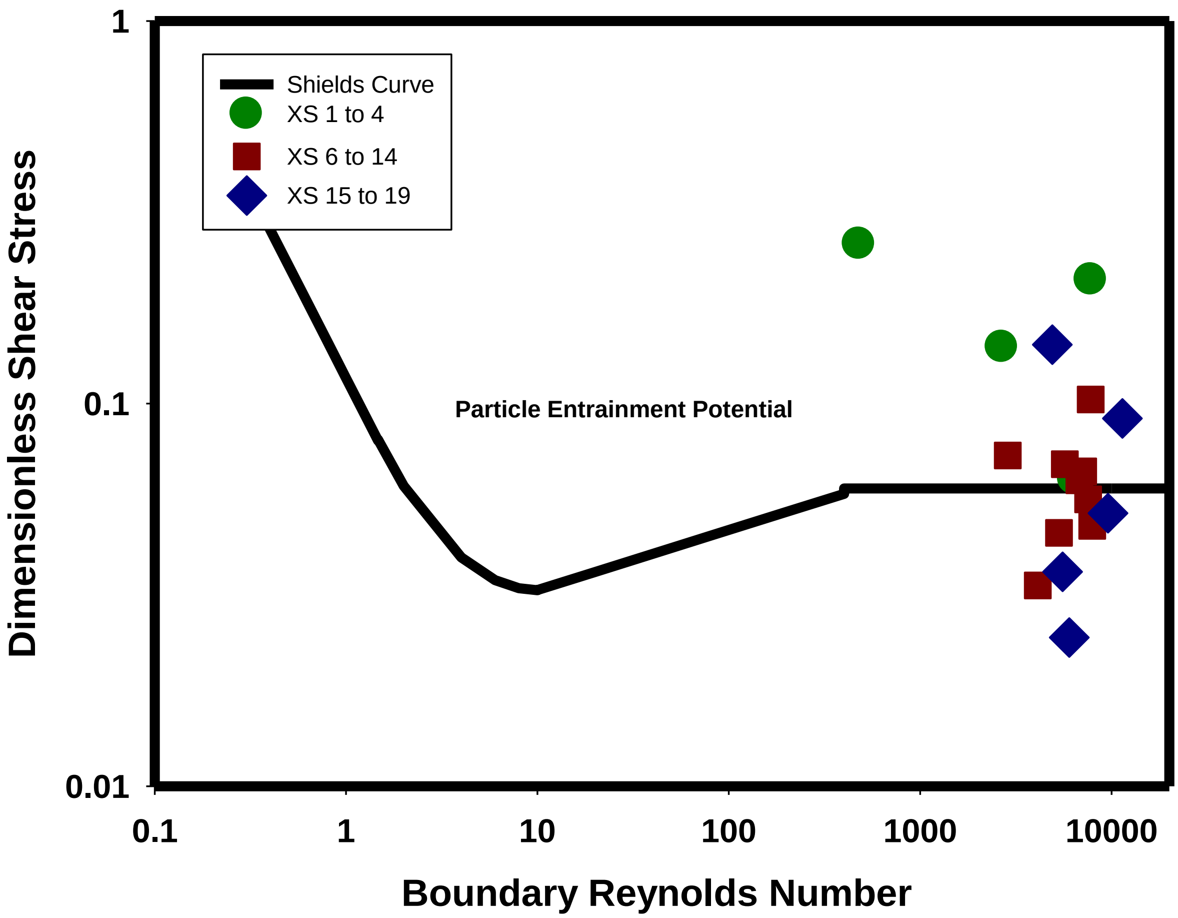


Figure 24. 2017 calculated dimensionless shear stress and Boundary Reynolds number per cross-section plotted against the critical shear stress for particle entrainment curve at 2.7 m^3s^{-1} discharge.

The 2017 Shields diagram (Figure 24) showed a noticeable decrease in sediment transport potential within the dredged zone, despite a narrowing and straightening of the channel, which should have yielded an increase in available shear stress. The main reason for the decrease in transport potential was the coarsening of surface sediment. No significant changes in sediment transport potential were predicted for the upstream and downstream reaches where no dredging occurred.

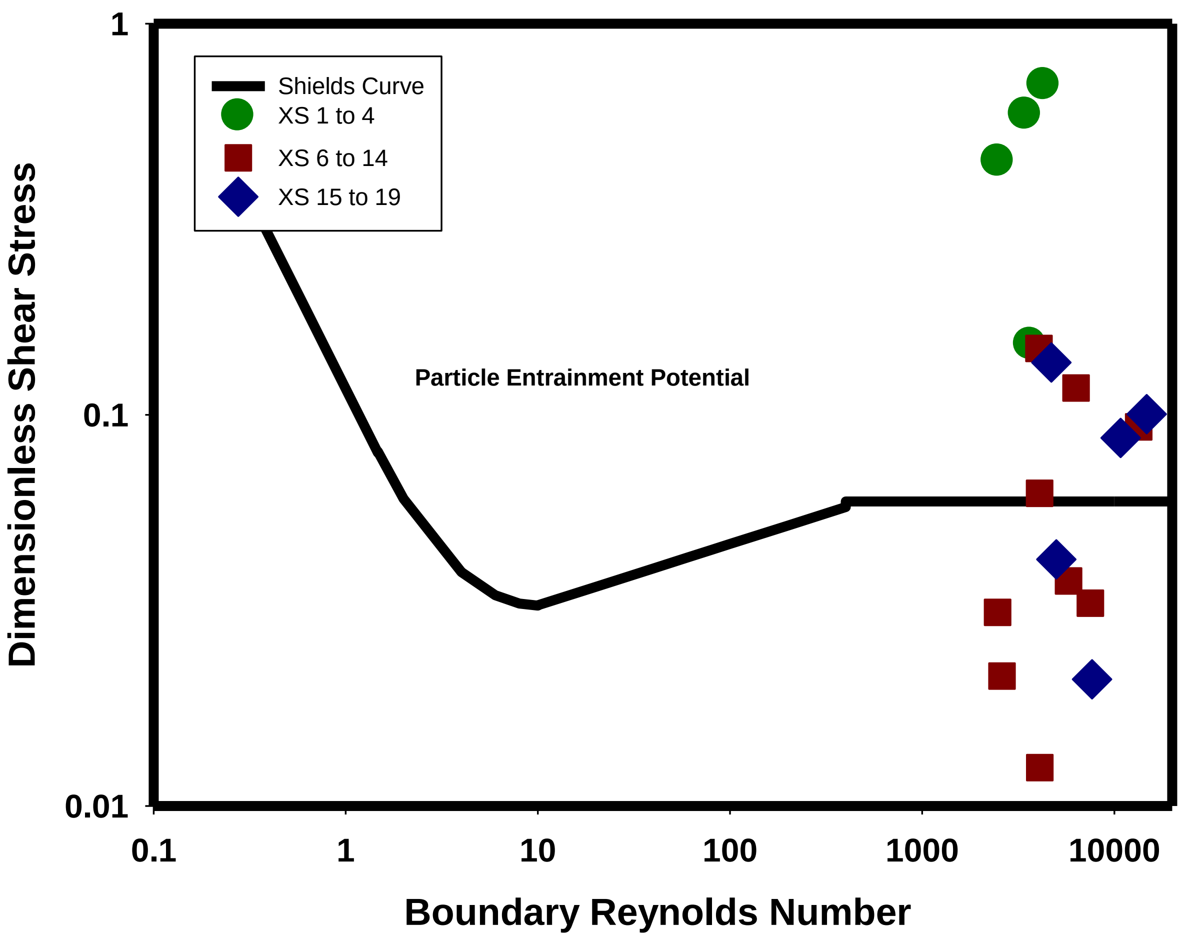


Figure 25. 2018 calculated dimensionless shear stress and Boundary Reynolds number per cross-section plotted against the critical shear stress for particle entrainment curve at 2.7 m^3s^{-1} discharge.

The 2018 Shields diagram (Figure 25) shows significant increase in sediment transport potential in the lower reach (cross-sections 1 and 4) with the largest values of dimensionless shear for the study. While the upstream reach (cross-sections 15 to 19) showed a similar pattern to previous years, the sediment transport potential within the dredged zone further decreased in 2018. The 2018 changes in sediment transport dynamics were directly related to the changes in grain-size distribution (Figure 15) and channel morphology presented in Figures 10 to 13 and Appendix A. As the channel re-achieved grade by increasing streambed elevation within the longitudinal profile, and the channel morphology transitioned from a single to braided channel, the sediment transport capacity decreased in the dredged zone.

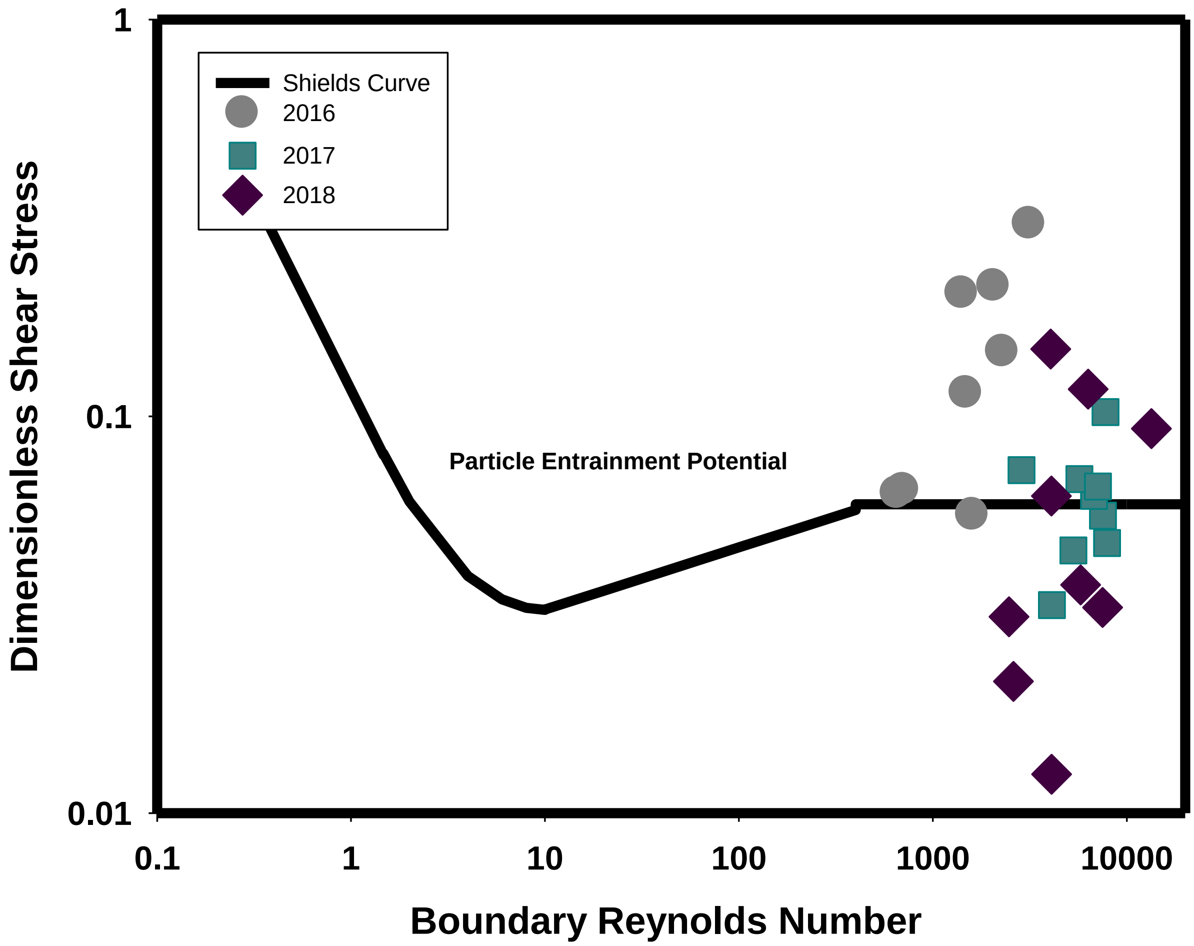


Figure 26. 2016 to 2018 dredged zone calculated dimensionless shear stress and Boundary Reynolds number per cross-section plotted against the critical shear stress for particle entrainment curve at 2.7 m^3s^{-1} discharge.

The net change in the dredged zone (cross-section 6 to 14) from 2016 to 2018 shows a reduction in sediment transport potential at 2.7 m^3s^{-1} discharge (Figure 26). While channel adjustments show minimal net changes to channel morphology, sediment analysis and Figure 26 provides evidence that the coarsening of surface sediment and changes in hydraulics impact shear. The decrease in shear reduces sediment entrainment potential within the dredged zone, despite the stream re-achieving grade. Therefore, there is no distinct relationship from 2016 to 2018 between the changes in stream bed elevation, grain-size distribution and flow velocity within the dredged zone. However, there was a clear trend where cross-sections displaying an increase in grain-size distribution showed a decrease in sediment transport potential within the dredged zone.

