

**SEDIMENT TRANSPORT AND BED MATERIAL ADJUSTMENTS IN THE
VICINITY OF WILSEY DAM: SALMON SPAWNING HABITAT IMPLICATIONS**

by

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ABSTRACT

Substrate requirements are an important component of the multifaceted spawning needs of salmon, and this research effort was directed at developing a greater understanding of sediment transport dynamics and bed material response in the Middle Shuswap River in consequence of the emplacement and subsequent management of Wilsey Dam. Downstream of Wilsey Dam the river provides spawning habitat for coho (*Oncorhynchus kisutch*), chinook (*O. tshawytscha*), pink (*O. gorbuscha*) and sockeye (*O. nerka*) salmon. This thesis suggests that sand dredged from deposits filling the upstream reservoir basin of the dam could be redeposited downstream when coupled with specific flow releases (≥ 100 cubic metres per second). This is seen as a viable option for sediment management on the Middle Shuswap River aimed at restoring sediment transport processes and preserving spawning habitat. Maintaining sediment transport processes after dam emplacement is an important consideration for ecological processes in rivers, consistent with the notion of holistic dam management (Ligon et al. 1995, Tharme 2003)

An experimental underwater Automated Grain Sizing method was developed for determining the median grain size (D_{50}) of glide facies throughout the 28.4 km study area. On this basis, estimates of viable salmon spawning habitat were updated from 2002 and mapped below ($190,906 \text{ m}^2$) and above ($387,265 \text{ m}^2$) Wilsey Dam. Grain size distributions showed a fining trend in the downstream direction for the Middle Shuswap River, with significant coarsening of bed substrate in the 0.2 km section immediately below the canyon downstream of Wilsey Dam. A one-dimensional (1D) sediment transport model, based on the Wilcock and Crowe (2003) transport equation, showed that sand reintroduced during spring freshet to a 1200 m reach below the dam flushed quickly through in the model. Gravel was also mobilized upon sand reintroduction. The model is an oversimplification of site conditions and would need to be field tested during sand reintroduction trials to establish model integrity.

Research undertaken in this thesis contributes to the growing amount of literature on the biophysical impacts of hydroelectric dams and presents ways dam operators can approach and mitigate disruptions to sediment transport process and their resulting ecological impacts.

PREFACE

This dissertation presents research conducted by Giles Shearing under the supervision of Dr. Bernard Bauer. Giles Shearing was the primary researcher and was responsible for the main study design, data collection, analysis, interpretation and writing of the content. Conceptual and analytical support were provided by Dr. Bernard Bauer, Dr. Mark Lorang, Dr. John Richardson and Dr. Theodore Fuller. All guidance provided by the Supervisory Committee and all literature referenced is correctly cited.

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Abbreviations

cms	Cubic meters per second
COSEWIC	Committee on the Status of Endangered Wildlife In Canada
D ₅₀	Median grain size in the distribution
D ₈₄	Grain size for which 84% of grains are smaller than in the distribution
D _{max}	Maximum grain size in the distribution
DFO	Fisheries and Oceans Canada (also called Department of Fisheries and Oceans)
DG	Digital Gravelometer by Sedimetrics ©
ENSO	El Niño Southern Oscillation
FWCP	Fish and Wildlife Compensation Program (BC Hydro)
GSD	Grain size distribution
HSB	Helley-Smith Bedload sampler
LLOGs	Low level outlet gates
MW	Megawatt
MSR	Middle Shuswap River
NSERC	Natural Sciences and Engineering Research Council of Canada
PDO	Pacific Decadal Oscillation
SFGS	Shuswap Falls Generating Station (at Wilsey Dam)
SFU	Simon Fraser University
SRH	Shuswap River Hatchery
UTM	Universal Transverse Mercator
UBC	University of British Columbia
WSC	Water Survey of Canada
X	Cross-section prefix

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Dedication

To Oliver and India, the future.

CHAPTER 1.0 INTRODUCTION

1.1 PROJECT OVERVIEW

Dam operators and environmental managers strive to restore sediment transport processes to regulated rivers without harmfully impacting downstream ecological processes (BC Hydro 2006; Inter-fluve Inc. et al. 2011; Riverbend Engineering and JR Merit 2011). This thesis considers the situation at Wilsey Dam, a 6 megawatt (MW) hydroelectric facility on the Middle Shuswap River (MSR) in British Columbia, owned and operated by BC Hydro, a provincial Crown Corporation. BC Hydro currently faces two major hurdles: 1) how to restore fish passage and reintroduce salmon above Wilsey Dam, and 2) how to manage and dispose of aggrading headpond sediment for the preservation hydro generation and downstream ecological and fluvial geomorphological processes. For 43 years, BC Hydro has managed accumulating sediment in the headpond by suction dredging (1972 to 1988) and stockpiling dredge sediment on land adjacent to the dam (1989 to 2009). There is great interest in how dredged sediment can be reintroduced to the river downstream in a way that avoids environmental harm. The thesis examines the consequences of sediment reintroduction downstream with regard to the potential for plugging the interstices of spawning gravel beds used by anadromous salmon, specifically fall-spawning chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*).

1.2 STUDY AREA

The Shuswap River extends from headwaters north of Green Bush Lake near Davis Peak to its confluence with Mara Lake, a distance of approximately 200 km. The Shuswap River is segmented into three main sections (Figure 1):

- The **Upper Shuswap River** comprises the headwaters and river flowing through the Monashee Mountains. The Upper Shuswap River flows approximately 60 km southwest past Greenbush Lake into Sugar Lake Reservoir. At the outlet of Sugar Lake is Sugar Lake Dam, a flow regulating structure managed by BC Hydro. The

Sugar Lake confluence with the Upper Shuswap River is located at UTM: 11U 393588.13 m E., 5589770.90 m N.

- The **Middle Shuswap River** begins immediately downstream of Sugar Lake Dam and extends approximately 32 km to Wilsey Dam, then another approximately 24 km to Mable Lake, for a total of approximately 56 km. The Mable Lake confluence with the MSR is located at UTM: 11U 375687.40 m E., 5588427.94 m N.
- The **Lower Shuswap River** begins at the outlet of Mable Lake and flows approximately 64 km to Mara Lake, and ultimately feeding the Fraser River. The Mara Lake confluence with the Lower Shuswap River is located at UTM: 11U 355469.94 m E., 5621239.38 m N.

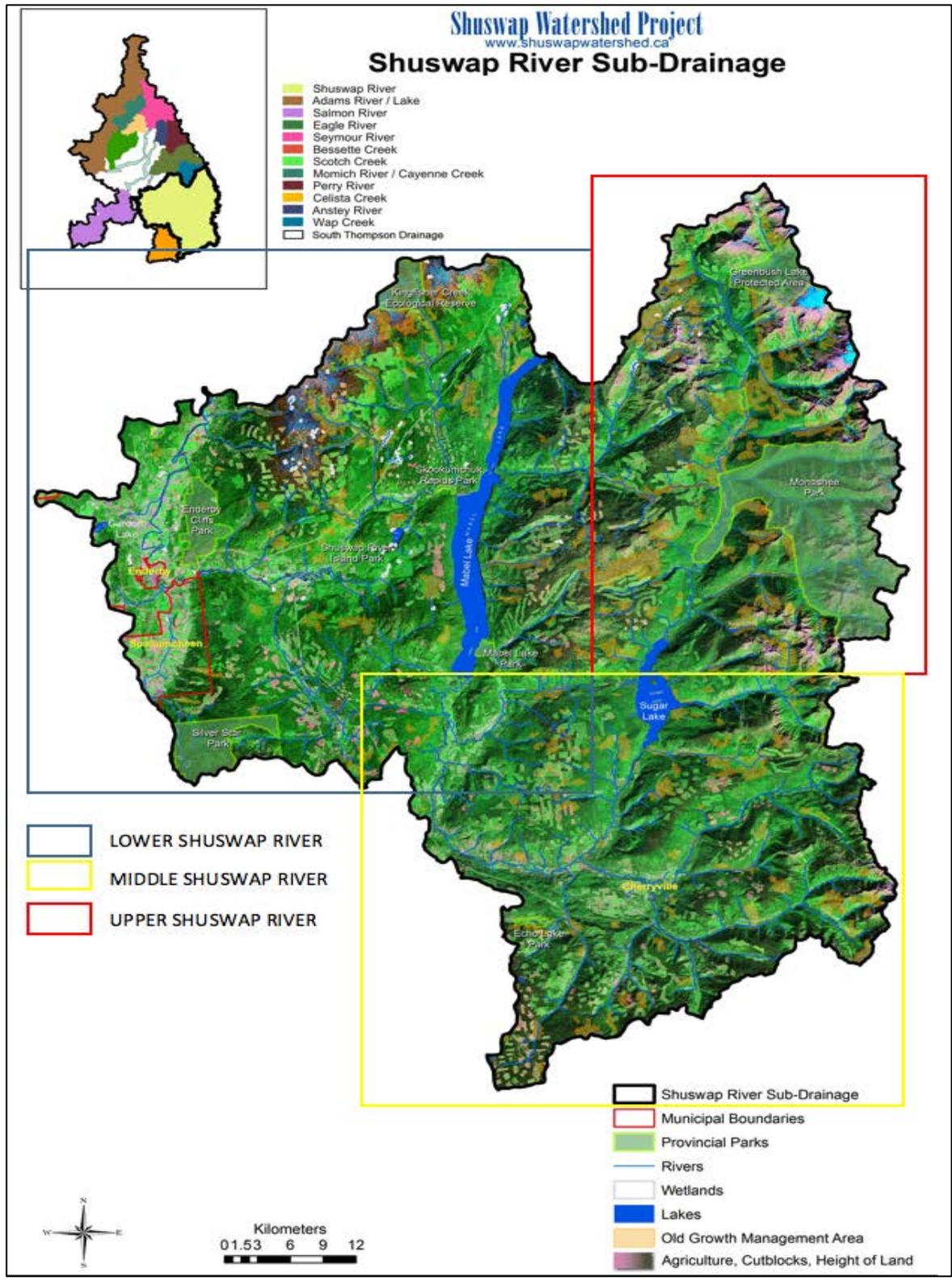


Figure 1. Shuswap River Watershed Map, British Columbia. Lower (blue square), Middle (red square) and Upper (yellow square) sections of the watershed identified. Map courtesy of J. Cooperman of the Shuswap Watershed Project.

This study focuses on a 28.4 km length of the 55.5 km long MSR, from upstream at The Meadows Campground (near Cherryville, B.C.; UTM: 385378.00 m E, 5570358.00 m N) to the downstream terminus at the Baily Bridge at Lawrence Road (UTM: 372308.57 m E, 5579887.62 m N) (Figure 2).

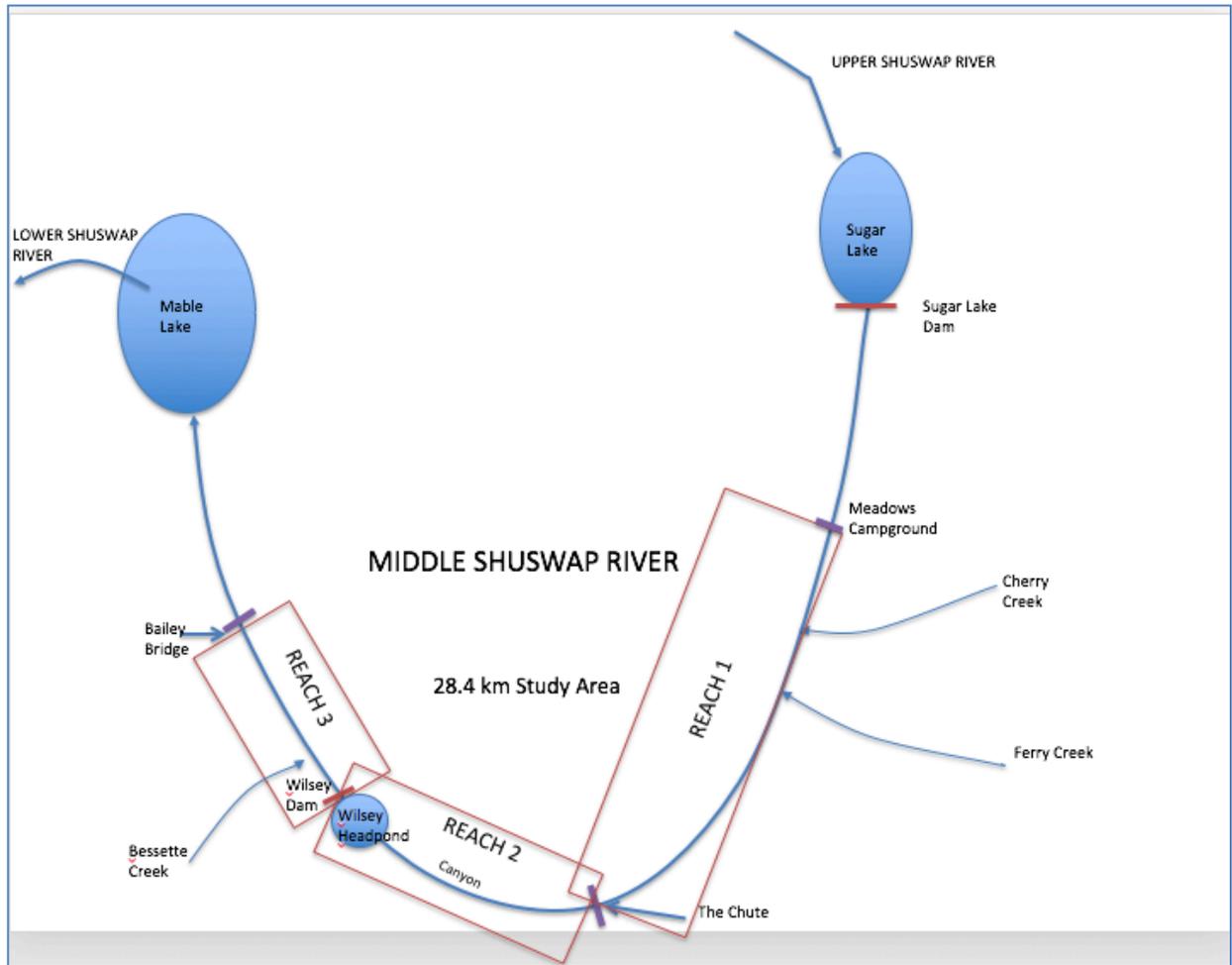


Figure 2. Overview Map of Middle Shuswap River (blue line). Reach 1, 2 and 3 identified by red rectangles, Wilsey and Sugar Lake dams (red lines), reach breaks (purple lines), and Mable Lake and Sugar Lake (blue ovals); map not to scale.

In the study area, the MSR has an average channel slope of 0.4% (105 m elevation change over 28.4 km), the same slope for the entire MSR from Sugar Lake Dam to Mara Lake. The drainage basin area is 1969 km². This 28.4 km stretch of river above and below Wilsey Dam was selected for the following reasons:

1. To capture the influence of major tributaries on the expected downstream fining trend in the river. The Meadows Campground, approximately 3 km upstream of Cherry Creek was selected as the upstream starting point in order to include Cherry Creek and Ferry Creek, the largest tributaries above Wilsey Dam.
2. Griffith (1979) observed that chinook utilize the river downstream of Cherry Creek whereas rainbow trout (*O. mykiss*) utilize the river upstream of Cherry Creek, up to Sugar Lake Dam. Therefore, the study area accounts for recorded chinook spawning sites upstream of Wilsey Dam. Chinook are one of the two target species of interest to Fish and Wildlife Compensation Program (the other is coho).
3. Salmon spawning below the Bailey Bridge is much less pronounced than in the reach between the Bailey Bridge and Wilsey Dam, making the bridge a suitable downstream terminus. Triton (1994) found that most salmon in the MSR spawn upstream of the Bailey Bridge.

For the purpose of investigating salmon spawning habitat, the study area is divided into three reaches, partitioned by the dam and the Chute, both river knickpoints. Note that for the purpose of describing downstream fining trends in Section 2.7.1, the study area is divided into five reaches that consider the influence of the three major tributaries, as discussed in Section 2.7.1.

Reach 1: The Meadows Campground to the Chute (16.2 km)

Reach 1 was delineated to identify potential salmon spawning areas from The Meadows Campground to the upstream start of the Chute. The Chute, found approximately 3.6 km upstream of Wilsey Dam, is a gradual falls 0.1 km long with an approximate slope of 4.6%. Two major tributaries, Cherry Creek (503 km² drainage area) and the smaller Ferry Creek (145 km² drainage area) empty into Reach 1 (Triton 1995).

Reach 1 is characterized by glide, riffle, pool morphology with intermittent deep pools and deep incised riverbed margins along natural bedrock and riprap armored banks. Reach 1 has an average water surface slope of 0.3%. Water surface slope was calculated using Google

Earth at an approximate water discharge of 19 cubic metres per second (cms). Note that from The Meadows Campground upstream to Sugar Lake Dam (i.e., upstream of the study area), the average water surface slope increases to 0.6%.

Reach 2: Chute to Wilsey Dam (3.6 km)

Reach 2 was delineated to identify potential salmon spawning areas between the Chute and Wilsey Dam. Reach 2 is characterized by approximately 0.5 km of glide, riffle, pool channel morphology at the upstream and downstream extents of the reach (i.e., during low water) and approximately 3 km of deep pools through a canyon upstream of the Mable Lake Road bridge. The average water surface slope in Reach 2 is 0.08%.

Reach 3: Wilsey Dam to Bailey Bridge (8.6 km)

Reach 3 contains known and potential spawning areas between Wilsey Dam and the Bailey Bridge. Reach 3 is characterized by a short 0.4 km long canyon immediately downstream of Wilsey Dam followed by 8.2 km of glide, riffle, pool morphology mixed with intermittent deep canyon pools and deep incised riverbed margins along armored banks. The average water surface slope in Reach 3 is 0.2%. Note that from downstream of the Bailey Bridge to Mable Lake the MSR has an average water surface slope of 0.09% as the river enters the floodplain.

1.3 OBJECTIVES AND HYPOTHESES

The overarching question for this thesis is whether natural sediment conveyance in the river has been disrupted by dam emplacement and operation to a degree that far exceeds that of other natural disruptions such as localized sediment sources and sinks. The research is motivated by the pragmatic need to determine whether sediment aggraded immediately upstream of Wilsey Dam can be reintroduced downstream in such a way as not to impact spawning habitat used by anadromous salmon in a negative way. The risk associated with sediment reintroduction downstream is that salmon spawning beds below Wilsey Dam will result in accumulation of fines in the interstices of existing gravel (i.e., reducing intra-gravel

dissolved oxygen needed by incubating salmon eggs (Carter 2005)), or that suitable spawning gravel from the bed will be mobilized, resulting in channel degradation. The latter process may occur because of large-volume flushing flows released from the dam concurrent with the addition of sand, which can mobilize larger grains (Venditti et al. 2010).

Downstream fining trends are well documented in many rivers (Gasparini, Tucker, and Bras 1999; Rice 1999; Frings 2008; Venditti et al. 2015). Therefore, sediment size data were collected to examine downstream fining trends in reaches above and below Wilsey Dam as a potential indicator of dam related impacts to MSR. This forms the first research objective.

Objective 1 is to assess whether there is a downstream fining trend, based on grain size distributions (GSD) obtained from 53 sampled glide facies within the 28.4 km study area, and to determine if there is a statistical difference between three major influencing factors in the MSR (i.e., dams, falls and tributaries).

- a. H_{10} . No discernable downstream fining trend exists in any of the reaches.
- b. H_{1a1} . The downstream fining trend is present in the all river segments.
- c. H_{1a2} . A downstream fining trend is present only in the river segment defined by the dam and not the natural river segments.

Salmon production depends in part on the abundance and availability of spawning habitat. The most recent estimate of spawning habitat area was undertaken by Guy and Uunila (2002). Hence, the second objective of this thesis is to update the estimate. A plan is currently under discussion to provide fish passage around Wilsey Dam to allow salmon access to suitable spawning habitat above the dam. If salmon reintroduction efforts above Wilsey Dam are unsuccessful, protection of downstream spawning habitat becomes that much more critical for the reproductive success of anadromous salmon in the MSR.

Objective 2 is to determine the area of available spawning habitat for coho and chinook based on the GSD of 53 glide facies above and below Wilsey Dam.

Construction and operation of Wilsey Dam has resulted in sediment deposition above the dam in the headpond and backwater channel. This is a problem for dam operation and management. Therefore, the third objective was to use a 1-dimensional (1D) sediment flux model to assess flushing flows versus reintroduced sediment loads on adjusting bed characteristics.

Objective 3 is to examine the impact of reintroduced fine sediment (and gravel augmentation) on GSD within a 1200 m salmon spawning reach from Wilsey Dam to Bessette Creek using a 1D model.

- a. H_{3o}. Reintroduced fine sediment has a long residence time (i.e., one freshet season) and a fining effect on the existing gravel bed within the 1200 m model reach between Wilsey Dam and the Bessette Creek confluence.
- b. H_{3a}. Reintroduced fine sediment has a limited residence time on the gravel bed within the 1200 m model reach between Wilsey Dam and the Bessette Creek confluence and is entrained and transported with appropriately selected flushing flows within one freshet season without mobilizing gravels.

This sequence of objectives and the corresponding hypothesis for Objectives 1 and 3 will empirically gauge if Wilsey Dam is impacting sediment transport dynamics and anadromous salmon spawning habitat, and inform how sediment can be managed to synchronize sustainable power generation and ecological productivity.

1.4 BACKGROUND

A historical timeline of the BC Hydro Shuswap River project (i.e., Wilsey and Sugar Lake dams) is presented in Appendix 2. Section 1.4.1 describes the history of the MSR hydroelectric project in the context of this research.

1.4.1 History

In 1900, the B.C. Lieutenant Governor proclaimed Shuswap Falls on the MSR to be “one of the best water powers for electrical manufacturing purposes in the province” (French 1995).

In 1920, a United States firm, West Canadian Hydro Electric Company, prepared conceptual plans for a dam at Shuswap Falls (Benneyfield et al. 2001; BC Hydro 2005). By 1929, the West Canadian Hydroelectric Company had constructed two dams, Peers and Wilsey dams. Peers Dam (hereafter referred to as Sugar Lake Dam, its current name) was constructed at Brenda Falls, at the outlet of Sugar Lake Reservoir. Sugar Lake Dam (no generating capacity) was constructed to regulate upstream flows entering Wilsey Dam outside of the spring freshet. At Shuswap Falls, located approximately 28 km downstream of Sugar Lake Dam, Wilsey Dam was constructed. Originally there was only one three megawatt (MW) turbine for power production. The turbine was housed in the Shuswap Falls Generating Station, 180 m downstream of Wilsey Dam. Figure 3 depicts a plan schematic of the Wilsey Dam project from November 3, 1956.

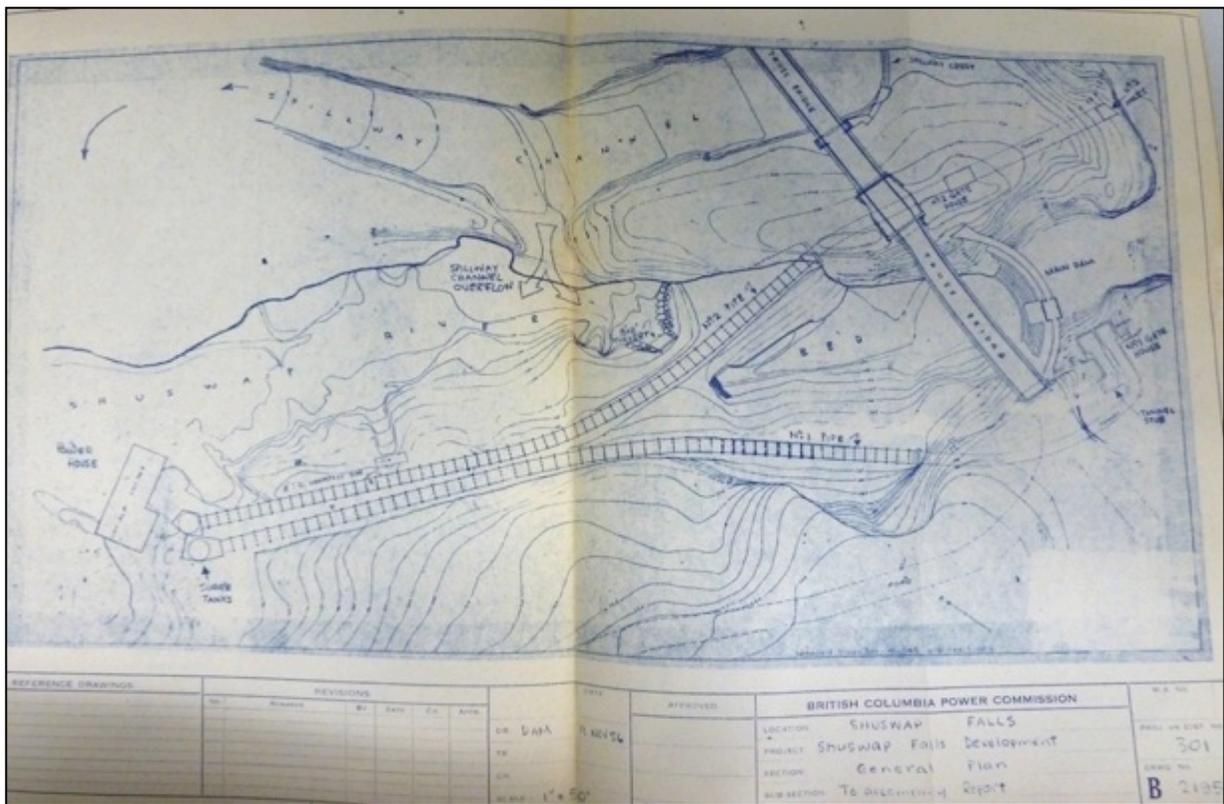


Figure 3. B.C. Power Commission's illustrated schematic of Wilsey Dam and Shuswap Falls Generating Facility on the Middle Shuswap River dated November 3, 1956. Courtesy of the BC Hydro Library and Archives.

In 1941, a second three MW generator was added to the powerhouse at Wilsey Dam (Triton 1995; Donaldson 1987). In 1942, Sugar Lake Dam was raised from 5.2 m to 13 m to provide additional storage, forming the 2,100-hectare Sugar Lake Reservoir found today (Heidstra 2005). In 1945, Sugar Lake Dam and Wilsey Dam were purchased by the BC Power Commission (Benneyfield et al. 2001; BC Hydro 2000) and in 1962, acquired by the then newly formed crown corporation, BC Hydro, the current owner (ARC 2001a).

Two low-level outlet gates (LLOGs) 1.2 m² built into the toe of Wilsey Dam during original construction were used from construction to 1970 to pass accumulated headpond sediment through the dam to the river downstream (Figure 4) (personal communication O. Langer, 2012). LLOGs were opened and closed with a capstan-type rising-stem screw hoists (BC Hydro 1991). The gates were opened every 5 years to flush sediment from the headpond (Lauga 1961).

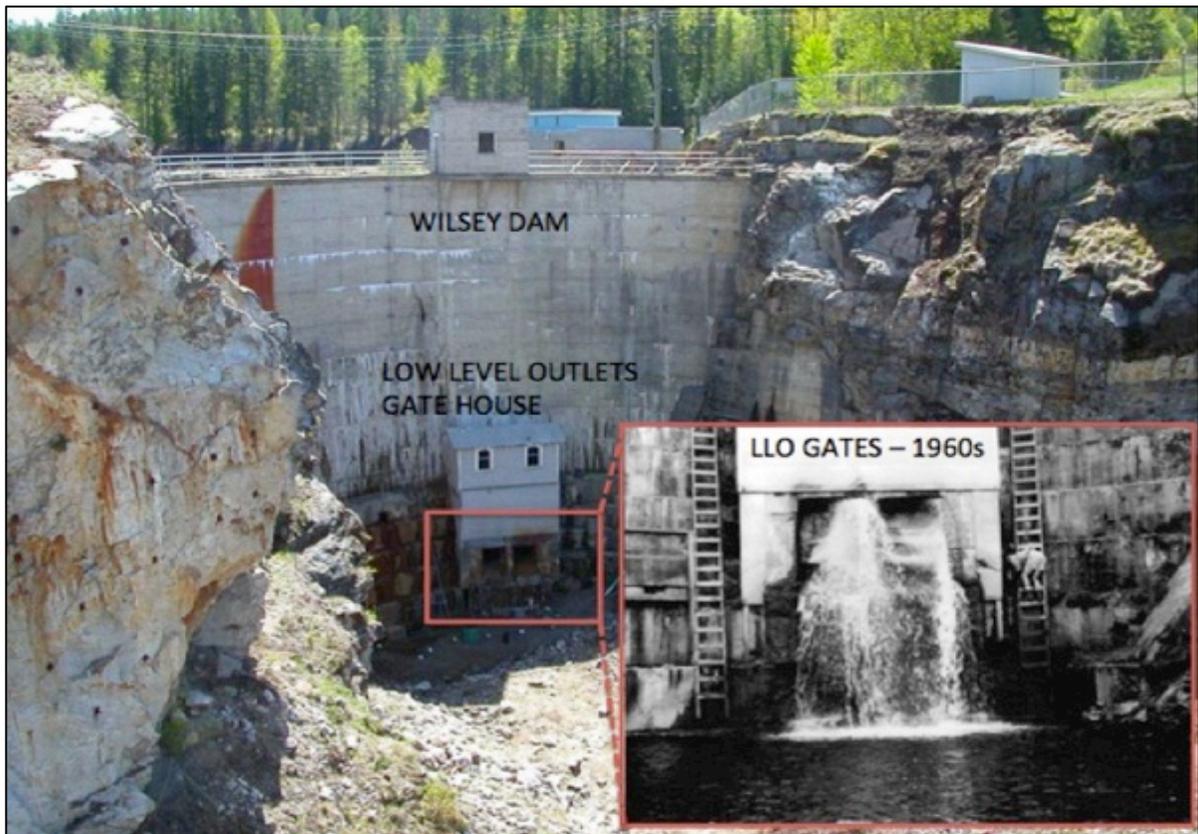


Figure 4. Wilsey Dam Low Level Outlet Gates in 2009 and pre-1960s. Photo credit G. Shearing, 2009. Historical photograph courtesy of BC Hydro Library and Archives.

The last major headpond sluice event was in 1966 during which approximately 280,000 cubic metres (m³) of accumulated sediment was reintroduced downstream over two weeks (Margolis 1988; Sigma 1993a). Figure 5 juxtaposes images of the headpond after sluicing (pre-1967) with current sediment accumulation levels.



Figure 5. Wilsey Dam headpond aggraded with sediment in 2012 (Photo credit. G. Shearing) and the headpond after a major sediment sluice prior to 1967. Coloured circles identify corresponding features in each photograph. Photo credit BC Hydro Library and Archives.

Photograph 1 depicts sand and gravel deposits passed through the LLOGs into the river after a sluicing event upstream of the powerhouse.



Photograph 1. Looking at Middle Shuswap River upstream of the Shuswap Falls Generating Station after a sluicing event pre-1967; note the presence of gravel conveyed by sluicing sediment through the low-level outlet gates. Photo credit. BC Hydro Library and Archives.

In 1970, retired Fisheries and Oceans Canada (DFO) biologist Otto Langer observed a sluicing event at Wilsey Dam. Langer described observing deceased fish downstream, their gills plugged with sand and fish stranded on channel margins. In 1971, DFO representatives, including Langer, met with BC Hydro staff to discuss their concerns about the use of the LLOGs and the associated impacts on fish and fish habitat downstream of the dam. DFO concerns included:

- *sediment was conveyed downstream while salmon eggs were incubating;*
- *suspended sediment levels were found to be deleterious to fish;*
- *fish stranding had been observed due to fluctuating downstream water levels; and*
- *anaerobic river conditions resulting from an increase in biological oxygen demand from organics imbedded in passed sediment (Edgeworth 1971).*

Both parties agreed that using the LLOG to sluice sediment would be replaced with annual dredging, the current practice (Edgeworth 1971). This was an important decision with long-lasting sediment and environmental management implications. Discontinuing rapid, large-volume sediment releases in favour of dredging is what has facilitated headpond sediment aggradation.

Various dredging methods have been employed since 1971; a summary of dredge methods and estimates of volumes removed is provided in Appendix 3. Suction dredging was used from 1971 until 1988. In all but two years of suction dredging, sediment was reintroduced to the river downstream. In the 1990s, suction dredgeate was piped onto adjacent land, including the long-decommissioned camp site for operators west of the dam. In 1989 and six times from 1997 to 2009, dredging was done using an excavator or crane with clamshell bucket.

In 1988, a significant rock excavation and dredge project occurred to remove a natural rock pier and accumulated sediment in the Wilsey Headpond. The pier protruded from the river right bank at the upstream end of the headpond and diverted the river thalweg towards the centre of the headpond, closer to Generator 1 (G1) intake on river left. During spills, water would route back towards the spillway, forming an eddy behind the pier that promoted sediment deposition. After removal of the rock pier and armouring of the river right bank, the river thalweg was made contiguous and aligned with the spillway. Sediment began to accumulate in the main section of the headpond on river left, now a large eddy. This reconfiguration of headpond morphology resulted in the current sediment deposition regime, leading to ongoing sediment aggradation behind both turbine intakes, G1 and G2. Figure 6 shows the rock pier in an undated photo prior to 1988, rock removal in 1988 and the headpond in its current configuration.

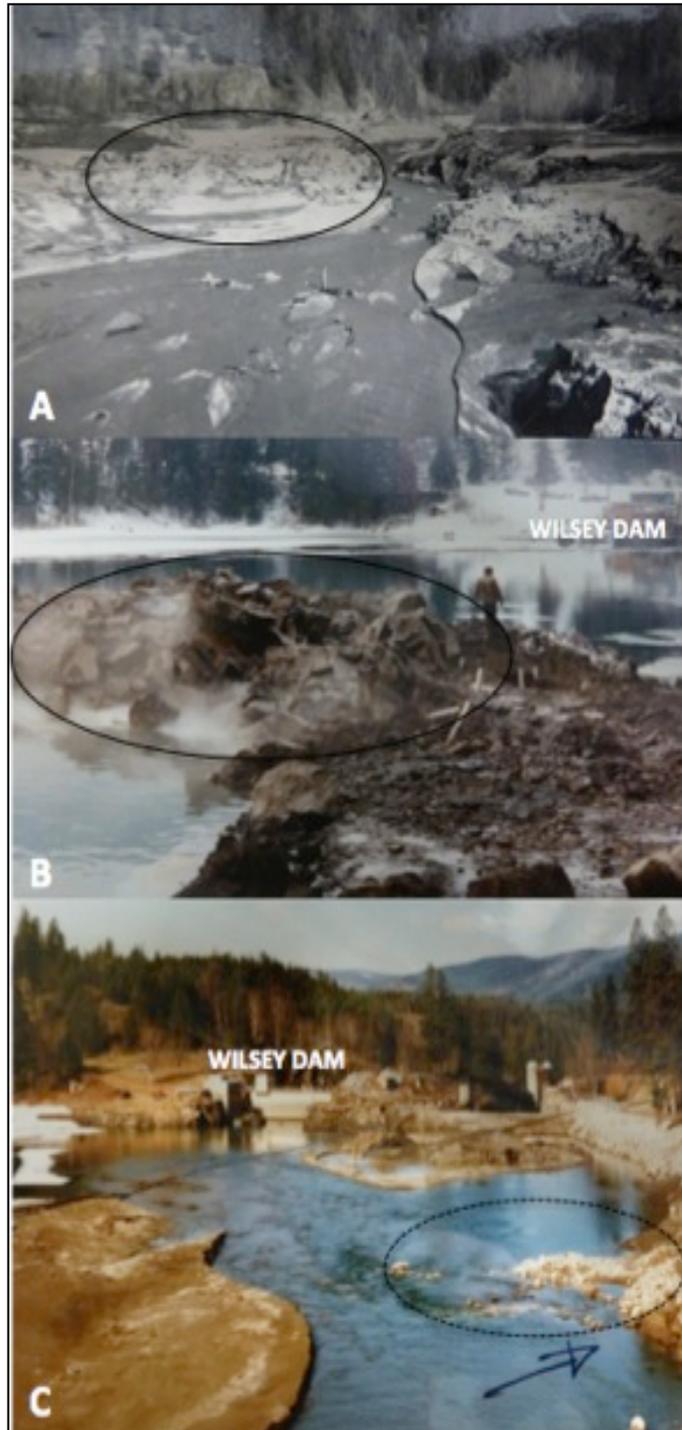


Figure 6. Removal of rock pier in existing river thalweg. Inset A. Circle identify the rock pier looking upstream prior to removal in 1988 (undated photo courtesy of the BC Hydro Library and Archives). B. Circle identifies the rock pier looking downstream during removal in 1988. C. Circle identifies rock pier location in headpond after removal in 1988. Photographs courtesy of the BC Hydro Library and Archives.

In 1989, BC Hydro and DFO agreed on a long-term plan for routine dredging at Wilsey Dam (Smith 1989b). In 1991, the LLOGs were sealed by placing bolted stainless steel bell-mouth plates over the inlet passages (Stewart 2005; Hodge et al. 2005) which may have included concrete infilling (personal communication, J. Maderyk, BC Hydro 2015). Although dredging occurred approximately 22 times from 1974 to 1999, it was estimated in 2002 that approximately 1 million m³ of sediment had accumulated in the headpond and backwaters (Guy and Uunila 2002). Dredging last occurred in August 2009 resulting in the removal of approximately 20,000 m³ of predominately fine sand ($D_{50} = 0.4$ mm). Dredgeate was stockpiled on BC Hydro owned lands immediately south of the headpond.

Sediment and wood that pile up against the G2 intake decrease flows through the intake and limits power production. G1 is less impacted by sand accumulated in the aggraded headpond. Sediment-laden water that passes through the intake is responsible for increased wear on the turbine runner and associated water passage infrastructure (personal communication A. Laidlaw, BC Hydro, 2012). The BC Hydro Dam Safety department monitors accumulated sediment behind the concrete dam (personal communication Win Van Gassen, BC Hydro Dam Safety, October, 2011). The inability to effectively manage sediment entering the headpond is directly responsible for decreased power generation and increased maintenance (personal communication A. Laidlaw, BC Hydro, 2012).

Dredging was never able to remove sediment at a rate equal to annual sediment load, estimated to be approximately 56,000 m³ per year (i.e., 280,000 m³ sediment sluice known to occur every five years divided by five) (Margolis 1988). Dredging now occurs every two to four years to ensure that sufficient water enters G2 for power generation and to supply minimum flow downstream in the event of a forced outage (i.e., by means of an emergency bypass valve) (BC Hydro 2005). The last large dredge occurred in August 2009 in which approximately 20,000 m³ of sediment was removed. Figure 7 shows the history of sediment management at Wilsey Dam.

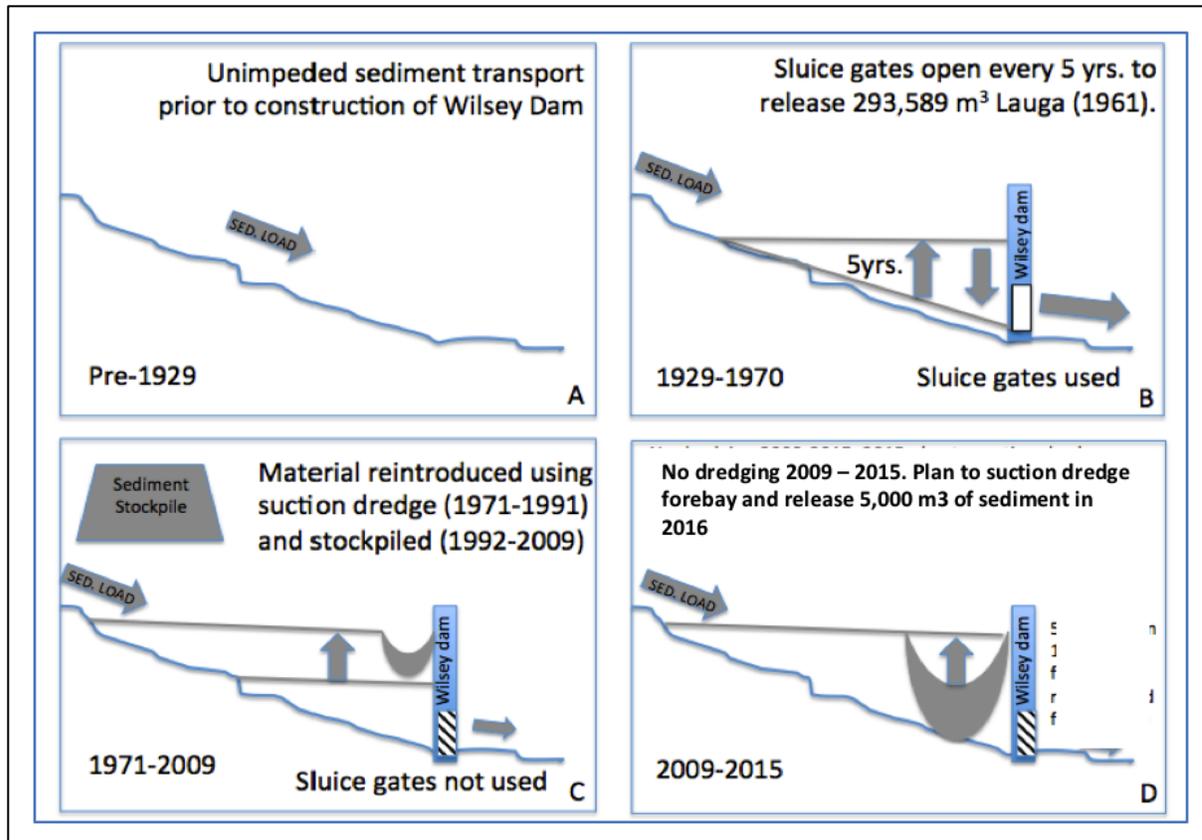


Figure 7. History of sediment management at Wilsey Dam. Inset A. Prior to dam emplacement in 1929 there was no sediment impediment. Inset B. From 1929 to 1970, sediment was released every 5 years using low level outlet gates. Inset C. Sediment was suction dredged and stockpiled on land between 1971 and 2009. Inset D. No dredging has occurred from 2009 to 2015; sediment release trials are planned for 2016.

A Water Use Plan for Wilsey Dam and Sugar Lake Dam was developed between March 2000 and April 2002. The Water Use Plan process involved numerous stakeholders, including First Nations, environmental regulators and members of the public. This was an example of holistic planning for environmental flow assessment (Tharme 2003). The Water Use Plan was finalized by BC Hydro in 2005. The Water Use Plan formalized requirements for ramping rates and minimum flow requirements designed to protect fish and their habitat below Wilsey Dam in addition to the requirements to undertake numerous environmental and social studies (BC Hydro 2005). While the Water Use Plan addressed critical flow, fish and wildlife and social management issues, it did not address impacts to spawning grounds resulting from an altered sediment transport regime or ways in which accumulating sediment could be managed at Wilsey Dam.

Channel degradation (i.e., riverbed coarsening) below Wilsey Dam has been noted previously (Lewynsky 1997; Lister 1990; Guy and Uunila 2002). Lister (1990) stated that insufficient gravel recruitment “could lead to degradation of the channel and possibly, some reduction in fish spawning bed quality.” The gravel bedded reach most significantly impacted by dam emplacement was suggested to be between Wilsey Dam and the Bessette Creek confluence (Guy and Uunila 2002).

1.4.2 Shuswap River Project Operations

1.4.2.1 Sugar Lake (Peers) Dam

Sugar Lake Reservoir has a seasonal storage capacity of 11 % of annual inflow (Bengeyfield et al. 2001). Approximately 45% of annual discharge occurs during the annual spring freshet (May to June) (Sigma 1993a; BC Hydro 2005). Sugar Lake Dam can slightly attenuate the onset of freshet as the reservoir fills; however, once the reservoir has reached capacity of 133.7×10^6 liters, Sugar Lake Dam is no longer able to regulate water flowing to Wilsey Dam (Sigma 1993a; BC Hydro 2005) (Photograph 2). Sugar Lake Dam allows for increased flow during the winter which increases power production during the cold season with highest energy demand (Bengeyfield et al. 2001). Lake productivity is considered low to moderate for fish production because of a “relatively high flushing rate, low nutrient levels” and low littoral productivity resulting from a 7 m reservoir draft (Smith 1989a).



Photograph 2. Looking north towards Sugar Lake Dam during freshet flows (May 2006). Air photograph courtesy of BC Hydro Photogrammetry.

The volume of water discharged from Sugar Lake Reservoir by means of Sugar Lake Dam is controlled by the seasonal installation (fall) and removal (summer) of spillway flashboards and low level outlet gates. It takes approximately six hours for water to travel from Sugar Lake Dam to Wilsey Dam (Sigma 1993a). The Water Use Plan prescribed a 5 cubic metre per second (cms) minimum flow requirement at Sugar lake Dam (BC Hydro 2005). Detailed ramping rates at Sugar Lake Dam for the protection of fish are shown in Table 1.