5.2.3. Manning's N Analysis

The Manning's N roughness coefficient is related to substrate size and is used to parameterize boundary roughness in flow equations (Limerinos, 1970). Limerinos (1970) suggests it is unlikely that determining the roughness coefficient for natural channels will be exact, thus two methods were used to evaluate the Manning N at each cross-section in this study. It is important to note that both methods were limited by the inability to accurately determine the spatial distribution of particle sizes in order to obtain a quantitative representation of the distribution within the reach. The channel-averaged Manning's N used to calibrate each cross-section for the HEC-RAS model, as proposed by Kim et al. (2010), was compared to a calculated value based on the Strickler equation (Strickler, 1923) described by Chow (1959), Limerinos (1970), and Arcement & Schneider (1989).

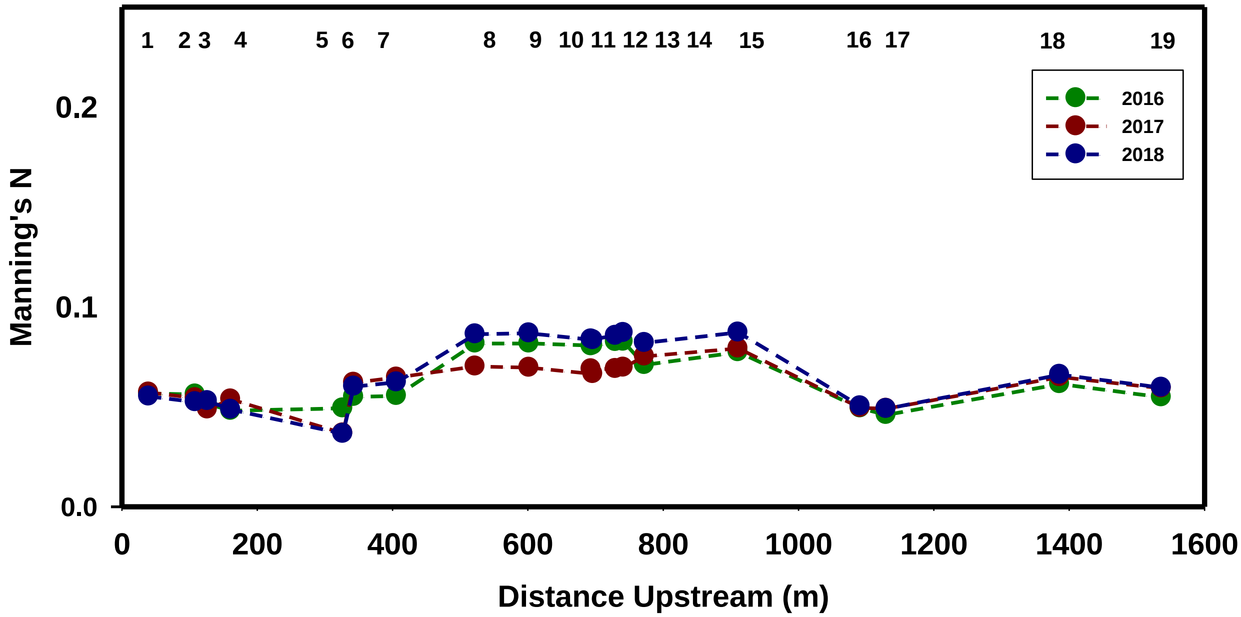


Figure 27. The 2016 to 2018 Stickler equation Manning's N (Stricker 1923) described by Chow 1959, Limerinos 1970 and Arcement & Schneider, 1989.

The different methods used to compute Manning's N assume that the calculated values (Figure 27) are influenced by the spatial D_{50} distribution within the reach. Based on the changes in D_{50} (Figure 15) and the changes in sediment transport potential (Figures 23 to 25), it is predicted the Manning's N would show a similar distribution trend throughout the reach, especially in the upstream cross-sections where no dredging occurred but the stream bed coarsened over the duration of the study. However, the data show that the smallest Manning's N coefficients are observed above and below the dredged cross-sections-this trend is evident from 2016 to 2018, despite changes in grain-size distribution. Therefore, channel morphology and vegetation cover have a significant influence on the calculated Manning's N perhaps more so than the observed changes in grain-size distribution.

The changes in 2017 Manning's N observed in the dredged zone are as predicted, where the changes in channel morphology and removal of vegetation and LWD influenced the decrease in coefficient despite a coarsening of the streambed. In 2018 the data show that the Manning's N is largest in the dredged zone due to the coarsening D_{50} trends presented in Section 4. This method does not assess the changes in roughness caused by spatial variability in bedforms, and changes in hydraulic radius. While it is difficult to both isolate and assess the spatial variability of geomorphic and hydraulic parameters affecting roughness within the reach, evaluating the Manning's N used to calibrate the HEC-RAS model waterlines accounts for the net impact of these parameters as they collectively impact hydraulics by altering the water surface elevation due to friction loss caused by channel roughness. While changes in water surface elevation and discharge variables calculated by HEC-RAS are influenced by the uncertainty of estimating Manning's N (Kim et al. 2010), the accuracy of the HEC-RAS model simulations (Tables 10 to 12) provides confidence in the ability of the model to predict the Manning's N throughout the reach. The data from the HEC-RAS models (Figure 27) show much greater spatial and temporal variability in Manning's N from 2016 to 2018 in comparison to the calculated values from empirical equations (Figure 27).

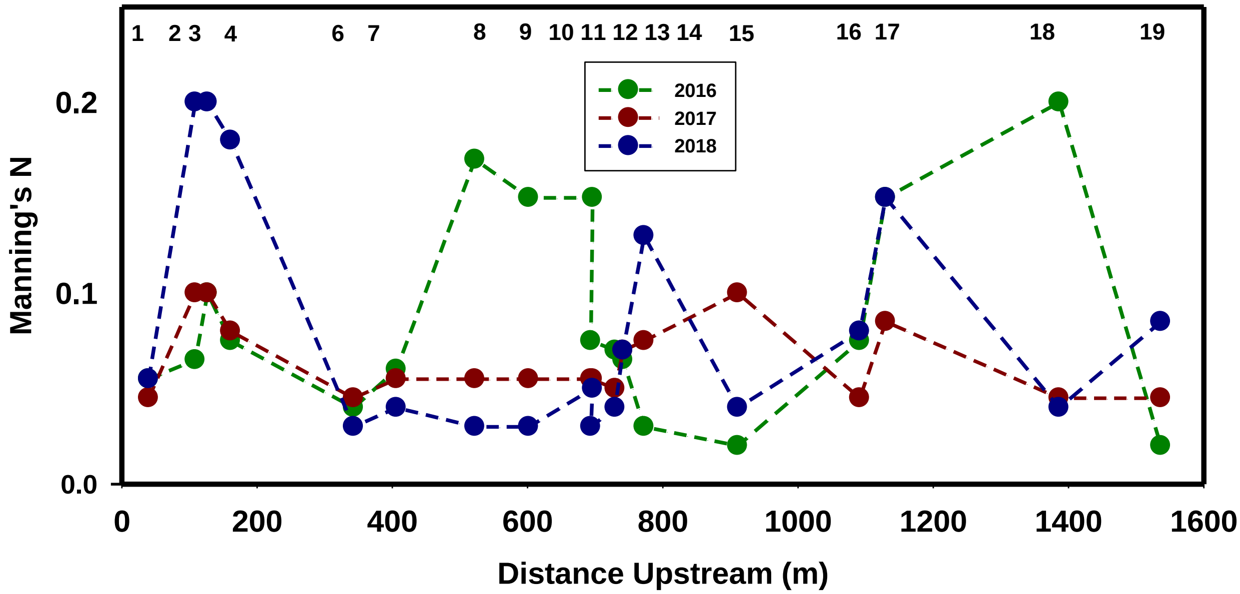


Figure 28. The 2016 to 2018 Manning's N per cross-section used to calibrate the HEC-RAS models.

The most distinct trends from the 2016 data show large Manning's N values at cross-sections 8 to 10 and 18. In 2016 cross-sections 8 to 10 were recognized to be an area of severe streambed aggradation dominant with LWD and willows within the bankfull, and between the braided channel effecting the Manning's N. The 2017 model suggests a decrease in the spatial variability and overall Manning's N, which was predicted based on the removal of vegetation, LWD, and channel adjustments caused by the dredging. The 2018 data show an increase in spatial variability within the reach. The most significant observed change is the decrease in Manning's N between cross-sections 8 to 10 and 18. Therefore it is assumed the reduction in Manning's N, where the reach was severely aggraded in 2016, has altered the flow hydraulics effecting sediment transport and channel adjustments between cross-sections 8 to 10.

Stream conditions including heterogeneous longitudinal profiles and abrupt changes in cross-section morphology within a modelled reach, limit model capabilities to compute increases in Manning's N at particular cross-sections. Despite potential uncertainty in the Manning's N coefficient, Fread (1988) argues that the process of computing Manning's N considerably reduces the error when predicting water surface elevation. Uncertainty from using HEC-RAS simulated water surface elevations and flow velocities in gravel-bed rivers to assess roughness coefficients increases as stream discharge decreases (Kim et al. 2010). Thus it can be argued that the process of using the Manning's N from HEC-RAS model simulations at a flood level discharge of 2.7 m^3s^{-1} provided an accurate method of evaluating the changes in roughness coefficients impacted by changes in hydraulic parameters caused by the dredging. By comparing the difference between both methods of computing roughness coefficients the impacts on Manning's N by different parameters can be evaluated. By comparing the year to year channel changes using both methods (Figure 29) the parameters influencing roughness that were impacted by the dredging can be determined.

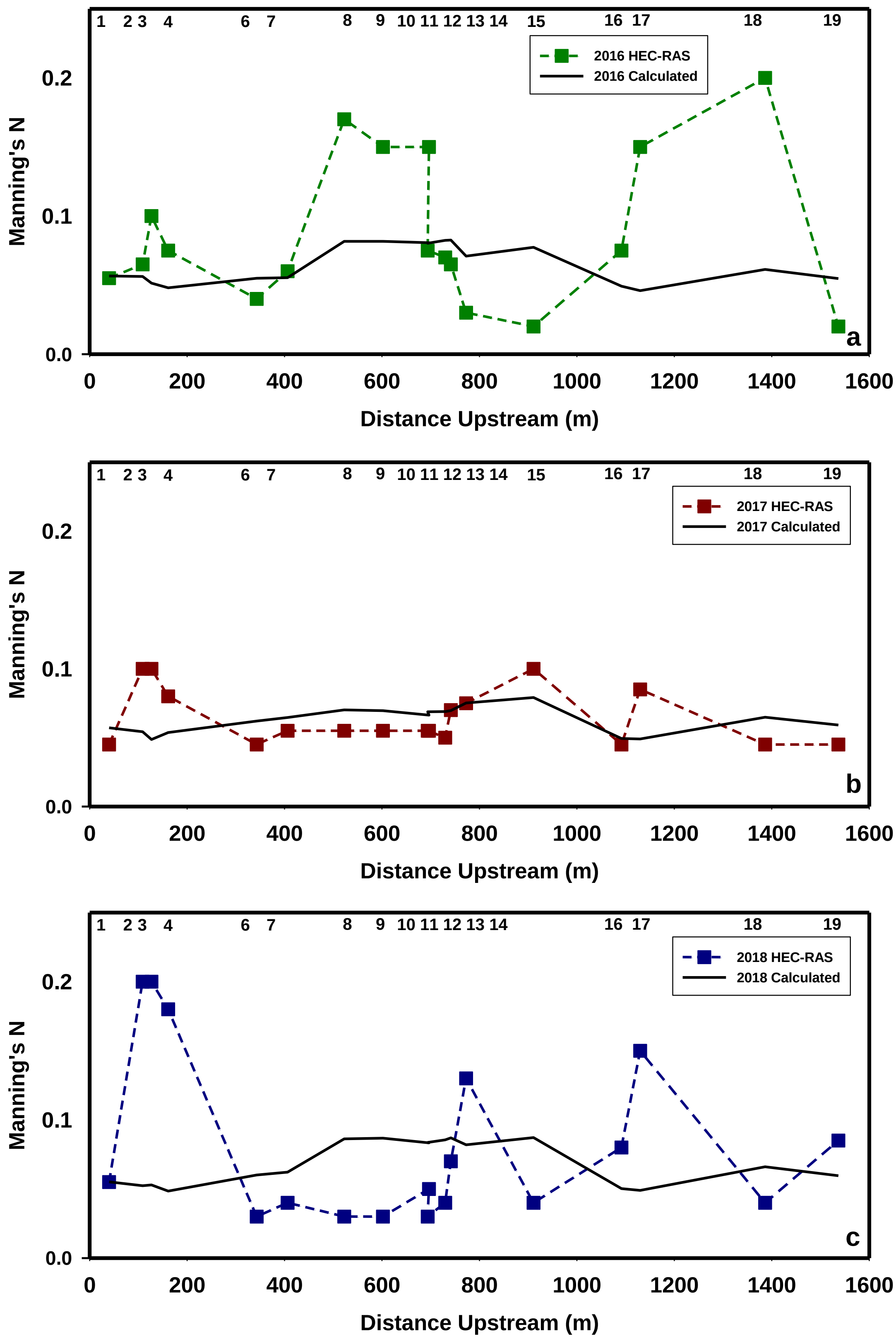


Figure 29. 2016 (a), 2017 (b), and 2018 (c) comparison of the calculated and HEC-RAS modelled Manning's N roughness coefficient per cross-section.