Table 1. Sugar Lake Dam Ramping Rates for discharge below the dam relative to fish life stages. Table reprinted with permission from BC Hydro (BC Hydro 2005).

Maximum Ramping Rates ¹		Down Ramp (cm/hr)		Up Ramp (cm/hr)	Daily Change (cm)	
Period	Life Stage	Day	Night	Day/Night	Down	Up
1 April – 31 July	Emergence	2.5	2.5	5.0	15	15
1 August – 30 September	Rearing	2.5	5.0	5.0	15	15
1 October – 31 March	Over Winter	0	5.0	5.0	15	25% $Q_{DDS(t-1)}$ ²

1 Rate determination based on gate discharge curves, reservoir level, and planned gate position changes. Actual downstream changes may be ± 50 per cent the planning criteria.

2 25% $Q_{DDS(t-1)}$ is 25 per cent of the previous day's discharge from Sugar Dam.

1.4.2.2 Wilsey Dam and Shuswap Falls Generating Station

Wilsey Dam is a concrete dam, 30 m high and 43 m long (Heidstra 2005; Stewart 2005). Figure 8 depicts the configuration of the dam project. The concrete dam was placed in the footprint of the historic Shuswap Falls within the original river alignment. Bedrock river-right of Wilsey Dam was blasted to create a spillway channel. The spillway bifurcates in the bedrock into the main spillway and an overflow saddle spillway where the spillway bends 90° and discharges water into the historic channel. The spillway elevates the headpond 1.2 m and flashboards installed in the fall (removed before spring) increase the headpond a further 0.9 m to 2.1 m (Heidstra 2005; Stewart 2005).



Figure 8. View west towards the Wilsey Dam hydroelectric project; major components identified (June 2009). Photo credit: BC Hydro Photogrammetry Department.

Wilsey Dam impounds a 7-hectare headpond, approximately 0.3 km long by a maximum width of approximately 0.2 km (Margolis 1988; Bengeyfield et al. 2001). There is an approximately 2 km backwater effect upstream into a bedrock canyon (Bengeyfield et al. 2001). The original headpond drawdown was 8 m. The current drawdown ranges from 3 m near the intakes to less than a meter throughout the remainder of the headpond, at low water. A large gravel bar is present in the headpond separating the gravel bedded channel thalweg from the sand-bedded headpond eddy. A new gravel bar observed in 2012 has formed since 2009 between the headpond and canyon indicating continued upstream sediment aggradation in the backwater channel.

Two penstocks, one steel and one wood, convey water to the generating station approximately 0.17 km downstream of Wilsey Dam. Licensed water diversion into the penstocks for power production is 31 cms (Sigma 1993a; Bengeyfield et al. 2001). The Water Use Plan prescribed a minimum flow requirement at Wilsey Dam of 16 cms (August 15 to December 31) and 13 cms (January 1 to August 14) (BC Hydro 2005) for the benefit of aquatic life, specifically spawning fish. Retrofitted onto the steel penstock for Unit 2 is an emergency hydraulically controlled bypass valve, a mechanism that allows BC Hydro to achieve minimum flow requirements during unplanned station outages (e.g., a turbine failure or downed powerline). The environmental operating guidelines for ramping rates and minimum flow requirements became conditions of the provincial Water License (No. 120949) in 2005 (BC Hydro, 2005).

1.5 SEDIMENT, DAMS AND SALMON

1.5.1 Sediment

Sediment transport is a critical component of river ecology. Transported sediment forms complex substrate arrangements that define the ecological niches used by a river's unique aquatic communities. Stanford et al. (2005) describes the river as a Shifting Habitat Mosaic, an intricate arrangement of habitat patches used by aquatic species that are subject to numerous and constantly changing fluvial processes. These instream patches are influenced by flooding, cut and fill alluviation, sediment transport and deposition, the hyporheic interplay between surface water and groundwater (e.g., upwelling and downwelling), channel avulsion, entrainment and settling of wood debris, and the formation and destruction of fluvial forms (e.g., bars, wetlands, side channels, riparian vegetation) (Stanford et al. 2005). Quantifying the ecological consequences of shifts to habitat patches is challenging given the seemingly unlimited combinations of biological responses to changing physical conditions (Stanford et al. 2005). To understand how the interplay between physical and biological processes in a river occurs, one must first consider how morphologic changes to a river occur.

Important factors that initiate and facilitate sediment transport include, shear stress applied to the bed, particle collision, saltation, grain rotation, grain size (and density), grain shape, proportion hiding or exposed, level of bed armoring (pavement), grain organization (e.g., imbrication), mixture of grain size, presence and influence of frazil ice, channel slope, eddies between grains and flow rate (Lorang and Hauer 2003). There are four main modes of sediment transport within the river's water column. Contact load is where sediment particles move along the riverbed, not becoming suspended. Saltation load is where sediment particles move in a ballistic trajectory, where the particle is suspended briefly before falling back to the riverbed. Suspended load is where flow velocity is sufficient to transport particles in suspension within the water column. Wash load is the transportation of very fine sediment and does not generally represent a significant portion of transported sediment and is found near the water surface (Gordon et al. 2004).

1.5.1.1 *Downstream Fining*

In general, many gravel bedded rivers like the MSR exhibit a downstream fining trend, from boulder complexes near the mountainous headwaters to gravel bedded mid reaches to small gravel and sand bedded floodplains (Rice 1997). The primary causes of this downstream trend is abrasion and hydraulic sorting (Moussavi-Harami et al. 2004). Downstream fining trends are not always linear and often contain significant variation. One source of variation can be tributaries, where sediment loading and flow velocity can shift sediment texture and channel form downstream of the tributary confluence and its delta (Moussavi-Harami et al. 2004). Mean grain size is commonly used to assess longitudinal difference between morphological facies (Church and Kellerhals 1978; Luo et al. 2012).

Possible reasons for variation in the downstream fining trends include tributary discharge and sediment inputs, shifting channel bottoms, natural instream controls (e.g., log jams, boulders) stabilizing instream and riparian vegetation, bank erosion, non-alluvial sources (e.g., eroding soils from land disturbance), movement of bedload in waves, abrasion, biotic disturbances (e.g., female salmon redd excavation) mainstem hydraulic controls, and the presence of dams, diversion structures and other instream anthropogenic structures such as bridge pilings and abutments (Church and Kellerhals 1978; Rice 1997; Bunte and Abt 2001; Gottesfeld et

al. 2004; Musselman and Tarbox 2013; Moussavi-Harami et al. 2004). Church and Kellerhals (1978) warn that not all grain sizes move in unison and therefore it may be appropriate to examine narrower ranges of grains as was done in this research by examining a truncated GSD.

Methods for determining the downstream fining trend are discussed in Section 2.3 and 2.4. Results are presented in Section 3.2 and a discussion of results in Section 4.2.

1.5.1.2 Gravel Augmentation

Gravel augmentation is the process of adding gravel to a river. Commonly the aim is to restore the gravel bed characteristics and associated ecological productivity to pre-dam conditions (Bunte 2004). Repairing or enhancing salmon spawning and rearing habitat is a common driver for gravel augmentation projects. The degraded bed below dams is temporarily raised with an influx of gravel in a process referred to as “fill” and then subsequently transported with flushing flows in a process known as “scour” (Bunte 2004). The time scale of “fill and scour” gravel augmentation differs for longer-term channel aggradation and degradation processes that can occur over years and decades (Bunte 2004). Bunte and McDonald (1999) estimate that it takes on average one year to move spawning-sized gravel 100 m.

BC Hydro uses gravel augmentation periodically and in some instances, annually at a select number of hydroelectric facilities. At Walter Hardman Dam located near Revelstoke, B.C., BC Hydro places 5000 m³ of native river gravel from accumulations upstream of a diversion weir into a high-flow overflow channel into Lower Cranberry Creek, the historical river channel (BC Hydro 2006). Gravel is side-cast over the spillway and conveyed downstream using the river’s natural flushing flows. The Walter Hardman project aims to increase aquatic benefits in a modified flow regime reach by ensuring sufficient substrate suitable for the spawning needs of kokanee salmon (*O. nerka*) and rainbow trout (*O. mykiss*) (BC Hydro 2006).

On Vancouver Island, an important salmon spawning reach between BC Hydro's Comox Dam and a diversion dam results in the permanent loss of approximately 90,000 m² of spawning habitat in the Puntledge River (Silvestri 2007). In addition, the downstream reach has been subject to numerous large water spill events resulting in the loss of spawning-size gravel. A gravel augmentation project was undertaken to restore salmon spawning grounds and to increase historical low returns of summer chinook salmon (*O. tshawytscha*) and steelhead trout (i.e., anadromous rainbow trout) (Silvestri 2007). Average summer chinook returns at the time had dropped from 3,000 to 600 (Silvestri 2007).

Elk Falls Canyon (ELK) occurs in the Campbell River on Vancouver Island below John Heart Reservoir, impounded by John Heart Dam (BC Hydro owned and operated). In July 2008, approximately 90 m³ of washed spawning-sized gravel was placed into the canyon by helicopter (Pellett 2009). The objective of the project was to create spawning habitat previously lost to erosion during dam water spill events in the absence of a replenishing upstream gravel source. Previous gravel augmentation projects on the ELK have occurred in 1999, 2002, 2004 and 2005 (Pellett 2009).

Run of the river projects (i.e., that have limited upstream water storage) such as Wilsey Dam, that do not significantly attenuate the flow regime, can trap sediment upstream of the dam (Bunte, 2004). Trapped gravels unable to travel downstream contribute to downstream channel degradation by not replenishing the degrading reach with sediment now accumulated upstream. The reach below Wilsey Dam is important to spawning salmon because it is at present the upstream terminus of spawning grounds on the MSR. Spawning salmon who enter the canyon reach below Wilsey Dam commonly drop back into the upper extent of the spawning reach immediately upstream of and adjacent to the Shuswap River Hatchery (SRH). Therefore, gravel replenishment and retention is important for sustained use of this spawning reach.

Small sediment grains conveyed past a dam may contribute to river bed breakup, where saltating particles crashing into larger particle grains help to maintain riverbed mobility and sediment equilibrium (Lorang and Hauer 2003). A mobile bed ensures that all clast sizes can

be mobilized within the forces available (e.g., gravity slope forces, tangential shear force, bank-full excess shear stress, collision of saltating particles). In the absence of fine-grain induced bed mobility, larger grains may become immobile, more difficult to entrain, and/or become armored (Gomez 1983). As the riverbed coarsens in the absence of fine-grained sediment, the ability for bankfull shear stress to reach critical entrainment levels of available sediment is reduced. When considering the downstream reintroduction of fine-grained material and larger gravel, one must consider the additional momentum exchange between saltating particles that may not be considered in conventional sediment transport models as spawning-size gravels could be removed from the spawning reach without a suitable upstream source replenishing gravels. As a result, the existing volume of spawning gravel may be reduced and the overall maximum grain size (D_{\max}) may further increase.

1.5.2 Dams

1.5.2.1 Overview

Hydroelectric dams provide substantial benefits to society. Benefits include inexpensive and instantaneous power generation, low power rates for users (e.g., public and industry), a renewable resource, flood mitigation, year-round water for agriculture, and government revenue (Vancouver Sun 2015; BC Ministry of Energy and Mines 2016). However, dams are not without their disadvantages, including both environmental and social impacts.

Social challenges include, but are not limited to, the displacement of people and their communities and the loss of farm land, an especially significant challenge for large reservoirs. For construction of the Three Gorges Dam in China, 1.13 million people were relocated and the resulting farmland loss totaled 62,000 acres (Jackson and Sleigh 2000; Biggs 2001). In British Columbia, approximately 2,000 people were relocated from the floodplains of the Columbia River to make way for Arrow Lakes Reservoir, impounded by Hugh Keenleyside Dam (Wilson 1973). J. W. Wilson writes extensively about the resettlement effort on Arrow Lakes, for which he was directly involved, in his 1973 book, *People in the Way: The Human Aspects of the Columbia River Project* (University of

Toronto Press). Resettlement as described by Wilson included the movement of cemeteries, resettlement of homesteaders to new modern town-sites, the loss of farmland, and the distrust, anguish and upheaval of all lives involved, from company representatives, to most significantly, the people whose land was lost.

Although dams are conceived of as having long functional lifespans, upstream sediment accumulation can create “intergenerational potential-loss from accelerated reservoir siltation” (Wild et al. 2015), meaning in some cases, future generations inherit a socio-economic-environmental challenge that must be considered by early generations against the “short-term” potential of inexpensive power. The environmental impacts of dams are well studied. In British Columbia between 2004 and 2014, approximately \$25 million was spent per year by BC Hydro studying environmental and social impacts of hydroelectric operations (Hill and Graham 2004).

Environmental impacts of dams include an altered flow regime (i.e., the timing of water released from the dam does not satisfy the needs of all biota dependent on the river before dam emplacement), interruption of sediment transport processes (e.g., reservoir aggradation and downstream channel degradation), prevention of fish migration (Jakeman et al. 1999; Hanrahan, Dauble, and Geist 2004), loss of biodiversity, soil erosion, reduced littoral productivity and fragmentation reducing aquatic and terrestrial habitat connectivity (Mapes 2016).

1.5.2.2 Dams & Sediment

Dam emplacement alters a river’s natural flow and sediment transport regimes, creating upstream and downstream impacts. Dam emplacement creates an area of calmer waters upstream, where suspended sediment goes from a transport state to a settling state (Julien 2010). Bedload is often entirely trapped upstream where the dam reservoir acts as a sediment sink (Julien 2010). Without a mechanism for sluicing accumulated sediment downstream, and a proven operating scheme for its use, sediment will gradually aggrade until most of the backwaters are in-filled (Williams and Wolman 1984; Julien 2010).

Sediment aggradation and insufficient conveyance of sediment is problematic in many dammed rivers throughout the world. Lake Powell, impounded by Glen Canyon Dam in Arizona 1966, saw a 90-95% downstream sediment reduction post-dam construction between 1983 and 1986 (LaGory et al. 1992). In the Rhine River which originates in Switzerland, approximately 170,000 tones of gravel was added downstream of the Iffezheim Dam annually to prevent channel incision (Kondolf 1995).

In China, two years after construction of the Three Gorges Dam in 2005, the Yangtze River conveyed only half the volume of sediment when compared to 2002, a loss attributed to emplacement of the dam (Xu et al. 2006). A World Bank study from 1987 found that 50 cubic kilometers (km^3) of sediment is trapped behind the world's dams every year. In addition, the same study found that by 1986, one fifth of the global storage capacity of reservoirs had been consumed by 1100 km^3 of sediment (Mahmood 1987).

Downstream of dams, flow velocities can be attenuated or their timing altered, gravel can be depleted by high flushing flows (spills), and a lessened volume of historical sediment loading from upstream can degrade, armour, and incise the channel and modify the rate at which lateral movement of the channel occurs (Kondolf 1995; Warrick et al. 2015). The occurrence of upstream channel aggradation and downstream channel degradation resulting from dam emplacement is well documented (Williams and Wolman 1984; Ligon et al. 1995; Kondolf 1995; Schmidt and Wilcock 2008; Pellett 2009).

Williams and Wolman (1984) studied 1,817 cross-sections downstream of 21 dams and found that that dams can trapped up to 99% of sediments. Sediment aggradation in reservoirs prevents a resupply of sediment, essentially cutting off the natural sediment supply to the downstream reach. Kondolf (1995) described water flowing past the dam as “sediment starved.” The channels immediately downstream of dams degraded on average 0.1 to 1.0 m/yr. for the first 5 to 10 years, after which rates of degradation slowed. Range of degradation at all sites was from 1 m to 7.5 m (Williams and Wolman 1984). In general, channel degradation was most severe immediately downstream of the dam, lessening further downstream; however, there were sites where degradation appeared much further

downstream near 1300 km (Williams and Wolman 1984). The geomorphic consequence of dam-induced downstream channel degradation were noted to be reduced sediment transport because of flatter gradients, undermining of instream structures and decreased capacity to transport tributary sediment contributions (Williams and Wolman 1984).

The downstream distance required to achieve a pre-dam sediment transport regime varies. For Canton Dam on the North Canadian River and the Gavins Point Dam on the Missouri River (Nebraska / South Dakota boarder), downstream channel naturalization were estimated to be 200 to 500 km and 1300 km downstream, respectively before natural conditions not influence by dams were observed (Williams and Wolman 1984).

Sediment sluiced during low flows through improper management of the low level outlets resulted in massive fish kills at the Los Padres Dam in 1980 (Kondolf 1995). This resulted in the dam owners moving to a dredging program similar to what is done at Wilsey Dam (Kondolf 1995). In California at the time of publication, Kondolf (1995) noted that the Department of Fish and Game had become wary of sediment conveyance schemes after the improper use of the conveyance mechanisms. Apprehension to sediment reintroduction comes from those who feel that reintroduced sediment can only be released in a deleterious way compared with those who believe that when done correctly, sediment reintroduction is important process in restoring the river's natural sediment transport process. Kondolf (1995) noted that in 1986 one scientific branch of government called a sand and gravel release deleterious whereas another scientific branch described the net benefit of the project. To ensure proper implementation of a sediment reintroduction scheme, the management plan must outline site-specific requirements and be designed in cooperation with environmental regulators.

Operators of new dams in the Pacific Northwest are required to open their sluice gates or lower their diversion weirs on an annual basis during high flows (Fuller et al. 2016). Operators also clean out their headponds when they become full by using excavators to remove sediment from the headpond and placing the material below the intake or diversion structure for passive transport (email. B. Naito, DFO to G. Shearing, Feb. 28, 2013).

1.5.2.1 Aberfeldie Dam Case Study

This case study presents an example of a sediment release trial with promising results. The dam is Aberfeldie Dam, a 25 MW hydroelectric dam on the Bull River, owned and operated by BC Hydro. The Aberfeldie headpond is approximately 130 m wide and 900 m long (Langford et al. 2012). Northwest Hydraulic Consultants (NHC) estimated that the total Aberfeldie headpond volume had been reduced from 1.47 million m³ to 510,000 m³ as a result of accumulated sediment (NHC 1998, 1999). The headpond is now approximately 70% full of sediment with wetted depths of 0.3 to 1.5 m at low water (Langford et al. 2012).

Headpond substrate is comprised predominately of silt to silty-sand sediment sizes (Langford et al. 2012). The median grain size of sediment (D_{50}) in the headpond is 0.5 millimetres (mm) (range 0.1 to 1.5 mm) according to NHC (2005) and 0.0013 mm according to Langford et al. (2012). The difference in D_{50} may be attributed to sample location; Langford et al. (2012) sampled from the shore and anticipated larger grains towards the centre of the main channel whereas NHC sampled from a mid-channel bar at low flow. The wide range of particle sizes in the headpond were said to result in increased bed armouring, making the current headpond riverbed less likely to erode under conventional critical shear forces and possibly reducing erosion on lower bed layers (Langford et al. 2012).

Sediment was dredged in 2014 and 2015 using a 75-horsepower suction dredge. Dredgeate was reintroduced over the spillway into the Bull River downstream of the dam (Figure 9). During active dredging, increased suspended sediment was observed only down the length of the spillway; however, once downstream of the spillway, the contribution of the reintroduced sediment was not discernable from background water clarity.

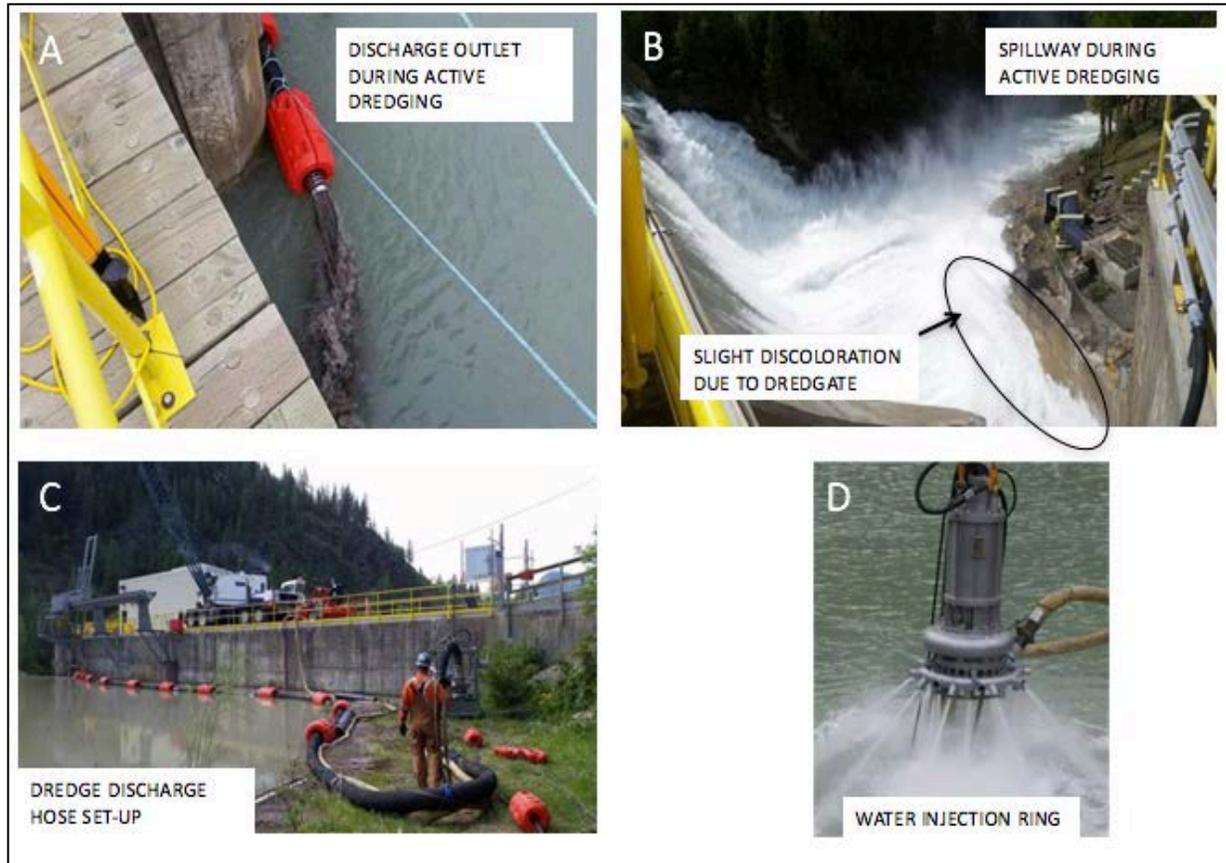


Figure 9. Photographs of BC Hydro suction dredging project at Aberfeldie Dam on the Bull River, B.C. A. Dredgeate being released into the spillway during freshet. B. Dredgeate mixing in spillway flows. C. Configuration of the suction dredge system. D. Photograph of 75 HP suction dredge pump and water injection ring used to increase dredge rate efficiency. Photo credit: G. Shearing, 2014.

The project was timed to make use of sufficient flushing flows capable of entraining and transporting sediment (i.e., > 100 cms). Water discharge rates taken during the project were from the Water Survey of Canada website for station 08NG002: “Bull River near Wardner, B.C.” Flows ranged from 106 to 130 cms with a mean discharge over the project duration of 118 cms.

Turbidity in the Bull River during active dredging at Aberfeldie Dam remained within 12 Nephelometric Turbidity Units (NTU) of the background and in some instances, the background sample site recorded higher turbidity than downstream sites, suggesting highly variable sediment transport pulses (Figure 10). In general, all three monitoring stations (i.e., US1 400 m upstream of the dam and DS2 and DS3, 1.3 km and 8 km downstream of Aberfeldie Dam, respectively) maintained a similar trajectory of turbidity measurements,

suggesting that sediment in suspension moved equally in transported volume from upstream to downstream with little deposition.

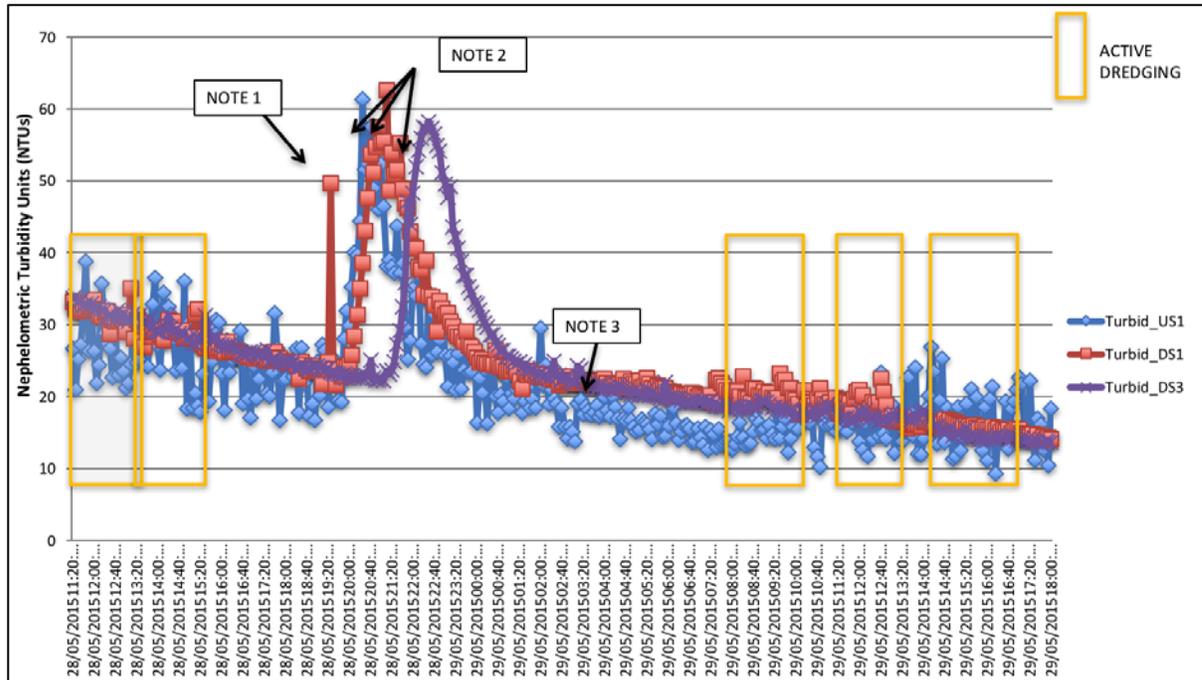


Figure 10. Turbidity data (in NTU) from May 28 at 11:20 hours to May 29 at 18:00 hours for dredging operations at Aberfeldie Dam, Bull River, British Columbia. Yellow rectangles show periods of active dredging. US1 is located 200 m upstream of the dam (control), DS1 is located 400 m downstream of the PH below the sediment release and DS3 is located 1.5 km upstream of the Bull River confluence with the Kootenay River. Note 1: Unexplainable downstream spike in turbidity 3 hours and 20 minutes after dredging stopped for the day May 28. Note 2: A sequential turbidity peak from upstream to downstream sites during a turbidity spike in-between active dredging. Note 3: Downstream turbidity 5 to 12 NTU greater than upstream control site.

This ABN case study suggests that aggraded headpond sediment can be reintroduced to similar rivers during high spring flows. Sediment released was within a range of turbidity that occurs naturally during freshet and appears to travel downstream with other transported sediment. This preliminary study suggests that sediment reintroduced to high receiving flows is likely not deleterious to aquatic life.

1.5.2.3 Sediment Mitigation Engineering

Numerous engineering solutions have been developed to help prevent accumulation of sediment behind dams. Solutions are generally engineered to target one of the following three causes of sediment disruption developed by Wild et al. (2015):

1. minimizing sediment inflow through catchment management (e.g., limiting deforestation and loss of riparian habitat);
2. preventing inflowing sediment from settling by hydraulically routing sediment beyond the reservoir (e.g., open low level gates (e.g., Elko Dam on the Elk River, B.C.); and,
3. Removing sediment after it has settled (e.g., dredging, sluicing).

Recent innovations in dam technology and construction help to reduce impacts to both rivers and usefulness of the dam. Inflatable dams have existed since the 1950s but are gaining popularity and being supplied by manufacturers such as Dyrhoff UK Ltd., OnSite Central Ltd. Obermeyer Hydro, Inc. and Hydrotech Engineering LLC. These dams can be inflated to impound water and deflated to allow sediment and other debris to travel past the dam. For some new run-of-the-river dams in British Columbia, it is a requirement that accumulated headpond sediment be reintroduced downstream annually (e.g., Upper Mamquam Dam near Squamish, British Columbia, operated by TransAlta) (email comm. B. Naito to G. Shearing, February 28, 2013).

1.5.2.4 Dam removal

Dam removal has seen renewed interest over the past five years, especially in the United States, after the recent removal of the Elwha and Glines Canyon dams on the Elwha River and the Condit Dam on the White Salmon River. Accompanied with rigorous scientific study, the removal of these three dams presented unique opportunities to manage and observe the fate of sediment aggraded behind each dam (PacifiCorp 2011; Randle et al. 2015; Brew et al. 2015; Warrick et al. 2015).

During removal of the Condit Dam in Washington State in 2011, approximately 1.8 million m³ of sediment was sluiced to the river downstream, most over a 6-hour period (note: headpond sediment continues to migrate downstream) (PacifiCorp 2011; Warrick et al. 2015). Although significantly more sediment was reintroduced to the receiving environment

than the downstream reach had capacity for (e.g., resulting in a temporary rise in riverbed elevation of up to 2 m), most of the sediment was silt and fine sand that travelled as suspended load (PacifiCorp 2011). Sediment that moved as bedload or settled was removed over time under natural flood conditions (personal communication Dr. Andrew Wilcox, University of Montana researcher studying Condit Dam removal, March, 2014). For Condit Dam removal, the United States National Marine Fisheries Service concluded in a biological opinion that removal of the dam and resulting sediment flush would not “jeopardize the continued existence of salmon and steelhead or adversely modify designated critical habitat [in the White Salmon River]” (PacifiCorp 2011).

Sediment behind the Elwha and Glines Canyon dams was stabilized during a slow drawdown, a 4-year dam removal process preventing headpond sediment from being conveyed downstream instantaneously (Warrick et al. 2015). Of the sediment released to the river, approximately 90% of the 10.5 megatons of sediment was conveyed to the Elwha River delta within the Strait of Juan de Fuca in years one and two (Warrick et al. 2015). This resulted in the river mouth expanding by 3.5 million tons of sediment (Warrick et al. 2015). An effort was made during these dam removal projects to stabilize sediment in the reservoir and revegetate the banks, helping to slow rates of sediment erosion and transport from accumulated reservoir sediment.

1.5.2.5 Role of Dams in a Changing Climate

Within an ecological context, dams are often thought of solely in terms of disrupting natural flow regimes by establishing regulated and managed flow systems (Poff et al. 1997). For salmon and trout, climate change may result in warmer water temperatures and less available water (Groves et al. 2008; Null et al. 2013; van Vliet et al. 2013). Dams with upstream water storage have the ability to release cooler water during dry and water depleted summer months. Null et al. (2013) observed that longitudinal temperature profiles in streams downstream of dams can be cooled by dam releases. This water is often derived from deeper cooler water in the reservoir. Null et al. (2013) also suggests that reservoirs might be considered a mitigating tool for offsetting warmer summer waters through cold water releases but cautions that for unregulated river sections downstream of the influence of the

dam, the presence of warmer waters may be less impacted by cooler reservoir waters and therefore still pose challenges to fish. Van Vilet et al. (2013) note that one unknown is how well fish will adapt to streamflow and water temperature changes, which would determine the need for the mitigating effects with reservoir released flows.

1.5.3 Salmon Spawning

Salmon spawning habitats are complex arrangements of biotic and abiotic components interacting on multiple temporal and spatial scales. Describing these complex arrangements in the context of fluvial geomorphology is the focus of interest in the emerging field of habitat geomorphology (Lapointe 2012). This field of science studies the interplay between the physical processes that influence biotic processes (e.g., regulated flows from dams altering downstream fish habitats) as well as the ecological processes that influence the physical state of the river (e.g., sediment transport caused by salmon redd excavation). In a rock tracing experiment, researchers found that salmon through redd excavation could move grains 150 m downstream and up to 180 mm deep and concluded that salmon could have an important influence on sediment transport dynamics in the reaches in which they spawn (Gottesfeld et al. 2004). Salmon excavating redds have also been found to decrease algae and invertebrate densities, concentrations of fine sediment around the nest and increase fine accumulation outside of nests, impacts considered profound to the spawning reach (Moore and Schindler 2008).

The relationship between the biological needs of spawning salmon and the physical characteristics of the habitat is contextual and complex (Lapointe 2012). Even physical habitat requirements within populations can vary (Lapointe 2012). Salmon are extremely adaptable when selecting spawning sites and may select marginal habitat if required (personal communication R. Bailey, Fisheries and Oceans Canada). Proceeding are examples from other studies that have observed “non-textural determinants of [redd] site selection” that may lead salmon to select one site over another (Lapointe 2012). Table 2 summarizes the traditional and emerging factors that are thought to influence spawning site selection.

Table 2. Traditional and emerging factors that influence the selection of salmon spawning sites. Table adapted from Geist and Dauble (1998), Moir and Pasternack (2010) and Lapointe (2012)

Traditional Factors	Emerging Factors
Substrate Size	Longitudinal and transverse bed slope
Water Velocity	Channel morphology (channel pattern, channel islands, bedforms and lateral activity)
Water Depth	Hyporheic water temperature, dissolved oxygen, pH and conductivity
	Use of previously prepared spawning grounds where gravel is less embedded
	Preference of salmon to spawn below lakes as opposed to river systems above lakes
	Near-bed velocity gradient
	Vertical hydraulic gradient (upwelling and downwelling)
	Substrate depth, stability, permeability, and porosity
	Hydraulic conductivity and transmissivity
	Presence or absence of natural bedforms (e.g., dunes and/or riffles) and their type, shape, amplitude, frequency, etc.
	Rate of bedform migration
	Presence of groundwater springs
	Proximity to good rearing habitat
	Avoidance of gravel with high fine content near eroding banks or of loose gravel in the channel thalweg leading to egg pocket scour.
	Selection of riffles could be attributed to channel constrictions that force well-oxygenated water into the hyporheic zone providing a good source of dissolved oxygen for incubating embryos

In 2010, Moir and Pasternack published research that found that although similar habitat types were available, chinook tended to cluster their redds in certain morphological units (e.g., riffles, riffle entrances and lateral bars) with moderately high velocity (median 0.45 ms¹) and shallow depth (< 0.6 m). They also found that substrate preference is not independent of preference for suitable flow velocities (Moir and Pasternack 2010).

1.5.3.1 Salmon in the Middle Shuswap

Four species of anadromous fish spawn below Wilsey Dam: chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), sockeye salmon (*O. nerka*), and pink salmon (*O. gorbuscha*) (Ministry of Environment 2014). A single record of anadromous dolly varden (*Salvelinus malma*) exists in the Fisheries Information Summary System database from 1984 (Ministry of Environment 2014). Fluvial sport fish species from the Salmonidae family include kokanee salmon (*O. nerka*), rainbow trout (*O. mykiss*) and cutthroat trout (*O. clarkii clarkii*) (Environment 2014). Other sport fish species include mountain whitefish (*Prosopium*

williamsoni), lake trout (*S. namaycush*), and bull trout (*S. confluentus*) (BC Ministry of Environment 2014). Note that this fish assemblage is typical of moderate to large streams across Southern B.C.

Non-sport fish species in the MSR include redbside shiner (*Richardsonius balteatus*), northern pike minnow (*Ptychocheilus oregonensis*), bridgelip sucker (*Catostomus columbianus*), largescale sucker (*C. macrocheilus*), longnose dace (*Rhinichthys cataractae*), peamouth chub (*Mylocheilus caurinus*), prickly sculpin (*Cottus asper*) and slimy sculpin (*Cottus cognatus*) (BC Ministry of Environment 2014).

Prior to construction of Wilsey Dam, chinook and possibly sockeye were known to ascend and spawn above Shuswap Falls, a somewhat gradual step-pool falls with gradients that were not too steep for salmon (French 1995; Bengueyfield et al. 2001). In addition, anecdotal evidence suggests that chinook may have been found in Sugar Lake above Brenda Falls (i.e., the current location of Sugar Lake Dam) (French 1995). Pre-dam conditions for access would have facilitated a greater distribution of spawning salmon throughout the MSR watershed.

A fish ladder was included in initial development plans for a dam at Shuswap Falls (French 1995). However, in 1913, the Chief Fisheries Inspector concluded a fish ladder at such a tall dam (30 m) was too technically challenging and expensive, and would result in undue hardship for the proponent, especially in the absence of a commercial or sport fishery and abundant salmon returns (French 1995). This conclusion did not account for the importance of the run to local Indigenous people. Ultimately, in the 1928 / 1929 Annual Report, the Canadian Fisheries Branch recommended against a fish ladder at Wilsey Dam (Bengueyfield et al. 2001). As such, 1928 was the last year salmon were able to access the MSR above Shuswap Falls (Hirst 1991).

Trials of transplanting chinook above Wilsey Dam occurred in 1977, 1978, 1993 and 1995 (Fee and Jong 1984; Triton 1995; BCRP 2003). Trials in 1977 and 1993 specifically saw a good number of transplanted chinook successfully spawn and rear above Wilsey Dam (Fee and Jong 1984; BCRP 2003). Surveys for salmon post-transplant found that juvenile chinook

reared between Wilsey Dam and the Chute (i.e., 3 km upstream of Wilsey Dam), upstream of the Chute to near the Cherry Creek confluence and into the lower section of Ferry Creek upstream of the confluence (Triton 1995; Griffith 1979). The hope was that out-migrating fish would not experience mortality from turbine entrainment and would be successful in their journey to ocean. In 1998, DFO recommended continued trials of transplanting salmon above Wilsey Dam (DFO 1998). In 2012, a soft-hatchery (i.e., in-situ incubation) above Wilsey Dam was proposed but was unsuccessful in acquiring funding (personal communication James Pepper, Okanagan Nation Alliance, 2012).

Bengeyfield et al. (2001) noted that by 1985, MSR chinook escapement had dropped to 500 fish per year. To mitigate weak returns, a land based salmon hatchery was started just downstream of Wilsey Dam in 1984 on a trial basis (Lister 1990). Between 1985 and 1986, DFO constructed the Shuswap River Hatchery (SRH) which remains in operation (Bengeyfield et al. 2001). The SRH rears chinook and coho. In general, annual returns of chinook comprise 80 to 90% hatchery fish and 10 to 20% wild stock (personal communication S. & L. Wolski, Shuswap River Hatchery, September 2011). Post-hatchery escapement for chinook was 4000 and 5000 in 1990 and 1991, respectively, up from 1500 in 1989, a success attributed to hatchery supplied stock (Triton 1995). Overall returns to the MSR have decreased in recent years (see Sections 1.5.3.2 and 1.5.3.3). Table 3 shows the general spawning life-cycle of MSR salmon.

Table 3. Arrival and spawning times of four salmon species that spawn in the Middle Shuswap River downstream of Wilsey Dam (Sigma 1993a).

Species	Arrive	Start	Peak	End
chinook	1 Aug	15 Sept	25 Sept	7 Oct
sockeye	1 Sept	Late Sept	15-20 Oct	1 Nov
coho	unknown	15-30 Oct	5-15 Nov	1-15 Dec
kokanee	15 Sept	mid Sept	5-6 Oct	late Oct

Mountain whitefish (*Prosopium williamsoni*) compete with rearing salmon for food and are also believed to be a major predator on salmon eggs in the MSR (personal communication S. Wolski, June 2012). A significant mountain whitefish population was observed above Wilsey Dam in 1995 (Triton 1995). Mountain whitefish populations below Wilsey Dam are also

considered significant (personal communication S. Wolski, Shuswap River Hatchery Manager). Research assessing the interaction of mountain whitefish and salmon has not yet been undertaken; however, such research would provide insights into the degree to which the current mountain whitefish population negatively impacts the freshwater life-stages and populations of anadromous salmon.

A Fish and Wildlife Compensation Program report on MSR salmon stocks suggests there are limited options for pink and sockeye habitat restoration (FWCP 2011b). Pink do not return in great numbers and are not managed to the same degree as coho and chinook. Further, sockeye are known to have the greatest ability of all salmon to adapt to different spawning conditions (Burgner 1991). Therefore, this research assumes that spawning habitat identified as suitable for coho and chinook salmon is also suitable for sockeye and pink salmon. Coho and chinook have different spawning methods and fluvial requirements, described below in detail. Carrying capacity models done by Triton (1995) suggest the MSR is capable of handling significantly more 0+ and 1+ Chinook and rainbow trout above Wilsey Dam (Triton 1995).

1.5.3.2 Interior Fraser Coho in the Middle Shuswap River

Interior Fraser River Coho entering the Thompson River basin have a lower homing fidelity than most salmon (i.e., weak tendency to return to their natal stream) (IFCRT 2006). Unlike MSR chinook, attributing coho to a watershed population is difficult. This leads to weak genetic structure within watersheds (personal communication R. Bailey, DFO, 2012). Coho migrating up the Thompson River select system branches (e.g., Adams, Eagle or Shuswap rivers) depending on which option provides optimal routing conditions identified by the fish sooner in their migration than their natal stream confluences. Therefore, coho may not spawn in the river from which they emerged (personal communication R. Bailey, DFO, 2012). Low homing fidelity makes understanding the number of individuals and their trend within the population and genetic structure difficult.

MSR coho are considered part of the South Thompson sub-population (IFCRT 2006). Coho escapement to the MSR has generally increased from critically low returns observed in the mid 1990s. In 2002, Interior Fraser Coho were listed “Endangered” by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (Irvine 2002). Agriculture and land development were then seen as (and may still be considered) serious pressures significantly impacting the productive capacity of streams used by Shuswap River coho (IFCRT 2006).

DFO escapement estimates for MSR coho from 1975 to 2012 (provided by R. Bailey, DFO) are illustrated in Figure 11. Between 2002 and 2012, returns greater than 1000 were observed in 2004 and 2007. Since 2007, annual returns in three out of five years have been close to the 30-year average of 803 fish returning. Bengueyfield et al. (2001) recommended coho as a target species for reintroduction above Wilsey Dam.

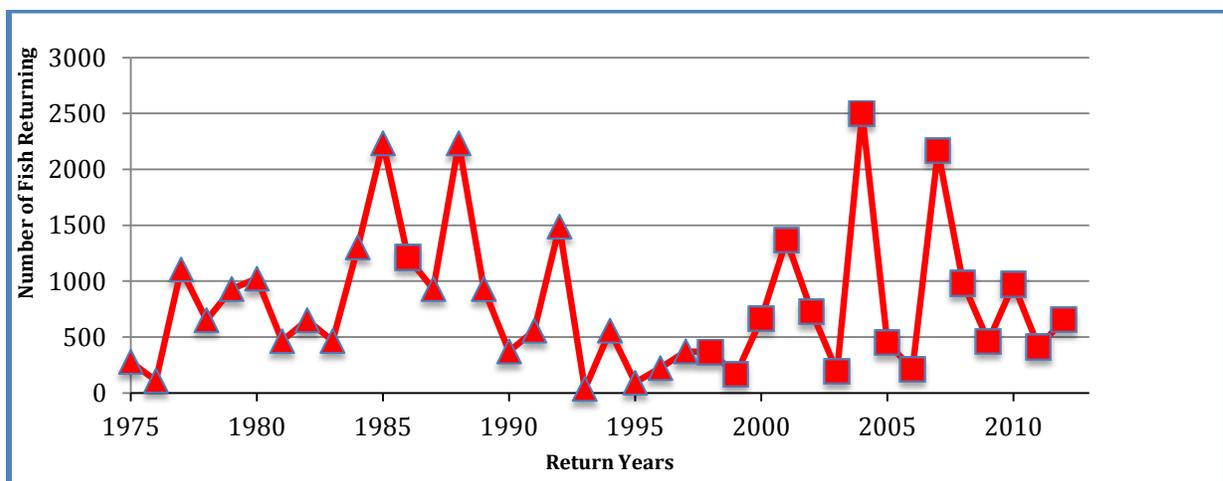


Figure 11. DFO escapement estimates using aerial surveys (red line) of coho salmon to Middle Shuswap River from 1975 to 2012. 1975 to 1997 surveys by Fisheries Officers (triangles). The red line presents aerial survey results from Fisheries Officers (triangle markers) between 1975 and 1997 and Scientific Branch staff (square markers) from 1998 to 2012. 1998 to 2012 surveys by Science Branch staff (squares). Data provided by R. Bailey, Fisheries and Oceans Canada.

Adult coho enter the MSR from mid-October to the end of November with spawning occurring late October to December in the river mainstem, side channels and Bessette, Harris and Duteau creeks (Fee and Jong 1984; Triton 1995; ARC 2001a). Spawning in the MSR occurs earlier than reported in general species descriptions by Sandercock (1991). Eggs are

eyed by late January and fry emerge in May (Triton 1994b). Coho generally return to spawn at 3 years of age (Irvine 2002).