In 2016 the most significant differences between roughness coefficients at a cross-section were observed at cross-sections 8 to 10 and 17 to 18. The difference in the values of the two roughness coefficients is the result of limitations with the calculated method. Specifically, the calculated method does not account for the spatial variability in hydraulics created by instream objects, dense shrubby riparian vegetation on mid-channel bars and stream-banks, and other features that are not captured within the individual cross-section surveys. In comparison to the 2016 and 2018 models (Figure 29), the 2017 model shows less variation between methods attributed to increased hydraulic homogeneity between cross-sections within the study reach (Figure 22), which allows for more accurate estimates of the Manning's N (Kim et al. 2010). A decrease in the variation of channel morphology and hydraulic parameters within a reach allows channel roughness estimates to have less uncertainty. The 2018 model shows a similar relationship between the two methods as observed in the 2016 model, based on hydraulic outputs and channel adjustment data presented in Sections 4 and 5.

The use of empirical formulas to accurately estimate roughness coefficients is limited by discharge and is best applied to rivers having a greater discharge than 400 m^3s^{-1} (Kim et al. 2010) which is not comparable to Creighton Creek. In contrast, the use of field measurements and HEC-RAS model simulations to estimate channel roughness is less susceptible to uncertainty caused by variation in discharge as confirmed by Kim et al. (2010) and allows for hydraulic variables within a reach to accurately estimated using at a wide range of flows. In Creighton Creek, grain size was not the dominant roughness element–

roughness was largely determined by morphological changes and channel adjustments between cross-sections.

5.3 Salmonid Habitat

The establishment of channel reference sites and follow up surveys collecting spatial and temporal geomorphic data can help to understand relationships between salmonid habitat and landscape level geomorphic processes (Lapointe, 2012). This study provided insight to developing future restoration objectives, through using localized habitat indicators to better understand the spatial and temporal relationships between geomorphic elements affected by natural and anthropogenic disturbances. While Creighton Creek historically provided habitat for Chinook Salmon (Walsh, 2010), only IFC were present in the system for the duration of the study. A main objective of this study was to assess the impact of the 2017 emergency dredging on the IFC habitat in Creighton. This study was limited by the availability of water quality and biological data required for a complete habitat assessment.

The limiting geomorphic habitat parameters are dependent on the life cycle of the Coho and vary with seasonality. IFC habitat parameters were modelled using 0.100 m^3s^{-1} discharge as observations showed habitat was most critical during the summer and fall months where average flows were assessed to be 0.100 m^3s^{-1}. While stream temperature is a critical limiting factor (Hassler, 1987; Roberge et al., 2002) there was insufficient data available to assess and compare fluctuations in stream temperature and water quality throughout the duration of the study. Stream slope is an important limiting habitat parameter (Decker & Irvine 2013, Montgomery et al. 1999, and Reeves et al. 1989). Coho typically spawn in streams with a gradient of 1-3 %. However, for the duration of the study from 2015 to 2018, IFC were observed spawning throughout the study reach, including in areas where slope was less than 1 %. Of the candidate habitat descriptors, substrate grain size, depth of flow, and flow velocity were chosen for use in this study.

Net changes in channel geometry and surface grain size are often independent of each other, as observed in Creighton Creek. The surface D_{50} data from each cross-section were used to evaluate spawning habitat based on preferred substrate sizes of 5-35 mm (Table 2). Creighton Creek experienced a substantial net increase in grain-size distribution over the duration of the study (Figures 15, and 21). The coarsening of the streambed corresponded to a decrease in substrate sorting which was indicated by the increase in standard deviation from 2016 to 2018 (Appendix C). The changes in D_{50} distribution from 2016 to 2018 were used to assess changes in IFC spawning habitat (Figure 30).

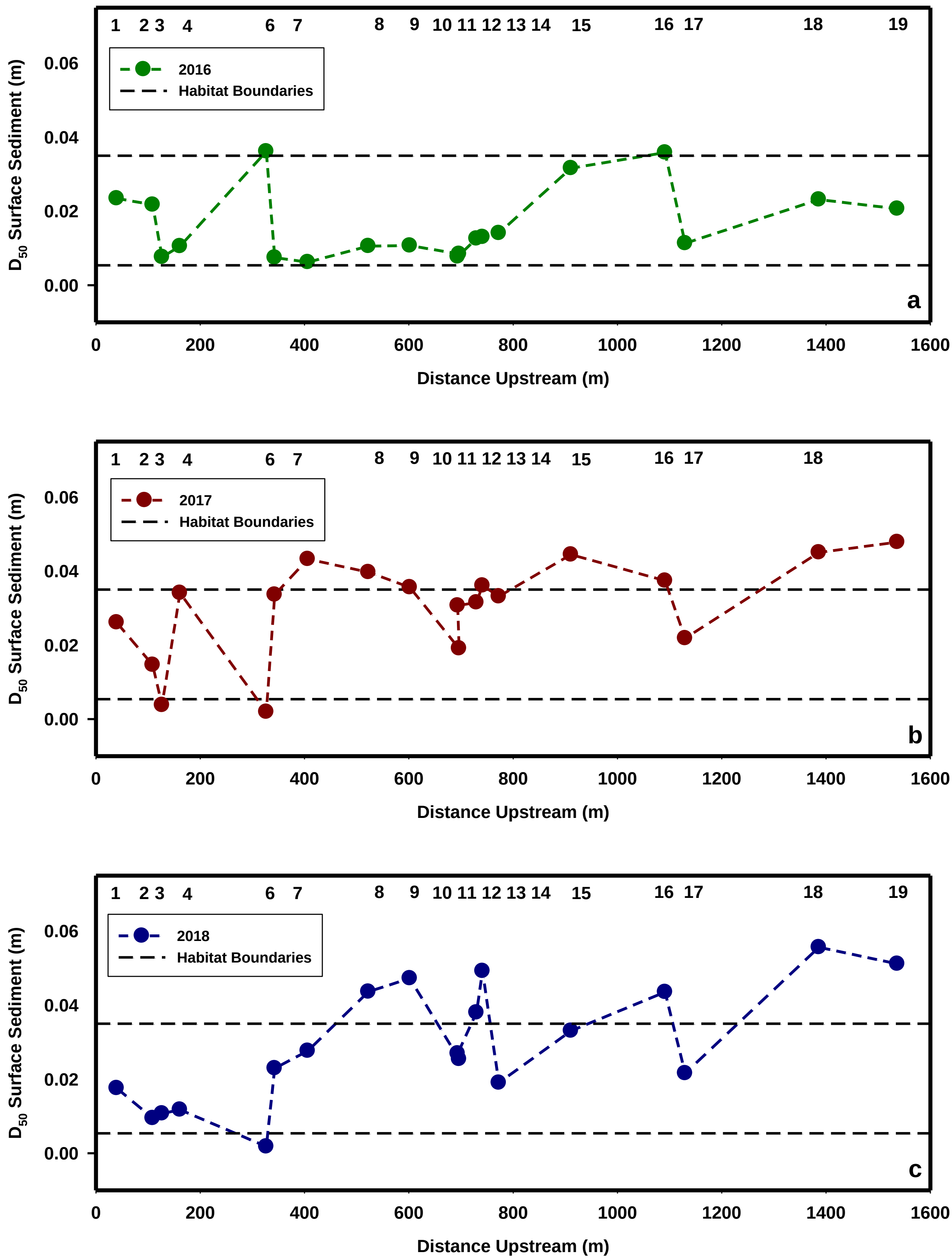


Figure 30. 2016 (a), 2017 (b), and 2018 (c) changes in D_{50} distribution at each cross-section including habitat parameters. The ideal D_{50} for spawning Coho is 0.0054 to 0.0350 m (Chambers et al. 1954, Koski 1966, Kondolf & Wolman 1993).

The greatest amount of viable spawning habitat was present in 2016 (Figure 30). In that year, the D_{50} at cross-sections 3 and 6 to 11 was near the lower threshold for spawning substrate size. In 2016, viable spawning habitat was present at each cross-section within the reach, excluding cross-section 5, which was influenced by a nearby bridge. A significant coarsening trend was observed from 2016 to 2017, due to the high freshet flows and emergency dredging. The greatest change was observed where dredging occurred between cross-sections 6 and 15, leading to a significant coarsening of the stream bed and exceedance of the habitat parameters at several cross-sections. From 2016 to 2017, spawning habitat decreased with eight cross-sections no longer providing suitable spawning habitat for IFC due to coarsening of the streambed. From 2017 to 2018 there was no distinct reach-scale trend observed but rather a fining trend present downstream of the dredged zone, and a general decrease in viable spawning habitat upstream. Habitat loss was observed in 2018 as the substrate coarsened at cross-sections 8 to 9, 12 to 13, and 18 to 19. Overall, Creighton Creek experienced a reduction in suitable spawning due to the changes in D_{50} distribution through the course of this study.

Depth of flow is a critical habitat parameter for juvenile and spawning Coho. Due to model limitations, it was not possible to simulate the low flow conditions that would be present for juvenile Coho during a summer drought. However, historical field observations within the study reach (Minor & Hesketh, 2003) indicate that during the summer, sections of Creighton Creek de-water and do not provide viable juvenile habitat. The depth of flow for spawning Coho was evaluated by modelling 0.100 m^3s^{-1} discharge. DFG (2002b) and Sandercock (1991) suggest the spawning habitat parameters for depth of flow range from 0.10 to 0.36 m.

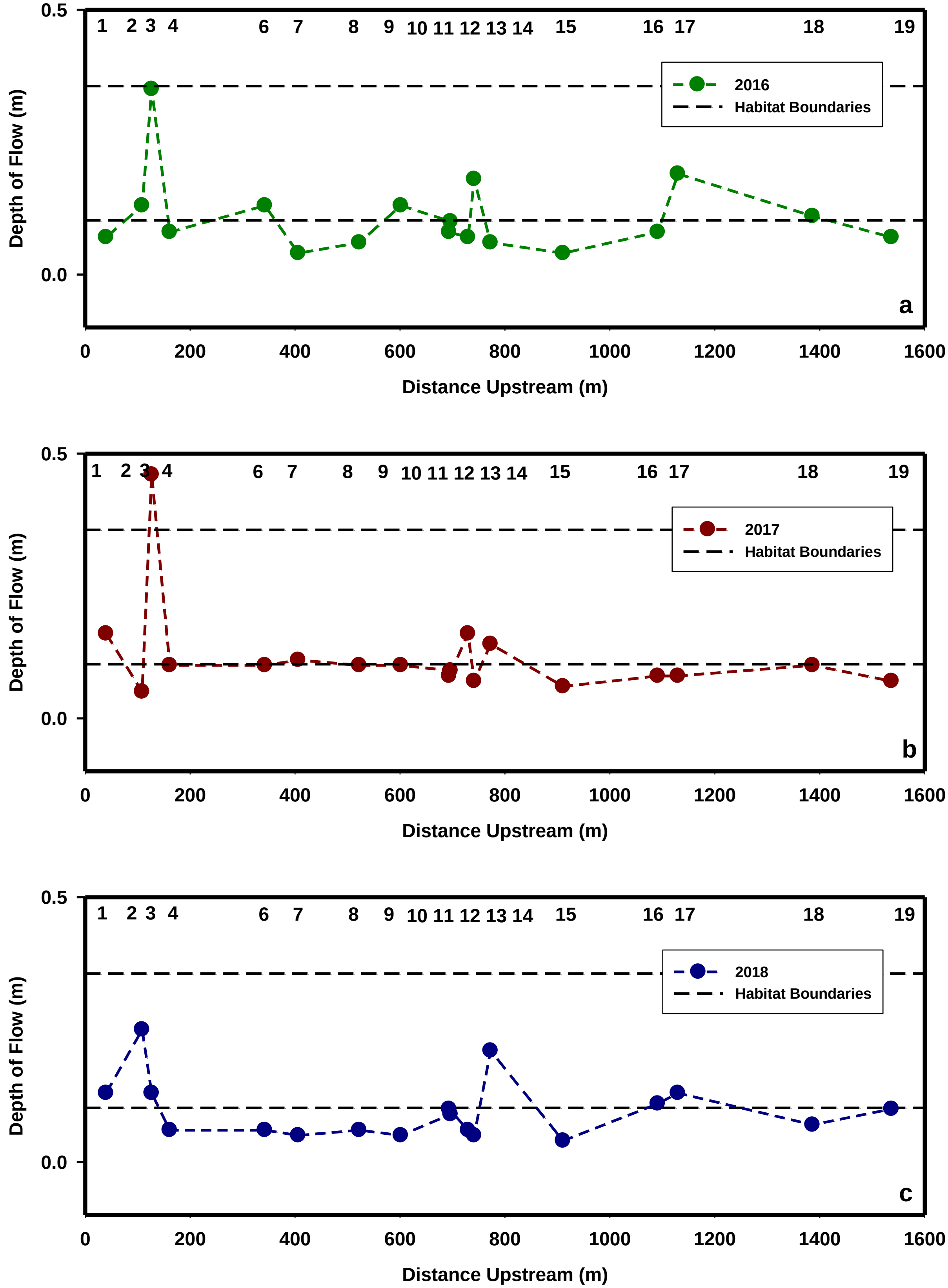


Figure 31. 2016 (a), 2017 (b), and 2018 (c) HEC-RAS 0.100 m^3s^{-1} simulated average depth of flow at each cross-section. The ideal habitat parameters for spawning Coho, 0.10 - 0.36 m (DFG, 2002b; Sandercock, 1991).