Coho redd sites are generally selected by the suitability of gravel size (generally less than 150 mm) and flow velocity (Sandercock 1991). Water depth at redd sites is on average 300 mm and water is well oxygenated (McPhail 2007). However, coho will select sub-optimal habitat sites if optimal sites are at maximum capacity (personal communication R. Bailey).

For coho, the dominant male accompanies female in excavation, although not in equal effort. Eggs emerge 3 months after hatching; fecundity varies, with egg numbers between 1,724-6,906 in Alaska to 1,900-3,286 in Washington (Sandercock 1991). Coho eggs are the smallest salmon eggs, ranging between 4.9-8.4 mm (Sandercock 1991). Coho are the more elusive of the salmon species, making collection of field data more challenging (personal communication R. Bailey, 2012). MSR coho are known to rear in off-channel habitats with wood cover (ARC 2001a). Coho salmon have longer freshwater residency times than other salmon on average.

1.5.3.3 *Chinook in the Middle Shuswap River*

MSR Chinook are part of the Fraser River's South Thompson Age 0.3 Chinook Aggregate that includes the Middle and Lower Shuswap Rivers, Lower Adams River, Wap Creek, Little River, Seymour River, South Thompson Mainstem and Maria Slough (Pacific Salmon Commission 2004). MSR Chinook are included in the Thompson geographical region and South Thompson/Shuswap sub-region (DFO 2011).

Numerous studies of MSR chinook have provided insights into their region-specific spawning requirements (Griffith 1979; Fee and Jong 1984; Lister 1990; Sigma 1993a; Triton 1994b; Triton 1995; ARC 2001a; ARC 2001b; Guy and Uunila 2002; Bocking and Gaboury 2002). Study findings generally agree that chinook spawn as much as 9 km below Wilsey Dam, with most spawning occurring within the 3.5 km downstream of the dam (ARC 2001a; Guy and Uunila 2002; personal communication S. Wolski, Shuswap River Hatchery, 2012). Few redds are found downstream of the Bailey Bridge at Lawrence Road, 9 km downstream

of Wilsey Dam (Guy and Uunila 2002; ARC 2001a; personal communication S. Wolski, 2012). One hundred and five (105) redd locations were compiled and published by Guy and Uunila in 2002. Fifty-six (56) redds occurred 3.5 km downstream of Wilsey Dam and 50 redds occurred within a further 5.3 km downstream to the Bailey Bridge (Triton 1994a). Only five redds were found from the Bailey Bridge 15 km downstream to Mable Lake (Triton 1994b; Guy and Uunila 2002). Substrate and flow velocities in the MSR floodplain 15 to 18 km upstream of Mable Lake are considered poorly suited to the requirements of spawning chinook as a result of a low gradient and sandy bottom channel bed characteristics (ARC 2001a; Minor 2007).

MSR chinook start entering the Fraser River system in July and commence spawning in mid to late September and finish by mid-October (Triton 1994b). Fry emerge in April; some migrate immediately downstream to Mable Lake whereas others use off-channel and side channel refuge for initial rearing. Most fry migrate into Mable Lake within approximately 60-90 days and leave Mable Lake approximately 90-150 days post emergence (Triton 1994b).

In 1993, MSR chinook were observed holding in deep pools up to 5 to 6 weeks prior to spawning (Triton 1994b). Holding pools and holes (small pools) are an important habitat component of chinook spawning habitat. A limited amount of holding pools above Wilsey Dam has been noted as a factor that may affect the successful spawning and rearing activities of reintroduced salmon (personal communication S. Wolski, Shuswap River Hatchery Manager 2011).

Triton (1994) found that MSR chinook redds average 1 to 2 m from redd crest to tailspin deposit. Griffith (1979) observed MSR chinook spawning in water depths of 0.6 to 1.0 m and flow velocities less than 0.15 metres per second (m/s) over fine substrate. Chinook eggs, which are considerably larger than the eggs of other salmon species, require significantly more intra-gravel dissolved oxygen flow than other salmon species (McPhail 2007). Water depth and velocity requirements for chinook are presented in Table 4.

Table 4. Tally of numerous studies on ocean-type Chinook spawning requirements for water depth and flow velocity. Modified from Table 2, p. 322 in Grout and Margolis (1991).

Source	Water Depth (mm)		Water Velocity (cm/s)	
	Range	Mean	Range	Mean
Briggs (1953)	280 - 410	320	30-76	-
Vronskiy (1972) & Collings et al. (1972)	300 - 450	-	30-68	-
Smith (1973)	-	389	18.6-80.5	49.7
Bovee (1978)	100 - 1200	300	10-100	40
Chapman et al. (1986)	to 7000	-	37-189	>100

Figure 12 presents escapement estimates of chinook returning to the MSR between 1975 and 2012. In general, aerial surveys and mark / recapture estimates between 2005 and 2012 were similar. In 2010, mark / recapture findings were greater than aerial surveys since numerous chinook that year spawned in Bessette Creek, just upstream of the confluence with the MSR and were not originally seen using aerial surveys (personal communication R. Bailey).

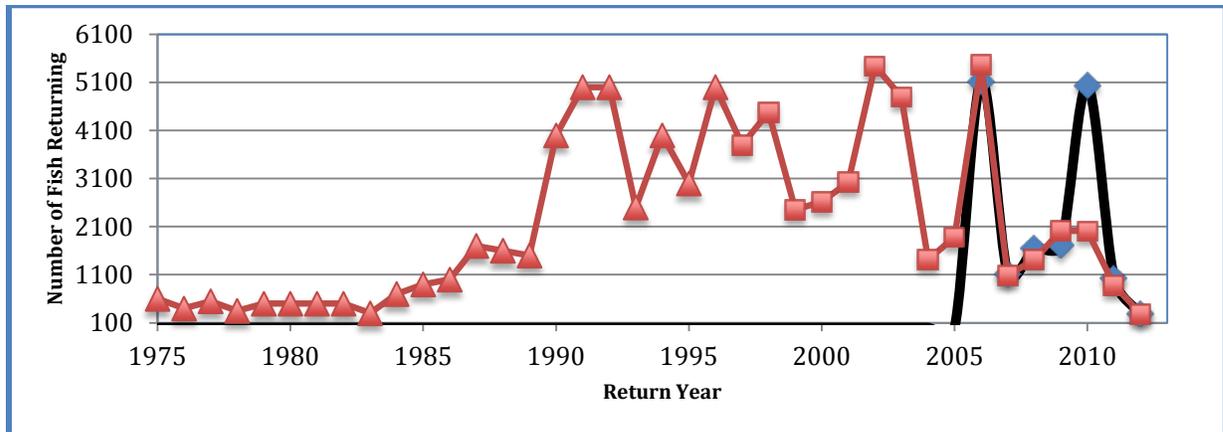


Figure 12. DFO escapement estimates using mark / recapture (black line) and aerial surveys (red line) of chinook salmon to Middle Shuswap River from 1975 to 2012. 1975 to 1997 surveys by Fisheries Officers (triangles). 1998 to 2012 surveys by Science Branch (squares). The red line presents aerial survey results from Fisheries Officers (triangle icon) between 1975 and 1997 and Scientific Branch staff (square icon) from 1998 to 2012. The black line presents mark recapture (M/R) estimates from program commencement in 2005 until 2012. Data provided by R. Bailey, Fisheries and Oceans Canada.

A significant decline in MSR chinook escapement occurred in 2012; only 236 chinook returned compared with the 30-year average return of 2,188 individuals. Many of the returning fish were hatchery brood, further indicating vulnerability of wild stocks. Ocean-

type chinook declines were observed throughout the Fraser River Basin in 2012 (personal communication R. Bailey, DFO, 2013).

Small numbers of returning chinook are likely the result of both natural and anthropogenic pressures. Natural pressures include the frequencies of climatic cycles, including El-Niño-Southern Oscillations (ENSOs) and Pacific Decadal Oscillations (PDOs) climatic occurrences that result in cyclical ocean temperature changes (personal communication R. Bailey DFO, April 2012). Other natural pressures include predation (e.g., eagles, trout), superimposition of redds resulting in egg mortality, insufficient food resources during rearing, and physical factors (e.g., rock slides, fine grain redd entombment, and egg pocket scour) (Lapointe 2012). Anthropogenic pressures include overfishing, pollution and habitat alteration, among others.

Two developmental types of chinook spawn in the MSR and Bessette Creek systems, 4₁ ocean-type (sub yearling) and 4₂ stream-type (yearling), respectively (DFO 2011; Burgner 1991). Although sympatric, stream-type and ocean-type chinook have coexisted with nominal genetic contributions to one another for 1,000 to 10,000 years, described by Waples (2001) as “effectively behaving as separate biological species.” The following sections describe the unique attributes of the two chinook types.

1.5.3.3.1 Ocean-Type Chinook

Approximately 95% of chinook returning to the MSR are 4₁ ocean-type and spawn in the river mainstem (ARC 2001b). MSR ocean-type chinook are also referred to as “Upriver Brights”, a genetic cousin of Columbia River Upriver Brights with similar life-histories. Upriver Brights were likely once a single population prior to Cordilleran ice sheet recession some 11,000 years ago (personal communication R. Bailey). Most ocean-types out-migrate three to five months after emergence, with most returning at age four although up to 35% return as jacks, 3 and 5 year olds (Triton 1994b; Pacific Salmon Commission 2004; DFO 2011). The majority of ocean-type chinook spawn in the river mainstem approximately 3.5 km downstream of Wilsey Dam (ARC 2001a).

MSR ocean-type chinook are assigned Conservation Unit (CU) number 15 (CU15). CU15 returns were forecast to be abundant in 2011, but have seen a decline since 2010, as shown in Figure 12 (DFO 2011). Ocean-type chinook are known to migrate along the continental shelf without migrating into the central Pacific Ocean and are therefore more susceptible to year-round fishing pressures, unlike coastal populations with central Pacific migration routes (Waples 2001).

1.5.3.3.2 Stream-Type Chinook

Stream-type chinook in the MSR system typically spawn in smaller streams, including Bessette Creek. Tributaries confluent with Bessette Creek, Duteau and Harris creeks, are used in years where flow is sufficient for migration into these streams (ARC 2001a). Stream-type chinook may also use the river mainstem to spawn (ARC 2001b). Unlike ocean-type chinook, stream-type juveniles overwinter and out-migrate after their first or second year. Stream-types are found to have large ocean-migrations and return to the river months before spawning occurs, generally in the late spring or summer (DFO 2011). Bessette Creek stream-type chinook are considered a conservation priority assigned Conservation Unit No. 16 (CU16). CU16 was identified a stock of concern in 2011 escapement forecasts (DFO 2011).

CHAPTER 2.0 METHODS

2.1 HYDROMETRIC DATA

The Water Survey of Canada (WSC) operates hydrometric station 08LC003 titled “Shuswap River Near Lumby” approximately 1.1 km downstream of the SFGS. Records of historical water discharge (in cms) and water elevation (in metres) beginning in 1911 are publically available from the WSC.

2.2 FIELD MEASUREMENTS

2.2.1 Underwater Automated Grain Sizing

Determining GSD in the MSR was done using a modified Automated Grain Sizing (AGS) method (Graham, Rice, and Reid 2005; Graham, Reid, and Rice 2005). Standard methods for AGS were modified to allow for sampling of submerged grains. Underwater sediment was digitally imaged using a high-quality, submersible digital camera. This is in contrast to conventional AGS in which dry grains are sampled, usually on gravel bars during low water (Graham et al. 2012). Sampling submerged grains was important for investigating grains in-situ where salmon are known to spawn. Digital grain samples were collected at 78 sites within the study area over two days in September 2012. Only results from 53 sites were considered valid (see Section 2.4 for more discussion) and used in analysis. Digital Gravelometer (DG) by Sedimetrics[®] was used for image processing and determining GSD.

Samples were collected from glide facies upstream of the riffle crest where salmon are known to spawn (Lapointe 2012). Photograph 3 depicts numerous salmon redds (tan-coloured circles) on the MSR below Wilsey Dam just downstream of Deer Pool (i.e., a deep pre-spawn holding pool).



Photograph 3. Salmon redds (tan-coloured circles) downstream of Deer Pool in the Middle Shuswap River, British Columbia (Triton 1995).

Because salmon excavate below the bed surface, the initial aim of the grain sampling was to sample sub-surface conditions. However, undertaking numerous bulk excavations required for detailed analysis of subsurface conditions was not feasible given field time and resource constraints. An emphasis was therefore placed on getting numerous GSD samples throughout the study area rather than a small number of surface/subsurface measurements. Bulk excavations tend to take upwards of one to two days and can include the excavation of metric tons of material (Bunte and Abt 2001). An attempt to sample fine sediment in the distribution using clay aerial sampling discussed by Hassan and Church (2000) was too significant a task for collecting and processing samples from 78 sites and beyond the time allocated to data collection.

In the absence of subsurface samples, an assumption was made that surface GSDs would equal subsurface GSDs. Kellerhals and Bray (1971) discuss the relationship between surface

and subsurface particles. Their voidless cube model suggests that in non-stratified and well sorted gravel beds, the distribution of grains can be considered similar (Kellerhals and Bray 1971). Although there was a combination of very-well sorted grains and less well sorted grains (stratification) in the MSR sample sites, the assumption was made that surface and subsurface distributions were similar and was applied to the sediment transport modeling exercise described in Section 2.9.

A 12-ft. pontoon boat (cataraft) was used to carry field personal and equipment, and to access sampling sites (Figure 13, Plate A). All samples were collected from sites with glide morphological facies (i.e., uniform flow and minor surface turbulence). Selection of glide facies was consistent with stratified site selection used by others (Buffington and Montgomery 1999; Rennie and Millar 2004). At each site, a six-metre-long collapsible steel ruler was laid perpendicular to the flow at randomly selected start locations (Figure 13, Plate B). Samples were collected on river-left or river-right, depending on the most accessible shore for docking the boat. The steel ruler was marked every metre for five metres with fluorescent orange paint; the one-metre space between markings ensured no overlap between photos. Thirty centimeter markings at one cm intervals were marked outward from the metre mark to provide scale to the photo taken. A handheld camera (Sony CyberShot TX10) was submerged immediately below the surface of the water and photos were taken every metre for 5 metres with the ruler placed at the top or bottom edge of the photo. A total of five photos were taken at each site. A handheld GPS was used to mark waypoints at the start and end of the ruler. Care was taken not to walk upstream of or stand on rocks in the sample area. A field assistant held a sun shield made from a 1 m² corrugated plastic sheet with a wood handle to block sun from the photos and prevent shadows (Figure 13, Plate C). The field lead took all photos to minimize sampling method uncertainty (Figure 13, Plate D).



Figure 13. Four steps used to collect photographs used underwater automated grain sizing. A. docking the boat. B. Laydown the steel ruler onto the riverbed. C. Field Assistant holding steel ruler using the sun shield to prevent shadows in AGS photos. D. Underwater photograph collected.

For this research, gravel photos from each glide are assumed to be representative of unsampled grains within the remainder of the glide of grain size range measured (Bunte and Abt 2001). This assumption was not rigorously tested, but it is not unreasonable to conclude that the methods provide an assessment of the gross trends in grain size in the downstream direction (Bunte and Abt 2001).

Each site with multiple images was treated as a unique sample with a distinct sample area and number of rocks counted. In general, a larger area was sampled in the presence of larger grains in upstream reaches, and smaller area sampled in the presence of smaller grains in downstream reaches. This was the result of water depth at which the camera could be submerged. In upstream sites, the channel width was narrower and deeper; in downstream

sites, the channel widened and became shallower. At some upstream sites, the area sampled was insufficient to adequately determine the number of very larger grains (e.g., boulders) present in the glide.

All methods for determining particle size distribution in wadeable, gravel-bedded rivers contain errors that depend on the skill of the surveyor, the accuracy of the measurement methods, and the capacity to sample a large enough number of rocks to yield reliable statistical representations of grain classifications within the GSD (Bunte and Abt 2001). Underwater AGS was selected over conventional methods for the following reasons:

- Rapid field data collection and therefore more sites sampled (78 sites in 2 days). Time required to sample each site averaged 5 to 10 minutes from landing the boat, determining the start location, photographing the transect, and re-launching the boat.
- Reduced bed destruction, especially when working in active spawning grounds.
- No need to transport heavy samples to the laboratory for size analysis.
- Less time wading in swiftwater making sampling safer.
- Easier pooling of samples (i.e., photos) for aggregate GSD analysis. For example, photo samples from areas where salmon spawn could be analyzed separately from the entire reach and later can be pooled to include the entire cross-section to determine bed roughness for modeling.
- AGS requires less training and experience than more traditional gravel bed sampling methods (e.g., pebble counts; clay-aerial sampling, bulk excavation); therefore, less opportunity for operator error.
- Spatial scale of grid counts is flexible. By changing the height of the camera one is able to evaluate sediment structure at the fine scale and at a larger scale (Bunte and Abt 2001).

There are a number of disadvantages to using the underwater AGS method when sampling submerged grains, including:

- Underwater sampling must be done at low water (in order to acquire the image safely and in clear water) but the water needs to be deep enough to submerge the camera below the water surface and capture a sufficient number of grains per photo area. A consistent depth below the water surface and above the riverbed relative to the size of the grains being measured is ideal but challenging to achieve.
- Light attenuation caused by taking photos underwater made grains slightly less distinctive in contrast, which is used by the software to separate grains.
- Use of a sampling quadrat (perforated polyvinyl-chloride pipe) was attempted but was found to be challenging to work with in flowing water. As such, a steel ruler was used to provide scale to each photo. This resulted in extensive time spent measuring and cropping images.
- Clear water, as is found on the MSR, is required to photograph underwater.

AGS can over predict the occurrence of angular, platy and bladed particles, and under predict the occurrence of particles partially hidden (Bunte and Abt 2001). Both errors tend to cancel each other when analyzing large streambed areas (Bunte and Abt 2001).

For this research, GSD attributes were explored using the Wentworth scale. Grains were processed using millimeters and the Psi scale, the inverse of the Phi scale. The Wentworth scale for converting mm and Phi sizes is provided for reference in Appendix 4.

2.3 DIGITAL GRAIN-SIZE ANALYSIS

Underwater AGS photos collected from the MSR were analyzed using Digital Gravelometer (DG) software by Sedimetrics[®]. DG is used to measure GSD from photographs. DG starts photo processing by first applying image colour transformations. Next grains are separated based on form and contrast and lastly grains are measured and counted. DG generates a suite of statistical outputs and grain sizes; the entire GSD was used for modeling and D_{50} examined for discussion (Overstreet 2012). The DG output option selected for sampling method was grid-by-number, an output option that produces similar results to a Wolman grid sample (Graham, Reid, and Rice 2005). Unlike a grid sample that selects only certain rocks

from the sample area, DG uses every grain in the photo (i.e., within truncation limits set by the user) making it easier to obtain a larger sample size from a smaller area (Sedimetrics 2013). The four general steps to determine GSD for Underwater AGS photos is shown in Figure 14. They include taking the underwater photo (Step 1), scaling and cropping the image (Step 2), applying necessary image modifications (Step 3) and processing the image using DG (Step 4). In Step 1, the photo is taken by lowering the waterproof camera right below the water surface and taking the photo directly above the area of interest. In Step 2, the scale in ImageJ is derived from the ruler and the remainder of the square is cropped based on the ruler side dimension. In Step 3, colour modifications in iPhoto © and ImageJ are applied to remove within grain colour differences. In Step 5 modified photos are upload to DG and run through the 8-step process in DG to produce a GSD.

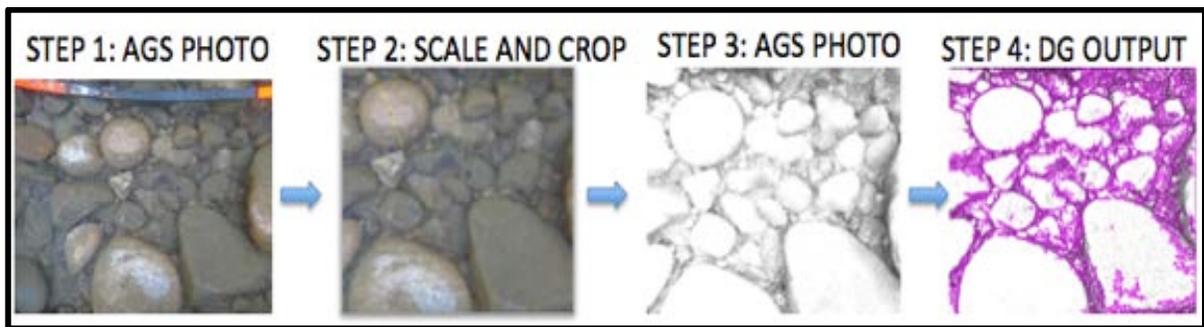


Figure 14. General steps required to collect, transform and process images for a modified Automated Grain Sizing method for images collected from the Middle Shuswap River, British Columbia. Step 1 is to take photograph in the field. Step 2 is to scale and crop the image. Step 3 is to apply filters to the photograph to remove within grain segmentation. Step 4 is to process the modified image using Digital Gravelometer by Sedimetrics. ©.

DG generally takes less time to process a sample site than conventional methods (e.g., laboratory or field sieving or measuring using a gravelometer). With ideal grain texture (i.e., one colour shade per grain) and contrast, processing the photos using DG to obtain a suite of statistical data can take 1-2 minutes (personal communication Dr. Marwan Hassan, September 6, 2012). However, with this project the overwhelming proportion of granite rocks in the distribution (i.e., multi-textures and contrasting colours), paired with slightly dulled image quality resulting from sampling submerged grains, significantly increased image processing times, between 20 and 40 minutes per photo. Including infield data collection and image processing, overall sampling time for one site averaged 25 to 50

minutes. The proceeding sections describe a series of tests used to modify raw photographs in an effort to improve the performance of DG's data outputs.

2.3.1 Image Modification

After taking photos of submerged grains, a series of modifications to the raw images were required to improve the ability of DG to identify grains. Image modification was a desktop exercise using image modifying software (i.e., ImageJ and iPhoto by Apple Inc. ©). All raw images were straightened using iPhoto © and cropped using ImageJ (<http://rsb.info.nih.gov/ij/>) based on the ruler markings in each photo (Figure 15). The cropped dimensions of the five photographs from each site were made the same (e.g., all 30 cm by 30 cm).

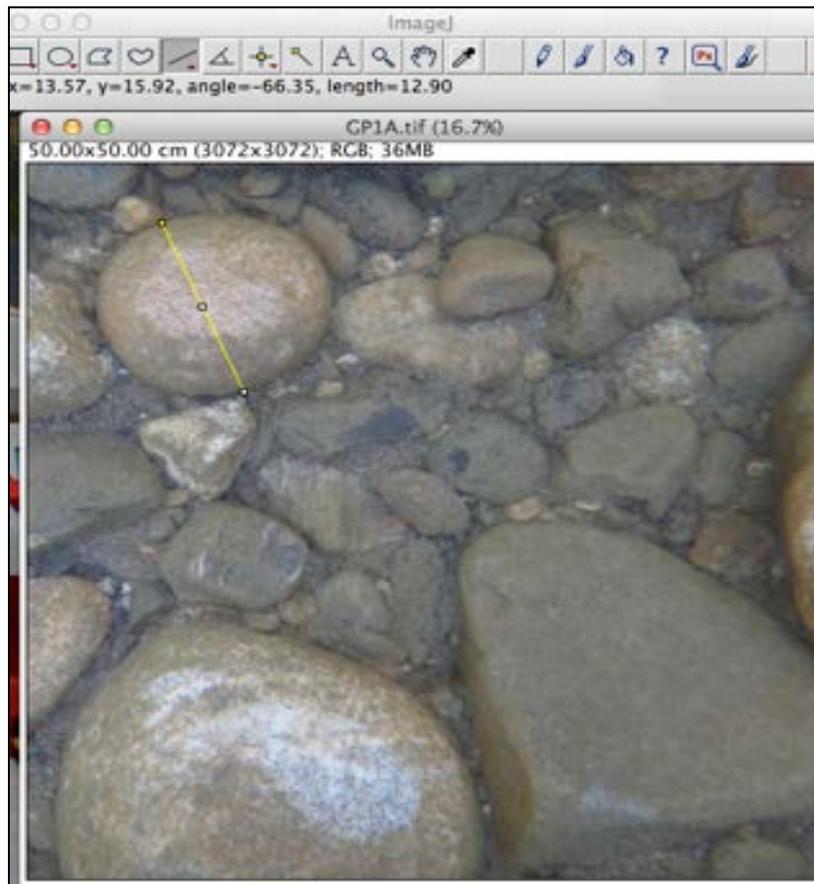


Figure 15. Screenshot of ImageJ software used to crop image GP1A from the Middle Shuswap River, British Columbia to 500 cm² based on the scale provided by the metal sampling ruler (cropped out of image in this figure).

2.3.2 Image Modification Tests

A number of tests were required to improve data output produced by DG. This was a result of the texture and colour contrast within individual rocks that made identification of grains by DG difficult. The result of processing raw images was an over-segmentation of one grain into numerous smaller grains (e.g., counting 1 rock as 20 smaller rocks). A common challenge of grain identification noted in previous studies was hiding and imbricated grains; however, these grain organizations were not observed at the sites sampled (Sedimetrics 2005; Graham et al. 2005, 2012).

2.3.2.1 *Image Test 1*

The aim of Image Test 1 was to determine if and how raw images could be made process-ready using simple transformation techniques available in ImageJ. One image was selected for all tests for the ease of comparing DG output results. Eight different images modifications were tested. A lower truncation of 2.0 Psi was used along with all other DG default settings. Figure 16 depicts nine images, the raw image (Image Transformation (IT)2-A) and eight different transformations:

1. IT2-A original image
2. IT2-B 8-bit grey scale
3. IT2-C 16-bit grey scale
4. IT2-D 16-bit Huang Transitional black and white
5. IT2-E overexposed
6. IT2-F sepia deep shade
7. IT2-G 32-bit gray scale
8. IT2-H black and white boost
9. IT2-I 16-bit grey scale with paint used to buff-out texture on larger rocks.

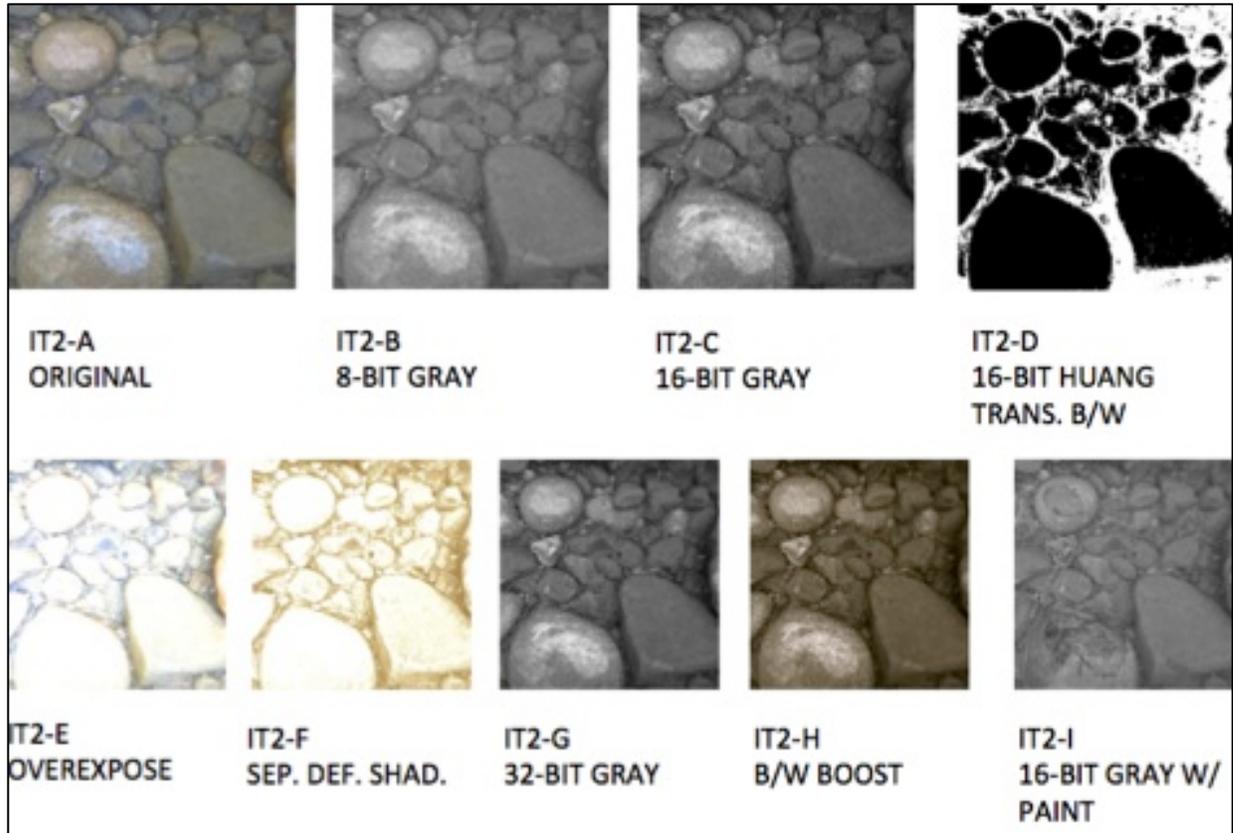


Figure 16. Raw image (IT2-A) and eight different modification treatments applied to image prior to Digital Gravelometer processing for Image Test 1, from the Middle Shuswap River, British Columbia.

Of the 9 images processed, IT2-E and IT2-F produced the best results, shown in Figure 17. In Figure 17, note the over-segmentation of individual grains within all photos. For images where grain modification was unsuccessful, the amount of grain segmentation is highest (e.g., IT2-B and IT2-C).

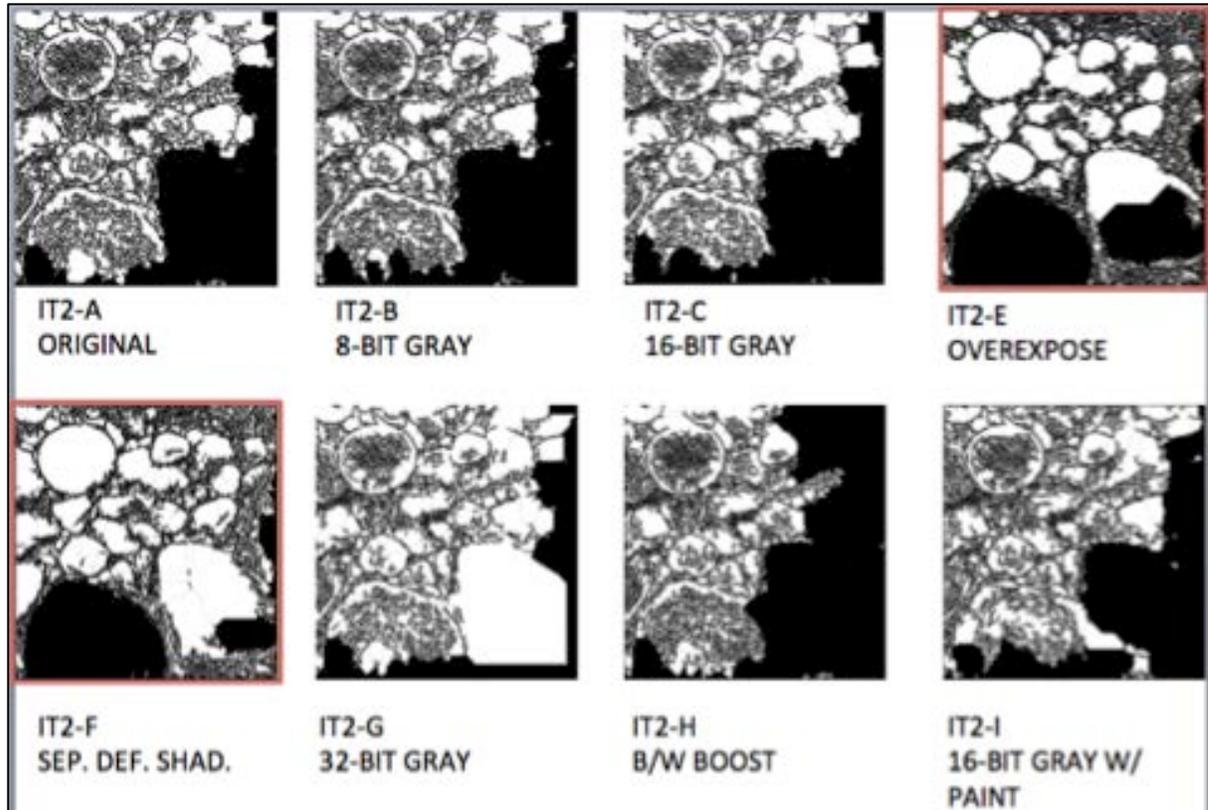


Figure 17. Grains selected by Digital Gravelometer for Image Test 1. IT2-E and IT2-F (red squares) were found to have the least within grain over-segmentation from the Middle Shuswap River, British Columbia.

The intermediate axis of the largest grain was measured for the three largest grains not touching the image border in the test image using ImageJ. The results were 129.0 mm, 62.5 mm and 61.1 mm. The D_{\max} identified by DG for IT2-F from DG results was 122.89 mm, closest to manual measurement (i.e., $D_{\max} = 129$ mm). DG outputs from the test are presented in Table 5. DG was not able to process IT2-D. The results demonstrated that IT2-E and IT2-F produced the best results because they had the least amount of over-segmentation of individual grains.

Table 5. Grain size distribution results for Image Test 1. Grain size separated into 5 categories, sand, granule, pebble, cobble and boulder. 2012.

Grain Size (mm)	PERCENT IN CLASS PER SITE									
	IT2-A	IT2-B	IT2-C	IT2-D	IT2-E	IT2-F	IT2-G	IT2-H	IT2-I	
Boulder (>256)	0	0	0	0	0	0	0	0	0	0
Cobble (64-256)	4.74	12.27	5.87	0	37.52	30.32	30.02	0	0	
Pebble (4-64)	93.34	85.40	92.45	0	61.23	68.71	68.94	97.66	98.23	
Granule (2-4)	1.93	2.32	1.68	0	1.25	0.97	1.04	2.34	1.77	
Sand (<2)	0	0	0	0	0	0	0	0	0	

2.3.2.2 Image Test 2

For Image Test 2, six random images were selected from the 78 sample sites and corrected in iPhoto © by modifying exposure (80 to 100%), contrast, definition, shadows and highlights based on the findings from Image Test 1. The extent of the image treatment was at the discretion of the image processor with the aim of reducing within-grain texture and increasing contrast. All images were made Sepia colour. A lower truncation of 2.0 Psi was used along with all other DG default settings. An example of this test is shown in Figure 18.

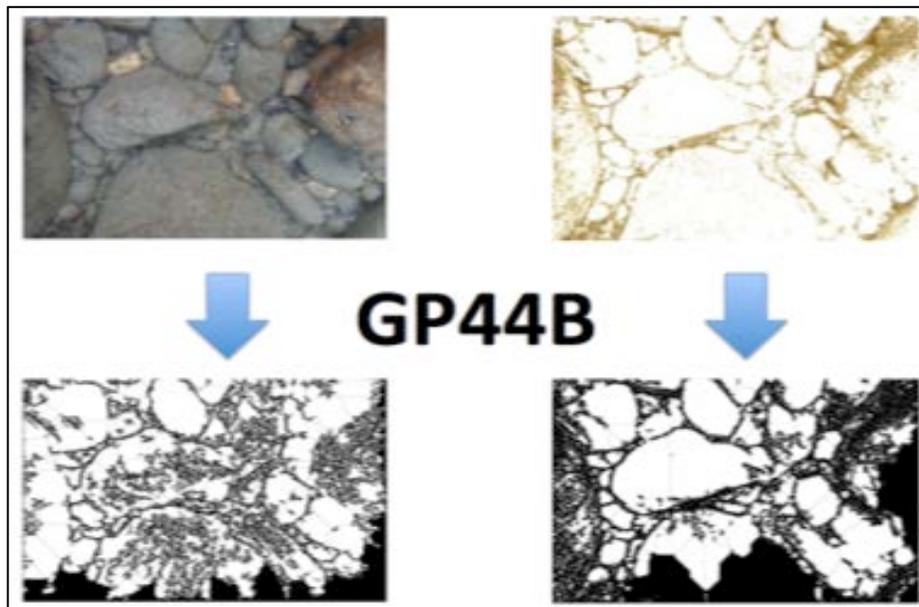


Figure 18. Comparison of raw and altered image. Raw image GP44B next to transformed image GP44B and the grains selected by Digital Gravelometer by Sedimetrics © from the Middle Shuswap River, British Columbia. Transformed image produced less within grain over-segmentation than the raw image.

Sepia tone was selected based on results from Image Tests 1. There were numerous Sepia images that DG would not process, as shown in Figure 19. As such, Sepia was compared directly to black and white images.

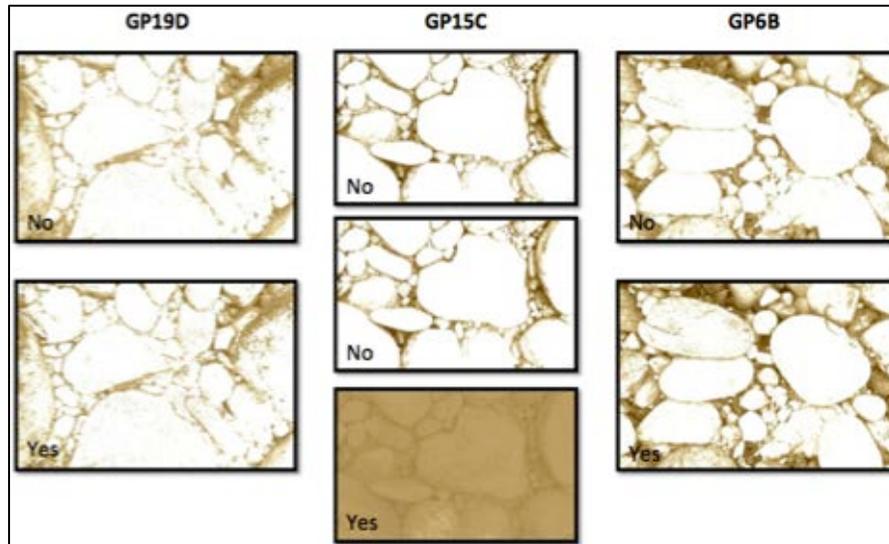


Figure 19. A selection of transformed images that were processed and not processed using Digital Gravelometer by Sedimetrics © from the Middle Shuswap River, British Columbia. Images with a “Yes” indicate that Digital Gravelometer was able to process the image. Images with a “No” indicate that Digital Gravelometer was not able to process the image.

In Figure 20, sepia color tone is compared with the same black and white image, the only modification being color tone. In general, contrasting shades remained equal between images with only slight variations in results. For the ease of data sharing, printing and modification, all subsequent images were black and white transformed. For three rocks (circled on both DG images in Figure 20), the water-shedding result on the black and white image better represents the actual grain size. File format between TIFF and JPEG was also tested and seemed to result in only minor differences. As such, all photos were made into JPEG files since they are smaller and easier for DG to process.

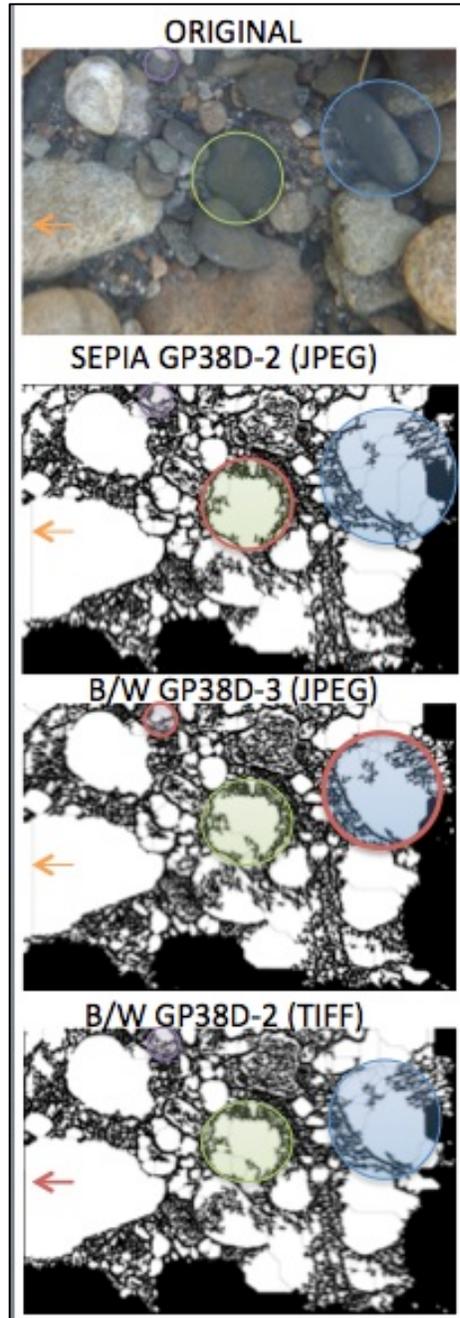


Figure 20. Digital Gravelometer results for a test image, including the raw image and three modified images from the Middle Shuswap River, British Columbia. Image GP38D was tested using the raw image, sepia image, black and white JPEG image and a black and white TIFF image. Arrows indicate an artificial line segmenting a large grain in the sepia and black and white image JPEG but not in the black and white TIFF image. Coloured circles identify rocks from the raw image used for the primary comparison.

2.3.2.3 Manual Count Test 1

A test was conducted to see how close results were when grains that were manually counted were compared to results from DG. The same image was used for both counts. For the manual count, the intermediate axes of 142 rocks was measured using ImageJ. DG was used for the automated count. Table 6 presents the results of the count truncated at 2.5 Psi (5.7 mm) and 7 Psi (128 mm). Although the results were not very similar, it was determined that DG likely did a better job of identifying minor contrasts not observed through manual counts. Further, the intermediate axis DG selected was likely different than the intermediate axis selected in the manual count. Measured rocks were marked with a black line in ImageJ to avoid duplicate counting (Figure 21). Very fine grains less than 1 mm were hard to differentiate and measure manually.

Table 6. Comparison of grain size distributions using an automated count by Digital Gravelometer by Sedimetrics © and a manual count using an observer measuring grains using ImageJ with a 2.0 Psi and 7.5 Psi truncation for site GP1A on the Middle Shuswap River, British Columbia (2012).

mm	Psi	Count in Class DG	Count in Class Manual	% in Class DG	% in Class Manual
5.7	2.5	261	23	48.1	16.2
8	3	131	29	24.1	20.4
11.3	3.5	50	23	9.2	16.2
16	4	41	16	7.6	11.3
22.6	4.5	23	16	4.2	11.3
32	5	15	10	2.8	7.0
45.3	5.5	10	8	1.8	5.6
64	6	9	11	1.7	7.7
90.5	6.5	1	3	0.2	2.1
128	7	2	2	0.4	1.4
181.0	7.5	0	1	0.0	0.7
Totals		543	142	100	100



Figure 21. Grains counted manually (black lines) using ImageJ that were used for comparison with grains counted using Digital Gravelometer by Sedimetrics © from the Middle Shuswap River, British Columbia.

2.3.2.4 Lower Truncation Test

DG allows users to apply a lower truncation value before generating output statistics. For this test, small grains incorrectly identified by DG were measured using ImageJ and compared with correctly measured small grains from a site downstream near the study area terminus (i.e., where most of the GSD was represented by a uniform grain size). Incorrectly identified grains averaged < 8 mm whereas correctly identified grains downstream were ≥ 8 mm. Therefore, a lower truncation of 8 mm was applied to GSD data obtained from all sites,

consistent with recommended lower truncation values of Graham et al. (2010). Note that for photographic methods in general, Bunte (2001) suggests truncation of 10 to 20 mm.

2.3.2.5 Conclusion of Tests

The following is a list of conclusions made from image tests:

- Transform raw images into black and white instead of sepia.
- Use JPEG files rather than TIFF files.
- For some modified images, DG would get “stuck” during processing and not allow the command to execute. For these images, a second and sometimes third image modification was required to make a clearer image the software could process.
- Some of the DG results did not provide a D_{max} , a known software error (personal communication David Graham, Loughborough University)
- The retouching tool in iPhoto © was used to reduce “blemishes” on individual grains that had a granite-like texture to prevent over-segmentation by DG with some success.
- In general, all default settings in DG were applied except for a lower truncation value of 8 mm (3 Psi).
- All DG results over predicted small grains (i.e., many large grains with one color are separated into one or more grains during grain identification and water-shedding) and this was corrected by the higher truncation value (8 mm).
- Image modification steps generally resulted in better grain identification.
- Photoshop was recommended by Marwan Hassan (UBC) to treat texturized grains.
- iPhoto© modification used in this research relies on sampler judgment; therefore G. Shearing modified all images.
- The image processor should consider the following:
 - o Maximizing contrast strengthens the ratio of dark to light aspects of the image. Increasing the exposure brings lighter rocks to the foreground and further separates dark and light rocks.
 - o Lighter rocks in the foreground of the original image can make image correcting granite-textured grains in the background difficult.

- Embedded grains (i.e., armored into the bed) are harder to correct because of the lack of defining edge line and touching fine grains which blur the true edge during image modification (whereas grains on the surface have better defined edges and are easier to “contrast-out” from adjoining grains)
- Care has to be taken not to over-contrast images such that two or more touching grains join together.
- Rocks laying upon other rocks of slightly different contrasts makes grain differentiation during image modification difficult.
- Correcting larger grains is sufficient since small grains require less correction when over-exposed.
- After exposure and contrast increased, textural attributes of grains may still be present that will cause DG to over-segment one grain into smaller grains. Using the retouch tool in iPhoto © removes such textural attributes and makes the grain appear entirely as one colour. This also removes groves and incisions present in the grain. Care must be taken not to blur grains showing 3 axes where blurring the dividing line between features could result in rocks being merged together.
- In a few cases, small grains laying on larger grains were “washed” out using the retouching tool.
- Grains on the bottom and right borders were also corrected so that the size of the grain excluded was not a larger grain made artificially small by DG grain segmentation.
- Grains with igneous intrusions of contrasting colour were easily corrected.
- For larger rocks, image modification may separate one grain based on two significantly contrasting colours juxtaposed (e.g., a black and white rock). The only solution is to try and blend the colours with the retouching tool and hope that DG picks up on the new grey colour.
- One rock laying upon a larger rock of contrasting or similar colours bisects the bottom grain making it appear to be two smaller grains.

2.3.3 Spatial Autocorrelation, Assumptions and Limitations

Spatial autocorrelation is an inherent characteristic of data collected in a similar geographical space. Although the statistical tests performed assume independence, collecting samples within the same river system implies some between-site dependence in terms of flow velocity, sediment input, channel slope, and bed mobility, etc. For this research, a stratified sampling scheme targeted the glide facies with the assumption that greater independence could be assumed if similar morphological facies were sampled and all other facies (e.g., riffles, pools) were avoided (Bunte and Abt 2001). This resulted in greater distances between sampling points and a greater likelihood of independence. Considerable effort was made to eliminate bias, however, the following sources of bias during photo collection and processing were identified:

- Operator error resulting in less than 5 photos per transect (e.g., blurry images, steel ruler bisecting photo).
- Raw images were cropped to within ± 0.5 mm precision.
- The GSD derived from DG is skewed towards larger grains with the use of a lower truncation value of 8 mm, removing the fine gravel (2 to < 8 mm) and sand (< 2 mm) particles from the GSD. The GSD also underrepresents very large grains that could not be included in the submerged camera's field of view (>181 mm).
- In general, deeper upstream glides had a larger photo area; shallower downstream glides had a smaller photo area. Therefore, the sample area and number of grains counted differed for each site.

The results presented in Section 3 assume the following:

- Spatial autocorrelation is negligible and therefore all samples are treated as independent.
- DG grain identification is representative of grains at the sample site.
- The GSD for each sample represents the entire glide facie (i.e., morphological unit).

Warrick et al. (2009) remarks that a substantial progression to streambed sampling would be made if a method for underwater sampling was devised. A limitation Warrick et al. (2009) identifies and was problematic for this research is that water depths at certain sites were insufficient to obtain an ample field of view to take a photo that captured D_{max} .

Limitations of the DG software include no means for image cropping or modification within the software. Without using the exact technique proposed by Graham et al. (2005), DG gets stuck on Stage 6 of 8 (i.e., selecting appropriate grains) for over-modified images. These images required subsequent modifications to reduce the level of within grain-texture before processing which increases processing time.

2.4 HEADPOND SEDIMENT CHARACTERIZATION

A sample was collected from the stockpile created by the 2009 dredge project to characterize sediment deposited above Wilsey Dam in the headpond (Photograph 4). A 250-ml glass jar was filled with sediment, and the sample was sent to an accredited laboratory for analysis. Okanagan Testing Laboratories provided a sieve analysis report included in Appendix 1. This GSD is taken as characteristic of the sediment being transported by the MSR above the dam.



Photograph 4. Looking south towards dredgeate stockpile formed during the 2009 dredging project at Wilsey Dam from which a sediment sample was collected to determine the grain-size-distribution of sand used in the sediment transport model in this research. Photo credit: G. Shearing, 2009.

2.5 BEDLOAD SAMPLING

Bedload sampling was conducted in the MSR downstream of Wilsey Dam and in Bessette Creek, upstream of the confluence with the MSR. Sample locations are shown on Figure 22. Sampling occurred on June 24, 2013 during the receding freshet. The WSC Station No. 08LC003 discharge reading was 220 cms which is high flow for the MSR (i.e., 15% greater than mean annual peak freshet discharge of 190 cms). Bedload sampling was done using general procedures described in the *Guidelines for Using Bedload Traps in Course-Bedded Mountain Streams* (Bunte, Swingle, and Abt 2007). A Helley-Smith Bedload Sampler (HSB sampler) was used with a 76.2 mm by 76.2 mm (3 inch by 3 inch) opening and a 600 mm long 500-micron mesh bag. At both sites, the HSB sampler was placed on the river bottom for 5.5 minutes. Bedload sediment in the bag was placed into pre-labeled plastic bags. Sample sites were selected to avoid sediment sinks (e.g., ponds and aggrading areas upstream of diversion structures) and gravel supply zones (e.g., eroding hill slopes, undercut banks, an aggraded bed behind a recently removed sediment trap like a log jam, bedload waves from degraded upstream reaches) (Bunte, Swingle, and Abt 2007).

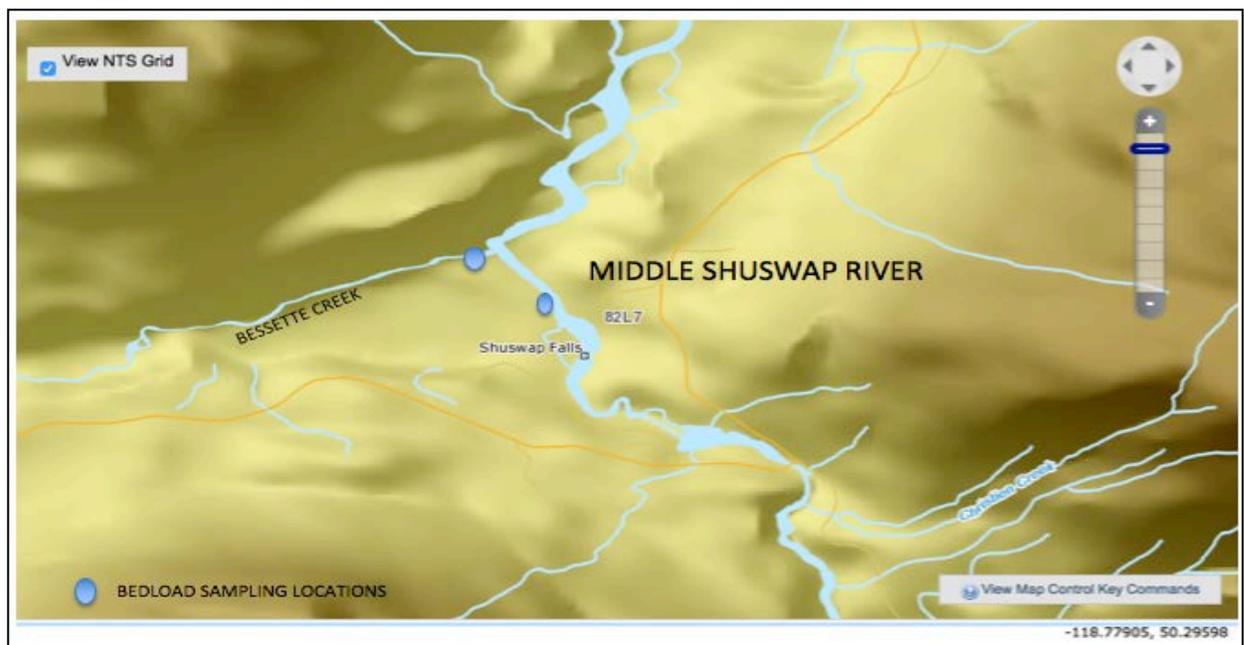


Figure 22. Locations of bedload samples collected in the Middle Shuswap River and Bessette Creek (blue ovals) on June 24, 2013. Map not to scale. Image courtesy of Natural Resources Canada Geospatial Data Extrication.

At the MSR site, bedload sampling was conducted at the head of a major point bar on river left adjacent to the Shuswap River Hatchery. With high flows, wading into the centre of the MSR mainstem was not possible. Instead, sampling across the head of the point bar was done as suggested in Bunte et al. (2007). Sampling in the MSR was done twice. Both times only a small amount of organic debris and an un-measurable amount of very-fine sediment was collected. It was concluded that insignificant bedload transport was occurring at this time and samples were not processed in the laboratory. Although the flow discharge rate was able to transport sediment, no sediment was being transported. The rate of bedload transport in the middle of the channel may have been different but the fast water was too unsafe to wade into to sample.

At Bessette Creek it was possible to wade into the centre of the channel (Photograph 5). The HSB sampler bag was near full after the 5.5-minute sampling time had ended. Bedload material was removed from the HSB sampler and placed into plastic bags for transport and subsequent laboratory analysis; grains stuck on the mesh bag were put into the plastic bag using water from a squirt bottle.



Photograph 5. Giles carrying the Helly-Smith Sampler before sampling in Bessette Creek approximately 50 m upstream of the Confluence with the Middle Shuswap River, June 24, 2013. Photo credit: B. Bauer.

At both bedload sampling sites, velocity measurements were taken using a portable handheld velocimeter (FlowTracker by SonTek). Water depth at both sites was approximately 1 m. Flow measurements were taken every 100 mm except the bottom measurement that was held 30 mm above the riverbed. Measurements were averaged at each site for later calculations.

In the laboratory, the Bessette Creek sample was oven-dried at 232 degrees Celsius for approximately 30 hours. Larger wood pieces were removed by hand, an effort sufficient to remove most conspicuous organic pieces. The sample was not chemically or combustion treated prior to weighing. After drying, the sample was divided into a manageable size for sieve analysis using a splitter. Two different laboratory technicians each undertook sieve analysis on the same sample for the fine-grain portion of the sediment below 1 mm. Larger grains between 1 mm and 12.5 mm were only sieve-sampled once. The first set of large-grain and fine-grain samples were processed using a student sieve set placed in a mechanical rocker for 10 minutes. The second round of fine-grain processing used a new sieve set and a commercial rocker (i.e., Ro-Tap® Sieve Shaker by W. S. Tyler™). Sieve sizes used in the laboratory were converted to half Psi-sizes for calculations. Bedload transport was calculated using the equation below. Results are presented in Section 3.1.

Weight (g) / Time (s) / Trap width (m) x Channel width (m) x 1000 = bedload transport (kg/s)

2.6 STATISTICAL DETERMINATION OF DOWNSTREAM FINING

Results were obtained for 53 sites, or 71% of all glides within the study area. Within each glide, an area approximately $\sim 0.5 \text{ m}^2$ was sampled. For this research, statistics were performed on pooled transect data with 3 to 5 glide photos. The number of rocks and sample area differ for each transect; therefore, the pooled GSD from each transect was treated like an individual sample. A linear regression was used as a reasonable approximation of the downstream fining curve. A lambda model (smoothing spline) was used to illustrate a general trend in the observed data. Tukey HSD and a Student's T Test were to compare changes between reaches. Downstream fining results are presented in Section 3.2.

2.7 DETERMINING AVAILABLE SALMON SPAWNING HABITAT

Understanding the location of potential salmon spawning habitat is important in assessing impacts related to sediment management and salmon reintroduction. Salmon spawning habitat areas were identified using sampled GSDs, aerial photographs and a suite of mapping software that enabled the production of five spawning habitat maps for the study area. Google Earth was used to input points from a handheld GPS, to measure distances and elevations, and to determine water surface slope. BC Hydro provided orthophotos at 0.5 m resolution from June 27, 2009 (i.e., most recent orthophotos to the study year) and a photogrammetric digital elevation model (DEM) based on the 2009 orthophotos. Associated Environmental Consultants Inc. (previously Summit Environmental) provided AutoCAD files with salmon spawning habitat area polygons from area estimates created in 2002. GPS points, air photographs, the DEM and the 2002 polygons were entered into Global Mapper[®] which was used to draw the habitat polygons used in the final 2012 maps. Maps were finalized in MicroStation[®] by Azimuth Forestry and Mapping Solutions Limited in Revelstoke, B.C.

Estimating available spawning habitat for salmon in the MSR was a three-step process, detailed in the preceding sections. Step 1 identified the optimal range of median grain size (D_{50}) for which salmon would be expected to use for spawning. Step 2 involved developing a classification scheme for spawning grounds used by coho and chinook using the range of D_{50} determined in Step 1. Step 3 involved using the classification scheme from Step 2 to identify coho and chinook spawning habitat in the MSR.

Estimating potential salmon spawning habitat involved the use of the following data:

- June 27, 2009 orthophotos¹ and DEM at an approximate river discharge of 93 cms;
- December 31, 2003 Google Earth images at approximate river discharge of 19 cms;
- D_{50} from GSD derived from AGS sample results;

¹ Discharge data on orthophotos from Water Survey of Canada Station No. 08LCO18

- Associated Environmental Consultants Inc. 2002 digital files containing salmon spawning habitat polygons and redd locations; and
- Spawning gravel D_{50} values from Washington State chinook and coho salmon redds presented in (Kondolf and Wolman 1993).

2.7.1 Step 1: Determining a Range of Suitable Spawning Substrate

Step 1 compared AGS results to the findings of Kondolf and Wolman (1993) and Guy and Uunila (2002) to determine a substrate range for which salmon are likely to excavate their redds and spawn. D_{50} for Washington State coho redds ($n = 28$) and chinook redds ($n = 75$) were used to define the average range of grain size tolerances for salmon spawning. The median grain size (D_{50}) was selected as it best describes the central tendency of the GSD (Buffington and Montgomery 1999). In addition, Kondolf and Wolman (1993) use D_{50} as one of the primary descriptors of spawning grain size, making a direct comparison possible.

The D_{50} from 12 AGS sample sites below Wilsey Dam were matched with 2002 redd sites identified in Guy and Uunila (2002). Redd locations next to and within the same morphological facie of the AGS sample (e.g., glides) were assigned the corresponding D_{50} . The smallest MSR D_{50} was used to define the lower end of the coho substrate range whereas the largest MSR D_{50} was used to define the larger end of the chinook substrate range, as compared with the D_{50} values from Kondolf and Wolman (1993). An effort was made to sample gravel directly adjacent to identified redd sites. Unfortunately, 2012 experienced very low salmon returns making spawning redds hard to find. Table 7 presents a range of D_{50} used to define the substrate preferences of MSR coho and chinook.

Table 7. Approximate range of spawning substrate tolerances derived from the D_{50} of salmon redd locations using automated grain sizing measurements and D_{50} measurements summarized in Kondolf and Wolman (1993) for the Middle Shuswap River, British Columbia (2012).

Source	MSR AGS Site D_{50} for both Coho and Chinook (n = 12) ^a	Washington State Coho D_{50} (n = 28)	Washington State Chinook D_{50} (n = 75) ^b	Chinook D_{50} Range	Coho D_{50} Range
D_{50} min	19 mm	10 mm	34 mm	34 mm	19 mm
D_{50} max	65 mm	35 mm	54 mm	65 mm	35 mm

^a Guy and Uunila (2002) did not specify which redd belonged to a particular salmon species. Therefore, Kondolf and Wolman (1993) was used to define the upper and lower bounds of coho and chinook substrate requirements, respectively.

^b A single Washington State record for chinook spawning in the Columbia River ($D_{50} = 78$ mm) was omitted as an outlier for the MSR.

2.7.2 Step 2: Applying the Range of Suitable Spawning Substrate

To classify potential coho and chinook spawning habitat, AGS sites throughout the study area were assigned to one of three categories based on D_{50} . If the AGS site D_{50} fell within the range of 19 mm to 35 mm, a spawning habitat polygon was delineated on the map for coho. If the AGS site D_{50} fell within the range of 34 to 65 mm, a spawning habitat polygon was delineated on the map for chinook. If the AGS site D_{50} fell within the narrow range of 34 to 35 mm, a spawning habitat polygon was delineated on the map for both coho and chinook. Sites with a D_{50} less than 19 mm or greater than 65 mm were considered outside the suitability range of both coho and chinook. In a few instances, polygons or sections of polygons from Guy and Uunila (2002), were applied without a matching D_{50} from this research (discussed further in Section 2.8.3). Those polygons were designated as habitat for both chinook and coho. Each classification was assigned a colour and hatching scheme. A summary of suitable spawning habitat ranges is presented in Table 8.

Table 8. Polygon classification of substrate D_{50} ranges for coho and chinook spawners in the Middle Shuswap River, British Columbia (2012).

Colour/Hatch Identifier	Species	D_{50} Range (mm)	Sources
Green Cross Hatch	Coho Habitat	19 - 35	MSR AGS Data, Guy and Uunila 2002, Kondolf and Wolman 1993
Orange Left Hatch	Chinook Habitat	34 - 65	MSR AGS Data, Guy and Uunila 2002, Kondolf and Wolman 1993
Blue Right Hatch	Coho and Chinook Habitat	34 - 35	MSR AGS Data, Guy and Uunila 2002, Kondolf and Wolman 1993

2.7.3 Step 3 – Mapping Suitable Spawning Substrate

Air photos from high flow (2009) and low flow (2003) periods were used to help determine spawning habitat polygons on the MSR. The geographical information system software GlobalMapper[®] was to undertake air photo interpretation. AGS samples were assumed to be representative of the entire glide facies, which rationalized expanding the habitat polygon beyond the small footprint of the AGS sample (Bunte and Abt 2001). All AGS sites with a D_{50} in the range of the classification scheme outlined in Table 8 were used to first identify sites suitable for spawning. In four instances, glides without an AGS sample were included using the original polygon from Guy and Uunila (2002). Findings from Guy and Uunila (2002) were compared with 2009 air photos and visual onsite inspections were undertaken during field work to confirm suitability for spawning. In some instances, spawning polygons created by Guy and Uunila (2002) were used to extend polygons beyond the glide facies. The final polygons were added to 5 maps that comprise the study area and are found in Appendix 9. Results are presented in Section 3.3.

2.8 SEDIMENT TRANSPORT MODELING

Sediment transport modeling is an important tool that can provide insight into how fine-grained sediment re-introduced to rivers may influence downstream biological and morphological conditions below sediment impounding dams. The model reach for the MSR begins at a point 0.67 km downstream of Wilsey Dam and extends to the Bessette Creek confluence, a 1.2 km reach classified as 'sediment starved' as a result of dam emplacement (Lewynsky 1997; Lister 1990; Guy and Uunila 2002).

The sediment transport model used comes from the excel model code in RTe-bookAgDegNormGravMixPW from the e-book developed by Dr. Gary Parker (Parker 1990, 2004). The excel model was converted to run in MATLAB ©² from a script written by Dr. Peter Nelson (Colorado State University). Dr. Ted Fuller (Simon Fraser University) made modifications to the MATLAB © script to accommodate additional grain size bins (i.e., the modified model uses 40 bins at quarter Psi intervals compared to 12 bins available in the Microsoft Excel © model), as well as additional time steps and input supply rates. The model (Parker 1990) and related versions (Cui et al. 1996, 2003, 2006a, 2008; Nelson et al. 2009, Fuller et al. 2016) have been used to successfully model morphodynamics for other river systems.

The model uses the bedload transport equation of Wilcock and Crowe (2003) to compute spatial and temporal changes in bed morphology, total gravel transport and GSD changes within the active surface layer (Parker 1990). Wilcock and Crowe (2003) developed a sediment transport equation that is similar to Parker (1990) which includes fine-grained sediment less than 2 mm.

The Wilcock and Crowe (2003) sediment transport equation was developed to model mixed sand and gravel sizes, and is of the following form:

² MATLAB © and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.

$$W_i^* = f(\tau/\tau_{ri}) \quad (1)$$

where τ is bed shear stress, τ_{ri} is a reference shear stress at weak transport stage, and W_i^* is the non-dimensional, fractional transport rate defined by:

$$W_i^* = (s - 1)gq_{bi} / F_i u_*^3 \quad (2)$$

where s = ratio of sediment to water density; g = gravitational acceleration; q_{bi} = volumetric transport rate per unit width of grain size i ; F_i = proportion of size i on the bed surface; and u_* = shear velocity

The hiding function equation

$$\tau_{ri}/\tau_{rs50} = (D_i/D_{s50})^b \quad (3)$$

where τ_{rs50} = reference shear stress, $b = 0.12$ for $D_i/D_{s50} < 1$ and $b = 0.67$ for $D_i/D_{sm} > 1$

Wilcock and Crowe (2003) note that the complete model must account for the reference dimensionless Shields Stress for mean size of the bed surface (τ_{rm}) as determined using:

$$\tau_{rm} = 0.021 + 0.015 \exp[-20F_s] \quad (4)$$

where F_s = the proportion of sand in the surface size distribution

The final transport function for W_i^* based on the observations of Wilcock and Crowe (2003) was based on observed trends in the flume data from Wilcock (2001) which resulted in:

$$W_i^* = \begin{cases} 0.002\phi^{7.5} & \text{for } \phi < 1.35 \\ 14 \left(1 - \frac{0.894}{\phi^{0.5}} \right)^{4.5} & \text{for } \phi \geq 1.35 \end{cases} \quad (5)$$

Where $\phi = \tau/\tau_{ri}$. Equations 3, 4 and 5 make up the surface based transport model of Wilcock and Crowe (2003).

The MATLAB model has 40 input requirements, eight of which are default settings that remained unaltered for the simulation exercise. Model assumptions include constant river width (0.055 km) and homogenous GSD throughout the model reach (at each segment). Bunte and Abt (2001) suggest that gravel bedded streams may have GSD uniform “over distances several stream widths long.” The model was unable to account for complex channel morphology and assumes a straight flume-like condition. The actual reach is characterized by two meanders that could facilitate greater deposition.

Nine model runs were undertaken. One model run assessed model response with no sediment inputs entered; therefore, no sediment passing through the modelled river. This was done to see how surface sediment reacted to flow velocity changes in the absence of sediment inputs (Cui et al. 2006a). The other eight runs tested sand inputs and sand-with-gravel inputs of equal volume on four different bed substrates, each with a unique GSD. For each of the nine model runs, change in surface D_{50} was calculated and presented as the primary indicator of bed-surface change. Change in channel bed elevation (net change in aggradation / degradation) and sediment flux and were also quantified using the Exner equation (Parker 2008).

Flow rates of 100 cms were chosen for modeling based on the lower quartile and minimum value of peak freshets from the historical hydrograph for WSC Station 08LC003 (summarized in Figure 23 and presented in full in Appendix 10). From an applied perspective, even during a freshet with relatively low flow (lower quartile of historical hydrograph), 100 cms would inform the dam operator about the volume of sediment that could be moved under this flow condition. It is assumed that flows higher than 100 cms would also have sufficient flow competence to move reintroduced sand.

The volume of sand ($D_{50} = 0.4$ mm) used in the model for downstream reintroduction was 10,000 m³, a quantity that could be expected to be dredged based on previous dredging works at Wilsey Dam since 1971. The volume of gravel ($D_{50} = 13.9$ mm) that was used in modeling for downstream augmentation was 5,000 m³. The gravel volume was based on similar volumes reported for gravel placement into Cranberry Creek at Walter Hardman Dam and a

reasonable amount that could be expected to be moved in a two-week period (BC Hydro 2006).

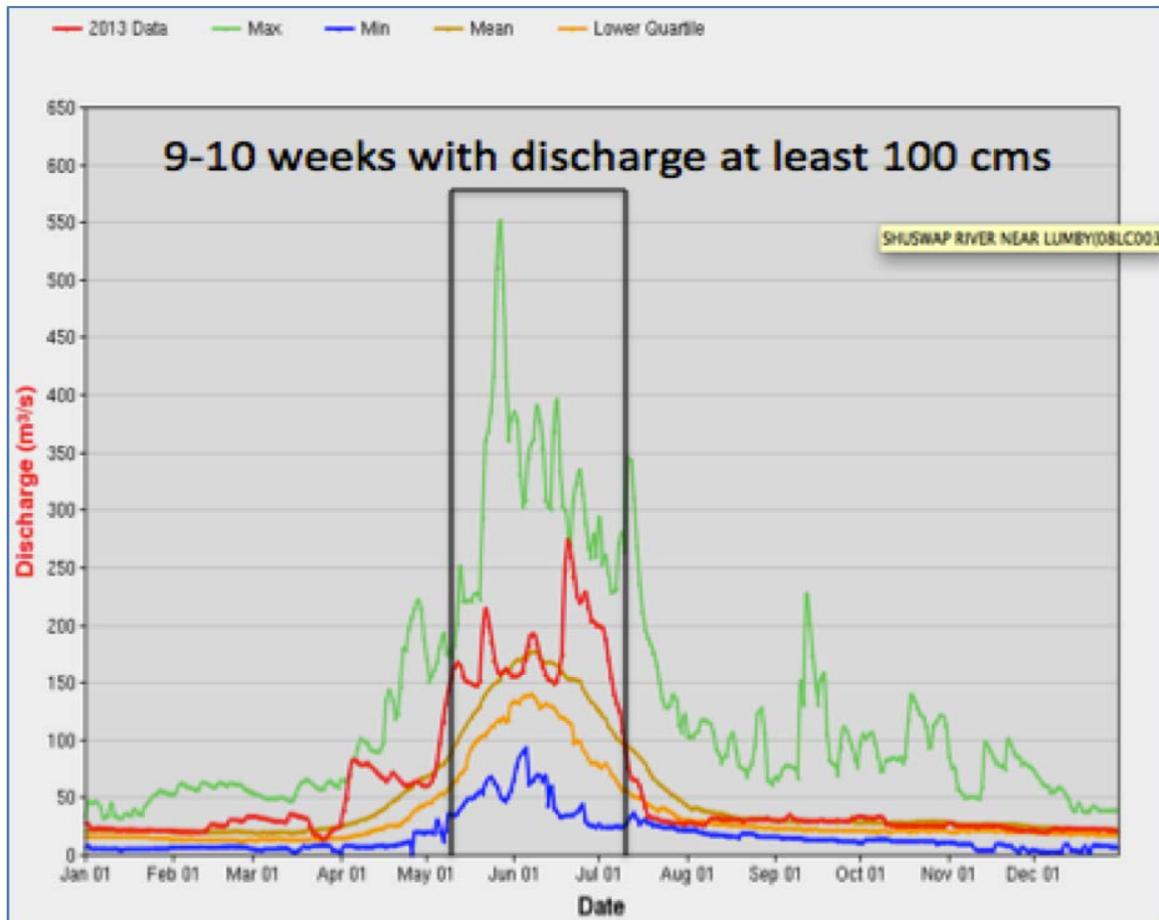


Figure 23. Duration of mean discharge (black outline) during the historical record (1912 to 2013) for Water Survey of Canada Station *Shuswap River Near Lumby* (station identifier 08LC003) located approximately 1 km below Wilsey Dam, British Columbia.

Surface and subsurface bed characteristics were defined using sample site GP52, a glide facie between the canyon terminus downstream of Wilsey Dam and the hatchery. As shown in Table 9, the GSD from sample site GP52 best represented the average of all five GSDs sampled in the model reach. GP52 also contained the largest number of grains ($n = 342$).

Table 9. Survey sites in the Middle Shuswap River model reach used to select a representative site for sediment transport modeling (i.e., GP52). Along the left column the grain sizes within the distribution, the number of photos per site and the number of grains counted in all photos per site are shown.

Grain Size (mm)	GP51	GP52	GP54	GP55	GP57	Averages	Std. Dev.
Dmax	135.79	99.41	113.95	97.75	87.24	106.83	18.78
D95	58.13	50.44	50.11	52.56	62.49	54.75	5.39
D90	42.43	38.35	36.28	38.66	43.21	39.78	2.93
D84	31.82	27.78	26.52	31.34	28.98	29.29	2.27
D75	25.07	22.91	20.82	23.85	21.06	22.74	1.82
D50	14.29	13.29	13.19	14.33	13.08	13.64	0.62
D25	9.92	9.89	9.91	10.11	9.67	9.90	0.16
D18	9.45	9.14	9.15	9.14	8.97	9.17	0.17
D5	8.29	8.21	8.31	8.26	8.20	8.26	0.05
Photos per site	4	4	4	3	5	4	
ngrains	201	342	228	169	171	222	

Figure 24 presents the GSD inputs used in the sediment transport model that characterize the riverbed GSD, the GSD of the released sand, and the gravel GSD used in gravel augmentation. A primary assumption in this modeling exercise is that the majority of sediment transport occurs during spring freshet when the flow has greatest capacity and competency. A headpond study undertaken by BC Hydro (1988) found that approximately 80% of the annual sediment load is transported during spring freshet. Therefore, the model was run for a total of ten weeks, which coincides with a freshet period extending from mid-May to mid-July. The model was run for two weeks with no sediment inputs, which allowed for initial river bed adjustments under baseline conditions. The second-time increment was a two-week, fine-sediment release. This was followed by a two-week flushing flow with no sediment introduction and then a two-week gravel augmentation (i.e., applied in only four of the eight runs). The final time increment of each model run was a two-week flushing flow to establish final conditions likely encountered at the end of the freshet. Model output was generated at each of the 12 cross-sections every 24 hours for the entire 10 weeks.

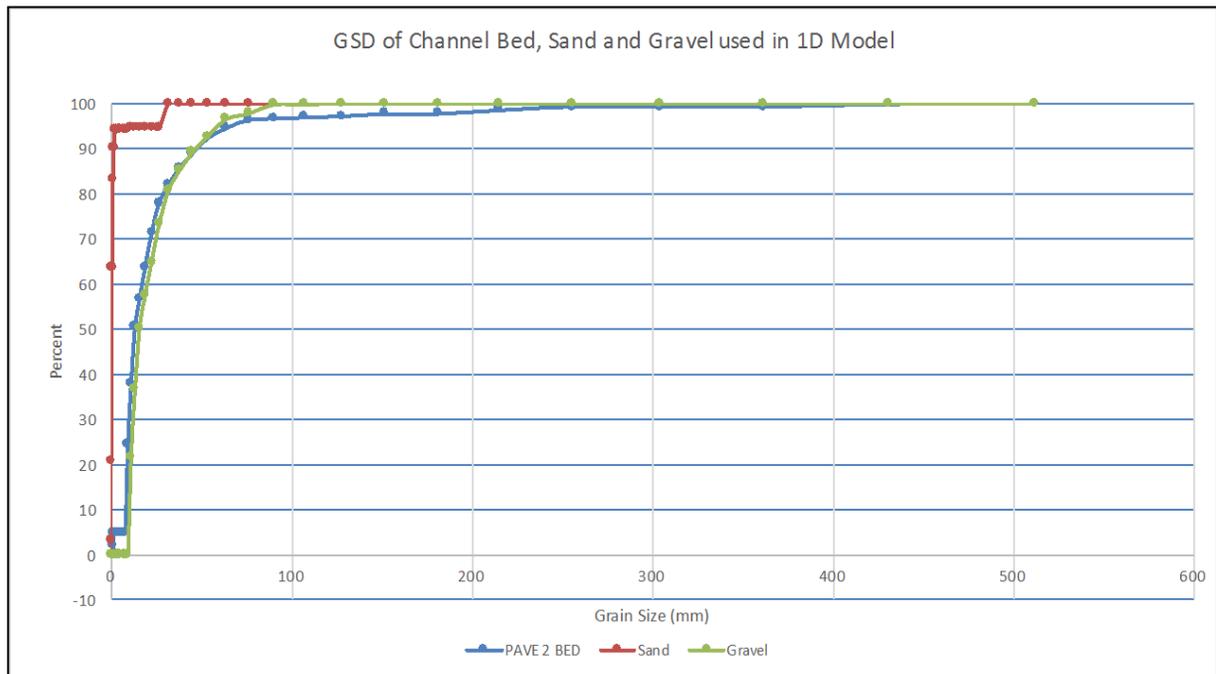


Figure 24. Grain size distribution of riverbed, sand input, and augmented gravel input for sediment transport model simulating conditions on the Middle Shuswap River, British Columbia (2012).

Table 10 lists sediment transport model characteristics. The model has 43 variables that the operator can change; however, those included in Table 10 are the variables input and altered for the model runs.

Table 10. Sediment transport model inputs used for modeling sediment change in the Middle Shuswap River, B.C.

Type of Input	Input Variable
Total model duration	10 weeks (70 days) May 12 to July 18 <ul style="list-style-type: none"> ○ 2-week initial bed adjustment period ○ 2-week sand reintroduction (10,000 m³) ○ 2-week flush ○ 2-week gravel release (5,000 m³) ○ 2-week flush For model runs without gravel augmentation, the sediment flush lasts for 6 weeks.
Flow Discharge	100 cms discharge / approximate median freshet discharge over historical hydrograph
Surface and subsurface characteristics	Selected GP52 as representative GSD in spawning grounds between Wilsey Dam and Bessette Creek confluence. Surface GSD = Substrate GSD (Kellerhals and Bray 1971)
GSD files	Surface changes (File: PAVE 1 (field data), PAVE 2, PAVE 3, PAVE 4)
Reintroduced Sand GSD	(D ₅₀ = 0.4 mm) taken from GSD of 2009 dredge material (Appendix 1)
Augmented Gravel GSD	(D ₅₀ = 13.9 mm) taken from GP50 glide immediately upstream of Wilsey Dam
Channel bed surface D ₅₀ PAVE 1 PAVE 2 PAVE 3 PAVE 4	15.0 mm 33.0 mm 13.2 mm 13.5 mm
Channel length	1200 m, divided into 12 cross-sections and 11 segments (i.e., segment is the distance between cross-sections) 100 m long
Channel width	55 m
Number of Model Runs	8 model runs using entire GSD
Sediment transport equation selected	Wilcock and Crowe (2003) sediment transport equation for the inclusion of grains smaller than 2 mm

Although GSD was truncated at 8 mm due to sampling limitations, there was a need to account for finer grains in the distribution below 8 mm. Sediment being introduced into the model reach from the headpond contains a large proportion of grains smaller than 8 mm. Therefore, all photos from GP52 were re-examined and a percentage of sand was derived,

estimated to be five percent (Figure 25). The GSD for GP52 was adjusted to account for the inclusion of finer grains for modeling purposes.

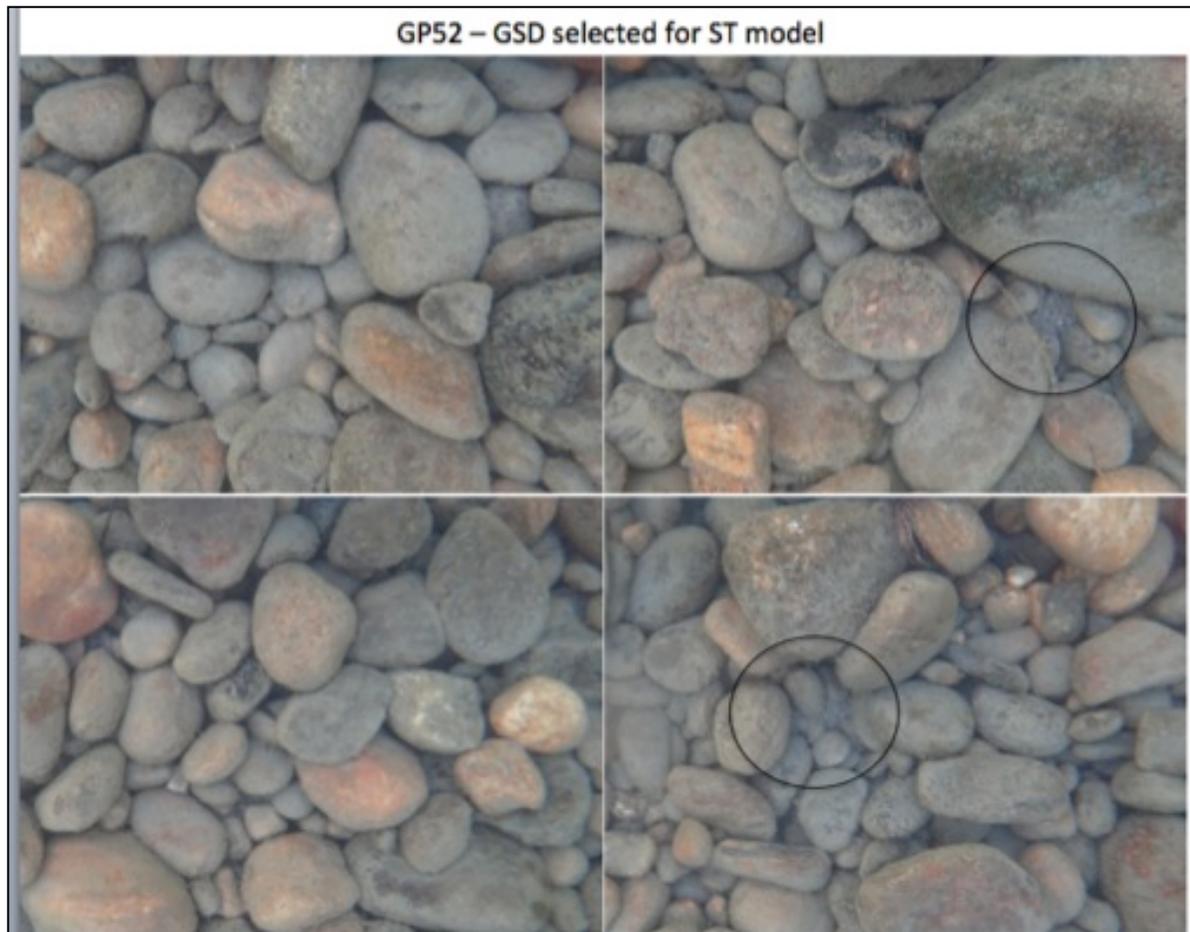


Figure 25. Four AGS photographs from sample site GP52 used to estimate percent of grain size distribution finer than 8 mm. Areas selected by visual observation to determine the percent composition of fine sediment are surrounded by black circles.

Four model simulations (PAVE 1 to PAVE 4) were run with both sand, and sand / gravel inputs, and each with a unique surface GSD (Table 11). PAVE 3 utilized the site GP52 GSD with a 5% sand fraction added. As noted earlier, the underwater AGS was believed to artificially truncate large grains, so to accommodate this in the model simulations, PAVE 1, PAVE 2 and PAVE 4 had differing sizes of larger grains added to their GSD. The selection of larger grains was done using a varying selection of large grains observed within the GP52 site. Each of PAVE 1 through PAVE 4 model simulations had two separate runs depending on whether they included sand reintroduction only (e.g., PAVE 1A) or both sand reintroduction and gravel augmentation (e.g., PAVE 1B). A-series runs (e.g., PAVE 1A)

present results for sand reintroduction (10,000 m³) whereas B-series runs (e.g., PAVE 1B) present results for sand (10,000 m³) and gravel (5,000 m³) reintroduction. Sediment transport model results are presented in Section 3.5

Table 11. Grain size distribution for four Wisley Dam sediment reintroduction model runs PAVE 1 to PAVE 4. Upper and lower truncation limits are highlighted in green.

Grain Size [mm]	Grain Size (Psi)	PAVE 1 Grain Count	PAVE 1 % Finer than	PAVE 2 Grain Count	PAVE 2 % Finer than	PAVE 3 Grain Count	PAVE 3 % Finer than	PAVE 4 Grain Count	PAVE 4 % Finer than
512.000	9.00	1	100.00	1	100.00	0	100.00	1	100.00
430.539	8.75	2	99.72	2	99.51	0	100.00	2	99.735
362.039	8.50	0	99.16	1	98.54	0	100.00	0	99.204
304.437	8.25	0	99.16	1	98.05	0	100.00	0	99.204
256.000	8.00	3	99.16	3	97.56	0	100.00	3	99.204
215.269	7.75	3	98.33	3	96.10	0	100.00	3	98.408
181.019	7.50	0	97.49	3	94.63	0	100.00	0	97.613
152.219	7.25	2	97.49	4	93.17	0	100.00	2	97.613
128.000	7.00	1	96.94	4	91.22	0	100.00	1	97.082
107.635	6.75	1	96.66	9	89.27	1	100.00	1	96.817
90.510	6.50	1	96.38	10	84.88	0	99.70	1	96.552
76.109	6.25	7	96.10	12	80.00	7	99.70	7	96.286
64.000	6.00	8	94.15	11	74.15	4	97.80	8	94.430
53.817	5.75	13	91.92	13	68.78	13	96.70	13	92.308
45.255	5.50	12	88.30	12	62.44	12	93.10	12	88.859
38.055	5.25	14	84.96	14	56.59	14	89.70	14	85.676
32.000	5.00	15	81.06	15	49.76	15	85.80	15	81.963
26.909	4.75	25	76.88	25	42.44	25	81.70	25	77.984
22.627	4.50	29	69.92	29	30.24	29	74.70	29	71.353
19.027	4.25	26	61.84	26	16.10	26	66.70	26	63.660
16.000	4.00	24	54.60	4	3.41	24	59.40	24	56.764

Table 11 cont. Grain size distribution for four Wilsey Dam sediment reintroduction model runs PAVE 1 to PAVE 4. Upper and lower truncation limits are highlighted in green.

Grain Size [mm]	Grain Size (Psi)	PAVE 1 Grain Count	PAVE 1 % Finer than	PAVE 2 Grain Count	PAVE 2 % Finer than	PAVE 3 Grain Count	PAVE 3 % Finer than	PAVE 4 Grain Count	PAVE 4 % Finer than
13.454	3.75	47	47.91	3	1.46	47	52.80	47	50.398
11.314	3.50	51	34.82	0	0	51	39.70	51	37.931
9.514	3.25	74	20.61	0	0	74	25.60	74	24.403
8.000	3.00	0	0	0	0	0	5.00	0	4.775
6.727	2.75	0	0	0	0	0	5.00	0	4.775
5.657	2.50	0	0	0	0	0	5.00	0	4.775
4.757	2.25	0	0	0	0	0	5.00	0	4.775
4.000	2.00	0	0	0	0	0	5.00	0	4.775
3.364	1.75	0	0	0	0	0	5.00	0	4.775
2.828	1.50	0	0	0	0	0	5.00	0	4.775
2.378	1.25	0	0	0	0	0	5.00	0	4.775
2.000	1.00	0	0	0	0	0	5.00	0	4.775
1.682	0.75	0	0	0	0	11	5.00	11	4.775
1.414	0.50	0	0	0	0	7	1.90	7	1.857
1.189	0.25	0	0	0	0	0	0	0	0
Totals	Grains	359		205		360		377	
	D ₅₀	15.0		33.0		13.2		13.5	

CHAPTER 3.0 RESULTS

3.1 GRAIN SIZE DISTRIBUTIONS

Determination of GSD using Underwater AGS involved field collection of 390 photos from 78 glides over 2 days. Photos from 25 sites were unusable due to poor image quality or because DG was unable to process the images; those data were not used. From the remaining 53 sites, 211 of 265 photos taken were processed resulting in 14,533 individual grains counted.

The raw data for each of the 78 glide facies sampled are presented in Appendix 5. Unused data was excluded from analysis for one of three reasons: 1) because the photos were too blurry for processing, 2) there were two or fewer photos that could be processed, or 3) there were fewer than 100 grains counted using DG. A table in Appendix 5 includes the site number (GP#), the number of photos out of 5 that were used for processing (photos/site), the number of grains counted in DG (n-grains), the elevation of the glide above sea level (elevation), the distance of the glide downstream of the first sample collected near The Meadows Campground (distance), the grain size representing the 84th percentile (D_{84}), the median grain size (D_{50}), and the maximum grain size counted within the sample (D_{max}). The results for each glide facie are summarized in Appendix 6.

3.2 BEDLOAD SAMPLING RESULTS

Bedload sampling was conducted in the MSR and Bessette Creek (see Section 2.1.4). Only Bessette Creek samples were processed (Table 12). There was not enough sediment captured in the MSR mainstem from two different sampling efforts to obtain results. The volume of bedload sediment measured was 355.86 gs^{-1} or 7.12 kg/s for the entire cross-section.

Table 12. Bessette Creek bedload measurements from June.