The 2016 model showed that IFC habitat is limited by depth of flow when Creighton Creek has a discharge of 0.100 m^3s^{-1} or less. The 2016 model provided minimal habitat at cross-sections 2, 3, 5, 6, 9, 10, 12 and 17. Upstream fish passage and access to thermal refugia may be limited at cross-sections where depth of flow is below the 0.10 m threshold. According to the 2017 model, spawning habitat improved at cross-sections 1, 4, 7, 8 and 14. Interestingly, where channel morphology transitioned from a braided to single channel due to dredging, the depth of flow did not significantly increase as predicted. As the channel re-achieved grade and adjusted to the dredging impacts in 2018, the only cross-sections providing spawning habitat were in pools located at cross-sections 3, 13, 16 and 17. Based on the 2016 to 2018 model simulations, depth of flow limits the availability of IFC spawning habitat. Areas of insufficient depth may cause fish passage barriers. Pool tailouts may be the only areas with suitable depth and such features are not common in this aggraded stream. Field observations suggested the dredging removed important habitat features such as pools and LWD previously present within the reach. In Creighton Creek, depth of flow is also strongly influenced by water extractions for irrigation, variability in seasonality, specifically precipitation and groundwater-surface water interactions.

Flow velocity is an important critical geomorphic habitat parameter because IFC have known velocity preferences for spawning (Table 2). Suitable flow velocity for spawning Coho was evaluated by modelling flow at 0.100 m^3s^{-1} (Figure 32) - a flow that was observed while IFC were spawning within the reach.

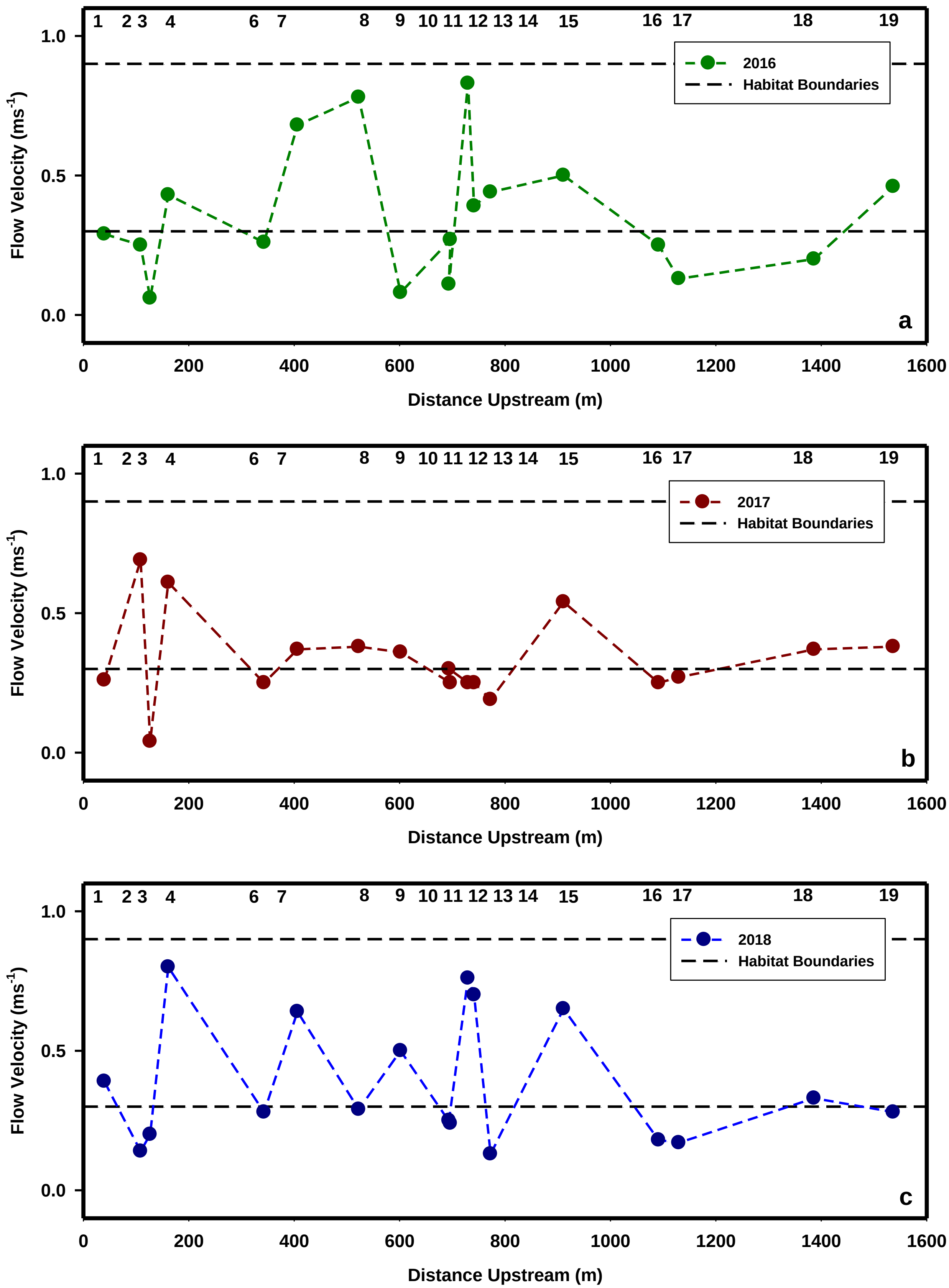


Figure 32. 2016 (a), 2017 (b), and 2018 (c) HEC-RAS 0.100 m^3s^{-1} simulated average flow velocity ms^{-1} at each cross-section. The dotted lines represent the critical velocity habitat requirements 0.3 - 0.9 ms^{-1} for spawning Coho salmonids (Bjornn & Reiser, 1991).

The modelled flow velocities (Figure 32) show that in 2016 IFC spawning habitat was limited in the upper zone at cross-sections 16 to 18. Although in 2018, some minor improvement occurred at cross section 18, a notable decline in habitat suitability occurred at cross section 19, which is likely attributed to substrate coarsening as no significant channel adjustments were observed. Below the dredged zone (cross-sections 1 to 4), habitat improved throughout the duration of the study despite no significant channel adjustments occurring in this zone. The most significant change in habitat was observed in 2017 within the dredged zone (cross-sections 6 to 14), where the reduction in channel complexity and streambed coarsening (Section 4) were the contributing factors decreasing flow velocity beyond the critical habitat limits of 0.30 to 0.90 ms^{-1} (Bjornn & Reiser, 1991). The spatial trends for the duration of the study from 2016 to 2018 indicate there was no substantial change in available habitat throughout reach. While habitat was degraded post dredging in 2017, the observed channel adjustments (Section 4) mitigated potential habitat degradation caused by the dredging. While the dredging decreased habitat value within the dredged sub-reach, the streams ability to re-achieve grade in 2018 positively impacted the availability of habitat within the dredged zone. The comparison of Figure 31 and 32 display the complex relationship between geomorphic parameters that limit IFC in Creighton Creek. Observations suggest that habitat based on modelled velocity and depth of flow are limited at discharge of 0.100 m^3s^{-1}. This habitat analysis highlights the linkages between hydraulic based habitat parameters and changes in channel morphology.

Chapter 6.0 Conclusion

6.1 Conclusions

The majority of stream modification initiatives occur in small catchments like Creighton and Bessette Creek. Less than 10% of modification initiatives include post restoration monitoring to evaluate whether restoration objectives were achieved, and to assess long-term impacts of the project (Holl et al., 2003; Palmer et al., 2005). In British Columbia, restoration initiatives do not typically assess how the flow regime impacts spatial and temporal ecosystem drivers within a watershed. The availability of quality spatial and temporal data along with additional resources, are the limiting factors that restrict the success of stream restoration initiatives.

During the study period (2015 to 2018) the lower reaches of Creighton Creek were modified by an emergency dredging operation that removed approximately 3000 cubic metres of sand and gravel over a distance of about 800 metres. Despite the extraction of sediment and reconfiguration of the channel (in 2017) from a multi-threaded, complex geometry to a single, linear channel, the system re-established itself after only one spring freshet in 2018. The study results suggested that:

- despite the 2017 emergency dredging operations Creighton Creek was able to re-achieve grade within one year of disturbance; and
- flow velocity increased noticeably in consequence of changes in channel morphology during and immediately after dredging operations (2017) thereby reducing available IFC habitat. In 2018 flow velocity returned to pre-dredging values (with spatial variability due to a more complex channel with pools and

riffles) and therefore habitat conditions were more like those in 2016 prior to dredging depth of flow trends were similar to velocity trends and strongly influenced by changes in channel morphology as a consequence of dredging. There was an increase in depth of flow in 2017 within the dredged zone, but no major changes were observed from 2016 to 2018 after the freshet recovery process. IFC habitat was (and continues to be) marginal in Creighton Creek at 0.100 m^3s^{-1} based on depth of flow.

- grain-size analysis showed a reach-scale coarsening trend from 2016 to 2018, and the magnitude of coarsening increased moving upstream. IFC spawning habitat based on the D_{50} decreased from 2016 to 2018 due to coarsening of the streambed throughout the dredged and upper zone.
- sediment transport potential was observed to be strongly influenced by grain-size distribution and shear stress. The dredged zone saw a reduction in transport capacity potential from 2016 to 2018, driven mainly by coarsening of the streambed, while the non-dredged zones showed no substantial changes.

Channel incisions upstream of the reach provided a large and constant supply of sediment. The large freshet flows led to the development of a surface armour or pavement, reflected in the coarsening of the streambed. The changes to hydrology and sediment supply in Creighton Creek from 2015 to 2018 are thought to be caused by changes in land-use within the watershed and climate change.

The relationship between geomorphic and hydrologic processes within Creighton Creek was not considered when developing the 2017 emergency dredging procedures. The dredging was intended to increase water conveyance and sediment transport capacity of the system by altering channel morphology through the removal of sediment and transitioning the stream from a braided to single channel. This was intended to maintain hydraulic capacity to reduce flooding and increase sediment transport within the reach to prevent aggradation. The study demonstrates that despite the emergency dredging, the channel re-achieved a graded state in the dredged zone after one freshet due to the availability of sediment supply. There is little evidence to reject the null hypothesis, and therefore it is concluded that the emergency dredging in Creighton Creek had little long-lasting impacts on the geomorphic processes influencing stream hydraulics and sediment transport potential. Rather, the long-term trends observed in the system (i.e., substrate coarsening and channel aggradation in the study reach) are attributed to watershed scale changes in hydrology and sediment supply, some of which are natural whereas others are human-induced.

Similarly, the study suggests that IFC spawning habitat based on the D_{50} distribution was negatively impacted due to coarsening, while velocity and depth of flow were not considerably impacted by the dredging. Thus there is little evidence upon which to reject the null hypothesis relating to any noticeable impacts of dredging on long-term IFC habitat. Rather, the reduction in spawning habitat quality based on D_{50} coarsening was also observed in the upstream zone where no dredging occurred, and therefore is similarly a watershed-driven process

6.2 Recommendations

The following recommendations arise from this study and a survey of the literature dealing with channel modifications and restoration initiatives; Stream modification efforts should evaluate and understand the relationships and interaction between the mechanisms and processes being altered during stream modification to ensure intended project objectives are not compromised.

i) Increasing post project monitoring for Creighton Creek would provide temporal data essential for understanding the long-term impact of unplanned modification initiatives in heavily modified streams relative to the natural geomorphic processes present within the system. This knowledge can be implemented in the development of future successful restoration initiatives that address channel adjustments, flow parameters, and salmonid habitat.

ii) Based on Creighton Creek acting as sediment transport corridor, it is recommended that future studies examine conditions downstream of the confluence in Bessette Creek, which is valuable salmonid habitat and the main tributary to the Shuswap River.

iii) It is recommended for future studies to establish a similar study site on Duteau Creek, where flow data are readily available, and flows can be controlled through a reservoir, in order to better understand how the hydrological cycle affects channel adjustments, sediment transport, and salmonid habitat in a more controlled system of similar size that was also dredged in 2017.

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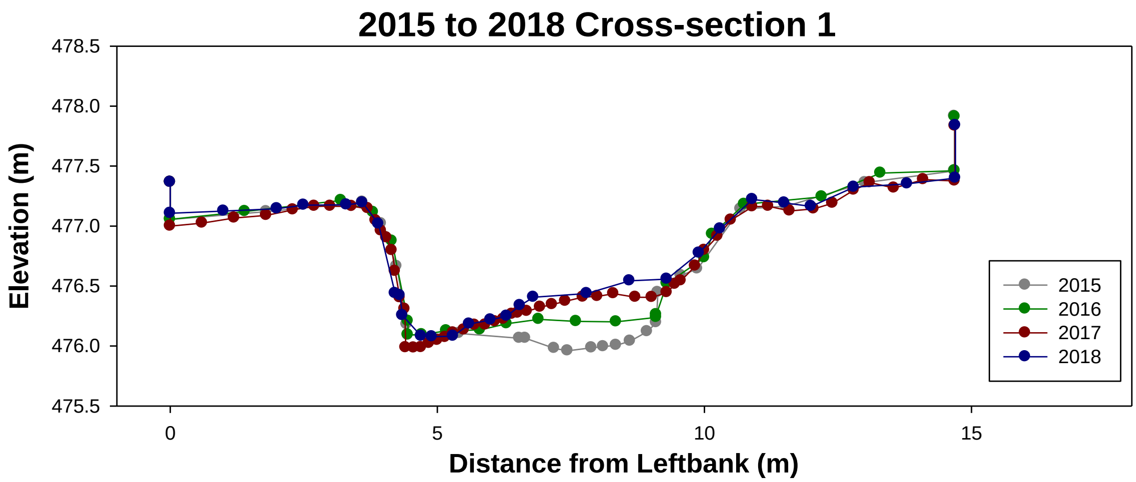
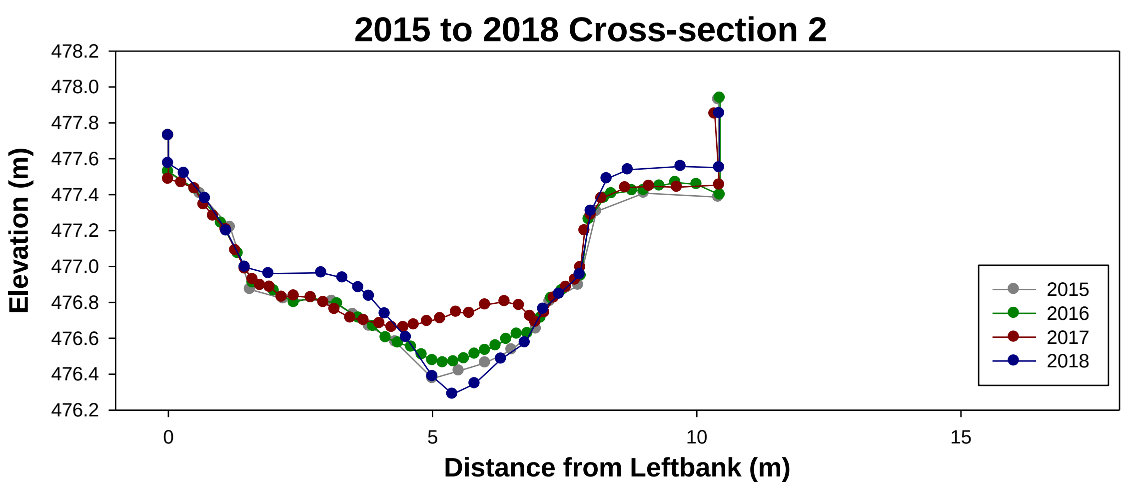
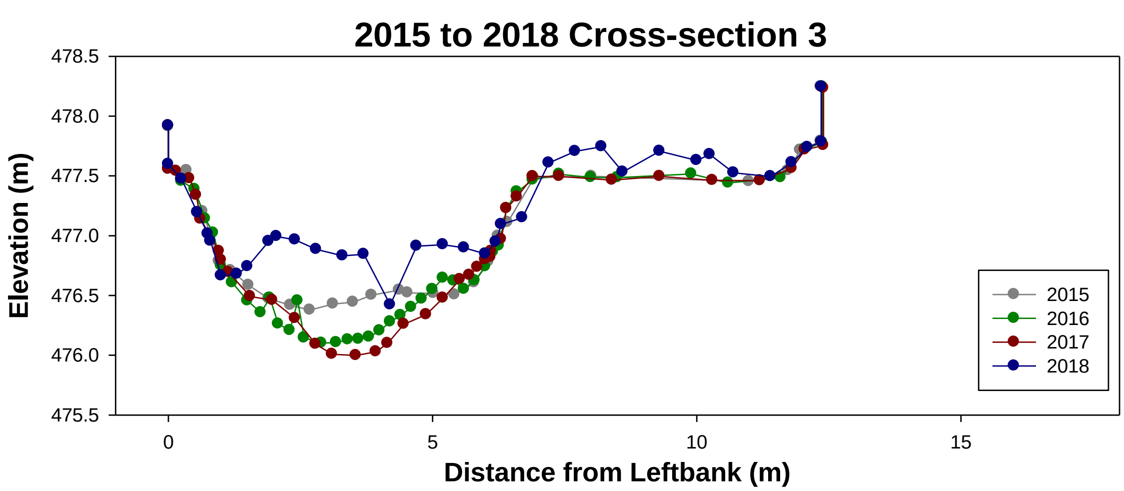
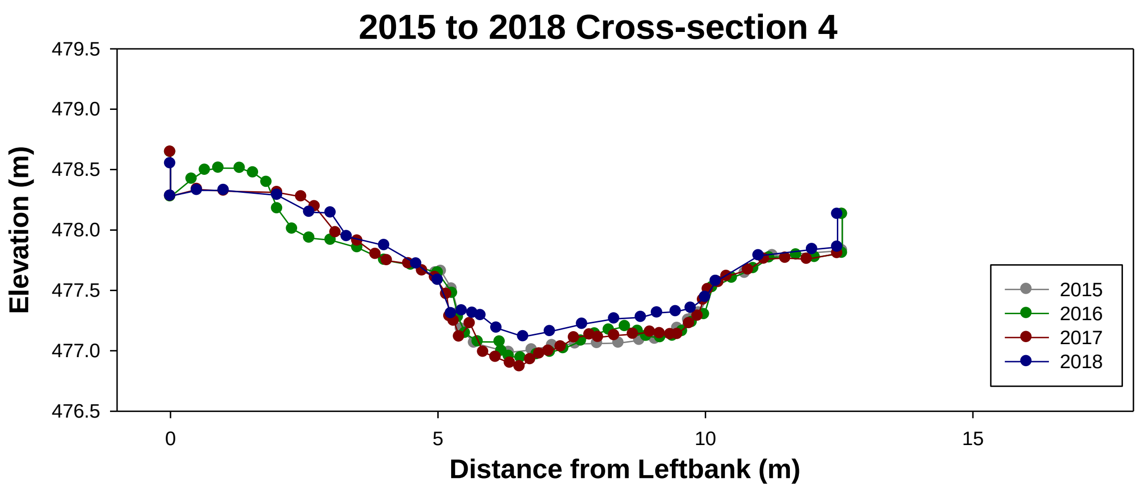
Appendix A: Cross-sections

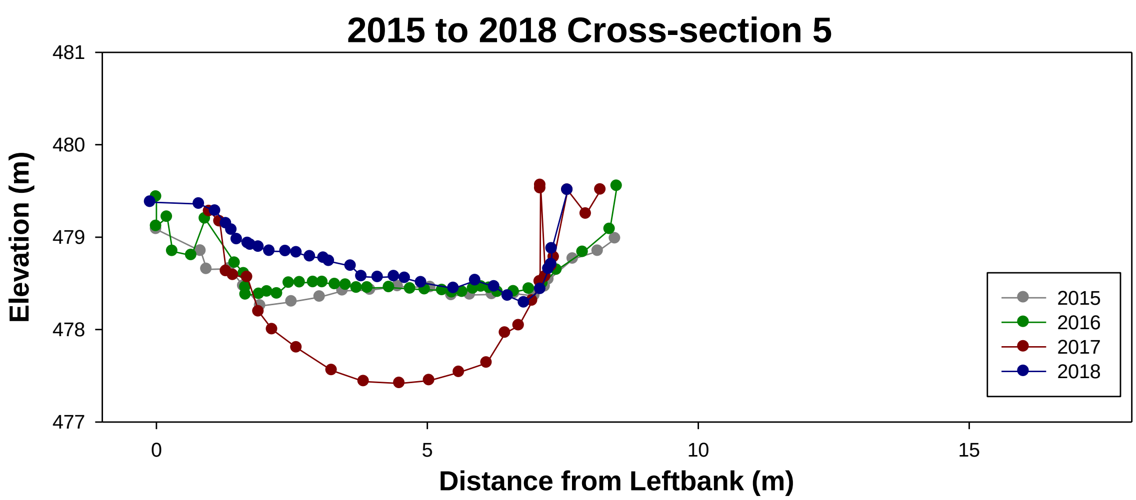
The following Appendix displays the 2015 to 2018 geo-referenced cross-section surveys. Each figure contains cross-section survey data from 2015, 2016, 2017 and 2018. Two representative horizontal X-scales were chosen at 18 m and 32 m to present the data.