Weight (g)	Time (s)	Weight/Time (kg/s)	Trap Width (m)	kg/m/s	Channel Width (m)	River bedload Transport (kg/s)
8.949	330	0.027	0.076	0.356	20	7.12

3.3 DOWNSTREAM FINING TREND

Linear regression with a fitted lambda model was used to assess the overall fining trend in the river. The Tukey-Honest Significant Difference (HSD) test and Student's T-test were used to show GSD differences between reaches. The study area was further divided into five sub-reaches for the purpose of examining the impact of tributary inputs of sediment and other geomorphic controls (i.e., knickpoints that control river gradient and Wilsey Dam) (Figure 26). The five reaches are:

Reach A – The Meadows Campground to upstream of Ferry Creek

Reach B – Downstream of Ferry Creek to upstream of Chute

Reach C – Downstream of Chute to upstream of Wilsey Dam

Reach D – Downstream of Wilsey Dam to upstream of Bessette Creek

Reach E – Downstream of Bessette Creek to the study area terminus upstream of the Bailey Bridge

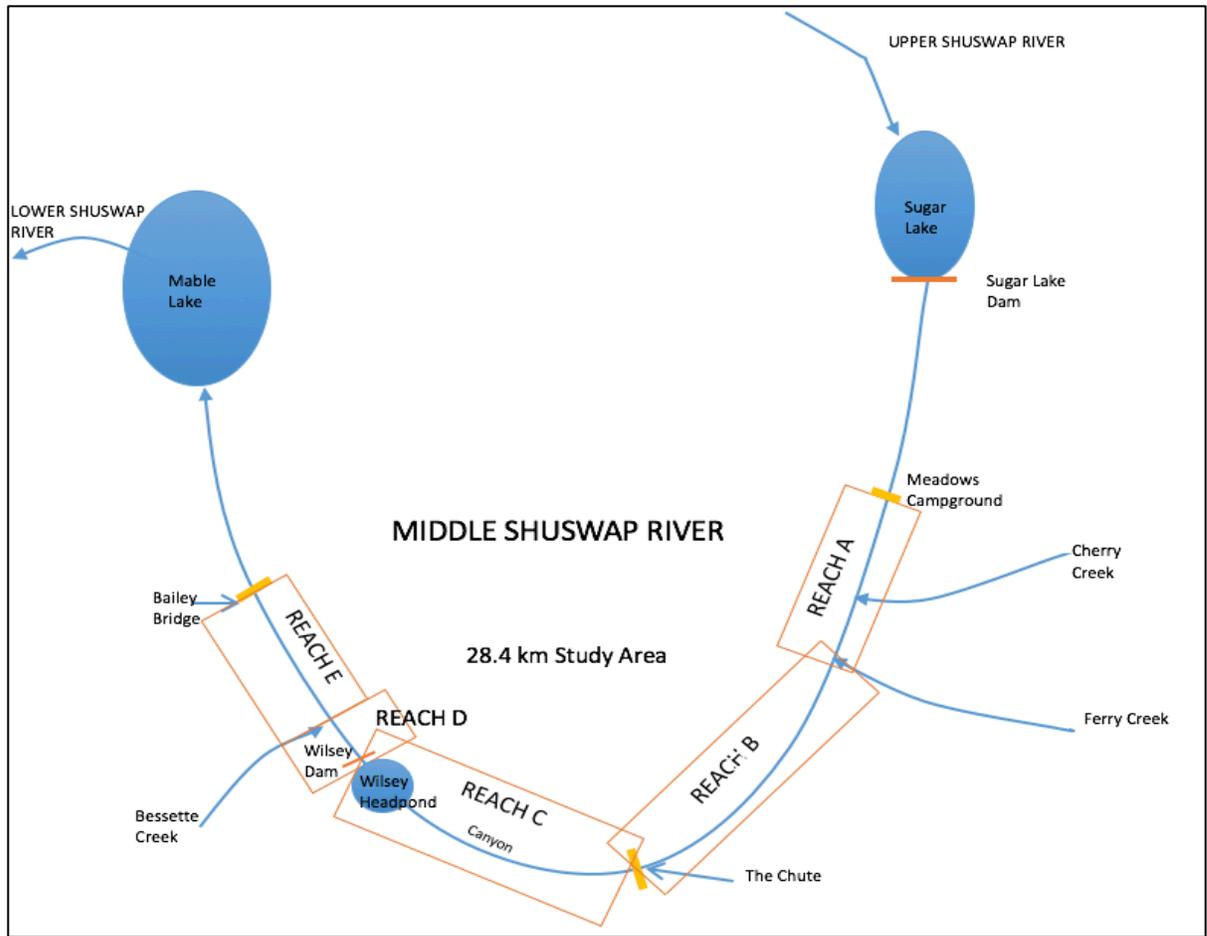


Figure 26. Reach breaks used in the assessment of downstream fining changes on the Middle Shuswap River, British Columbia; not to scale.

Determining the presence of a downstream fining trend was undertaken in support of Objective 1 (Section 1.2). The median grain sizes from 53 glide facies were used in determining if the 28.4 km study area exhibited a downstream fining trend (Figure 27). ΨD_{50} was plotted against downstream distance relative to position 0 m at Wilsey Dam. Negative distance values on the x-axis move away from Wilsey Dam in the upstream direction whereas positive values move downstream of Wilsey Dam.

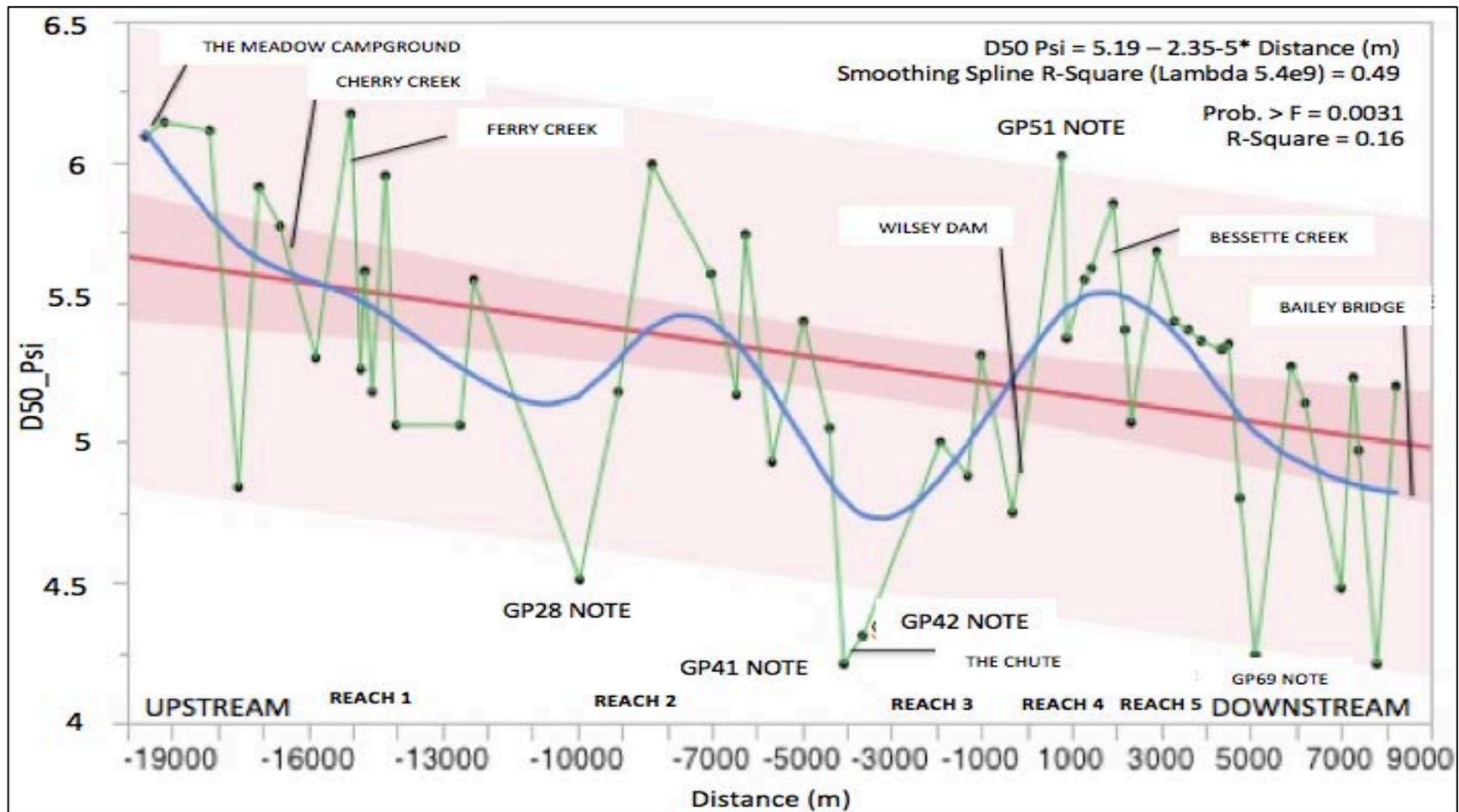


Figure 27. Change in D_{50} Psi over the 28.4 km study area with 90% confidence with a linear fit (dark red line) and smoothing spline fit (blue wave line) with $\lambda = 5.4e^9$ for the Middle Shuswap River, British Columbia. Darker confidence band is for the mean value of y for a given value of x whereas the lighter confidence band is the confidence interval for a single value of y for a given value of x . Black dots represent automated grain sizing data. GP28 occurs in a depositional zone after a 1.35 km glide. GP41 and GP42 occur upstream and downstream of the Chute, respectively which are both depositional areas. GP51 is the degraded sample site below Wilsey Dam. GP69 is challenging to explain and could have experienced selective gravel supply from an upstream gravel bar prior to sampling.

A downslope direction of the fit indicates that the MSR glide facies follow a downstream fining trajectory, with larger grains at the upstream extent of the study area and smaller grains at the downstream end. The dark red confidence bands around the fitted line represent the 90% confidence interval for the expected mean of y for a given value of x , for all values of x . The lighter (pink) confidence band represents the 90% confidence interval for a single predicted value of y for a given value of x , for all values of x (University of Tennessee 2012; JMP 2014). Most of the measurements fall within this latter confidence band, with a few noteworthy exceptions (discussed below).

A smoothing spline function (blue line) was applied to the scatter plot so a smoothing curve could help identify an overall trend in the noisy data points and to see if any relationship existed between ΨD_{50} and downstream distance. An R -value of 0.49 was observed with a λ value of 5.4×10^9 . The overall slope of curve indicates that the largest grain sizes are found near The Meadows Campground and decrease steadily towards two glides downstream of the Cherryville Golf Course at GP28. GP28 is at the downstream end of a 1.35 km reach at slope 0 which may suggest the presence of fines. Downstream of GP28, there is a slight increase in grain size through a reach over the next two sites (GP30 and GP31). After GP32, there is a downstream fining trend towards the toe of the Chute. Three sample sites downstream of the Chute toe were removed from analysis during GSD data analysis because of poor image quality but were relatively coarse. Slight coarsening observed in the λ model downstream of the Chute occurs within the backwater zone above Wilsey Dam, after which coarsening continues immediately downstream of the dam until the Bessette Creek confluence. Downstream of Bessette Creek, surface D_{50} resumes fining until the Baily Bridge. This is likely the result of a large contribution of fine grained sediment introduced to the system from Bessette Creek as demonstrated by bedload measurements; the gravel bedded section of the river moves into the upper floodplain within this reach.

3.3.1 Tributaries

Three major tributaries enter the MSR within the study area. GSD upstream and downstream of the three tributaries falls within the 90% confidence interval of the predicted y -values

(lighter confidence band). D_{50} PSI values upstream and downstream of Cherry Creek occur near the linear fit suggesting sediment loading from Cherry Creek does not significantly influence the downstream fining trend. Likewise, Ferry Creek occurs within the 90% confidence bands and therefore does not have a significant influence on the downstream fining trend. Fine sediment is observed downstream of both tributaries: 0.75 km downstream of the Cherry Creek confluence and 0.07 km downstream of the Ferry Creek confluence. Downstream of these glides with finer sediment, subsequent sites are slightly coarser. This peak and trough variation in measured GSD occurs throughout the study area.

3.3.2 The Chute

There is one geomorphic knickpoint in the MSR referred to locally as “the Chute.” Large sand and gravel bars occur upstream of the chute in a shallow sloped reach approximately 1.2 km long, a zone of sand and gravel deposition (Figure 28). GP 41 upstream of the Chute was sampled within a depositional zone that contained higher amounts of fine sediment (by observation) than other sites upstream of Wilsey Dam.



Figure 28. View west and downstream of bars within 450 m of the Chute crest and of 1.36 m high sand and gravel deposits upstream of the Chute.

3.3.3 Dam & Downstream

Below Wilsey Dam, one sample (GP51) falls outside of the 90% confidence interval. Downstream of GP51, substrate is less coarse and falls within the 90% confidence band. D_{50} downstream of Wilsey Dam is significantly coarser than upstream of the dam within the model reach, from the upstream extent of the headpond backwater to the Bessette Creek confluence.

GP69 occurs below the 90% confidence interval in Figure 27 and is challenging to explain. It is possible that increased fine grains were supplied from a large gravel bed upstream or that the lower Psi value could be attributed to variation in the site selected for sampling or from sampling error (e.g., sample collected too far upstream in the glide facie).

Reach differences are represented by box and whisker plots, Student's T-Test and Tukey-Kramer Honest Significant Difference (HSD) tests (Figure 29)

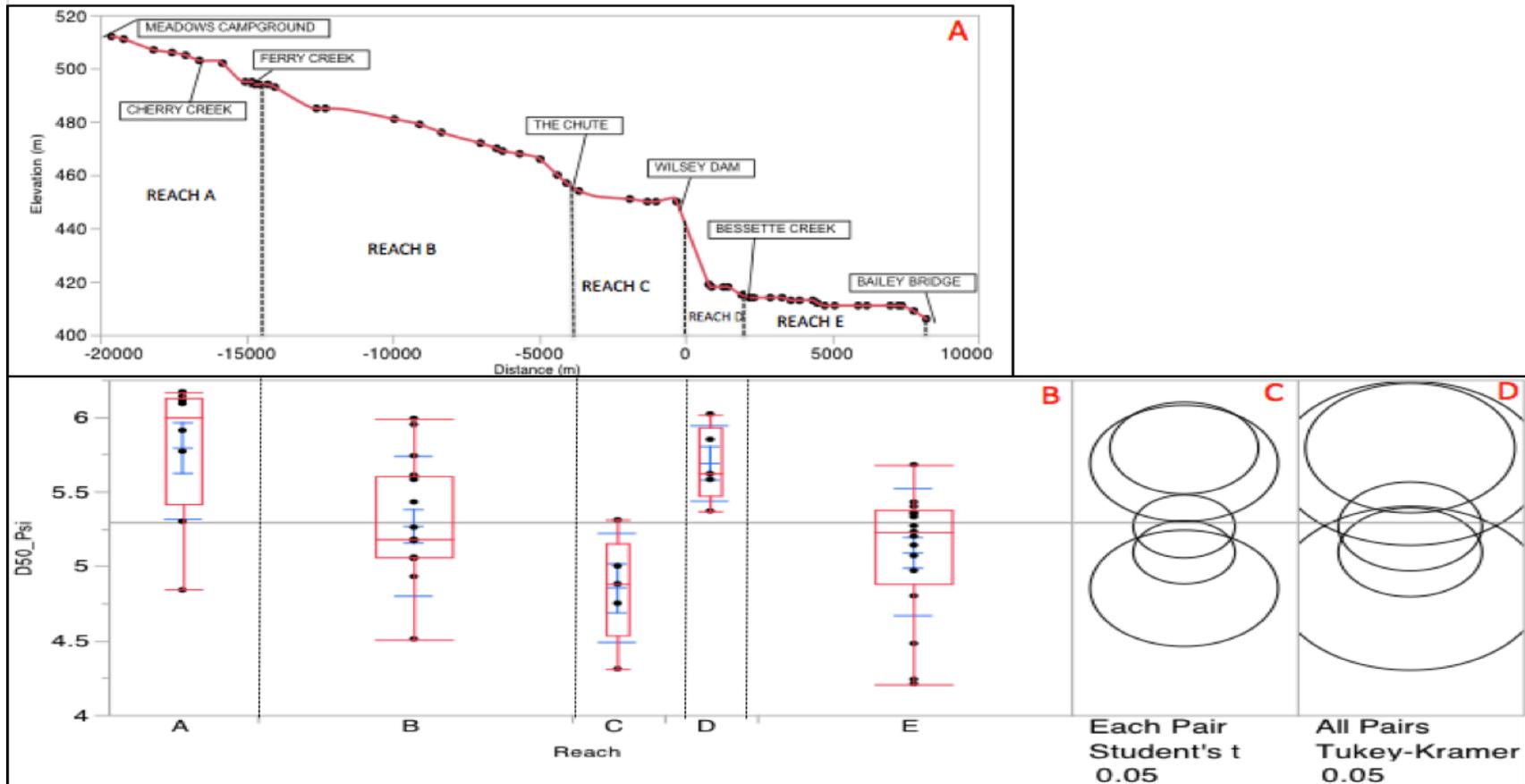


Figure 29. Differences between five reaches in the Middle Shuswap River study area. Inset A: a scatter plot showing elevation change over distance with the reach names and breaks identified. Inset B: box and whisker plots of the 5 reaches. Inset C: Student's T Test at 95% confidence illustrating differences between reaches. Inset D: Tukey Kramer HSD Test at 95% confidence illustrating differences between reaches. The further the circles in Inset C and D are from each other the greater the difference between reach. The black line through Insets B, C and D represents the mean between all sites, approximately 5.30 Psi. For Inset B, the red line inside the box plot is the median for the reach (e.g., Reach 2 is ~5.23 Psi), the top of the box is the 3rd quartile whereas the bottom of the box is the 1st quartile, the distance between the 1st and 3rd quartile is the interquartile range and the whiskers on the box extend to the upper and lower data points in the set (i.e., the minimum and maximum Psi sizes within the reach). For Inset B, the centre blue line represents the mean whereas the outer blue lines are the standard deviation. The inner blue lines around the mean are the mean error bars.

From the box and whisker plot (box distribution of data points and upper and lower quartile whiskers) in Figure 29, it is evident that Reach D, between Wilsey Dam and the Bessette Creek confluence, is coarser than the surrounding reaches and most similar to the coarsest reach above the Ferry Creek confluence (Reach A). This is likely the result of insufficient sediment recruitment from the aggrading headpond. The Student's T and Tukey-Kramer HSD tests inform further delineations between reaches. The angles of the circles indicate whether the means are statistically significant. Circles for means that are significantly different either overlap slightly or not at all. Circles for means that are similar overlap and create angles greater than 90 degrees. Results are summarized below.

3.3.3.1 Student's T-Test

The Student's T-Test (Table 13) was used to determine whether the five study sub-reaches were statistically similar with 95% confidence. Student's T-Test can be used to determine which of the 5 reaches have statistically similar means by testing each mean independently. Reach 1 (5.79 Psi), the most upstream reach, is significantly different from reaches 2 (5.27 Psi), 3 (4.85 Psi), 4 (5.69 Psi) and 5 (5.09 Psi) as it was measured as the coarsest substrate. Overall, Reach A and B, the coarser upstream reaches are most similar to Reach D downstream of Wilsey Dam. Reach D, immediately downstream of Wilsey Dam to the confluence with Bessette Creek, is significantly different from neighbouring reaches C (upstream of Reach D) and E (downstream of Reach D).

Table 13. Connecting Letters Report for Student's T Test for Reaches A, B, C, D and E within a 28.4 km study area in the Middle Shuswap River, British Columbia.

Reach Level				Mean Psi
A	A			5.79
B		B	C	5.27
C			C	4.85
D	A	B		5.69
E			C	5.09

3.3.3.2 Tukey-Kramer HSD Test

The Tukey-Kramer HSD Test (Table 14) was used to determine whether the five sub-reaches were statistically similar with 95% confidence by comparing all means together.

Table 14. Connecting Letters Report for Tukey-Kramer HSD Test for Reaches A, B, C, D and E within a 28.4 km study area in the Middle Shuswap River, British Columbia.

Reach Level				Mean Psi
A	A			5.79
B	A	B	C	5.27
C			C	4.85
D	A	B		5.69
E		B	C	5.09

Reach A is significantly different from Reaches C and E, but not significantly different from Reach D and Reach B. Reach C is the backwater reach above the dam where fine-grained sediment is deposited. Reach E is the farthest downstream and therefore at the terminus of the finding trend. Reach D (the coarse sediment zone below the dam) is significantly different from Reach C (the fine sediment zone above the dam) but not Reach E.

Results illustrate a dominant downstream fining trend in the river for the truncated grain size distributions from glide facies sampled. From reaches A to B to C a downstream trend exists, with A coarser than C. Reach C (the headpond and backwater) is much finer than Reach D. From Reach D to E a fining trend occurs with a mixture of different grain sizes as the river transitions from a gravel bedded riffle pool morphology to wider channel widths at the upstream beginning of the floodplain (i.e., downstream of the Baily Bridge and study terminus).

3.4 AVAILABLE SALMON SPAWNING HABITAT

On the basis of the D_{50} from glide facies from this research and prior habitat mapping undertaken by Guy and Uunila (2002) discussed in Section 2.8, estimates of salmon spawning habitat were made. Total spawning habitat was determined to be approximately 387,265 m² above Wilsey Dam and 190,906 m² downstream of Wilsey Dam (above Bailey Bridge). Tables listing the habitat polygon number, site number (GP#) and corresponding spawning areas for habitat upstream and downstream of Wilsey Dam are listed in Appendix 7 and 8, respectively, with accompanying maps in Appendix 9.

Table 15 presents estimates of total salmon spawning habitat from this study in 2012 compared with previous estimates from Guy and Uunila (2002) for the study area. Coho and chinook spawning habitat upstream of Wilsey Dam is approximately 80,725 m² and 258,269 m², respectively, with 48,271 m² of overlapping habitat for both species for a total spawning area of 387,265 m². Total coho and chinook spawning habitat downstream of Wilsey Dam is 36,997 m² and 105,286 m², respectively, with 48,623 m² of spawning habitat suited to both chinook and coho. The total spawning area below Wilsey Dam is equal to 190,906 m². Total spawning habitat in the 28.4 km study area equals 578,171 m². The 2012 estimate is approximately one-half of the estimate from 2002.

Table 15. Comparison of 2002 and 2012 estimates of anadromous salmon spawning habitat in the Middle Shuswap River, British Columbia.

Year	2012 US	2012 DS	2012 Species Totals (m ²)	2002 US (m ²)	2002 DS (m ²)
Species	(m²)	(m²)	Totals (m²)	(m²)	(m²)
Coho	80,725	36,997	117,722	-	-
Chinook	258,269	105,286	363,555	-	-
Chinook & Coho	48,271	48,623	96,894	-	-
Total US/DS Habitat	387,265	190,906		765,000	492,000
Total Habitat	578,171			1,257,000	

3.5 SEDIMENT TRANSPORT MODELING

Determining the fate of reintroduced fine sediment and augmented gravel on salmon spawning habitat downstream of Wilsey Dam was the aim of Objective 3. This objective was assessed using a 1D sediment transport model described in Section 2.9.

Changes in D_{50} within the 1.2 km spawning reach between Wilsey Dam and the Bessette Creek confluence for eight model runs (PAVE 1A, 1B, 2A, 2C, 3A, 3B, 4A, 4B) are presented in Figure 30. D_{50} is reported for twelve equidistant cross-sections throughout the 1.2 km reach (i.e., 100 m spacing between cross-sections) at the conclusion of the ten-week model run.

The target model result is a post-freshet substrate composition that is within an acceptable range of D_{50} for both spawning coho and chinook (from Tables 7 and 8). A target D_{50} for chinook is 50 mm (range = 34 mm to 65 mm). A target D_{50} for coho is 27 mm (range = 19 mm to 35 mm).

None of the model runs yielded a D_{50} of 34 mm, which is the middle of the grain size range that can accommodate both coho and chinook spawning, although PAVE 4B at cross-section 12 was close. PAVE 3A and PAVE 3B result in a riverbed substrate generally well suited to the spawning needs of coho ($D_{50} = 27$ mm) but not chinook. PAVE 2B result in a riverbed substrate generally well suited to the spawning needs of chinook ($D_{50} = 60$ mm), but not coho. The riverbed condition from runs PAVE 1A and 1B are considered too coarse for the spawning needs of both chinook and coho ($D_{50} = 135$ mm). Model runs PAVE 4A and 4B produce bed conditions well suited to the requirements of both chinook and coho depending on cross-section. Detailed model results are presented in Appendices 11 to 17.

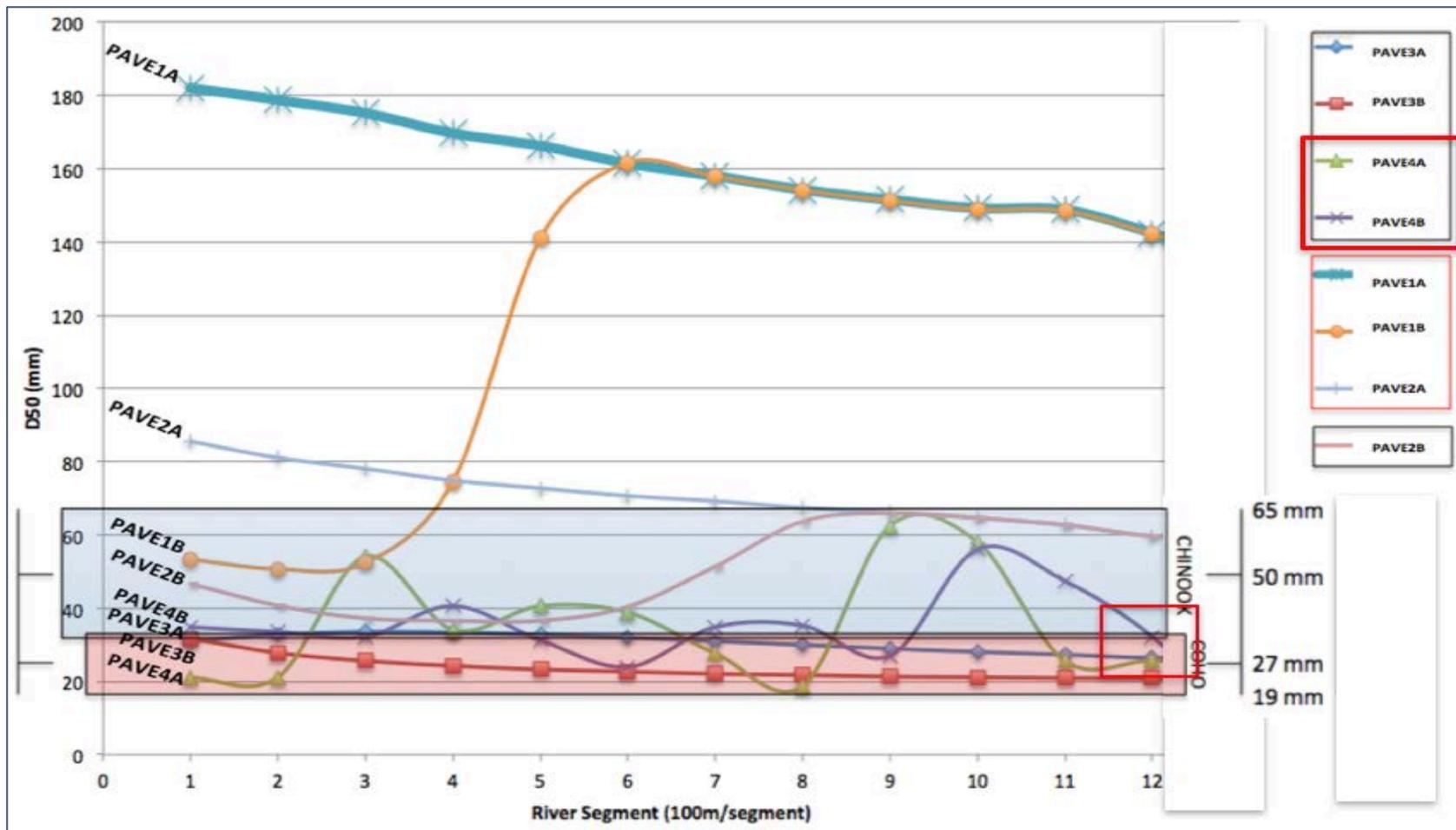


Figure 30. Changes in D₅₀ within 1.2 km spawning reach between Wilsey Dam and the Besette Creek for Pave 1 to Pave 4 model runs. Model runs resulting in spawning habitat suitable to either coho or chinook are highlight in the legend with a black box. Model runs resulting in a D₅₀ too coarse for the spawning needs of salmon are highlighted in the legend with a red box, including PAVE 2A for which more than half the study reach riverbed was too coarse. The blue rectangle on the graph indicates an ideal range of D₅₀ of spawning gravel size for chinook and the red rectangle an ideal range for coho.

3.5.1 Initial Model Run with No Sediment Inputs

The model was tested with no sand or gravel inputs using the surface GSD of the PAVE 4 dataset to determine whether the bed surface would reorganize itself as a consequence of the freshet flows. Even though the river reach below Wilsey Dam is known to be somewhat stable, it was not evident whether the use of the GP52 grain size distribution ($D_{50} = 13.5$ mm) at all cross-sections in the model would reproduce such stability. This approach is consistent with Fuller et al. (2016) who allowed the same model to “equilibrate to the imposed conditions” by letting the model run without inputs. Figure 31 shows the change in D_{50} with no sediment inputs during the initial model run while Figure 32 shows the change in bed elevation. A coarsening of the bed occurs in the first seven cross-sections (X1 to X7) from approximately $D_{50} = 35$ mm up until Day 30 to approximately $D_{50} = 50$ mm for the remainder of the run. Without sediment recruitment from upstream, there is a broad tendency toward coarsening across most cross-sections and an accompanying reduction in bed elevation. The winnowing of fine sediment from the bed material may explain the increase in D_{50} from 13.5 mm at the start of the model run to near 50 mm at the upper seven cross-sections.

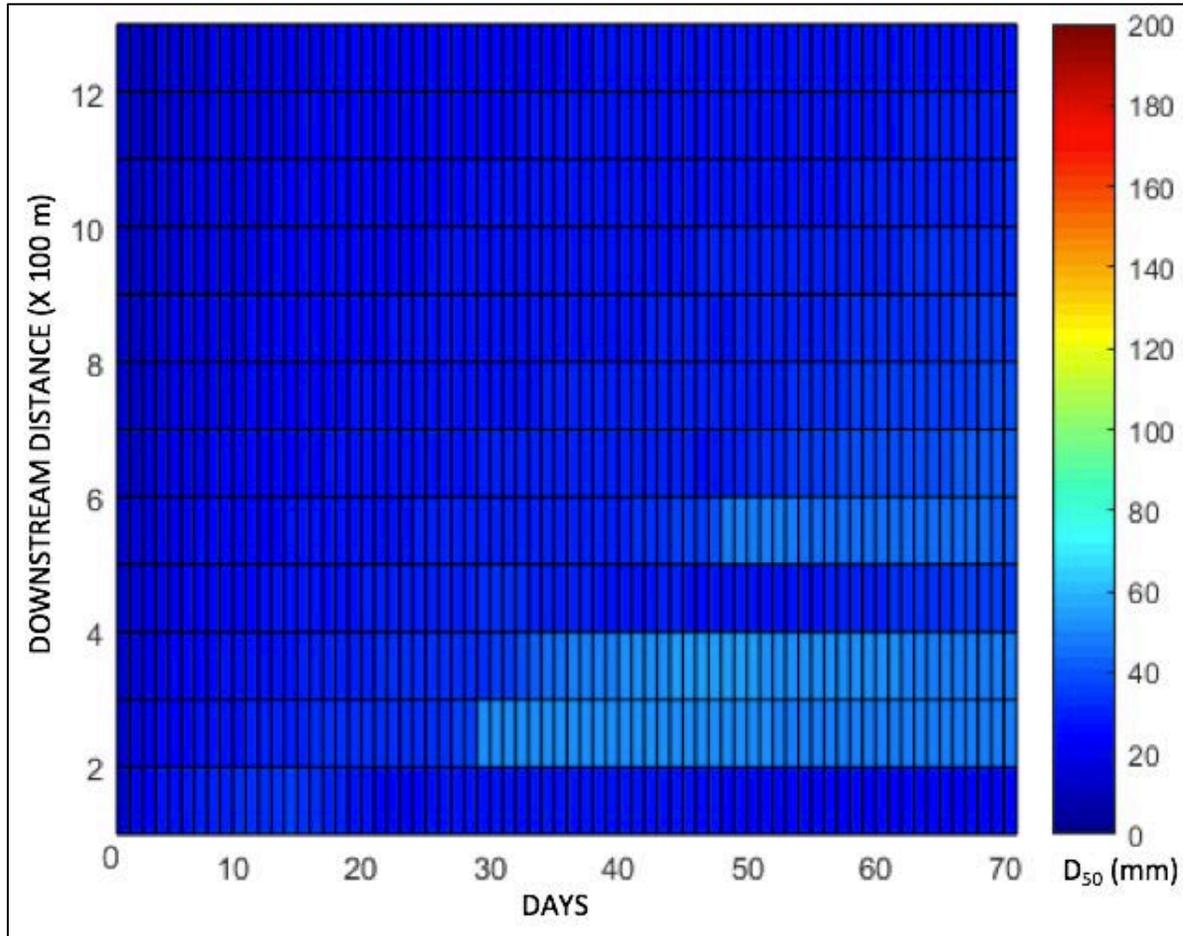


Figure 31. Daily change in bed surface D_{50} (mm) derived for the model reach (from PAVE 4 dataset) during a 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. Sand and gravel inputs omitted and timesteps eliminated from model to show how it runs without inputs.

Although change in D_{50} resulted from a model run with no sediment inputs, riverbed elevation remained relatively unchanged as shown by the uniform colour bands in Figure 32 where colour does not change significantly over the 70 days. X1 to X5 experience approximately 0.5 m drop in elevation (e.g., X3 drops from 418 m to 417.5 m). Elevations in X6 to X12 remain relatively consistent (likely the result of sediment recruitment from upstream cross-sections).

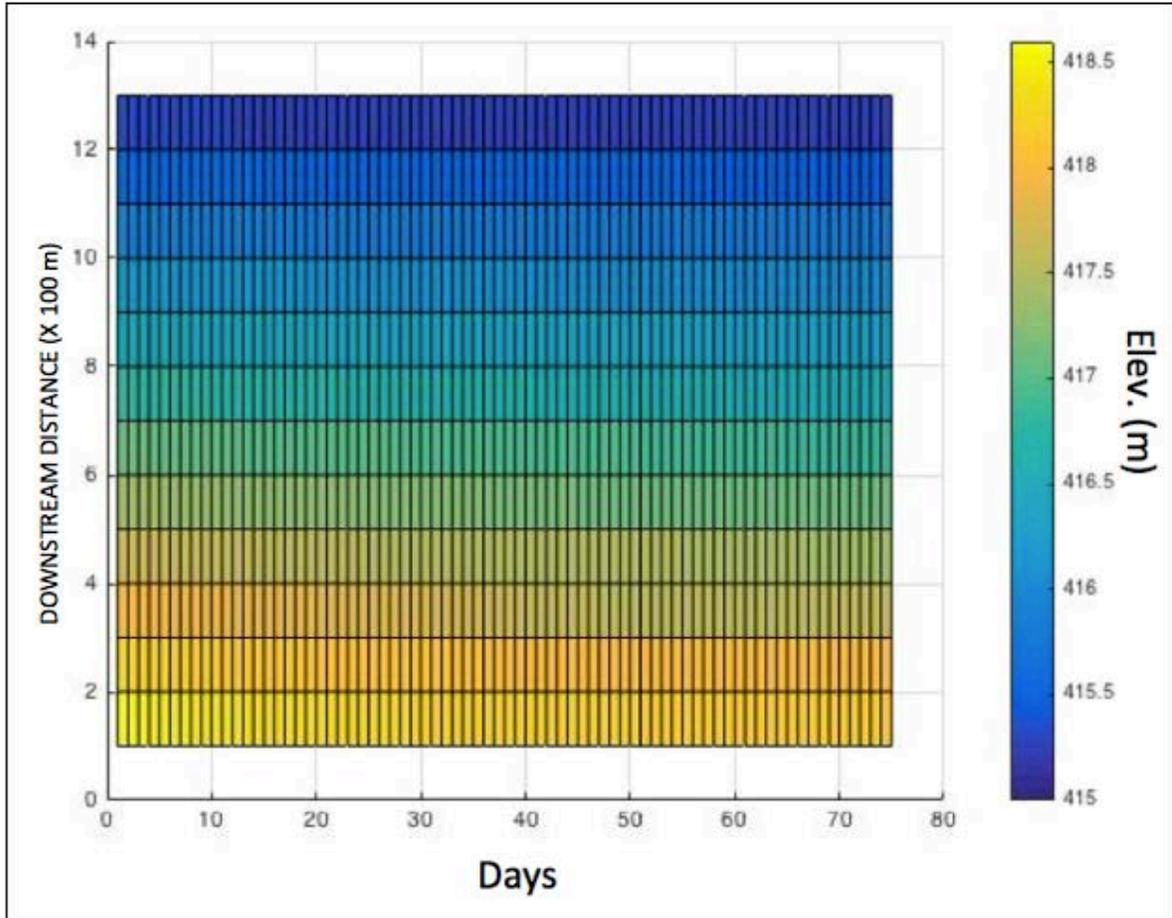


Figure 32. Daily change in bed surface elevation in the model reach (PAVE 4 dataset) for a 10-week freshet on the Middle Shuswap River, British Columbia. Sand and gravel inputs omitted and timesteps eliminated from model. Upstream segments experience channel bed degradation where as downstream segments remain stable.

Modeling results without sediment inputs suggest that the reach below Wilsey Dam should experience erosion during freshet flows with concomitant coarsening of the bed surface. This is likely due to the selection of the GP52 grain-size distribution as the starting condition for the bed, when in fact, the bed materials immediately downstream of Wilsey Dam are known to contain large boulders and cobbles not captured in the GP52 GSD. Nevertheless, these initial runs provide a good sense of the general stability of the model in simulating sediment transport conditions below the dam. The next section considers simulations that incorporate sediment feed from upstream (sand reintroduction and gravel augmentation), as might occur if the dredge material from the headpond or augmented gravel were reintroduced downstream of the dam.

3.5.2 PAVE 1A & 1B

PAVE 1 model runs use the GSD sampled from site GP52 with additional large grains added (see Table 11). Smaller grains are truncated at 8 mm with no additional fines included as was done with the PAVE 3 dataset. Twelve larger sediment particles between 128 mm and 512 mm were added to the PAVE 1 dataset to represent an estimate of larger grains observed within the field and not captured by the underwater AGS method used. The intermediate axis of these large grains was measured during AGS sampling at GP51.

Model results for PAVE 1A (Figure 33) indicated a significant coarsening influence due to the introduction of sand ($D_{50} = 0.5$ mm) in weeks three and four. During the two-week initial bed adjustment period, when background bedload contributions equal zero, the river maintains a constant D_{50} unlike the initial runs (without sediment feed) using GP52 without large cobbles added to the bed mixture. Once sand is introduced from upstream in PAVE 1A, there is a wave of bed coarsening that moves progressively downstream and becomes more evident in time. The coarsening trend persists well after the cessation of sand feed at the start of week six, with significant changes apparent through to week seven. Although such bed coarsening as a consequence of sand introduction seems counter-intuitive, the mobilization of coarse materials with sand feed has been noted by other researchers (e.g., Wilcock et al. 2001; Venditti et al. 2010). The upstream segment of the reach significantly coarsens from $D_{50} = 40$ mm to $D_{50} = 180$ mm.

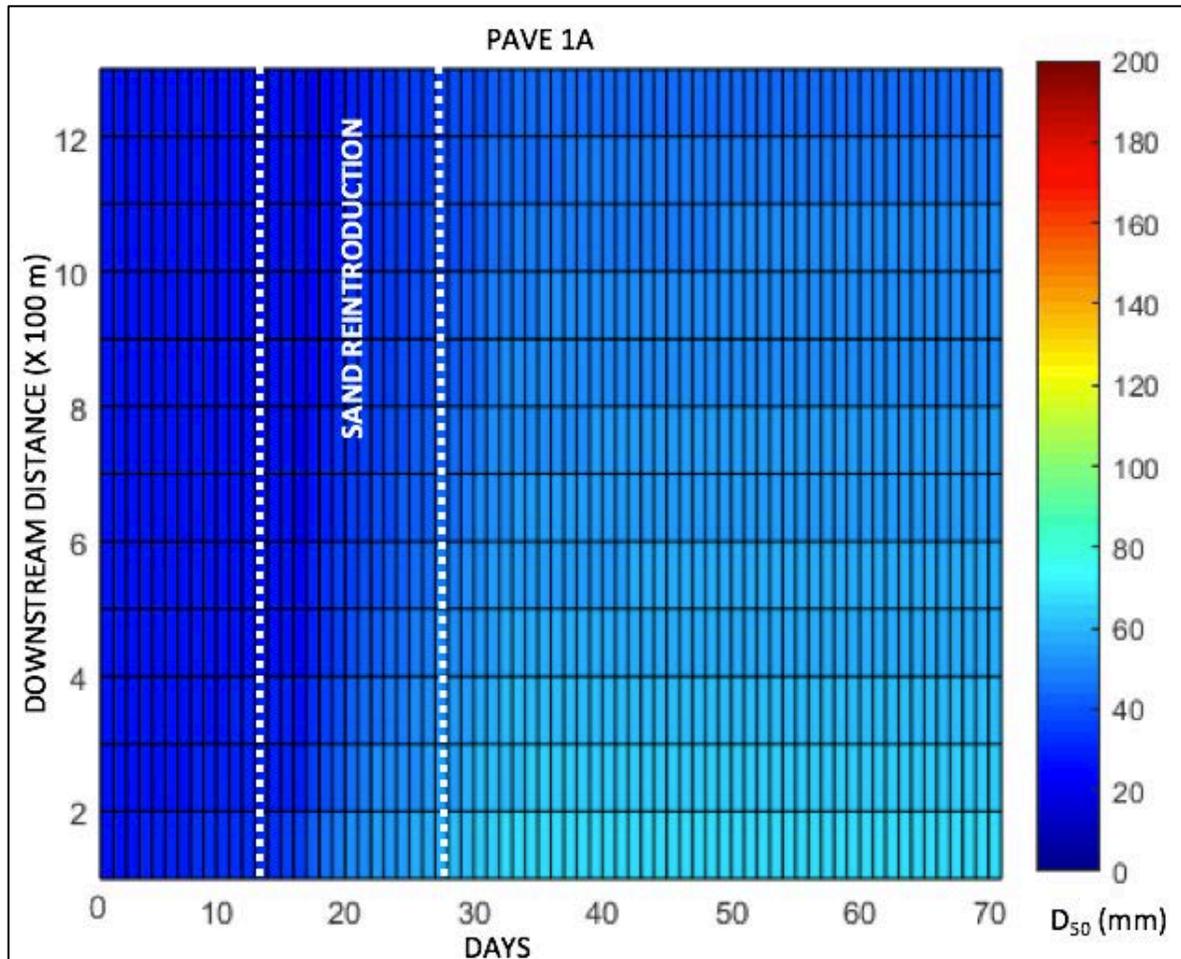


Figure 33. Daily change in bed surface D_{50} (mm) for model reach (PAVE 1 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. $10,000 \text{ m}^3$ of sand is introduced equally between Week 3 and Week shown by white hatched lines. Colour scale (D_{50}) indicates high coarsening relative to starting D_{50} (15 mm).

The PAVE 1B model run (Figure 34) maintains the same conditions as PAVE 1A except that augmented gravel is introduced in weeks 7 and 8. This is done to see how the bed responds to gravel addition in an effort to reduce coarsening and potentially mitigate bed erosion caused by the introduction of sand in weeks 3 and 4. The addition of $5,000 \text{ m}^3$ of gravel ($D_{50} = 13.9$ mm; from GP50) reduces the D_{50} in the upstream cross-sections from approximately 180 mm to below 40 mm. The likely explanation is the gravel coming from upstream is effectively deposited on the bed, in the interstices and on the surface of larger gravels and cobbles, within a downstream distance of only 300 to 400 m. The deposition of re-introduced gravel, with a D_{50} of 15.0 mm leads to a net fining of what was a very coarse bed surface. Farther

downstream, between X 6 to 12, the coarsening induced by earlier sand feed still persists, so there is a net coarsening in the model reach.