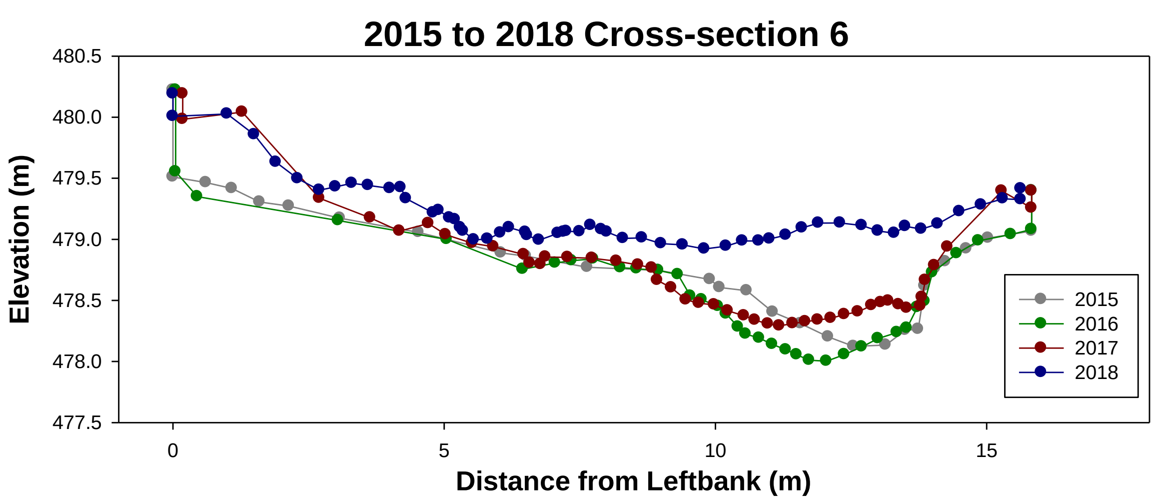


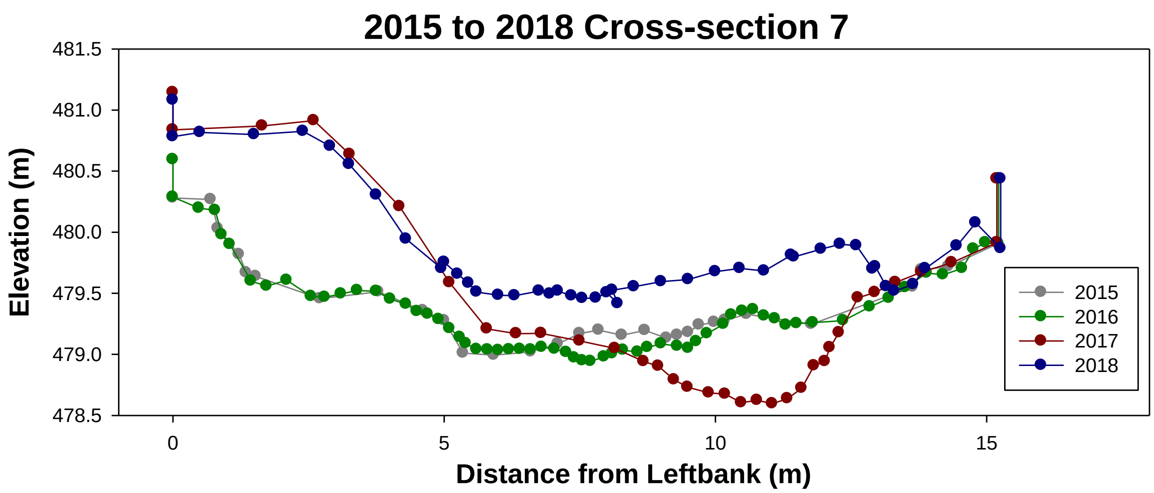


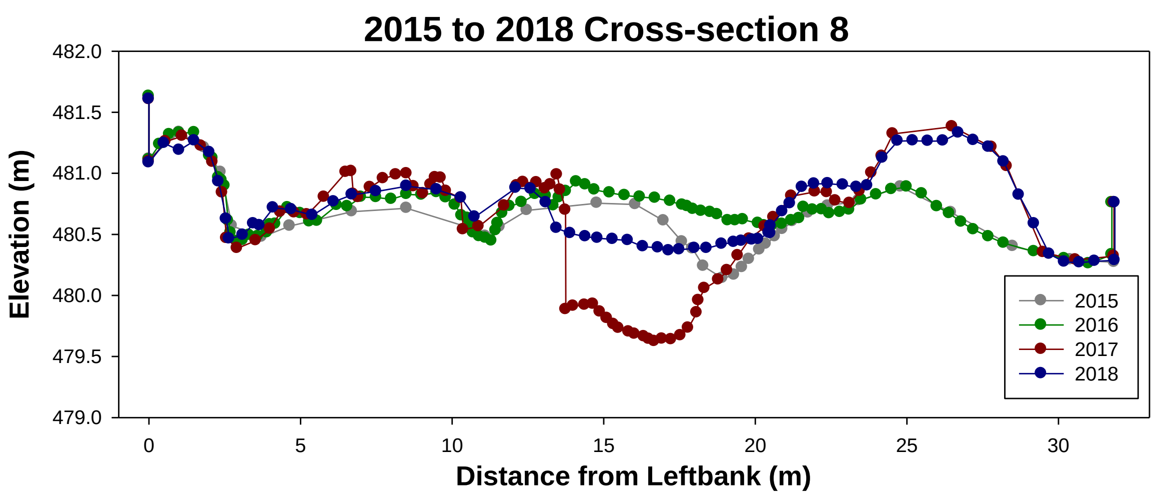


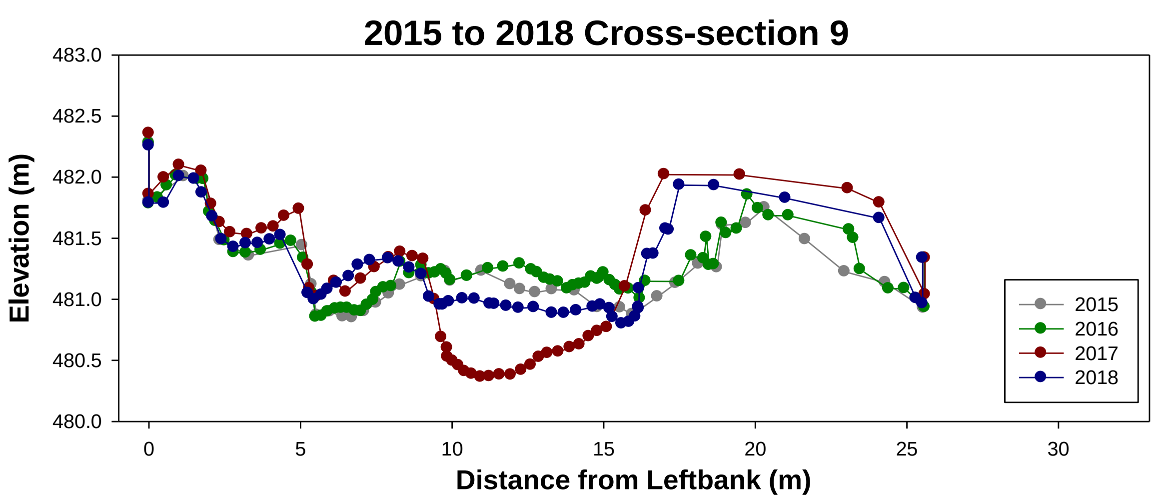

2015 to 2018 Cross-section 4
Elevation (m)
479.5
479.0
478.5
478.0
477.5
477.0
476.5
0
5
10
15
Distance from Leftbank (m)
2015
2016
2017
2018

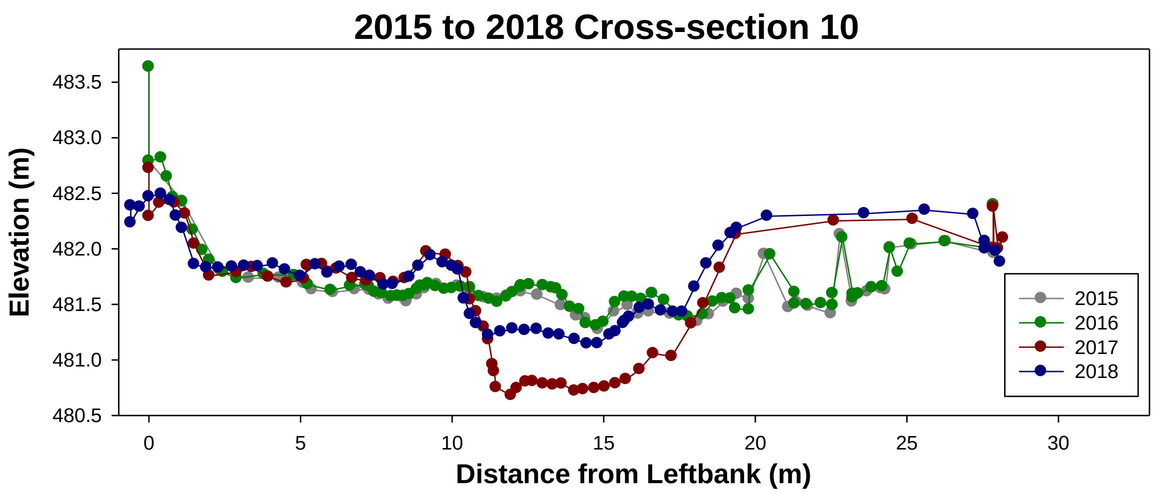

2015 to 2018 Cross-section 5
Elevation (m)
481
480
479
478
477
0
5
10
15
Distance from Leftbank (m)
2015
2016
2017
2018

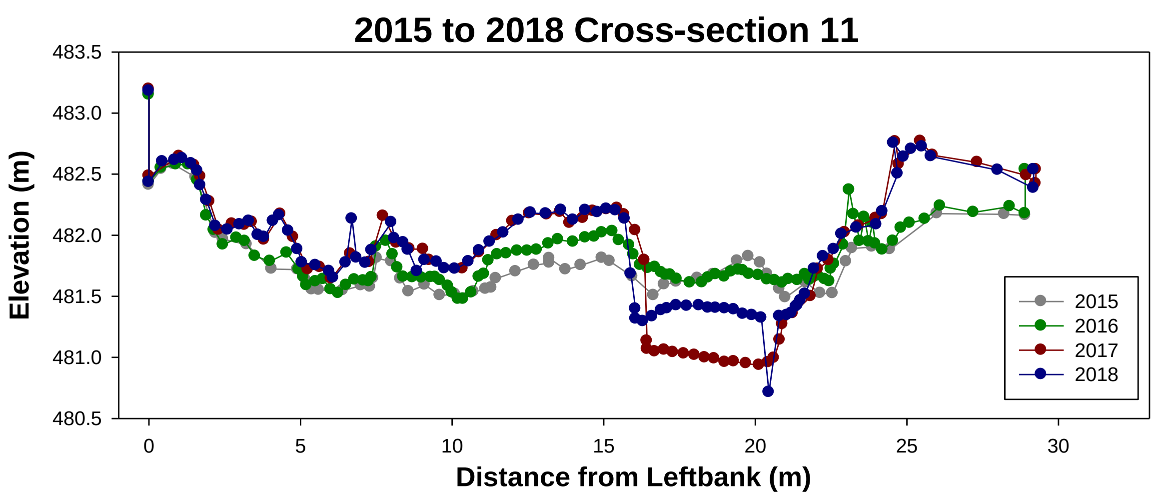

2015 to 2018 Cross-section 6
Elevation (m)
480.5
480.0
479.5
479.0
478.5
478.0
477.5
0
5
10
15
Distance from Leftbank (m)
2015
2016
2017
2018

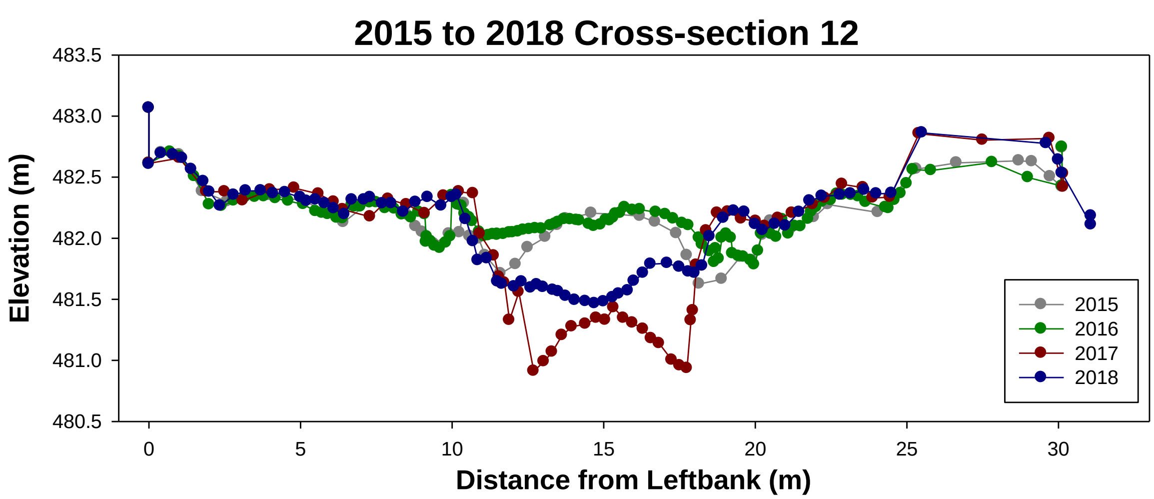

2015 to 2018 Cross-section 7
Elevation (m)
Distance from Leftbank (m)
2015
2016
2017
2018

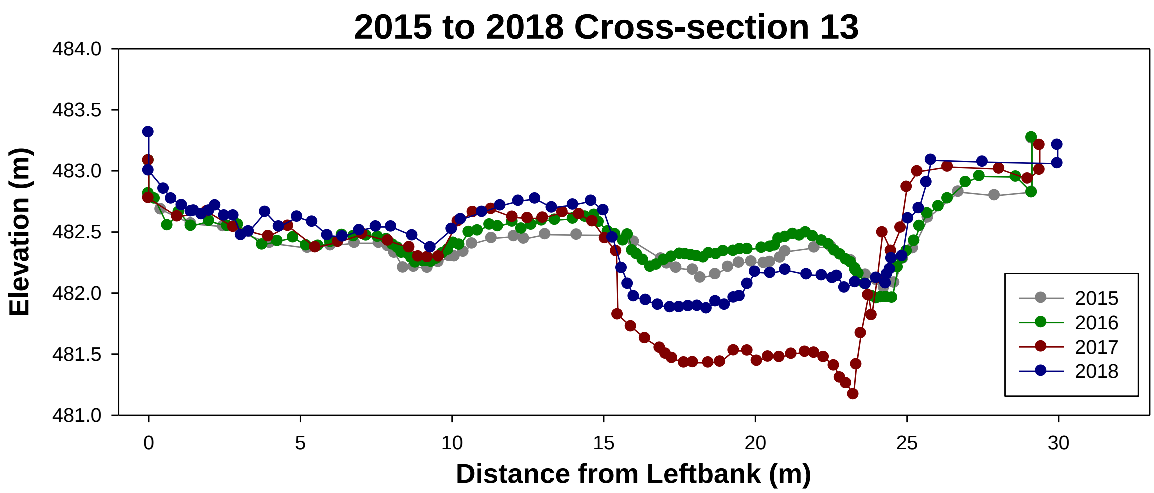

2015 to 2018 Cross-section 8
Elevation (m)
Distance from Leftbank (m)
2015
2016
2017
2018

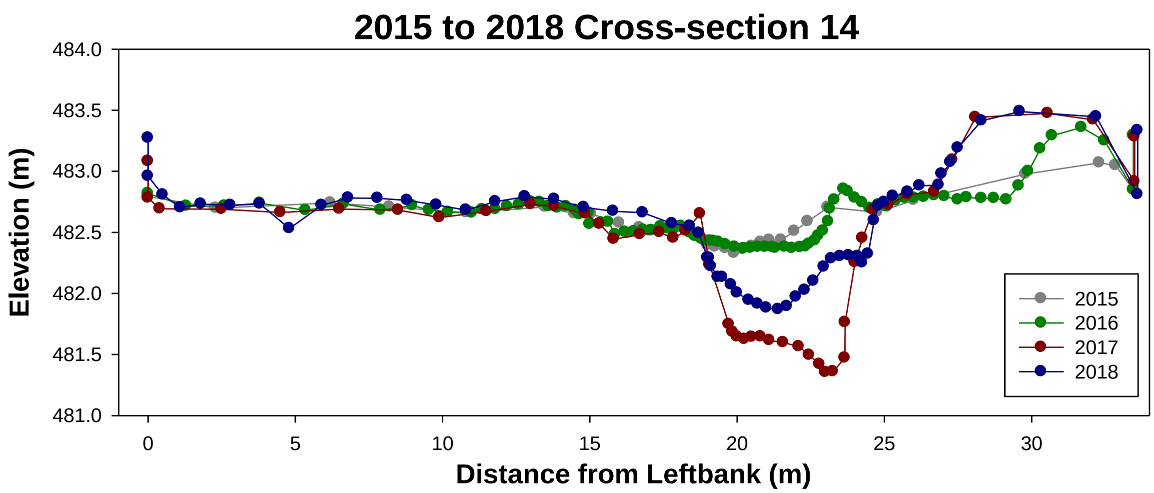

2015 to 2018 Cross-section 9
Elevation (m)
Distance from Leftbank (m)
2015
2016
2017
2018

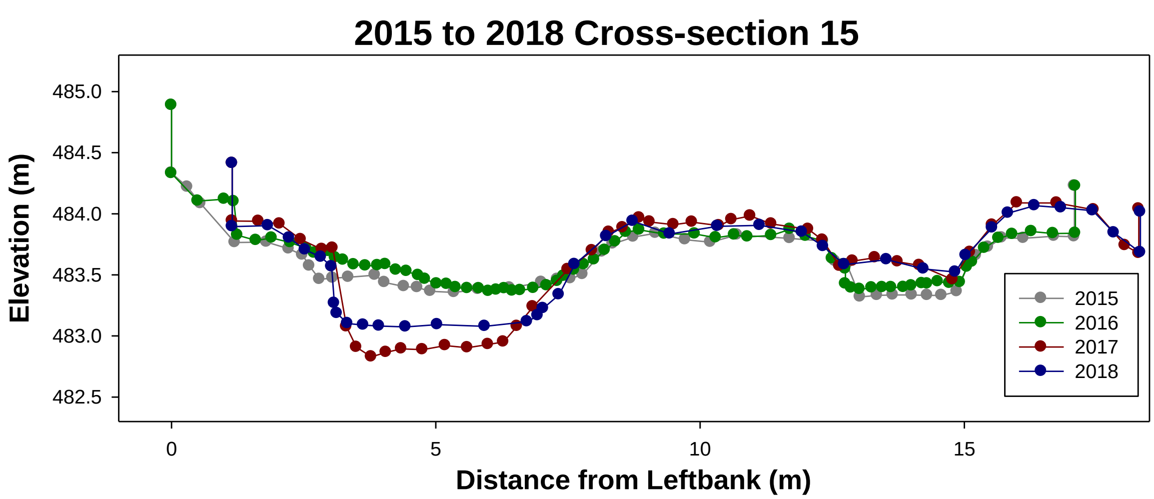

2015 to 2018 Cross-section 10
Elevation (m)
Distance from Leftbank (m)
483.5
483.0
482.5
482.0
481.5
481.0
480.5
0
5
10
15
20
25
30
2015
2016
2017
2018

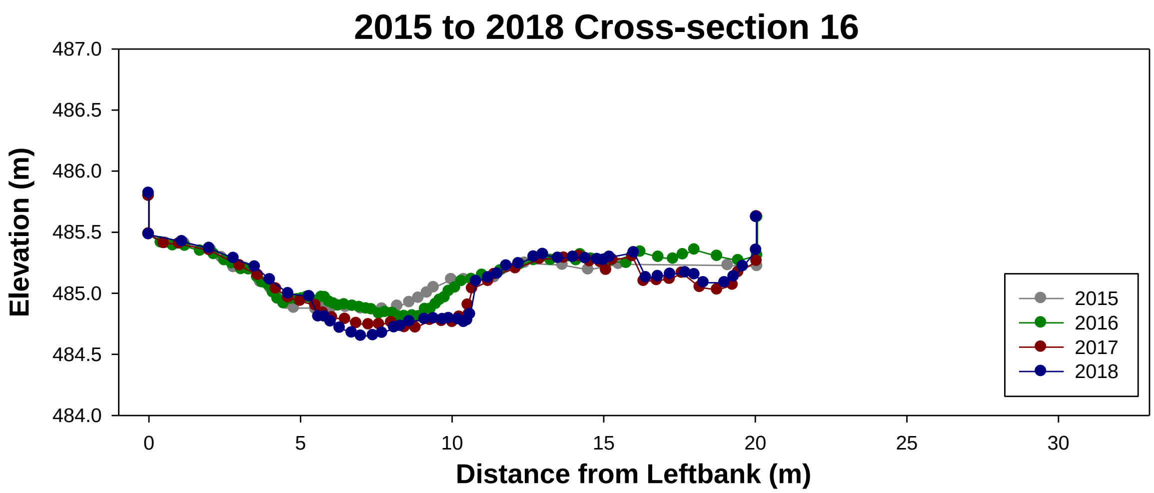

2015 to 2018 Cross-section 11
Elevation (m)
Distance from Leftbank (m)
483.5
483.0
482.5
482.0
481.5
481.0
480.5
0
5
10
15
20
25
30
2015
2016
2017
2018

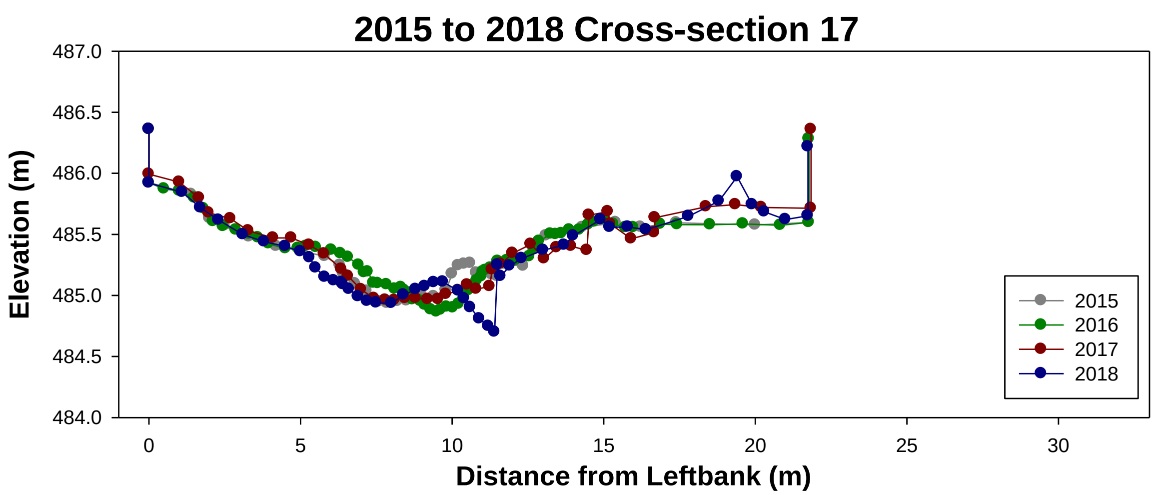

2015 to 2018 Cross-section 12
Elevation (m)
Distance from Leftbank (m)
483.5
483.0
482.5
482.0
481.5
481.0
480.5
0
5
10
15
20
25
30
2015
2016
2017
2018

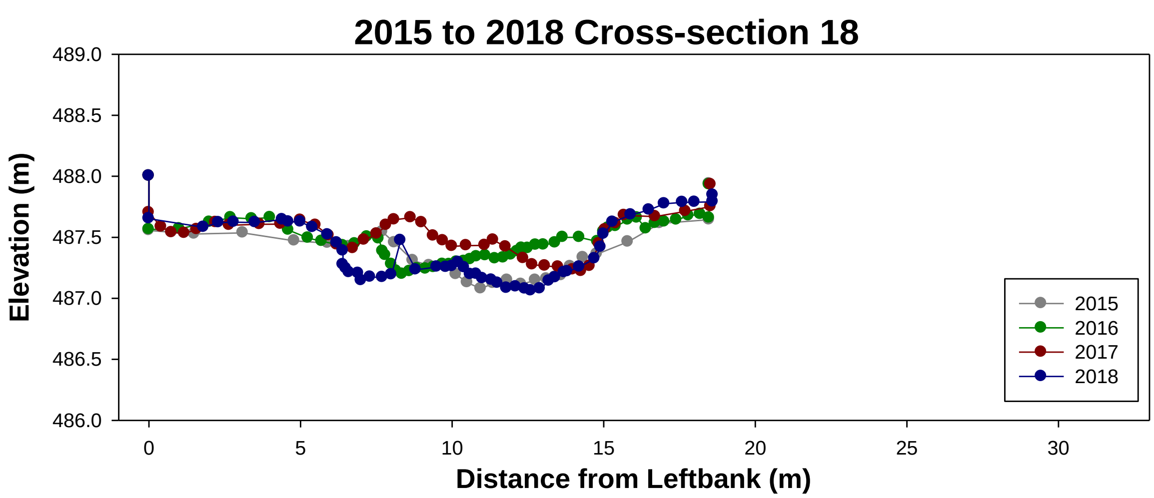

2015 to 2018 Cross-section 13
Elevation (m)
484.0
483.5
483.0
482.5
482.0
481.5
481.0
0
5
10
15
20
25
30
Distance from Leftbank (m)
2015
2016
2017
2018

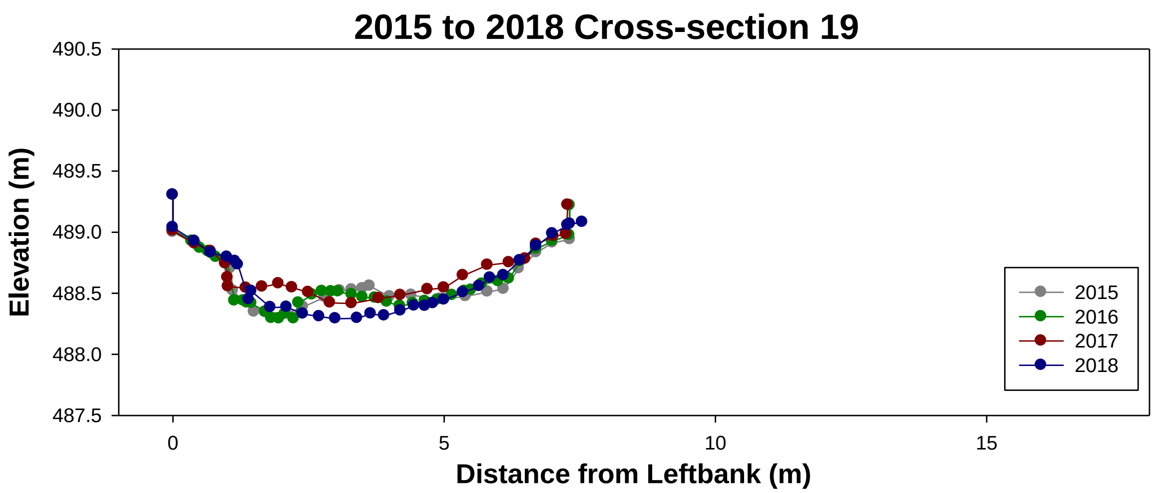

2015 to 2018 Cross-section 14
Elevation (m)
484.0
483.5
483.0
482.5
482.0
481.5
481.0
0
5
10
15
20
25
30
Distance from Leftbank (m)
2015
2016
2017
2018


2015 to 2018 Cross-section 15
Elevation (m)
485.0
484.5
484.0
483.5
483.0
482.5
0
5
10
15
Distance from Leftbank (m)
2015
2016
2017
2018


2015 to 2018 Cross-section 16
Elevation (m)
487.0
486.5
486.0
485.5
485.0
484.5
484.0
0
5
10
15
20
25
30
Distance from Leftbank (m)
2015
2016
2017
2018


2015 to 2018 Cross-section 17
Elevation (m)
487.0
486.5
486.0
485.5
485.0
484.5
484.0
0
5
10
15
20
25
30
Distance from Leftbank (m)
2015
2016
2017
2018


2015 to 2018 Cross-section 18
Elevation (m)
489.0
488.5
488.0
487.5
487.0
486.5
486.0
0
5
10
15
20
25
30
Distance from Leftbank (m)
2015
2016
2017
2018


2015 to 2018 Cross-section 19
Elevation (m)
490.5
490.0
489.5
489.0
488.5
488.0
487.5
0
5
10
15
Distance from Leftbank (m)
2015
2016
2017
2018

Appendix B: Sediment Data

The Gradistat Summary Data for the 2016, 2017, and 2018 Wolman Pebble Count Data.