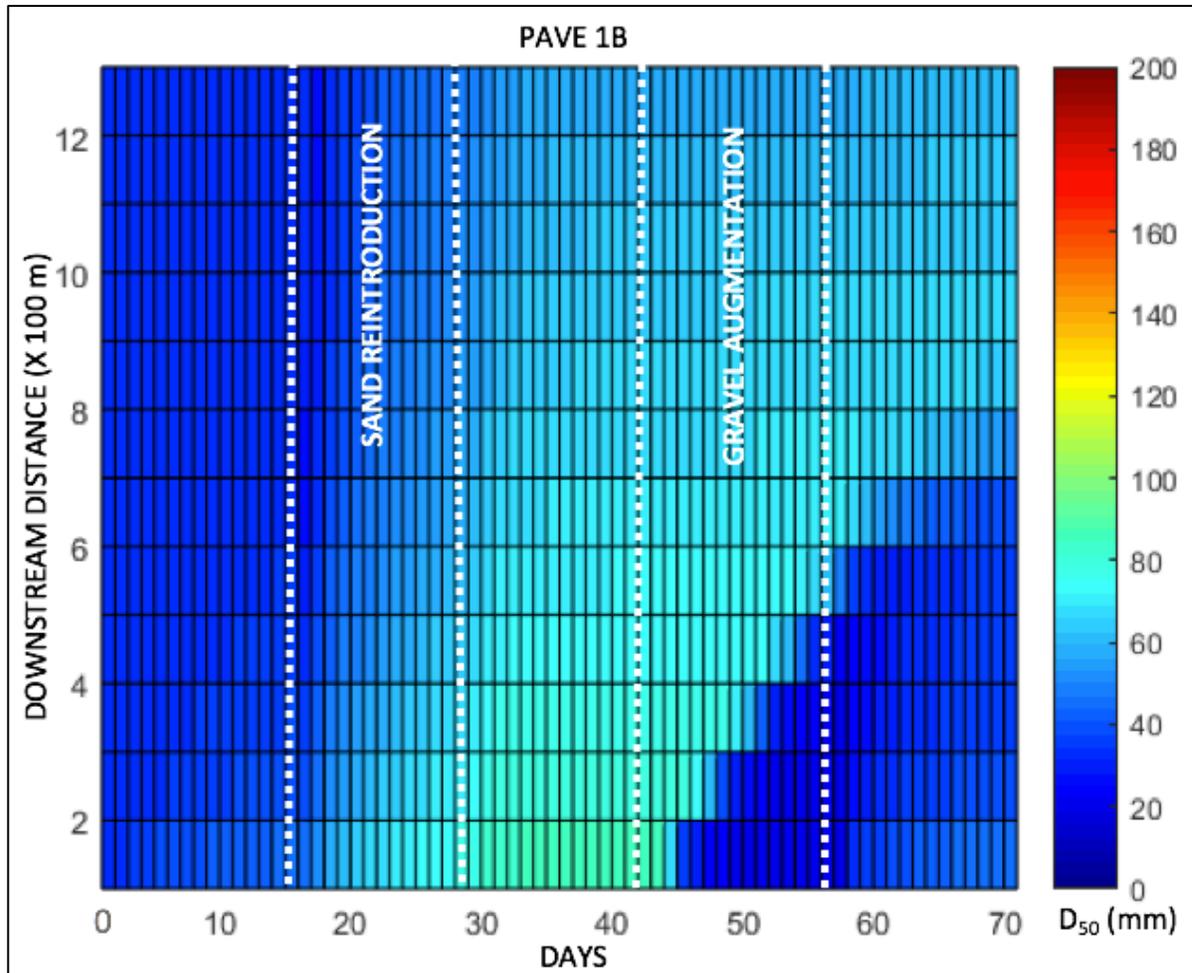


Figure 34. Daily change in bed surface D_{50} (mm) for model reach (PAVE 1 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. $10,000 \text{ m}^3$ of sand is reintroduced between weeks 3 and 4 and 5000 m^3 of gravel is augmented equally in weeks 7 and 8 shown by white hatched lines. Colour scale (D_{50}) indicates bed erosion is cross-sections 7 to 12, but fining in the upstream 6 cross-sections as a result of gravel inputs.

3.5.3 PAVE 2A & 2B

The PAVE 2 model run uses a modified GSD based on GP52 with the inclusion of coarse but not fine grains. The PAVE 2 dataset is truncated at 11.31 mm and contains many larger grains up to 512 mm, more than any of the other PAVE datasets (i.e., $D_{50} = 33.0 \text{ mm}$). The reason for the larger truncation value at the fine end of the GSD (11.31 mm vs. 8 mm) and

the addition of coarser material to the GP52 dataset was because this model simulation placed more emphasis on coarse material found in the upstream sections of the model reach. This dataset therefore most accurately reflects the reach around GP51 just downstream of the canyon below Wilsey Dam. Here, large cobbles and boulders were observed but not captured by Underwater AGS. In addition, minimal surface fines were present, as shown in Photograph 6. Thus, the intent of these model runs was to simulate the conditions immediately below the dam rather than farther downstream, closer to Bessette Creek.



Photograph 6. View east towards the MSR immediately downstream of the canyon below Wilsey Dam at site GP51. Note the abundance of cobbles and boulders; many too large to be captured by underwater AGS.

In Figure 35, the PAVE 2A data set acts similarly to PAVE 1A; riverbed D_{50} remains generally constant during the two-week initial bed adjustment period. Upon sand reintroduction, there is a minimal riverbed fining at all cross-sections before larger grains

start to mobilize. Upon completion of sand reintroduction, coarsening ends and the riverbed remains in a degraded state, not shifting to an aggrading state with the 100 cms flow.

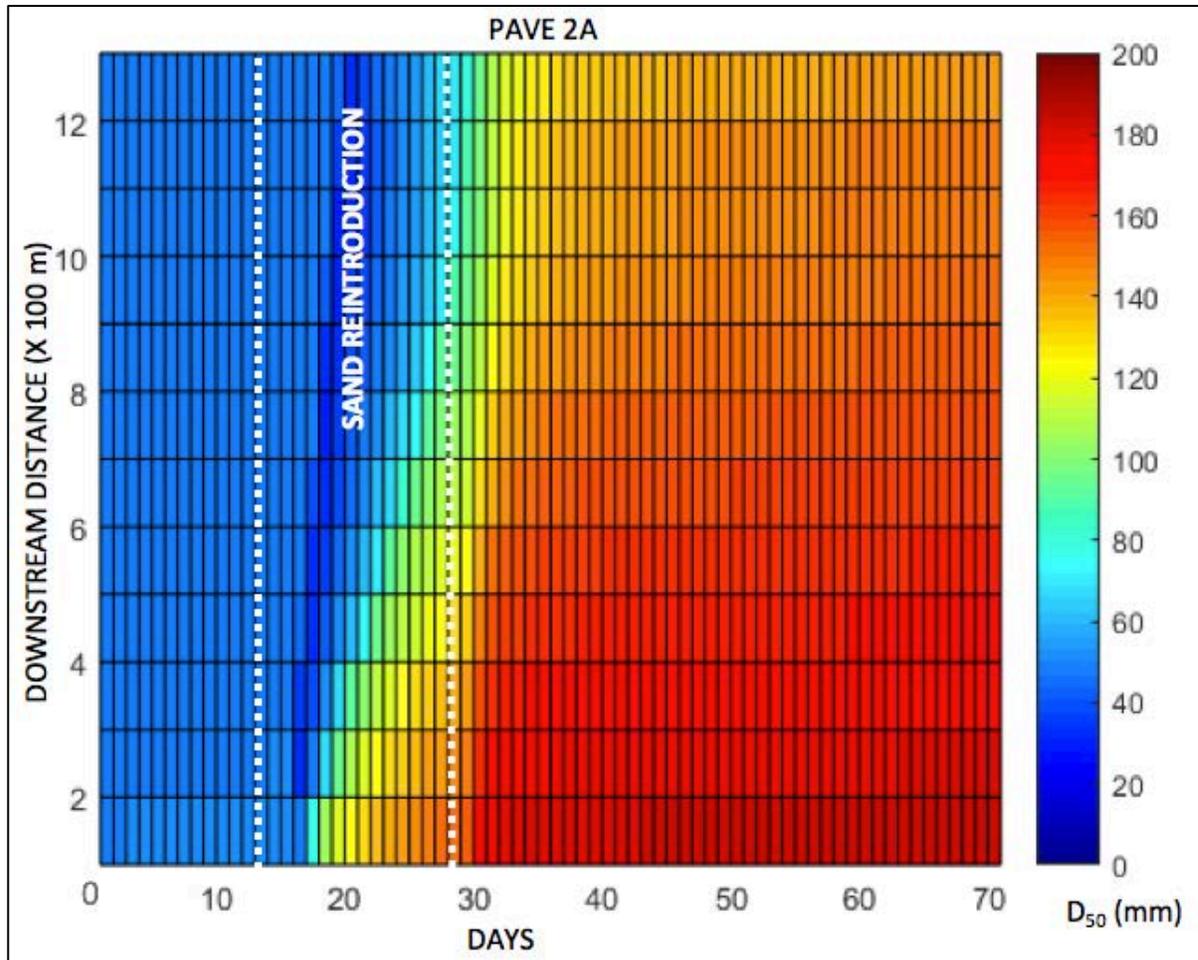


Figure 35. Daily change in bed surface D_{50} (mm) for model reach (PAVE 2 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. $10,000 \text{ m}^3$ of sand is introduced equally between Week 3 and Week shown by white hatched lines. Colour scale (D_{50}) indicates high amount of bed erosion across all 12 segments relative to starting D_{50} (33 mm).

PAVE 2B (Figure 36) had a similar coarsening trajectory to PAVE 2A until gravel was added to the model seven weeks into the run. At this point, fining of the bed occurred within the first three cross-sections upstream, going from $D_{50} = 80 \text{ mm}$ to $D_{50} < 30 \text{ mm}$. Upon completion of gravel augmentation at week eight, coarsening commenced again as gravel was entrained and transported downstream.

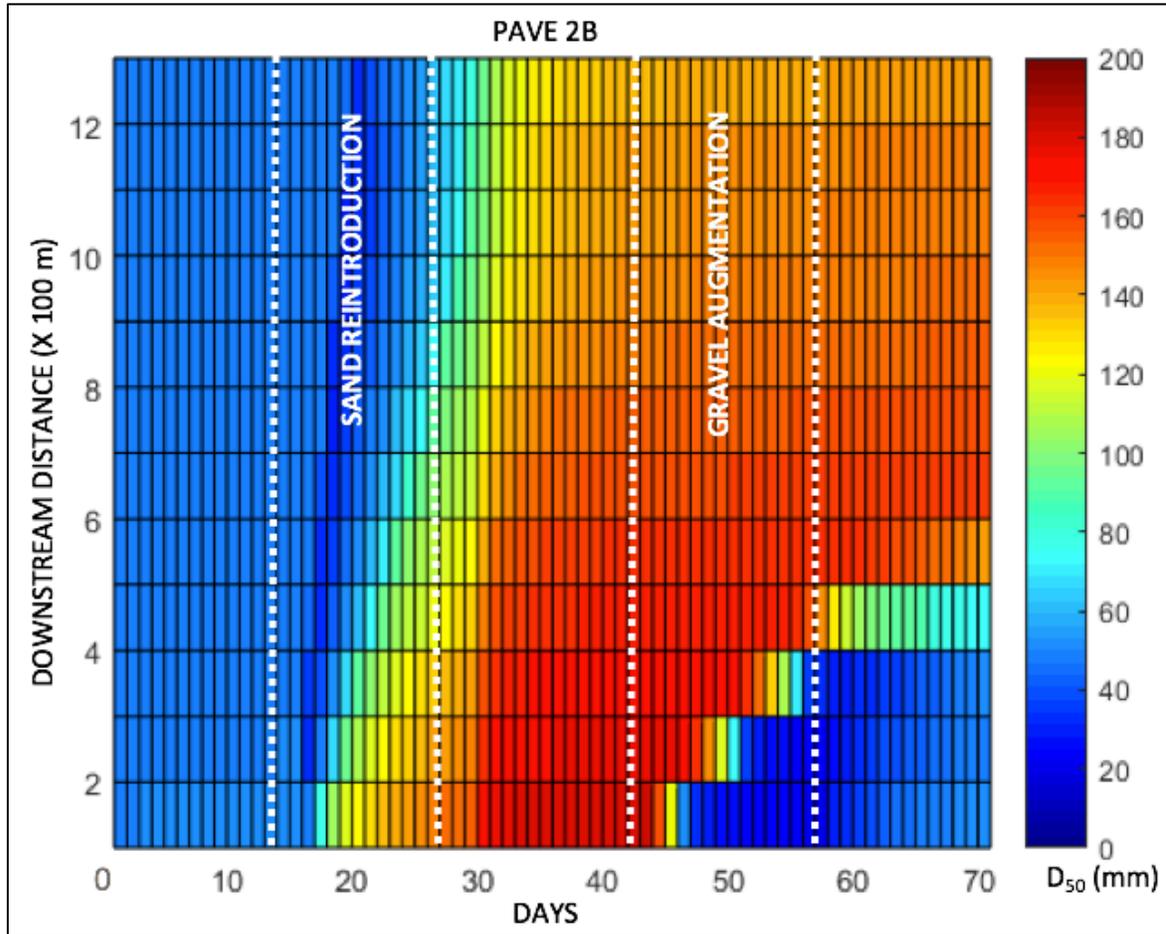


Figure 36. Daily change in bed surface D_{50} (mm) for model reach (PAVE 1 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. 10,000 m³ of sand is reintroduced between weeks 3 and 4 and 5000 m³ of gravel is augmented equally in weeks 7 and 8 shown by white hatched lines. Colour scale (D_{50}) indicates bed high amount of bed coarsening from originating bed D_{50} (33 mm) in cross-sections 5 to 12, and fining in the upstream 4 cross-sections as a result of gravel inputs.

3.5.4 PAVE 3A & 3B

The PAVE 3 model run uses median grain size from the GP52 GSD, the representative site selected to represent the 1.2 km model reach. Sand grains (D_{50} less than 2 mm) were added to the dataset as described in Section 2.4.

The PAVE 3A model run (Figure 37) shows that the two-week period without sediment feed leads to bed readjustments that yield widespread coarsening. X1 has the most extreme coarsening trend (from D_{50} 14 mm to D_{50} 32 mm), which suggests that fine-grained sediments were being winnowed from the upstream cross-sections and transported

downstream. After the initial two weeks of clear-water flows, the downstream cross-sections experienced only mild coarsening in comparison to the upstream cross-sections, which acted as the source contributing fine-grained sediments.

As soon as sand is introduced at Day 15, there is a rapid fining throughout the model domain. This suggests that the fine-grained materials introduced from upstream can be effectively transported across the reach and perhaps beyond X 12 within a 24-hour period. In addition, a significant proportion of this material must have been deposited in the model domain to yield the fining response. However, as sand feed continues for another 14 days, there is subtle, but general, coarsening of the bed surface. After completion of sand reintroduction at Day 24, the coarsening trend becomes very pronounced, and it progresses toward the end of the model run.

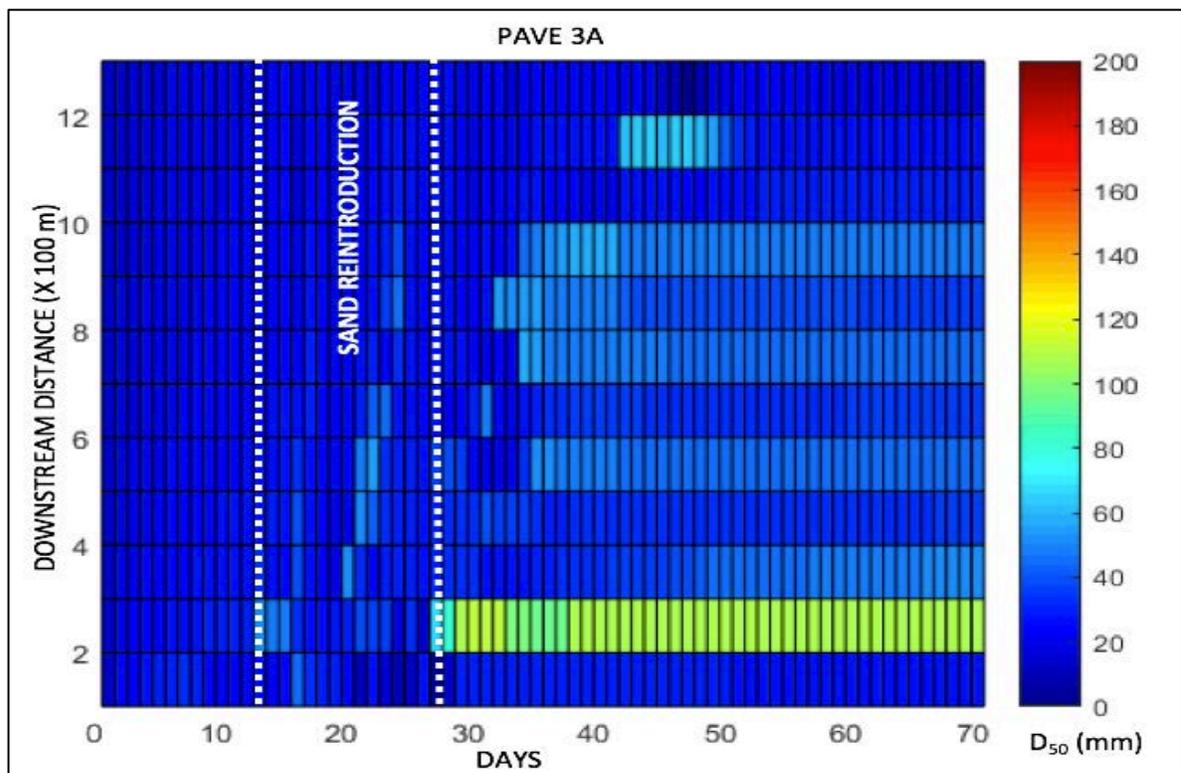


Figure 37. Daily change in bed surface D_{50} (mm) for model reach (PAVE 3 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. $10,000 \text{ m}^3$ of sand is introduced equally between Week 3 and Week 4 shown by white hatched lines. Colour scale (D_{50}) indicates high coarsening relative to starting D_{50} (13.2 mm) in segment 2, but relatively minor coarsening relative to other models run using PAVE 1 and 2 datasets.

PAVE 3B results (Figure 38) are identical to PAVE 3A for the first six weeks because the model inputs are the same. At week seven, gravel augmentation begins, and this leads to a fining trend being initiated for the upstream cross-sections even while the downstream cross-sections maintain the coarsening trend from the flushing flow period (weeks five and six). This suggests that the gravel is slow to move through the very coarse bed materials in the upstream cross-sections. As a consequence, sequential downstream cross-sections experience a fining trend from $D_{50} = 30$ mm to $D_{50} = 20$ mm. During the late flushing flows (weeks 9 and 10), the gravel material begins to translate downstream in a process that involves erosion in the upstream cross-sections (producing a coarsening trend) and deposition of the gravel material farther downstream (producing the initial fining trend during week 9). Toward the end of the model run, a general coarsening trend resumes.

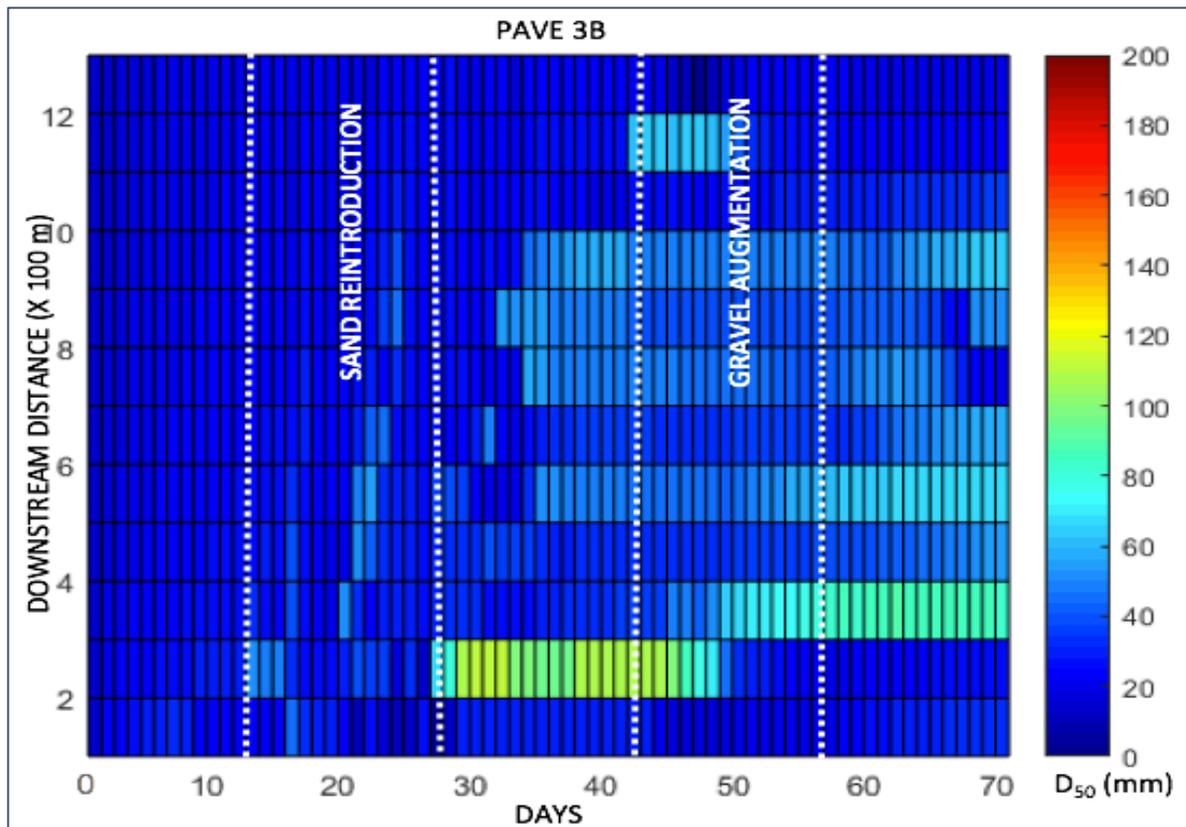


Figure 38. Daily change in bed surface D_{50} (mm) for model reach (PAVE 1 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. $10,000 \text{ m}^3$ of sand in reintroduced between weeks 3 and 4 and 5000 m^3 of gravel is augmented equally in weeks 7 and 8 shown by white hatched lines. Colour scale (D_{50}) indicates complex bed adjustments throughout the model reach. Segments 1, 2, 7, 10 and 11 have D_{50} similar to originating D_{50} (13.2 mm).

Model results from PAVE 1, PAVE 2 and PAVE 3 likely oversimplify the riverbed GSD because separately, they don't have sediment GSDs representative of grain size within the model reach. The PAVE 4 dataset presented in Section 3.5.5 uses the most representative GSD to the model reach and is used for all further analysis.

3.5.5 PAVE 4A & 4B

The PAVE 4 model runs best reflect the average grain size distributions below Wilsey Dam using the GP52 field sample. In addition, fine grains and larger grains were added to overcome the limitations of the digital methodology used to estimate GSD (see Section 2.4).

The PAVE 4A run (Figure 39) shows that the first two weeks during the initial bed adjustment period yielded coarsening, mostly in the upstream cross-sections. The greatest coarsening was in cross-sections X1 to X3, changing from $D_{50} = 14$ mm to approximately 35 mm. With sand reintroduction upstream, there was pronounced coarsening of the bed sediments, which moved downstream and became more pronounced with time. A number of complex riverbed responses are apparent, which provide a significant contrast to the results obtained in PAVE 1, 2, and 3:

- X1 remains relatively coarse but without significant changes in time, likely because much of the fine-grained sediment being introduced from upstream maintains a quasi-steady state in which neither deposition of fines nor mobilization of coarse grains occurs. In essence, a net transport surface is established in the upper parts of the model reach.
- The middle cross-sections experience extreme changes in bed composition, for reasons not immediately evident. However, these are very localized responses driven by sediment flux divergences from cross-section to cross-section over short time periods. In order to fully understand what drives these fluctuations in mean sediment size, shorter time steps in the model runs would be needed with a full examination of transport rates at neighboring cross-sections as well as tendencies toward erosion or aggradation.

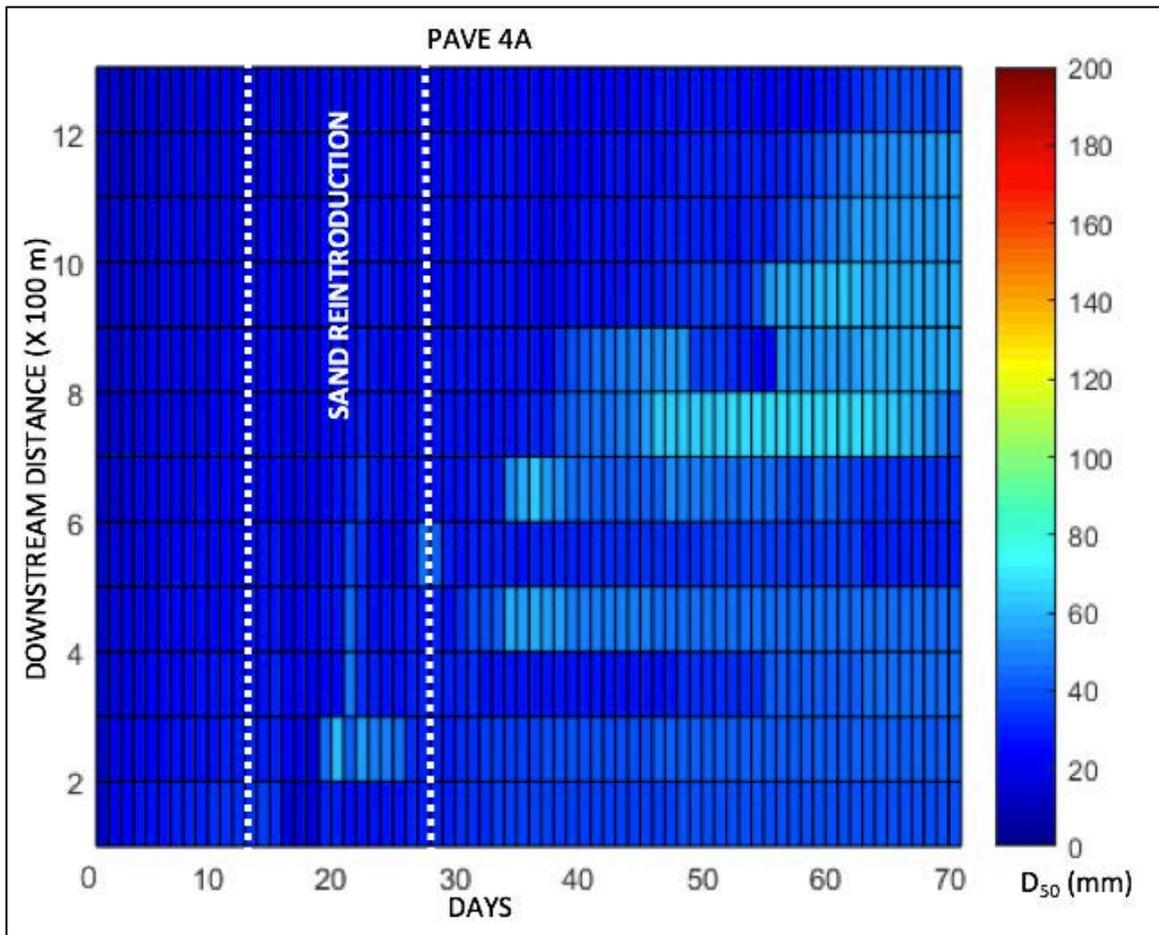


Figure 39. Daily change in bed surface D_{50} (mm) for model reach (PAVE 1 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. $10,000 \text{ m}^3$ of sand is introduced equally between Week 3 and Week 4 shown by white hatched lines. Total coarsening in the model run occurs up to $D_{50} = 80 \text{ mm}$, with numerous complex aggrading and degrading adjustments within segments.

After the end of sand reintroduction on Day 28, there is a coarsening of the bed at X1 within several days (i.e., up to approx. $D_{50} = 50 \text{ mm}$), and then the upstream cross-sections remain stable. Downstream of X4, a complex series of adjustments take place, which yield both fining and coarsening outcomes depending on which cross-section is considered. These results will be discussed in detail below along with a presentation on changes in bed elevation and transport rate.

The first six weeks of the PAVE 4B model run (Figure 40) produce responses that are identical to the first six weeks of the PAVE 4A model run, as expected. At week six, 5,000 m³ of gravel is added to the river over a two-week period. The addition of gravel results in fining at the upstream cross-sections where there was coarsening in PAVE 4A. In contrast, the downstream segments become coarser, perhaps as a consequence of larger grains being mobilized in the upper segments and being transported and deposited in the downstream segments. From X9 to X12, the resulting D₅₀ is fine, in part due to replenishment of gravel from upstream.

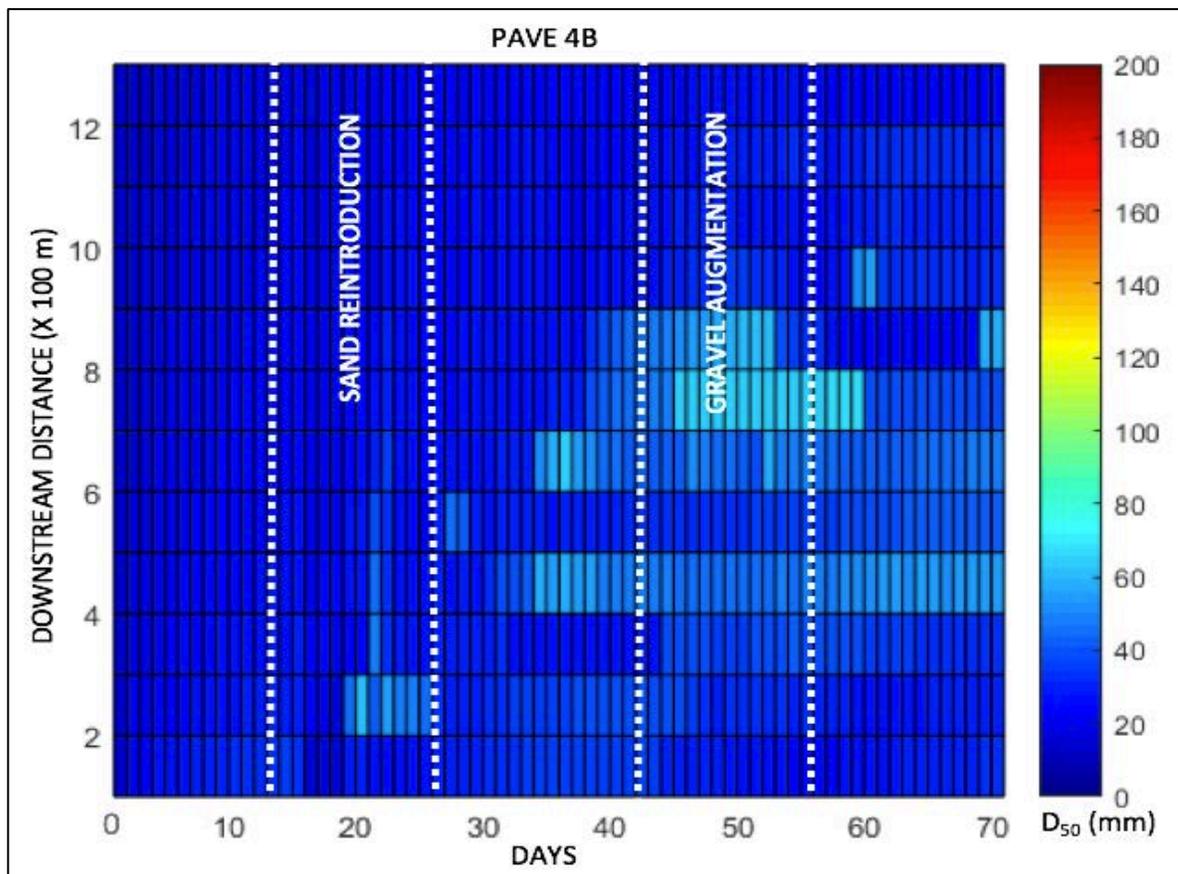


Figure 40. Daily change in bed surface D₅₀ (mm) for model reach (PAVE 4 dataset) during 10-week freshet (100 cms) on the Middle Shuswap River, British Columbia. 10,000 m³ of sand is reintroduced between weeks 3 and 4 and 5000 m³ of gravel is augmented equally in weeks 7 and 8 shown by white hatched lines. Colour scale (D₅₀) indicates complex bed aggradation and degradation between starting D₅₀ = 13.5 mm and D₅₀ = 80 mm.

3.5.5.1 ADDITIONAL PAVE 4B MODEL OUTPUTS

To best understand the sediment transport dynamics over the 10-week PAVE 4B model run, additional results were produced showing cumulative change in D_{50} , the transport probability distribution function, riverbed elevation change, sediment flux per channel width in kg/hr.^{-1} , and net channel aggradation and degradation. The complete set of all graphs from PAVE 4B can be found in Appendices 11 through 17. Selected outputs are presented below following the timeline of changes grouped into five key two-week time periods (i.e., initial bed adjustment period, sand feed, flushing flow, gravel feed, flushing flow).

3.5.5.1.1 DAY 0 TO DAY 14: CLEAR-WATER INITIAL BED ADJUSTMENT PERIOD

The model was run for a two-week bed adjustment period in order to allow the model bed surface to adjust toward a quasi-stable condition prior to sediment reintroduction. This period provides some sense of whether the initial conditions at the start of the model were realistic with respect to the bed being in equilibrium with the flow. In most of the model runs, there were some changes in the first two weeks, but they became relatively minor toward the end of the two-week adjustment flows. For PAVE 4B, the size of sediment being mobilized remained relatively constant during the first two weeks. Figure 41 shows the grain-size probability distributions for the material in transport for every cross-section at the beginning and end of the two-week interval. Although the shapes of the distributions are very similar, both spatially and in time, there are some changes in the dominant fractions. For example, on Day 1, 22% of the transported material falls in the 3 Psi (8 mm) size class and only 7% of the distribution is in the 0.5 Psi (1.5 mm) size class. By Day 14, the 3 Psi gravels make up only 14% of the transport distribution, which accounts for an 8% decrease. Also by Day 14, the percent of fines below 1 Psi start to increase in the transport distribution, suggesting an overall trend in which coarser materials were mobilized early in the adjustment period, followed by progressively finer sediment in transport toward the end of the period.

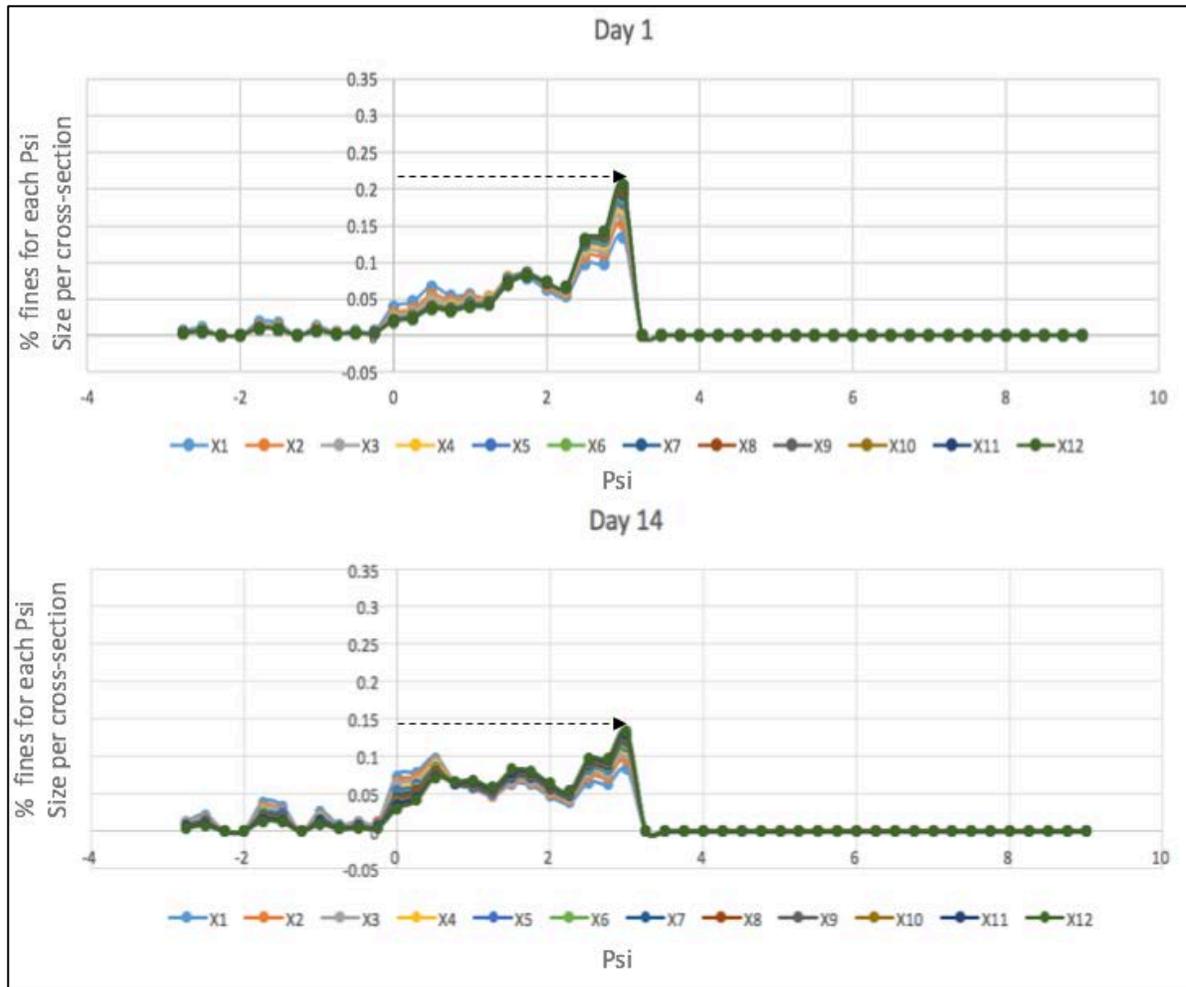


Figure 41. Change in transport probability distribution function between Day 1 and Day 14 for the PAVE 4B dataset. Transport PDF indicates which grains per cross-section are mobilized on a particular day in the model given 100 cms flow discharge. All 12 cross-sections presented as separate coloured lines (X1 to X12). Hatched arrow on Day 1 shows 3 Psi grains in transport to be 22% whereas 3 Psi grains on Day 14 are only 14%. The overall bed becomes more mobile as the model runs.

Figure 42 shows the changes in elevation at each of the cross-sections through time. The red box isolates the first two weeks of adjustment flows. It is apparent that the upstream cross-sections experienced the most degradation, due to the lack of sediment being recruited from upstream. In contrast, the farthest downstream cross-sections experienced no net change because sediment mobilization from upstream cross-sections provide a source of sediment that mitigates any erosional tendencies. Upstream bed elevation changes amount to approximately 400 mm at X1 and X2 and 200 mm for X 3 to X5, with less than 100 mm of degradation occurring in the middle cross-sections.

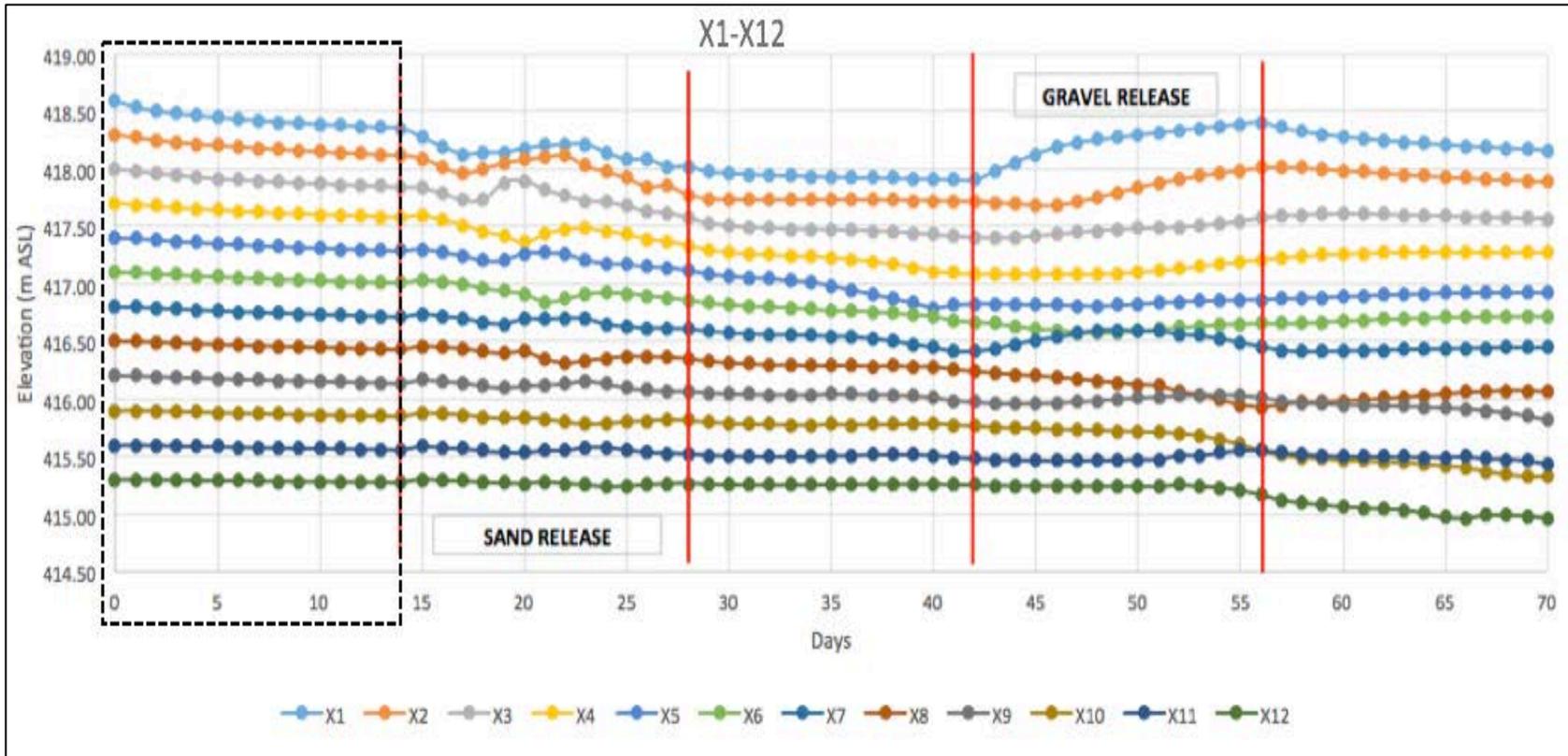


Figure 42. Daily change in riverbed elevation for weeks 1 and 2 (black rectangle) using PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Bed degradation in the upstream 6 cross-sections; downstream bed elevations remain relatively stable.

Cumulative changes in bed surface D_{50} for a select number of cross-sections through the model period is shown in Figure 43. During the first two weeks of the freshet, there is a steady increase in D_{50} (i.e., coarsening) at all locations. The cumulative change in the upstream cross-sections is more pronounced (e.g., 18 mm at X2) than in the downstream cross-sections (e.g., 9 mm at X12). There is also a tendency for the day-to-day changes to level off.