2016 Wolman Pebble Count Data

Cross-section	Mean (mm)	D_{90} (mm)	D_{50} (mm)	D_{10} (mm)
1	24.3	43.6	23.4	5.3
2	23.9	44.6	21.7	5.3
3	11.5	24.4	7.6	3.3
4	15.8	35.4	10.5	4.2
5	37.3	60.2	36.1	12.4
6	11.3	27.4	7.4	1.5
7	11.1	26.1	6.2	1.7
8	15.6	38.4	10.6	1.6
9	13.7	32.2	10.7	1.6
10	11.5	25.9	8.4	1.6
11	12.8	30.6	7.7	1.6
12	17.0	38.3	12.6	1.9
13	16.8	36.0	13.0	3.3
14	16.9	37.6	14.1	1.7
15	34.1	69.0	31.6	7.5
16	38.5	72.9	35.8	18.9
17	19.6	55.4	11.3	1.7
18	26.5	45.1	23.1	9.6
19	23.9	44.4	20.6	7.8

2017 Wolman Pebble Count Data

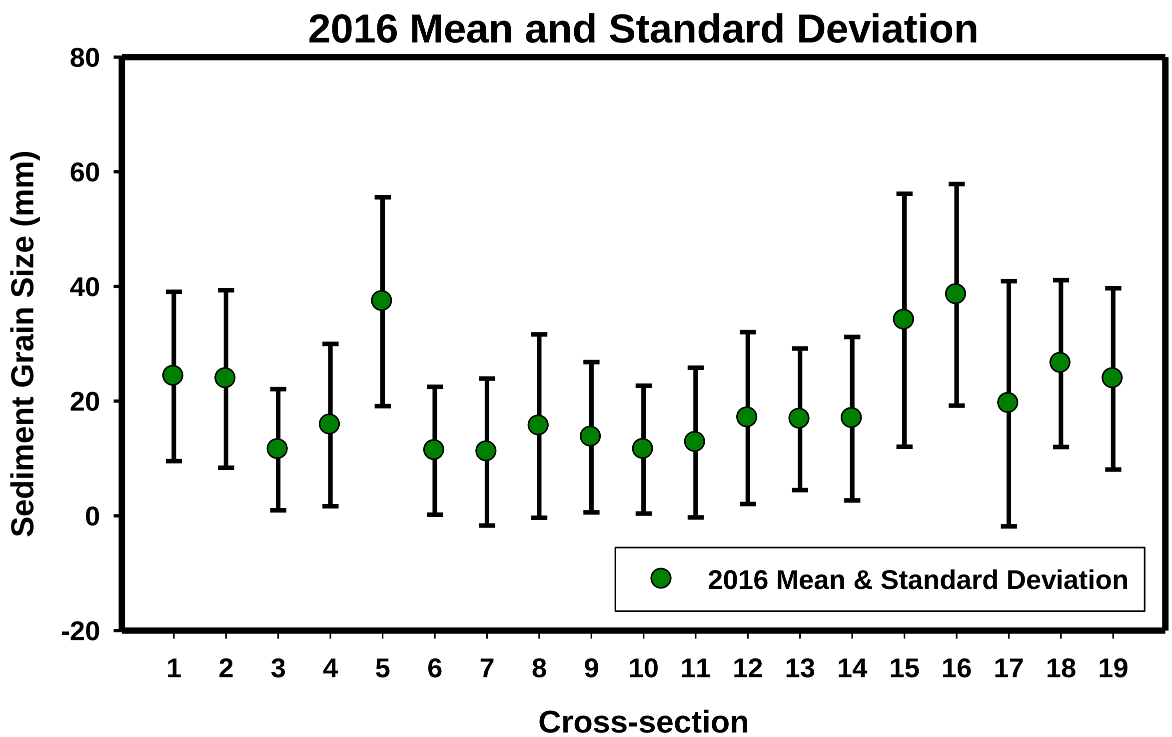
Cross-section	Mean (mm)	D_{90} (mm)	D_{50} (mm)	D_{10} (mm)
1	27.6	57.5	26.1	1.9
2	18.0	38.6	14.6	1.6
3	18.8	50.4	3.8	1.6
4	31.1	82.9	34.1	1.8
5	21.8	65.5	1.9	1.5
6	34.3	76.0	33.6	8.8
7	40.6	80.4	43.2	12.4
8	33.5	93.3	39.7	9.2
9	33.8	84.3	35.6	11.2
10	32.2	82.5	19.1	1.6
11	32.3	84.1	30.7	9.0
12	31.6	82.7	31.5	7.6
13	34.2	72.1	36.0	5.9
14	37.4	76.8	33.1	8.6
15	36.6	90.0	44.4	11.2
16	33.0	89.8	37.4	7.4
17	24.8	77.8	21.8	1.6
18	35.2	90.0	45.0	1.9
19	34.8	105.4	47.8	11.2

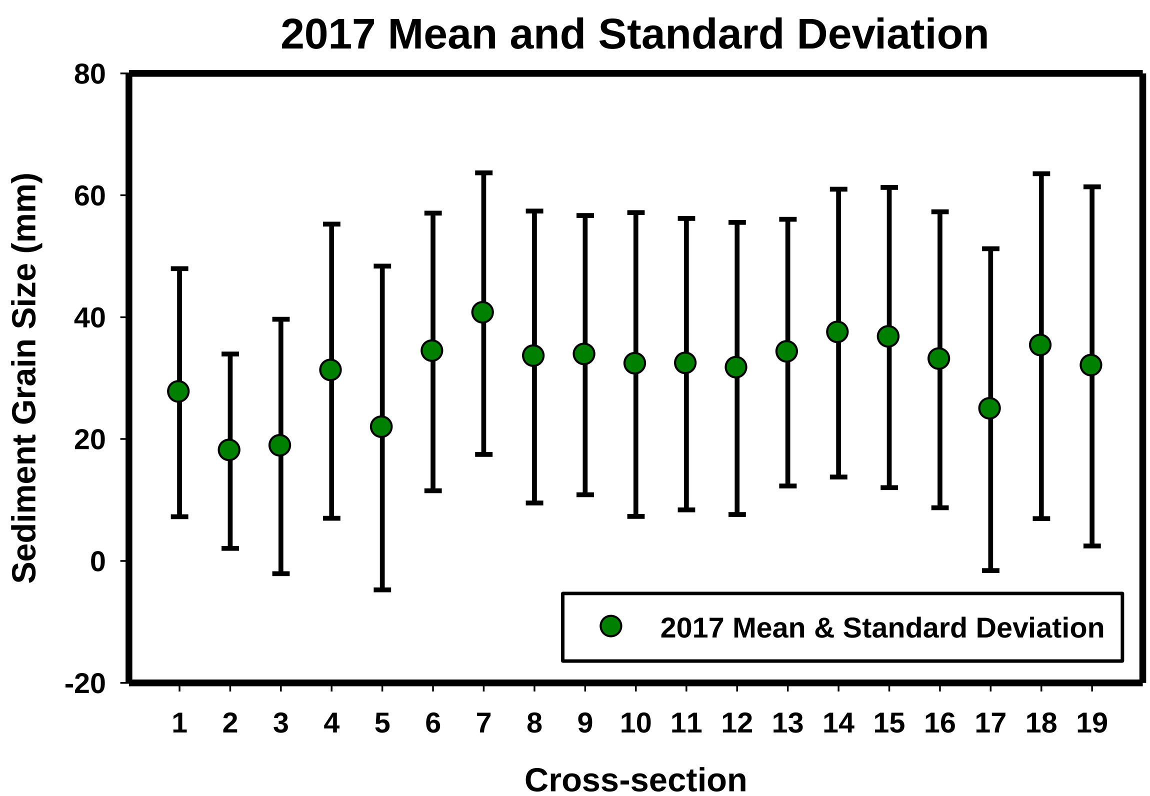
2018 Wolman Pebble Count Data

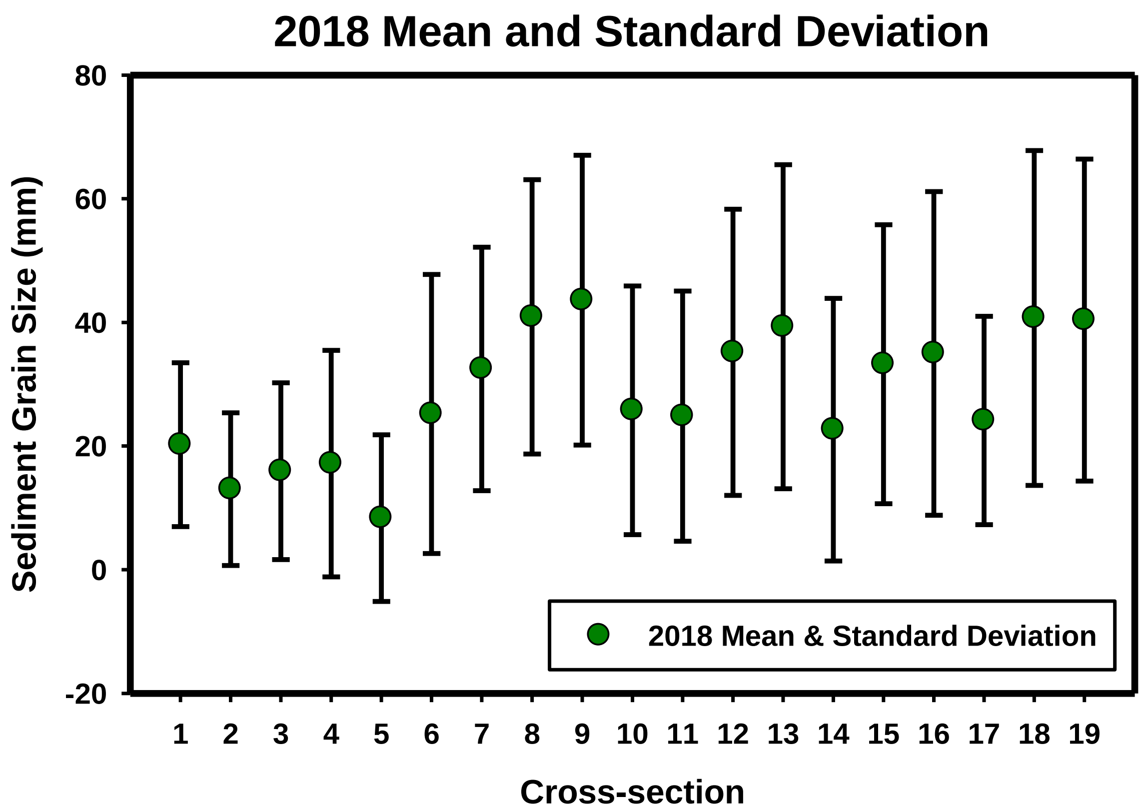
Cross-section	Mean (mm)	D_{90} (mm)	D_{50} (mm)	D_{10} (mm)
1	20.2	38.4	17.6	5.1
2	13.0	26.4	9.5	1.7
3	15.9	36.6	10.7	1.7
4	17.2	48.2	11.7	1.6
5	8.3	27.7	1.8	1.5
6	25.2	75.6	22.9	1.8
7	32.5	63.2	27.6	10.1
8	40.9	85.1	43.6	19.4
9	43.6	88.0	47.2	23.3
10	25.8	59.2	25.4	1.7
11	24.8	87.9	26.9	1.8
12	35.2	90.8	38.0	16.5
13	39.3	98.0	49.2	17.8
14	22.6	59.7	19.0	1.6
15	33.2	72.8	33.0	3.7
16	35.0	106.1	43.5	8.8
17	24.1	46.3	21.6	1.9
18	40.7	104.4	55.6	21.9
19	40.4	100.1	51.1	21.3

Appendix C: Sediment Mean & Standard Deviation

The mean and 1 standard deviation calculated with the 2016 to 2018 Wolman Pebble Count Data.







2018 Mean and Standard Deviation
Sediment Grain Size (mm)
80
60
40
20
0
-20
2018 Mean & Standard Deviation
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Cross-section