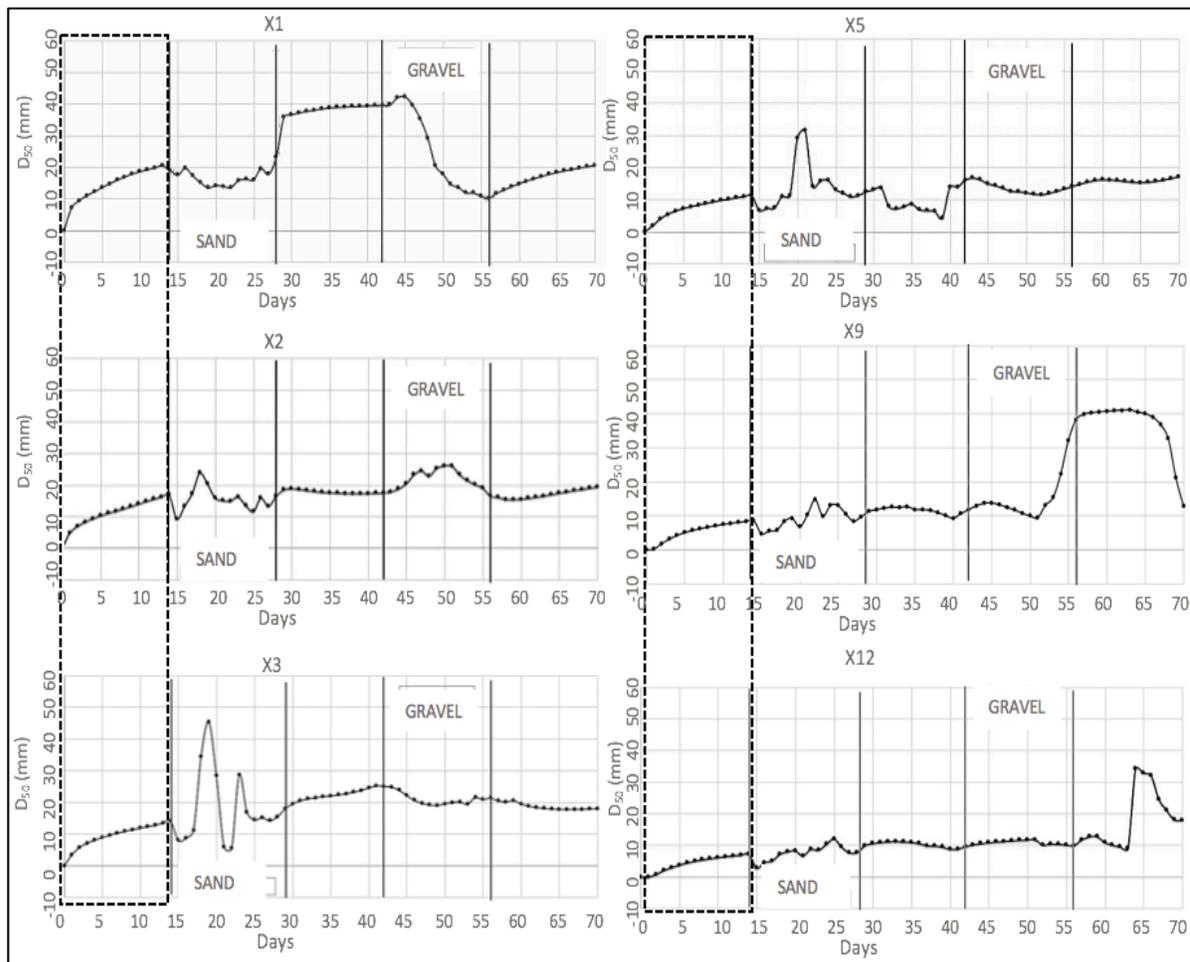


Figure 43. Daily cumulative change in D_{50} for cross-sections X1, X2, X3, X5, X9 and X12 for the first two weeks during initial bed adjustment period (black hatch rectangles) using the PAVE 4B dataset in the Middle Shuswap River model reach. Model shows bed coarsening in all 6 cross-sections.

Overall, degradation observed during the first two weeks is what would be expected given no upstream sediment contributions. The complete set of graphs depicting cumulative change in D_{50} are found in Appendices 11 and 12.

3.5.5.1.2 DAY 14 TO DAY 28: SAND REINTRODUCTION PERIOD

After the two-week bed adjustment period, 10,000 m³ of sand ($D_{50} = 0.4$ mm) was reintroduced evenly over a subsequent two-week period. Elevation changes in the upstream cross-sections show an erosional response early during the period of sand introduction (Figure 44). As mentioned above, this seems counter-intuitive, that providing a source of sediment from upstream would yield accelerated bed erosion, but this precise response has been reported by others (Curran and Wilcock 2005; Venditti et al. 2010).

A downstream-propagating trend of bed elevation oscillations is initiated that is most evident in cross-sections 3 through 9. These are indicative of complex bed responses at a localized level due to sediment being eroded from upstream being delivered downstream thereby causing bed aggradation. These very trends are evident in Figure 45, which shows net bed aggradation and degradation at selected cross-sections through time.

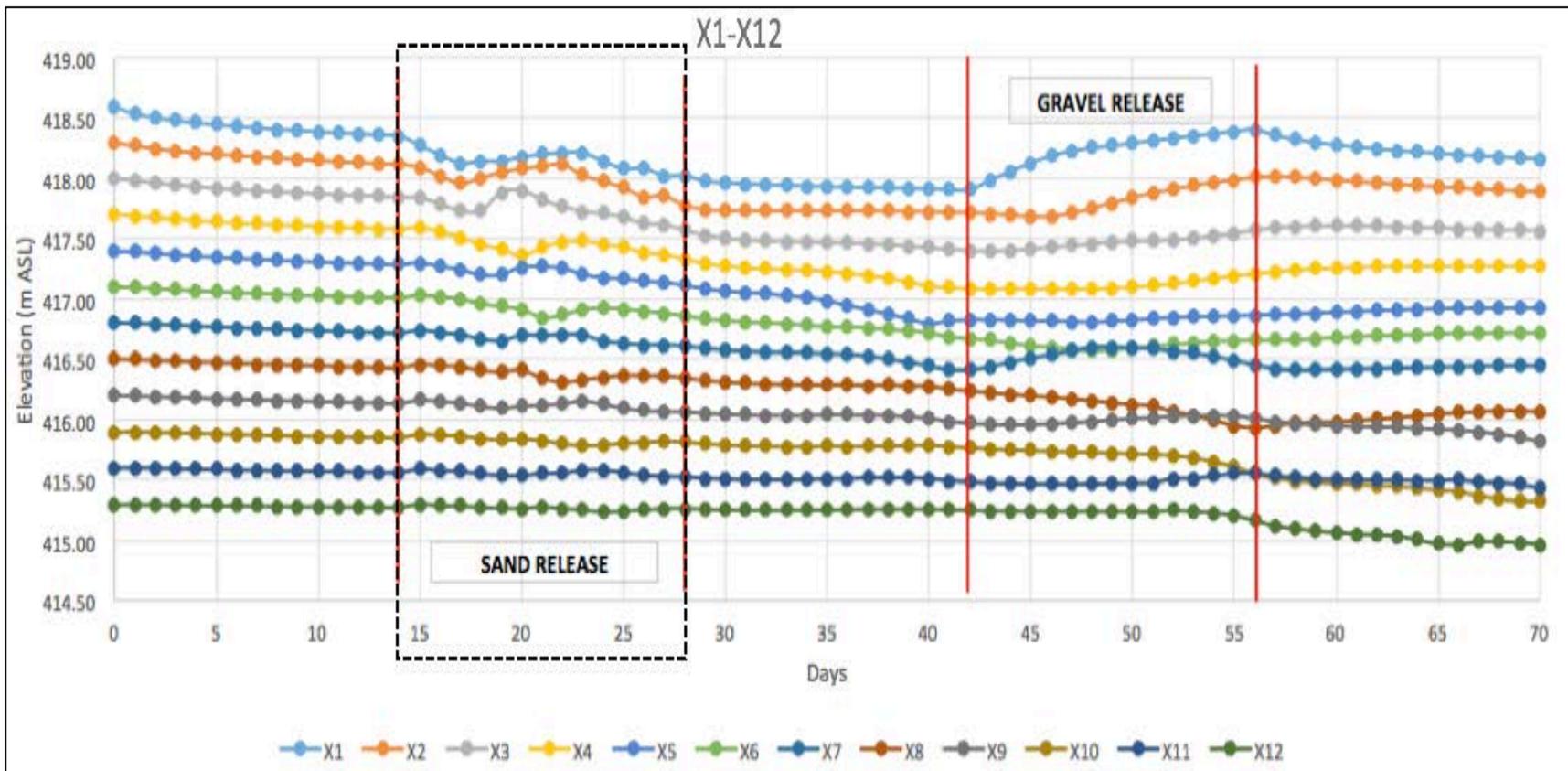


Figure 40. Daily change in riverbed elevation for weeks 3 and 4 (black hatched rectangle) using PAVE 4B dataset, in the Middle Shuswap River model reach. Channel degradation facilitated by sediment reintroduction. Bed adjustments through aggradation and degradation occur in each 12 cross-sections; the largest adjustments are in X1 to X6.

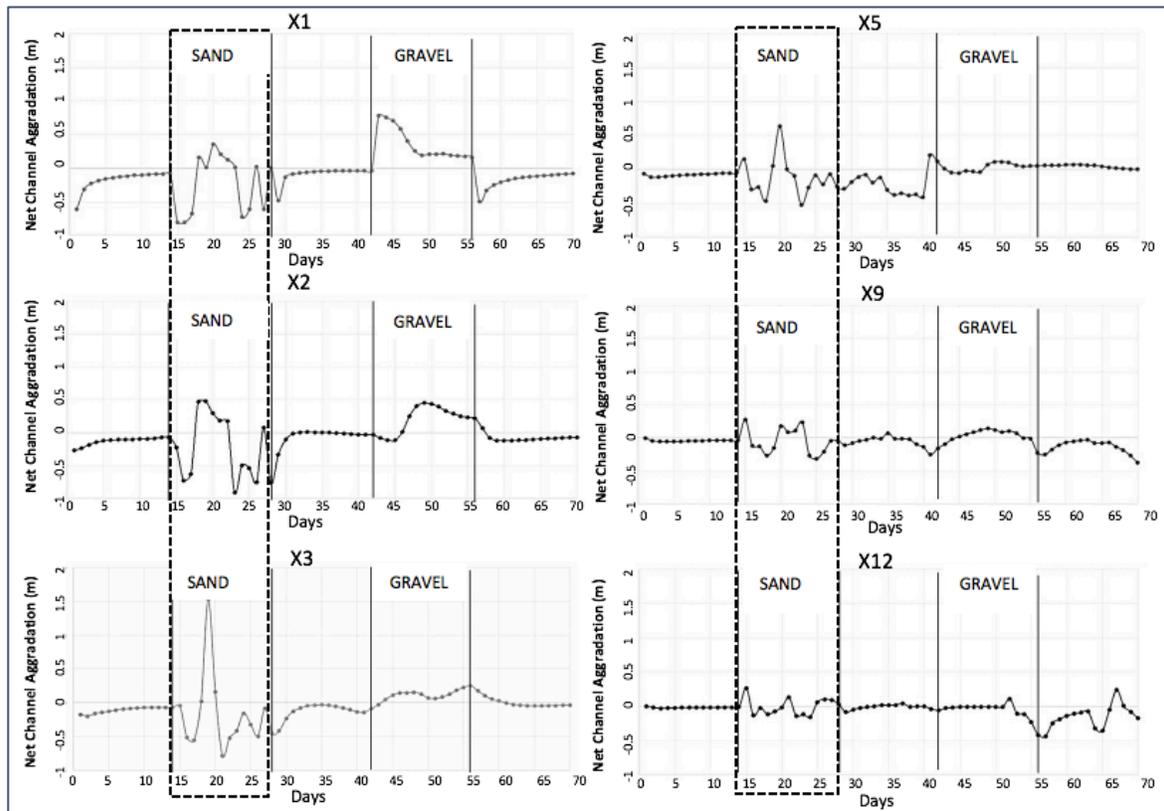


Figure 41. Net channel aggradation (+ values) and degradation (- values) for weeks 3 and 4 using the PAVE 4B dataset to simulate change in the Middle Shuswap River model reach. Black rectangle identifies weeks 3 and 4 of model run during sand reintroduction. Sand reintroduction causes channel bed to fluctuate between aggradation and degradation; each run ends with a similar trajectory of erosion upon completion of sand reintroduction suggesting that channel bed changes are temporary and recoverable during and after sand reintroduction, respectively.

During the period of sand feed, the bed elevation fluctuations range from 9 mm to 160 mm, with the greatest variability in the upstream cross-sections (X1 to X5) and the least variability in the downstream sites (X9 to X12). Additional cross-sections are presented in Appendix 14.

In order to understand why there were periods of aggradation and degradation during sand reintroduction, the sediment loading is shown in Figure 46. Prior to sand reintroduction, the sediment load decreases progressively as the bed adjusts itself to the imposed discharge conditions. Toward the end of the two-week adjustment period, the transport load is almost zero at the upstream cross-section although a load of approximately 400 kg hr^{-1} is maintained at the down-stream cross-sections due to sediment contributions from the upstream bed. Upon sand reintroduction, there is a rapid increase in sediment load to between 2000 and

3000 kg hr⁻¹ within the first day. After approximately three to four days (i.e., Day 17 and Day 18), the sediment load decreases to within the range of pre-sand reintroduction (approximately 500 to 1000 kg hr⁻¹) at most cross-sections, which is difficult to reconcile. Sediment load increases again after Day 18 and remains high (with some variations) for all cross-sections up to Day 28. Shortly after cessation of sand reintroduction, the sediment load decreases to pre-release values. A complete set of sediment fluctuation graphs are found in Appendices 16 and 17.

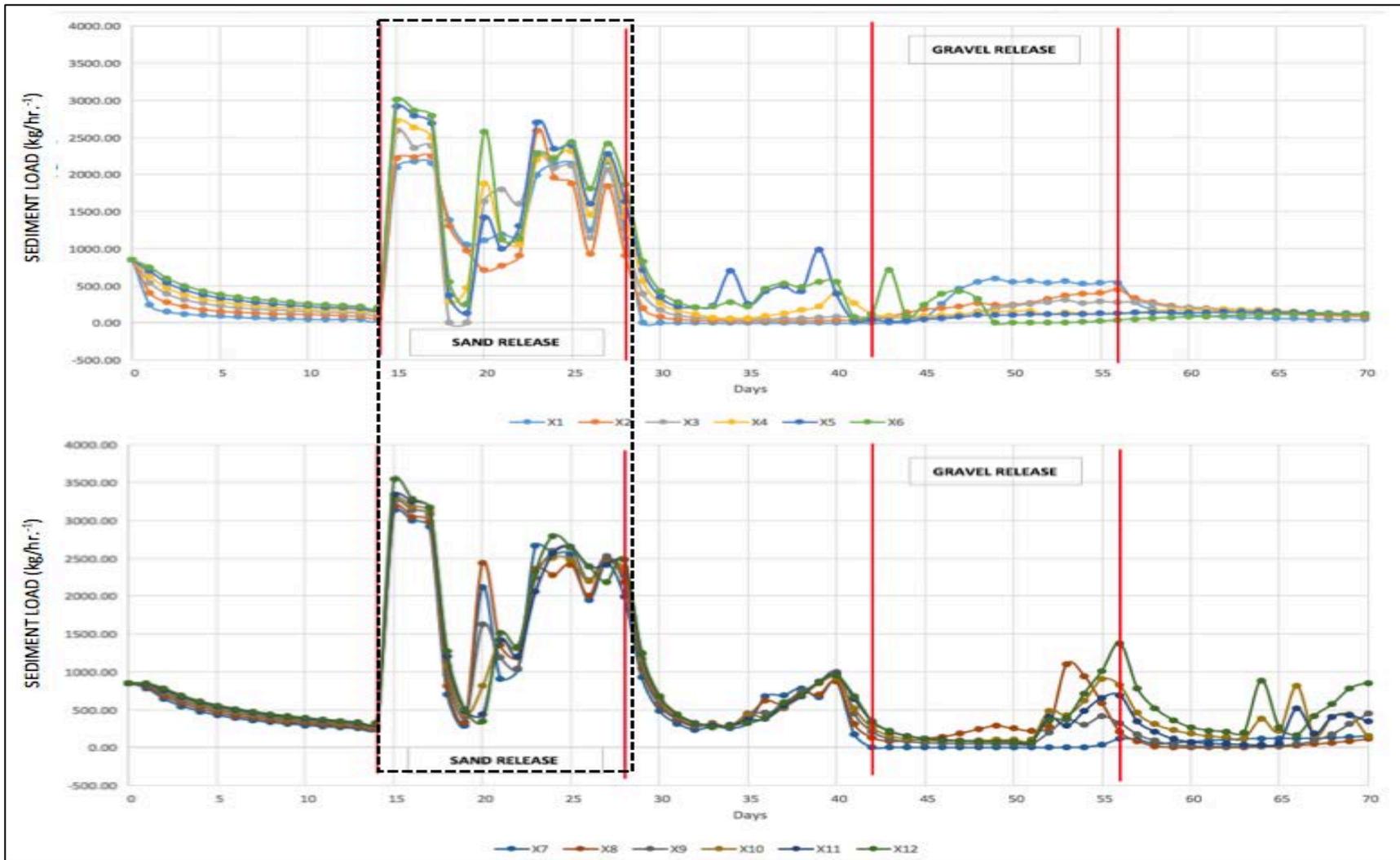


Figure 42. Daily change in sediment fluctuation (kg/hr^{-1}) for weeks 3 and 4 (hatched rectangle) for all 12 cross-sections (X1 to X12) in the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Daily sediment load fluctuations subject to selective transport of grains, resulting in wide ranging shifts in total material transported.

There appears to be a discrepancy between total transport rates shown by the model and those based on the sediment feed rate. Specifically, the volume of sand introduced to the model was $10,000 \text{ m}^3$ over a 14-day interval, which yields a sediment discharge rate of 30 m^3 per hour. The density of quartz minerals is 2650 kg m^{-3} with a porosity of 40% (or bulk density is approximately 1600 kg/m^3 for the sand from the dredge pile). Therefore, sand reintroduction rate is approximately $48,000 \text{ kg hr}^{-1}$ which is much greater than the model predicted peak transport rate of $3,000 \text{ kg hr}^{-1}$. One explanation for the discrepancy is that reintroduced sand is effectively flushed through the system as wash load, but those volumes should be reflected in the hourly time-step results from the model.

Cumulative changes in D_{50} at representative cross-sections are shown in Figure 47. At X1, the farthest upstream cross-section, the channel initially coarsens during the two-week adjustment period, and then becomes less coarse as sand is injected into the system. This slight fining trend occurs despite the fact that the riverbed experiences net erosion (see Figure 44). Immediately downstream (at X2 and X3) this initial fining response is very short in duration as larger grains from X1 are mobilized and moved downstream along with the sand that is being reintroduced at the upstream model boundary. Thus, there is a pronounced coarsening of the bed at approximately Day 18, which seems to coincide with the reduction in sediment load shown in Figure 46 and the pronounced bed aggradation shown in Figure 45. Although similar trends are evident at X5, the bed response is muted with downstream distance. At X12, for example, there are only minor fluctuations in bed aggradation/degradation (Figure 45) and a very subtle coarsening trend over the two-week period of sand reintroduction.

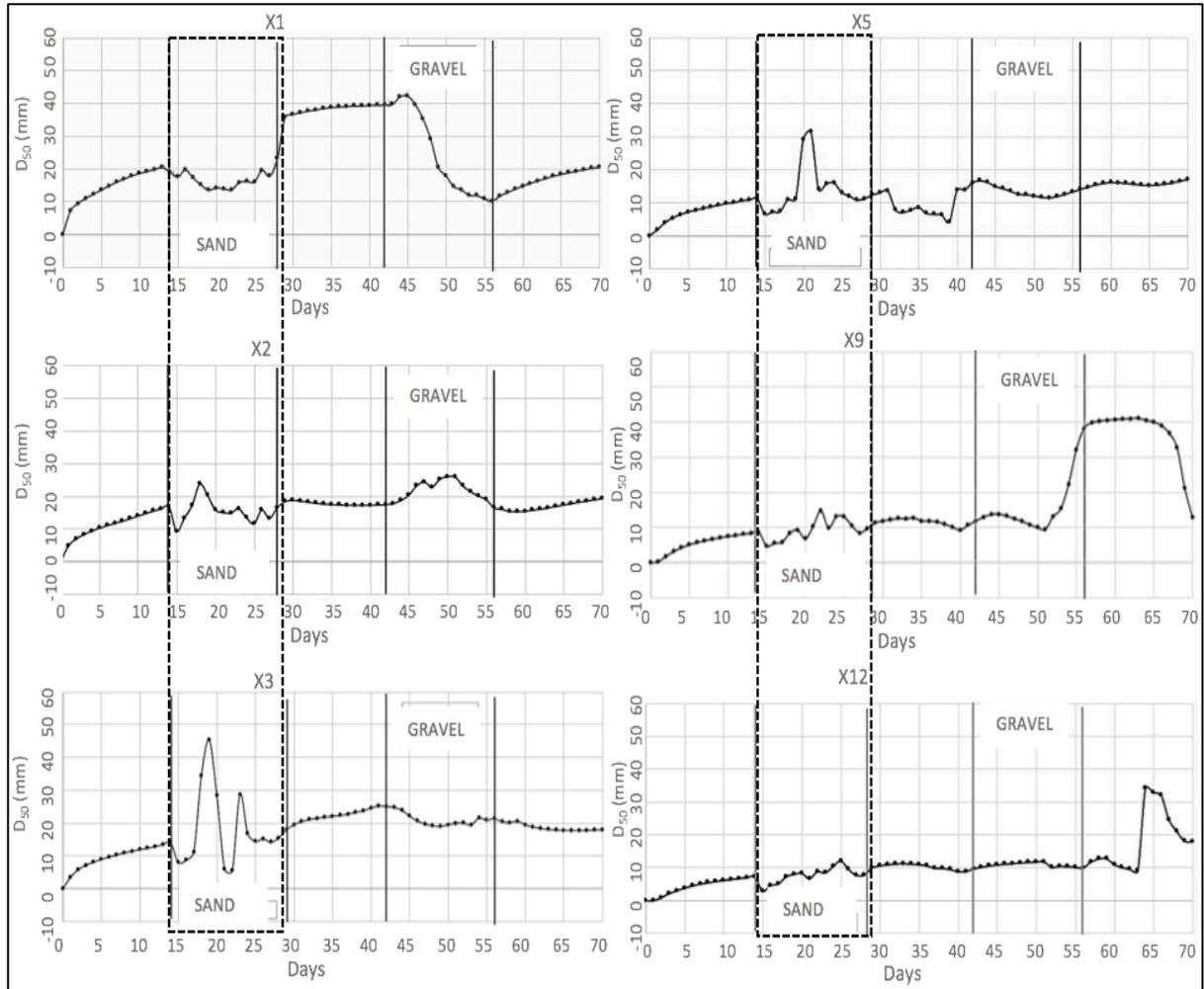


Figure 47. Cumulative daily change in D_{50} for cross-sections X1, X2, X3, X5, X9 and X12 for weeks 3 and 4 (hatched rectangles) using the PAVE 4B dataset that simulates change in the Middle Shuswap River model reach. During sand reintroduction, a complex sequence of coarsening and fining occurs suggesting the effective ability of reintroduced sand to mobilize the bed and temporarily deposit among existing grains.

Figure 48 shows the grain size distributions of sediment in transport at selected cross-sections during the sand reintroduction period. On Day 15, shortly after sand reintroduction, several small peaks in the grain size distributions appear at 6 and 8 psi. Note that the intervening grain sizes between the peaks at 6 and 7.5 psi do not indicate that these size fractions remained stable, but only that this size particle was not represented in the original grain-size distributions that characterized the bed surface and the sediment feed (refer to Table 11). The full set of graphs for the 70-day run can be found in Appendix 17.

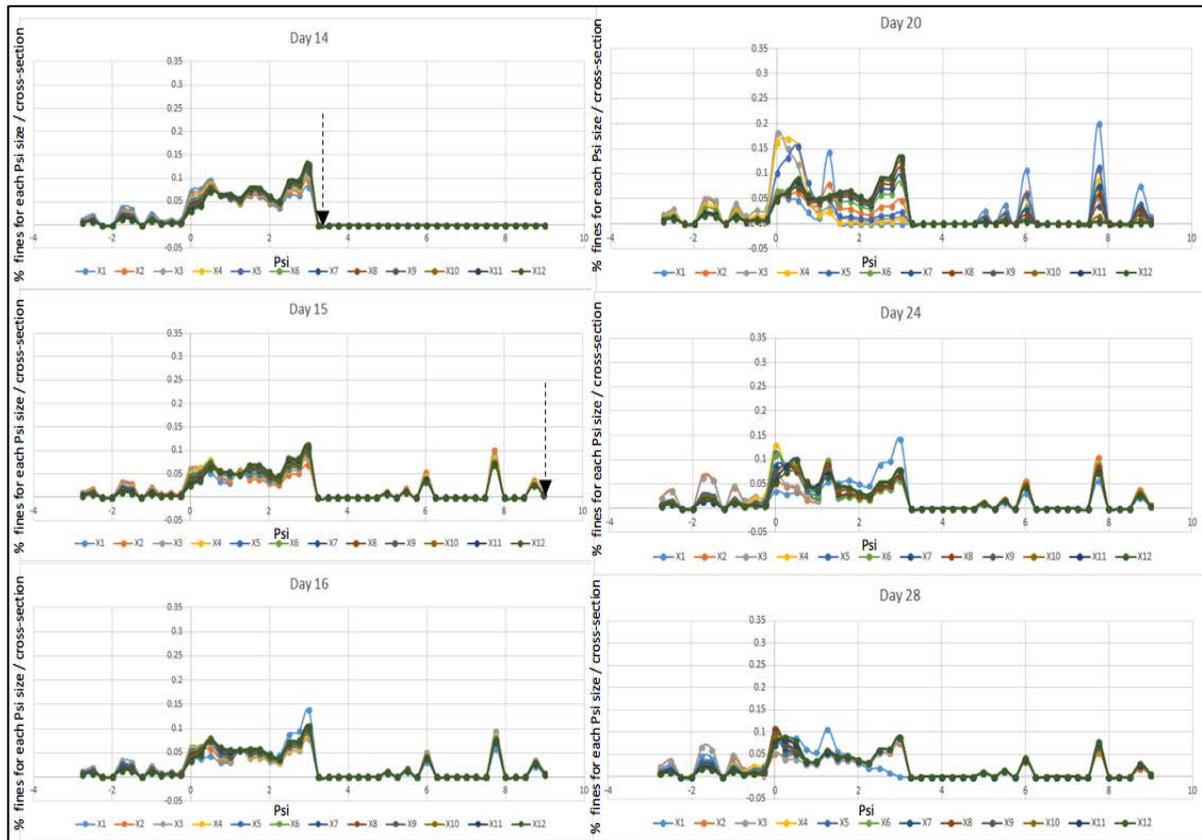


Figure 43. Change in transport probability distribution function for days 14, 15, 18, 20, 24 and 28 for the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Vertical arrows depict how large grains become mobilized within the distribution between Day 14 and 15. After sand reintroduction (Day 15), large grains previously immobile begin selective transport, up to grains 9 Psi in size.

3.5.5.1.3 DAY 28 TO DAY 42: POST-SAND REINTRODUCTION ADJUSTMENT PERIOD

After cessation of sand reintroduction, the bed elevation quickly stabilizes at most cross-sections with some exceptions at X4, X5, and X7, which continue to erode (Figure 49). Most of the upstream cross-sections have significantly lower bed elevations after the period of sand reintroduction, although this reduction in bed elevation becomes less apparent in the downstream direction. The farthest downstream cross-sections (e.g., X10, X11, and X12) appear to have degraded only slightly in response to sand reintroduction, suggesting that were net transport surfaces with a tendency for bed degradation that were mitigated by the sediment contributions from upstream locations.

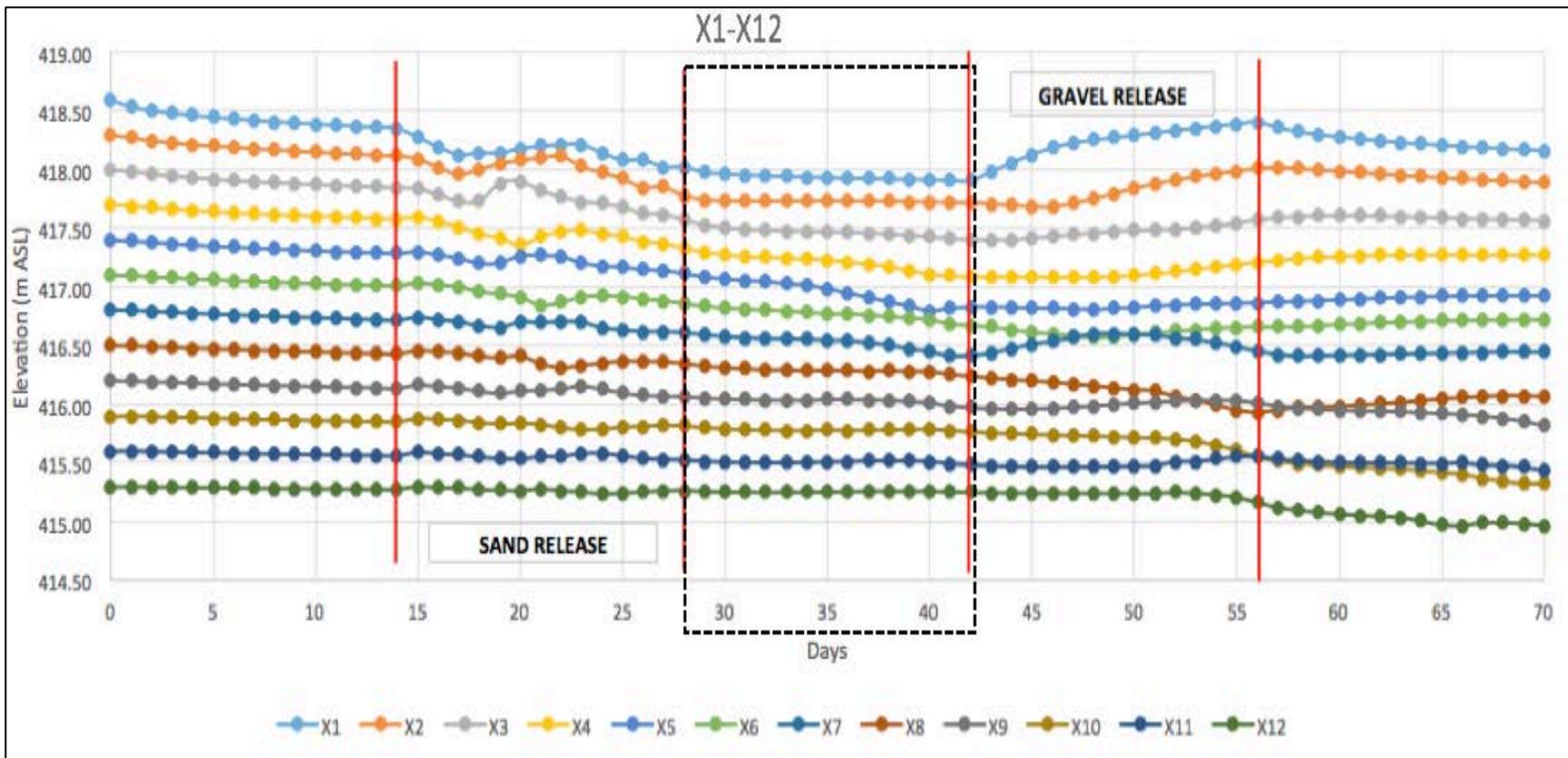


Figure 44. Daily change in riverbed elevation for weeks 5 and 6 (black hatched rectangle) using PAVE 4B dataset, in the Middle Shuswap River model reach. After sand reintroduction in weeks 3 and 4, X1 to X7 continue to degrade. X8 to X12 remain similar elevation to post-sand reintroduction levels.

During this second period of clear-water bed adjustment, grains larger than 3 Psi continue to be transported, although the percentage of the grain size distribution in these coarse fractions is less than during sand reintroduction (Figure 50). Toward the end of the adjustment period, the coarse fraction accounts for only a very small percentage of the overall transport load, with most sediment falling in the 0 to 3 psi classes (i.e., coarse sand and gravel).

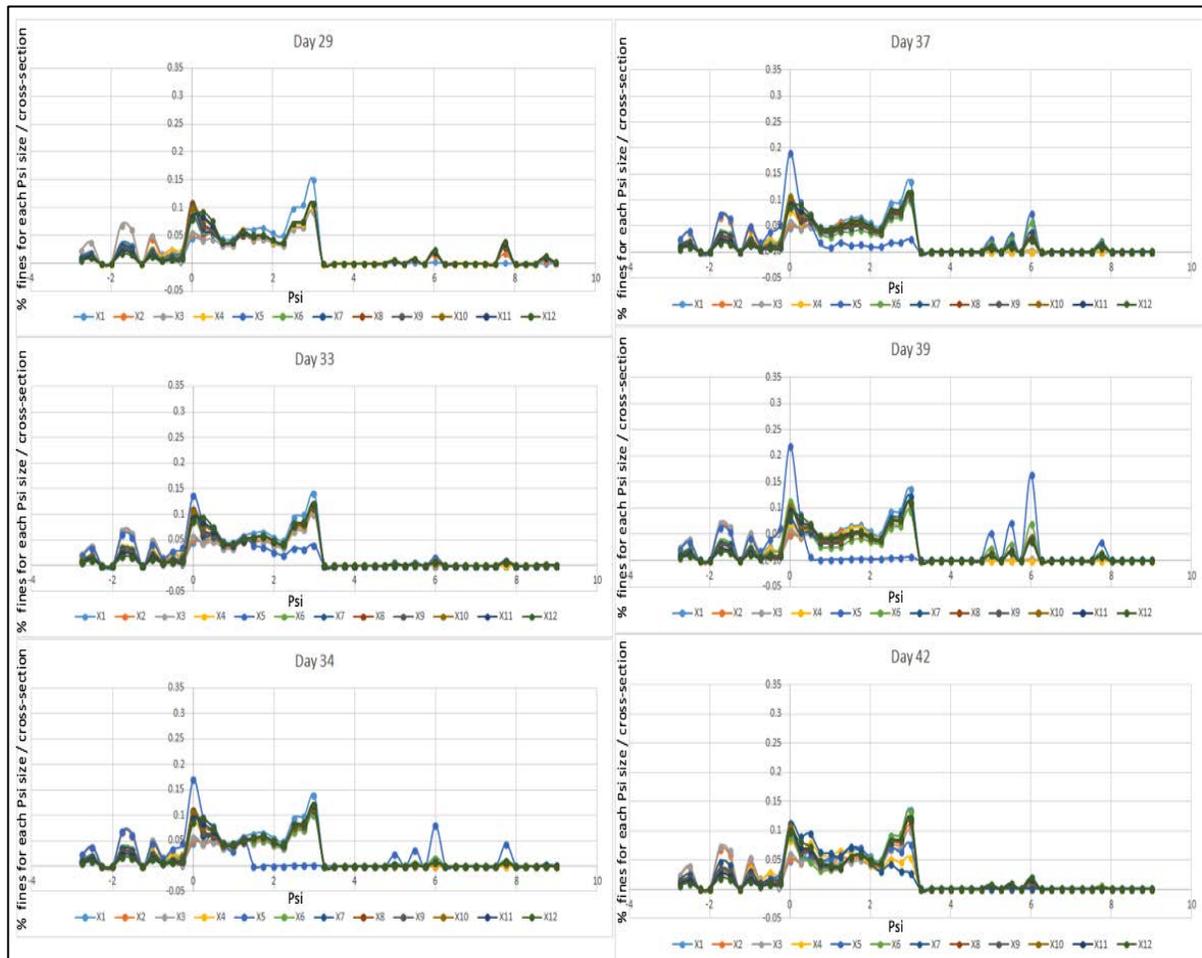


Figure 50. Change in transport probability distribution function for days 29, 33, 34, 37, 39, and 42 for the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Even with no sand or gravel inputs, larger grains remain mobile up to Day 39, reducing mobility by the end of week 6 (Day 42).

3.5.5.1.4 DAY 42 TO DAY 56: GRAVEL REINTRODUCTION PERIOD

Gravel was released into the model at a rate of 5,000 m³ spread evenly over Weeks 7 and 8 (Days 42 to 56) and had a D₅₀ = 13.9 mm. The original bed surface at the start of the model simulations (Day 1) had a D₅₀ of 13.5 mm. Unlike when sand was reintroduced to the model, at twice the volume rate, the reintroduction of gravel caused immediate aggradation (Figure 51). At cross-sections X1 and X2, the bed elevation increased progressively throughout the two-week period of gravel augmentation, forcing the bed elevation to return to initial conditions (pre-freshet) at the start of the model run. Cross-sections X3, X4, X5, X6, X9 and X11 also experienced net elevation increases by the end of gravel augmentation. Cross-sections X7, X8, X10 and X12 had early aggradation but then experienced bed degradation by the end of gravel augmentation. For some reason, X8 in the middle of the model reach experienced the most extreme bed reduction with no period of aggradation at any time during gravel augmentation.

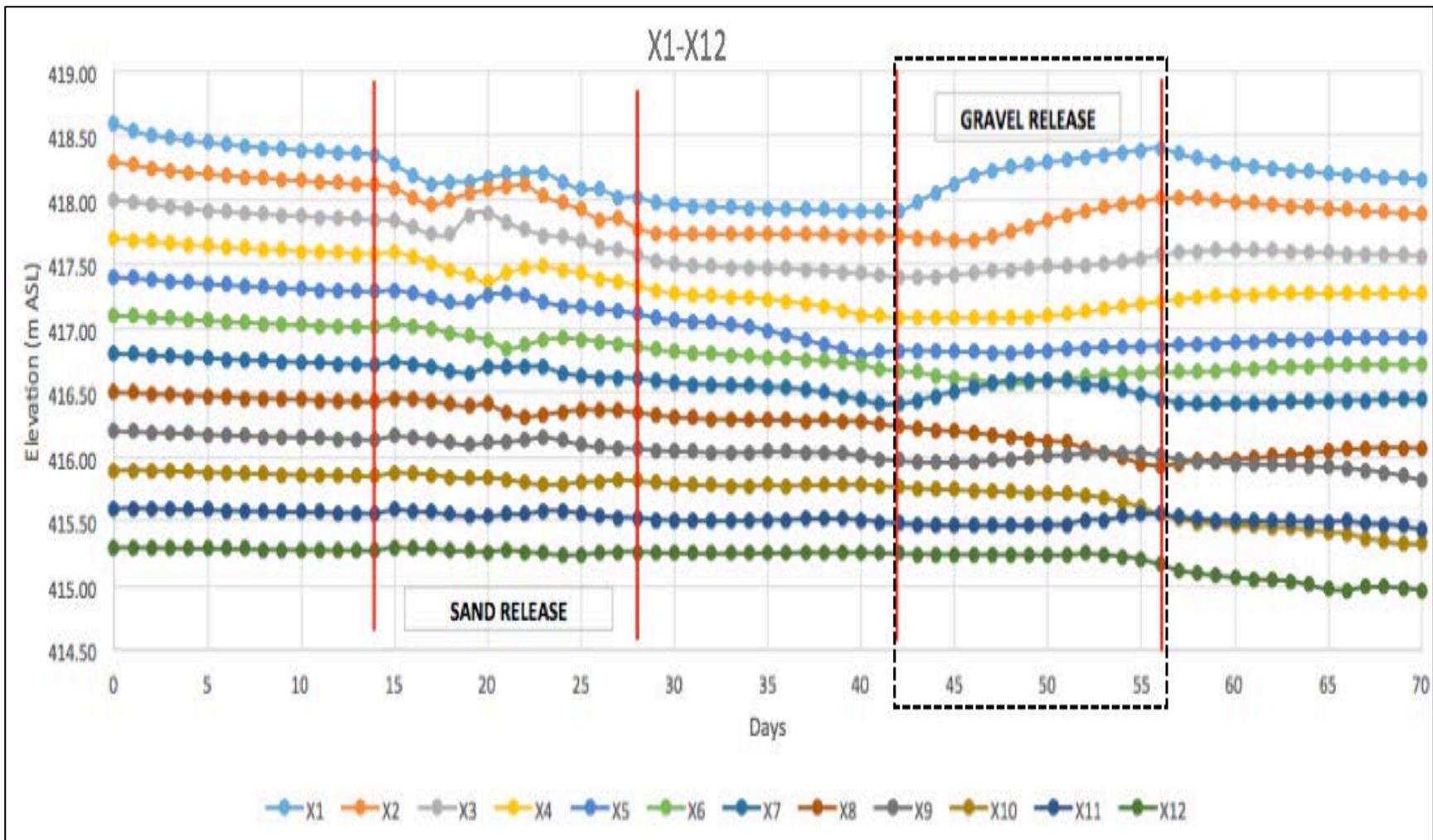


Figure 45. Daily change in riverbed elevation for weeks 5 and 6 (black hatched rectangle) using PAVE 4B dataset, in the Middle Shuswap River model reach. After gravel reintroduction in weeks 7 and 8, X1 to X7 continue to aggrade, raising in elevation up to 0.5 m. X8 to X12 continue to degrade although more rapidly than before gravel augmentation.

As shown in Figure 52, short-term oscillations in net aggradation or degradation that characterized sand reintroduction in Weeks 3 and 4, were absent during gravel augmentation in Weeks 7 and 8. At cross-sections X1 to X3, aggradation was progressively yielding a higher bed than prior to gravel augmentation. At X5, gravel augmentation corrected a prior trend of degradation, leading to a stabilized bed. At X9, gravel augmentation led to a transitory accumulation of sediment that is completely removed by the end of augmentation, leaving the bed elevation in the same position as before gravel augmentation. At X12, there is virtually no bed response through most of the gravel augmentation period, except at the very end when the bed is eroded quite substantially.

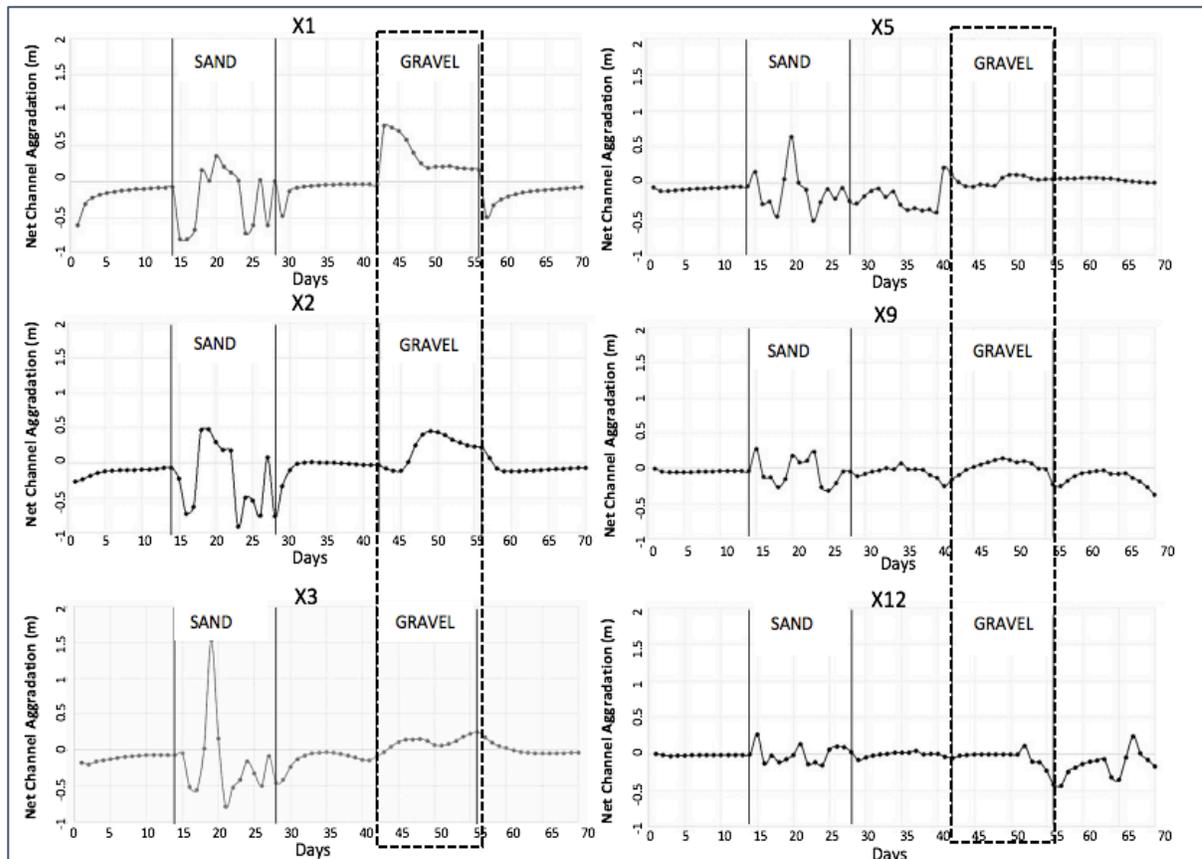


Figure 46. Net channel aggradation (+ values) and degradation (- values) for weeks 7 and 8 (black hatched rectangle) using the PAVE 4B dataset to simulate change in the Middle Shuswap River model reach during gravel reintroduction. Gravel reintroduction causes aggradation in the upstream reaches X1 to X5 and degradation in the downstream reaches X9 and X12.

Figure 53 shows daily sediment transport rate at six selected cross-sections during gravel augmentation (the remaining cross-sections are presented in Appendix 15). These six were

selected to span the entire model reach from X1 to X12. Sediment transport rates were generally much smaller during gravel augmentation than during the two-week sand reintroduction period, but there is also an apparent difference in response between upstream and downstream cross-sections. For example, at X1, X2, and X3, the two-week adjustment period after sand reintroduction was characterized by negligible transport rates, similar to what was experienced toward the end of the initial two-week initial bed adjustment period. These minimal transport rates occurred only a few days after the end of sand reintroduction, during which the transport rates were large at all cross-sections. In contrast, farther downstream (at X5 and X9), the two-week period after sand reintroduction was characterized by a decrease in transport rate for about eight days followed by an increase in transport rate, peaking just about Day 38, followed by a rapid decline in transport rate. With the start of gravel augmentation, the upstream cross-sections experienced an increase in transport rate whereas the downstream cross-sections remained unaffected (X5) or had delayed increases (X9 and X12). These trends suggest that introducing gravel into the system will lead to a muted transport response unlike that experienced during sand reintroduction. It takes more time for gravel to be transported downstream than sand, yielding a delayed response at the lowermost cross-sections.

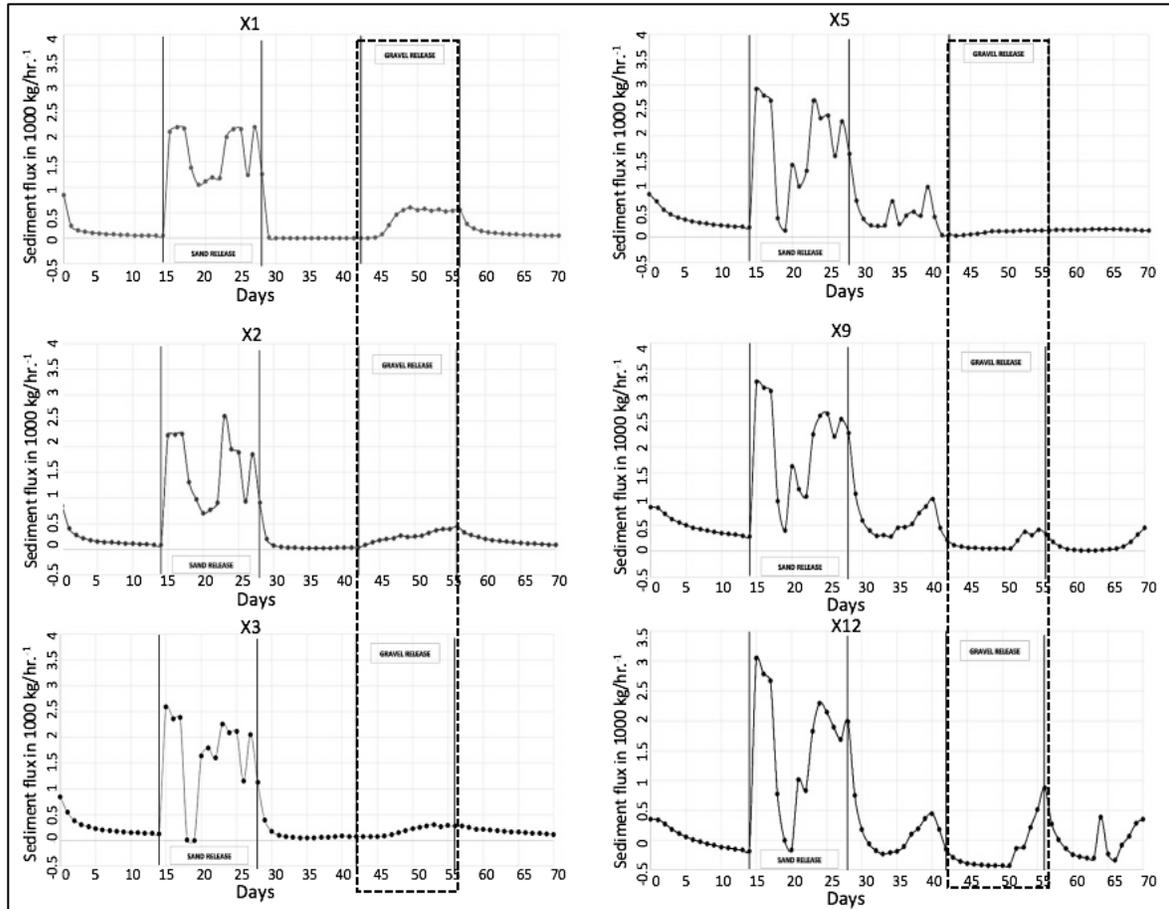


Figure 47. Sediment fluctuation in kg/hr^{-1} for weeks seven and eight (hatched rectangle) for cross-sections X1, X2, X3, X5, X9 and X12 of the PAVE 4B dataset simulating change in the Middle Shuswap River model reach during gravel augmentation. Sediment travelling down the model reach is much less than during sand reintroduction.

Figure 54 shows the accompanying changes in D_{50} at cross-sections X1, X2, X3, X5, X9 and X12. At X1, the period prior to gravel augmentation yielded an increase in D_{50} of approximately 400 mm, half of which occurred prior to sand reintroduction with the remainder occurring after sand reintroduction. During sand reintroduction, there were relatively minor changes with no net trend. However, immediately after sand reintroduction stopped and clear-water flows resumed, D_{50} increased markedly to its coarsest state. As soon as gravel augmentation began, D_{50} decreased and continued to do so until the end of the gravel augmentation period. These trends indicate that the continuous supply of fine-grained material (relative to the very coarse bed surface material at this upstream location) during the sand reintroduction or gravel augmentation period was critical in keeping the bed D_{50} in a finer state than its equilibrium state (i.e., cobbles). As soon as sediment supply is cut off, the

bed reverts to a coarse state. Interestingly, after the sand reintroduction phase, the bed was significantly coarser than after the gravel augmentation period, indicating that some of the gravel is retained in the bed.

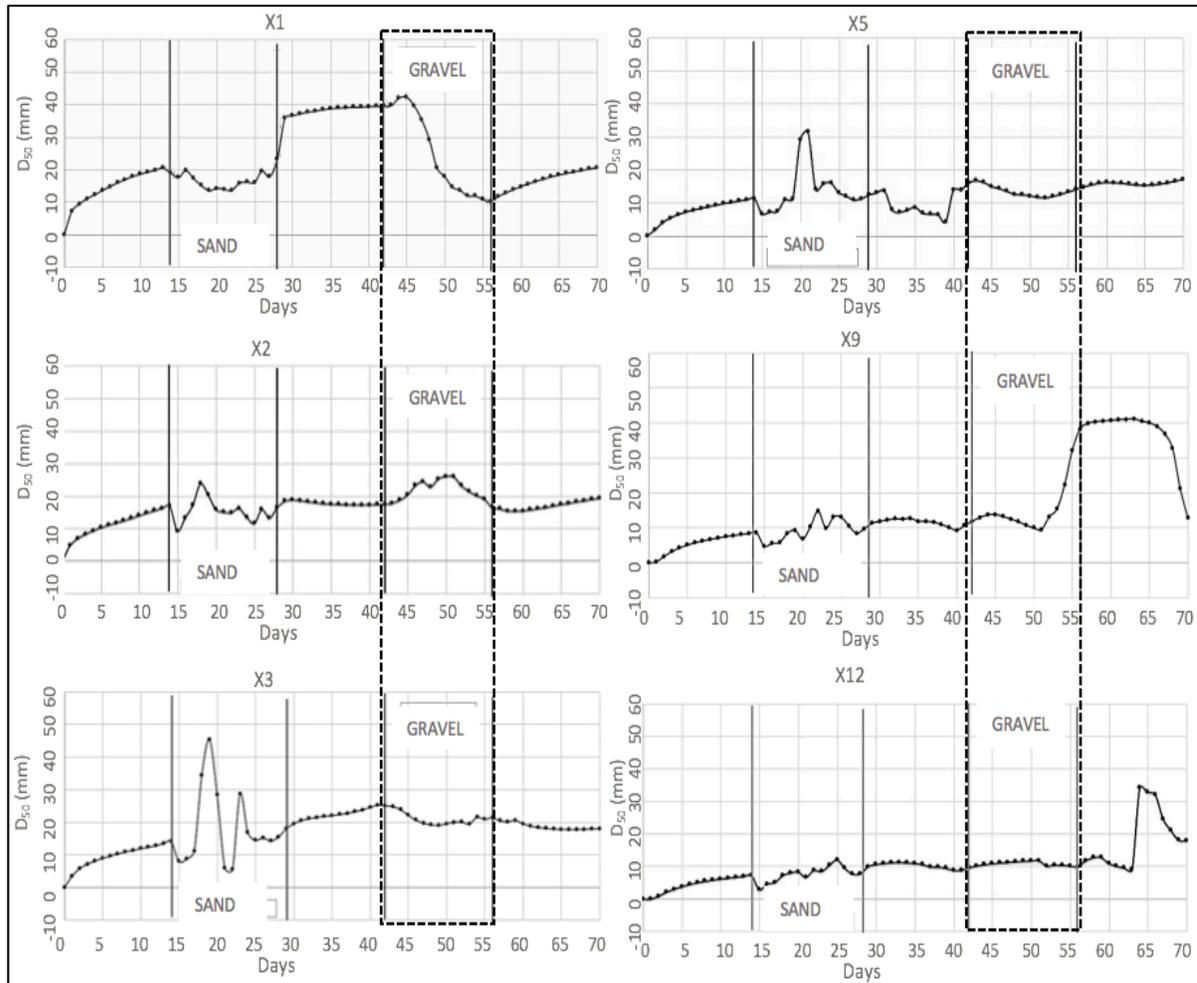


Figure 48. Cumulative daily change in D_{50} for cross-sections X1, X2, X3, X5, X9 and X12 for weeks seven and eight (hatched rectangles) of the sediment transport model using the PAVE 4B dataset that simulates change in the Middle Shuswap River model reach during gravel augmentation. Except with X9, gravel successfully corrects coarsening by aggrading the channel bed.

The changes in D_{50} immediately downstream of X1 are more complex because some of the material mobilized at upstream locations as a consequence of sand or gravel introduction are moved progressively downstream, and this includes not only the introduced sand and gravel but also any bed material that was mobilized. For example, at X2 there was an initial coarsening trend during the first two weeks, followed by variable coarsening and fining during sand reintroduction with no net change in surface D_{50} , followed by no changes in D_{50}

during the clear-water flows in Weeks 5 and 6. During the first week of gravel augmentation (Days 42 to 50), there was surface coarsening, likely driven by the mobilization and transport of coarse bed materials from upstream. The gravel with a $D_{50} = 13.9$ mm would not have caused such coarsening alone, unless only the coarsest components of the gravel mixture were selectively deposited on the bed. In either case, this coarsening trend during the first week of gravel augmentation was reversed during the second week, such that the net effect was no change to the surface D_{50} . Similarly, there was no net change in D_{50} at X5 (or at X12) as a consequence of gravel augmentation. At X9 there was a late increase in D_{50} that persisted into the subsequent clear-water flow period during Weeks 9 and 10.

3.5.5.1.5 DAY 56 TO DAY 69: POST GRAVEL REINTRODUCTION PERIOD

Upon completion of gravel augmentation, the model was run for two additional weeks to determine whether the bed would adjust toward some final equilibrium state at the end of the freshet prior to summer low flows. The most important issue is to understand the conditions at the end of the model simulations in comparison to the beginning in order to assess whether sand reintroduction and gravel augmentation leave any lasting impacts on the system.

As shown in Figure 55, most cross-sections experienced a net decrease in channel elevation or no net change as a consequence of the clear-water flows in the last two weeks of the simulation. For some cross-sections (e.g., X1), elevation decreases were about 500 mm, similar to what occurred during the initial two-week adjustment flows. In other case (e.g., X4, X5, X6), there was virtually no change during this final phase, suggesting that some sort of equilibrium had been achieved. The farthest downstream cross-section (X12) experienced the most substantial decrease in elevation during these last two weeks, in contrast to the relative stability that characterized the prior eight weeks.

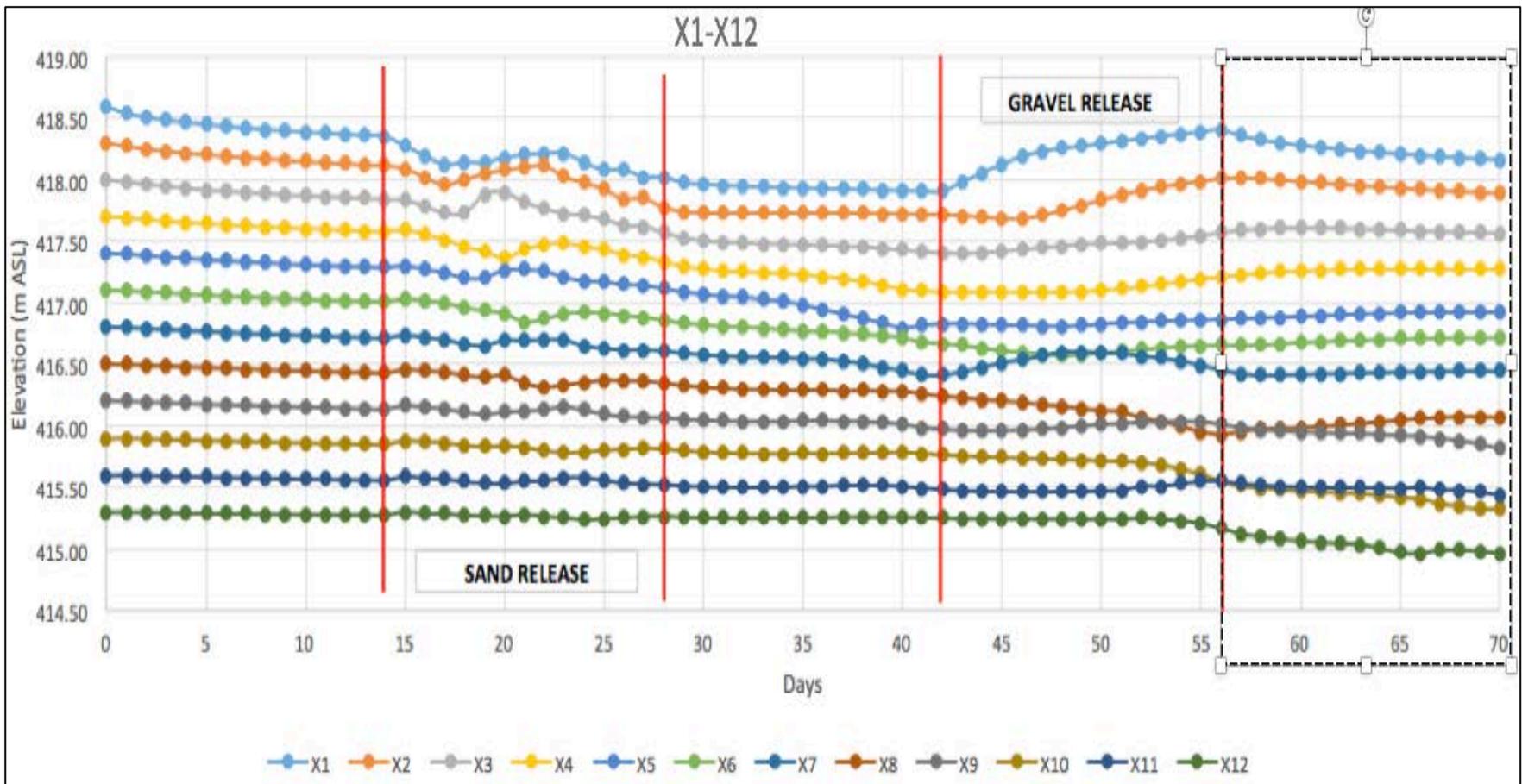


Figure 49. Daily change in riverbed elevation for end of freshet in weeks 9 and 10 (black hatched rectangle) using PAVE 4B dataset, in the Middle Shuswap River model reach after gravel augmentation. After gravel reintroduction stops X1 to X3 and X9 to X12 continue to degrade which middle cross-sections aggrade, X5 to X8.

During the last two weeks of the model run, the overall percentage of grains smaller than 0 Psi in the grain size distribution of transported material decreased, as shown in Figure 56. For Day 59, the percentage of grains just above 0 Psi dominate the transport distribution at 30% for X8. During the remainder of the model run, grains larger than 3 Psi continue to be transported up until Day 69. However, this is a consequence of holding the discharge in the model steady at 100 cms for the entire run. During a natural freshet, the flows during these last two weeks would be much smaller thereby reducing the volume and size of sediment being transported.

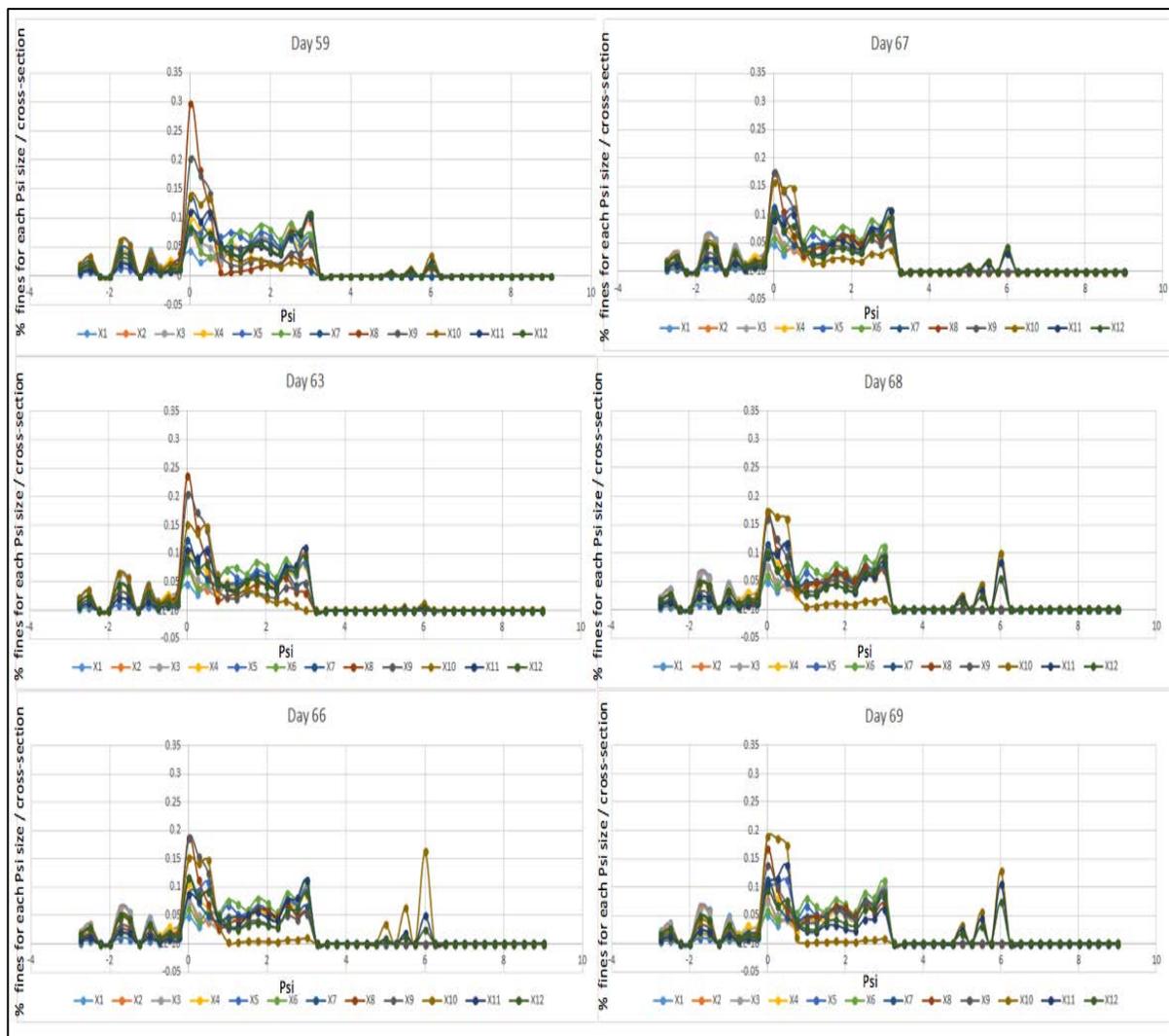


Figure 50. Change in transport probability distribution function for days 59, 63, 66, 67, 68, 69 for the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Towards the end of the model run, large grains become mobile, likely the result of fines from reintroduced gravel helping to mobilize larger grains along the channel bed.

3.5.5.1.5 DAY 0 to 69: SYNTHESIS

Grain-size distributions of sediment in transport at key times in the PAVE 4B model run are shown in Figure 57. Up until the start of sand reintroduction (Day 14), grains coarser than 3 Psi (8 mm) were not mobilized. On Day 15, grains up to 8 Psi (256 mm) were mobilized and this continued to the end of the sand reintroduction period at Day 22. In the interval after sand reintroduction and prior to gravel augmentation, coarse grains were also mobilized but at smaller sizes (only to 7 Psi) and at smaller percentages of the total distribution (less than 10% in comparison to 22% during sand reintroduction). During gravel augmentation, the mobilization and transport of coarse material decreases (Day 43), and after eight days into gravel augmentation, only the fine-grained fraction (< 3 Psi) was being transported. This suggests that gravel augmentation does not facilitate mobilization of the coarse fraction on the bed the same as sand reintroduction does, in part because gravel is being added to the model.

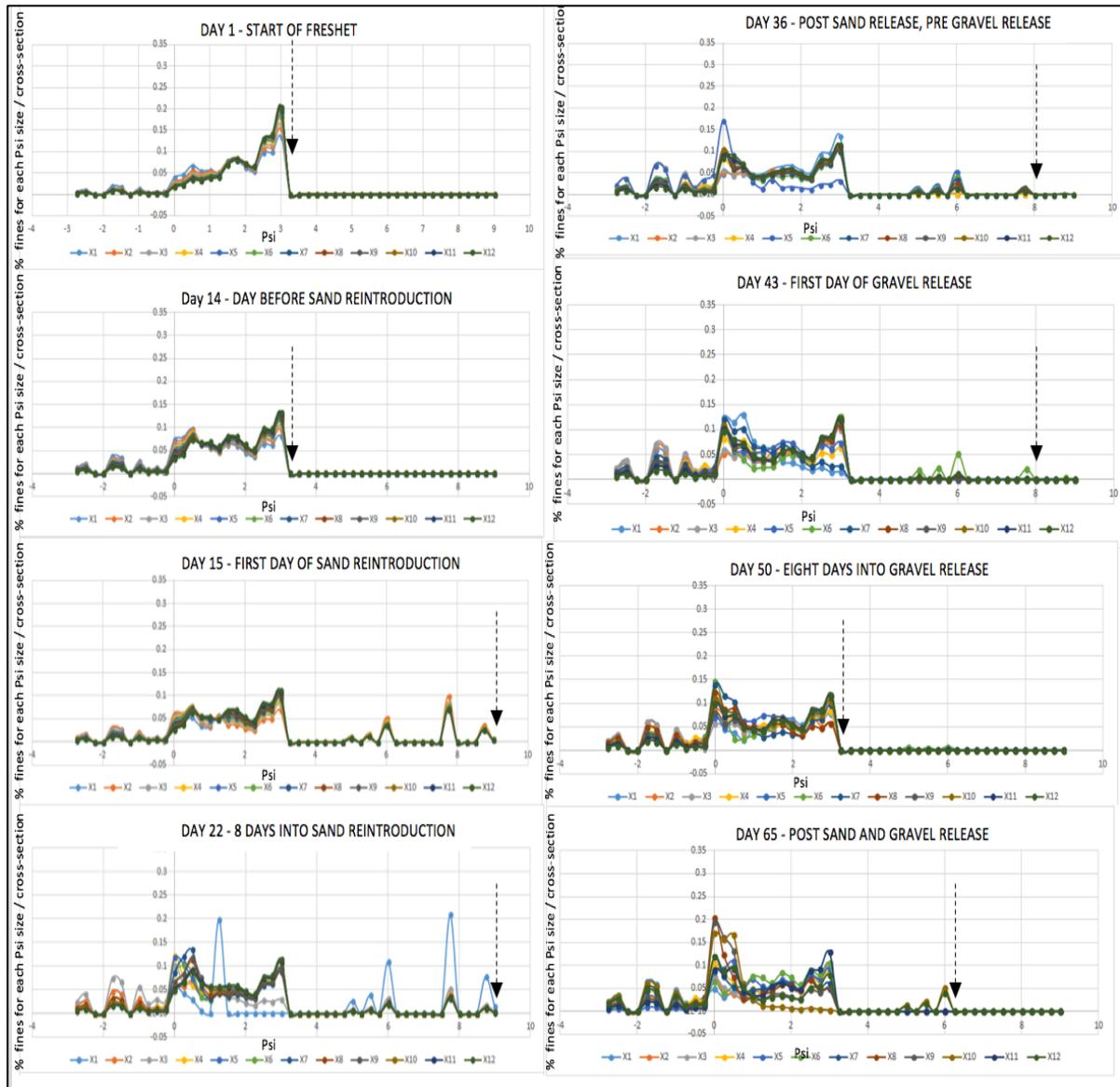


Figure 51. Change in transport probability distribution function for days 1, 14, 15, 22, 36, 43, 50 and 65 for the PAVE 4B dataset simulating change in the Middle Shuswap River model. The evolution of grains in transport is show at pivotal moments prior to and after sand reintroduction and gravel augmentation. In general, larger grains above 4 Psi are only mobilized after sand reintroduction and continue to the end of freshet. Arrows indicate upper Psi size mobile in the distribution.

Despite complex adjustments to the bed surface during the middle of the PAVE 4B run, leading to some extreme adjustments in bed surface D_{50} (Figure 58), the cumulative changes at the end of the simulation are comparatively small. All cross-sections began with a D_{50} of 13.3 mm (from GP52) and ended up with a final D_{50} less than 53 mm. In other words, the cumulative increase from the starting condition was between 10 mm and 40 mm depending on the cross section. Upstream cross-sections (X1 to X5) experienced coarsening of about 20

mm or more, while downstream cross-sections (X10, X11) experienced coarsening of about 30 mm or more. Interestingly, the middle cross-section (X6 to X9) appeared to have the largest excursions in grain size during the middle of the run (up to 50 mm), perhaps because of the gradual delivery of coarse materials from upstream into and through these central cross-sections. Figure 58 shows a wave-like peak moving progressively through these central cross-sections, which appears to arrive at X10 and X11 just before the end of the model run. The cumulative change at the end of the model runs in the central cross-sections was relatively minor (i.e., less than 20 mm). Thus, despite the overall coarsening trend at all of the cross-sections, the GSDs are still in the useable GSD range for coho and chinook salmon spawning.

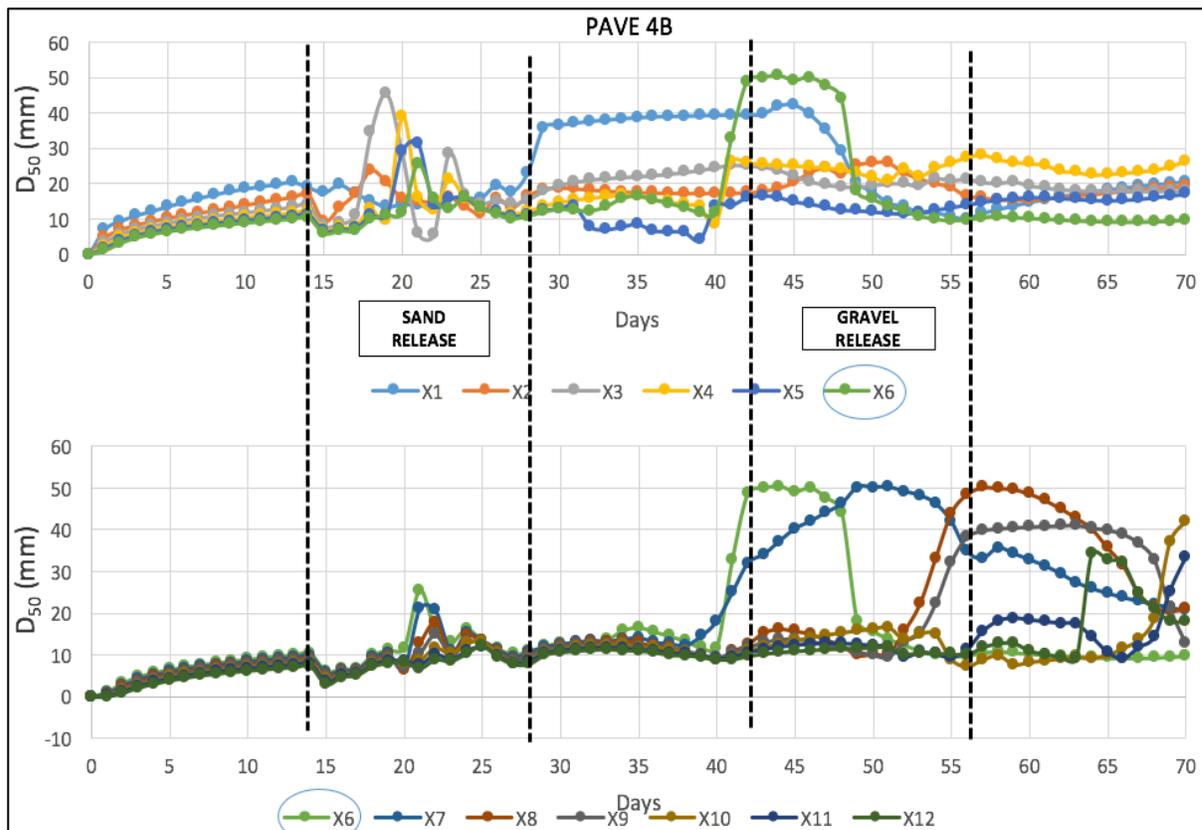


Figure 52. Cumulative daily change in D_{50} using the PAVE 4B dataset for the Middle Shuswap River model reach during sand reintroduction and gravel augmentation. Most shifts in channel bed D_{50} occur in X1 to X6. In X7 to X12, cumulative change in D_{50} remains relatively unaffected by sand reintroduction because large grains mobilized and replenished from upstream supply. However, upon gravel augmentation, downstream cross-sections experience significant increases in D_{50} , the result of gravel building up from upstream supply.

Gravel augmentation may help to mitigate channel bed degradation resulting from sand reintroduction because supplying gravel to the degraded river bed downstream appears to lead to aggradation and surface fining (relative to the very coarse sediment on the bed). Although some upstream gravel is mobilized by the reintroduction of sand, the resulting bed condition after one freshet season is still well suited to the range of gravel used by salmon for spawning. When gravel is added, the resulting bed condition improves, reducing further bed degradation.

By establishing permanent monitoring stations between Wilsey Dam and the Bessette Creek confluence to measure changes in surface GSD, the dam owner could properly assess whether post-sand-reintroduction gravel augmentation is necessary. In the event that gravel augmentation is implemented, there is sufficient gravel from the river thalweg immediately upstream of the spillway that could be harvested for passive reintroduction (i.e., stockpiled just upstream of the spillway during low flow for subsequent augmentation using natural flow conditions) as shown in Photograph 7.



Photograph 7. Looking upstream at lateral bar immediately north of headpond thalweg and potential source of gravel for gravel augmentation (July 17, 2008).

CHAPTER 4.0

DISCUSSION

4.1 UNDERWATER AUTOMATED GRAIN SIZE (AGS) ESTIMATION

The automated grain size (AGS) method has been used successfully for assessing surface sediments above the water surface, such as the tops of gravel bars during low-flow periods (Brayshaw 2012; Graham et al. 2012). Little effort has been devoted to sampling submerged grains using the underwater AGS method. For rivers containing highly texturized rocks, such as granite, significant image modification and laboratory time is required to prevent over segmentation of large rocks, a problem noted by (Adams 2013). Thus, image modification was required in order to achieve results for both small and large grains relative to the photographic image dimensions. Image dimensions depended on the depth of water, which controlled the height at which the photo could be taken in order to have a clear image. These constraints led to a lower truncation limit of 8 mm, similar to what others had experienced (Graham et al. 2005; Buscombe et al. 2010). In general, photos did not exceed a total surface area of 0.5 m² and only gravels and cobbles between 8 mm and 181 mm were successfully counted. Truncation limits resulted in a skewed GSD, with sand and smaller particles eliminated at the lower end, and coarse cobbles and boulders excluded at the upper end.

The quality of underwater photos taken in this study was considered good enough for Digital Gravelometer (DG) processing, although underwater photographs generally produce lower-contrast images than photographs taken of dry grains, as a result of light attenuation in the water column. The use of a sun shield to eliminate shadows in the photos was effective and consistent with the best practices (Buscombe et al. 2010). Since DG identifies images based on contrast, a duller contrast makes digital separation of the grains less effective. Collecting digital photographs on a sunny day using a light shield helped increase the contrast between grains. Low-contrast images were over-exposed using image modification software, which helps with DG water-shedding and grain segmentation steps.

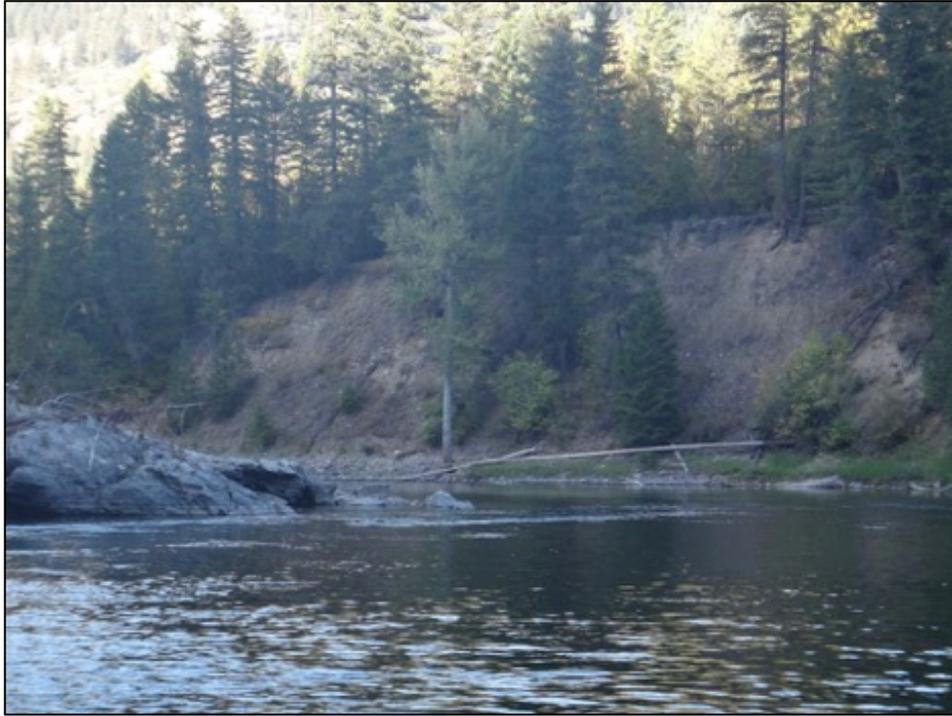
Assuming that a 100-grain Wolman pebble count would take 1.5 hours to collect including travel time between sites, using this approach would have taken approximately 14.5 eight-

hour days to complete all 78 sites. Using underwater AGS, the equivalent samplings effort was completed in two days. However, the time spent in the laboratory analyzing the images was significant, taking approximately 30 eight-hour days to process all 390 images. This presented a disadvantage relative to the Wolman approach but could be improved upon with advances in software background-subtraction, grain-water-shedding (Adams 2013) and cropping and retouching tools built in the DG software. The AGS method does yield a larger sample size with an average of 275 sediment particles per site, as well as a series of images that can be archived and analyzed in the future, if needed. Thus, both methods have distinct advantages and disadvantages yielding somewhat different outcomes with regards to the GSDs.

4.2 OBJECTIVE 1: DOWNSTREAM FINING TRENDS

Downstream fining trends are well documented in many rivers (Gasparini et al. 1999; Rice 1999; Frings 2008; Venditti et al. 2015). A statistically significant downstream fining trend is present in the MSR, although there is large variation between sites. Samples from upstream (GP41) and downstream (GP42) of the Chute and immediately downstream of Wilsey Dam (GP51) differed statistically from the trend. Large variability among sample sites could be attributed to a number of factors that have been recognized in the literature, including sediment patchiness, unique localized inputs, grain sorting, or the inability to transport coarse grain sizes at certain times of the year (Gasparini et al. 1999; Venditti et al. 2015). For example, Venditti (2015) refers to a “non-linear relationship between bed shear stress and sediment transport” that may explain the abrupt sand to gravel transition documented in many rivers like the Fraser River in British Columbia. Wilcock and McArdell (1993) found that complete mobilization of a sediment particle occurred at a shear stress approximately twice that required for incipient motion. Sediment patchiness has been documented within and between morphologic facies. These patches occur as free patches (i.e., the ability to migrate downstream as a patch) or forced patches (i.e., sediment patches that maintain GSD in the presence of sediment passing over in a transport state) (Nelson et al. 2015). Downstream variability in GSD could also be attributed to localized sediment inputs caused by bank erosion, bed armor disturbances during freshet flows, hillside sloughs contributing

colluvium, and tributary inputs. Photographs 7 and 8 show examples of local sediment contributions observed during field work.



Photograph 8. Natural eroding alluvium on an exposed bank in the canyon between the Chute and Wilsey Dam. September 18, 2012.



Photograph 9. Eroding foreshore near house built close to the river downstream of Cherryville Golf course.

Below Wilsey Dam, GSD measured at GP51 occurs outside the 90% confidence band, which indicates bed coarsening and channel degradation due to the interruption of sediment supply from upstream. The cause of channel degradation below dams is generally attributed to a lack of sediment recruitment (i.e., sand and gravel) due to aggradation of upstream storage headponds and reservoirs (Williams and Wolman 1984). Wolman and Williams (1984) described the downstream effects of dams on alluvial rivers, and noted that the rate of degradation downstream of dams decreases significantly after five to ten years of sediment starvation. Fuller et al. (2016) also found that for coarse gravel rivers tested in model conditions after dam closure that coarsening of the D_{50} was greatest in year 1 (D_{50} of 66 mm to 81 mm) and had increased only slightly to 86 mm by year 8. Aggradation in the headpond above Wilsey Dam has been occurring since 1972, and therefore the rates of degradation below the dam have likely been significantly reduced or stabilized. The total amount of channel incision within the 1.2 km salmon spawning reach from 1971 to present is unknown, but the downstream distance over which the impacts are felt is believed to be relatively limited (i.e., to the Besette Creek confluence depicted in Figure 25). At GP52, for example, the GSD is within the 90% confidence band of the general downstream fining trend for all the sites indicating no deviation from the observed trend. Indeed, GP52 is adjacent to the Shuswap River Fish Hatchery in a reach that is used extensively by spawning salmon. This suggests that there is sufficient gravel recruitment locally in the reach immediately below Wilsey Dam, perhaps by attrition and abrasion of larger cobbles and boulders or by some unknown volume of bedload contributed from upstream, unmeasured in this study, or that gravel remains in the reach, not getting flushed downstream.

Rivers with large dams can have significantly aggraded reservoirs and backwaters. The Wilsey Dam headpond transitions into a backwater channel within a narrow and confining bedrock canyon for approximately 2 km upstream of the headpond. Sediment deposition in the headpond and backwaters stem from a reduction in stream power (Dade and Friend 2015), which leads to an abrupt change in channel slope and resulting sediment deposition. Prior to the emplacement of Wilsey Dam, the headpond and backwater section of the river would have been a cascading falls with no anthropogenic sediment aggradation and little opportunity for deposition of fine-grained material (Figure 59).

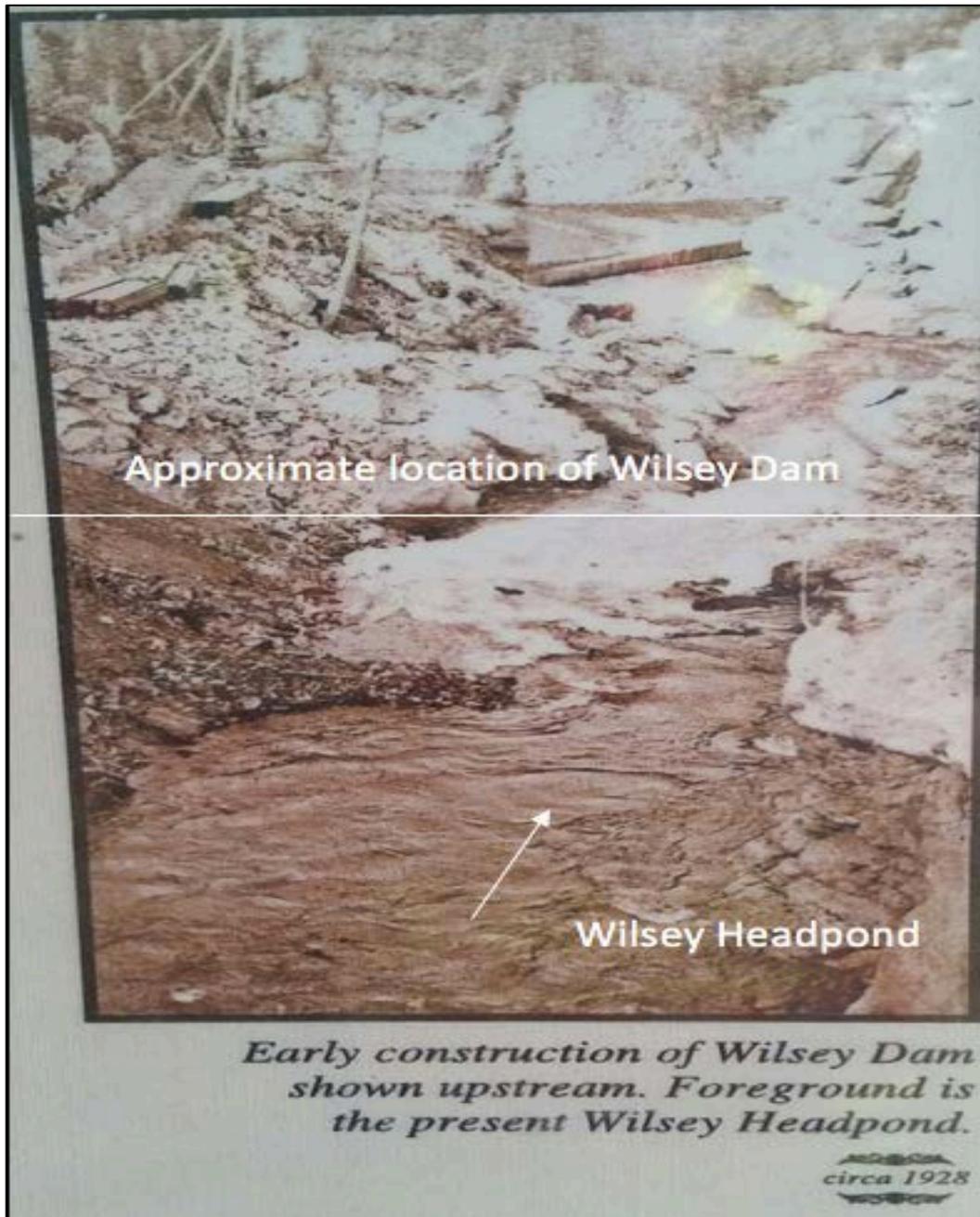


Figure 53. Historical river channel in the location of Wilsey Dam, 1928. Arrow shows flow direction. Horizontal line shows approximate location of Wilsey Dam. Photo courtesy of Cherryville Museum.

Tributaries can have a significant impact on river morphology, surface and subsurface GSD and therefore the downstream fining trend (Rice 1997). Of the three main tributaries in the MSR, Bessette Creek was found to have the greatest influence on downstream fining. Bessette Creek flows through extensive farm land with readily erodible alluvium, available

for erosion, entrainment and downstream transport. A discontinuity in coarsening below Wilsey Dam is evident at the confluence with Bessette Creek due to a large sediment loading of sand and gravel as indicated by bedload sampling (see Section 3.2), field observations and air photo interpretation. Sediment on the banks of the Bessette Creek confluence (Photograph 10) is noticeably finer than on the banks near the Cherry and Ferry creek confluences (Photographs 11 to 13).



Photograph 10. Bessette Creek Confluence with the Middle Shuswap River mainstem. Note the absence of large cobbles.



Photograph 11. Cherry Creek confluence with the Middle Shuswap River mainstem. B. Note the presence of large cobbles in the creek and right bank.



Photograph 12. Downstream of Cherry Creek confluence with the Middle Shuswap River mainstem.



Photograph 13. Ferry Creek Confluence with the Middle Shuswap River mainstem. Note the presence of large cobbles.

The sediment signatures of Cherry and Ferry creeks on the downstream GSD trend in the mainstem river were less pronounced than that of Bessette Creek. The fining influence of both Cherry and Ferry creeks (relative to sites immediately upstream) are localized influences that extend no more than a few hundred meters downstream. For both tributaries,

sites farther downstream are coarser than at the confluence which indicates an absence of tributary-induced fining. A tributary that contributes significant volumes of water but not sediment can still have a noticeable effect on downstream grain size within the overall fining trend (Rice 1999). Overall, Cherry and Ferry creeks provide insufficient volumes of sediment to redefine the downstream fining trends in the MSR.

Results presented in Section 3.2 provide statistical evidence for a downstream fining trend in the MSR on the basis of the truncated GSD measured using AGS. Some of the variability in the observed grain size trends may also be attributed to the sampling methods. The underwater AGS approach resulted in truncation bias. If the entire GSD has been sampled, the downstream fining trend might have been more pronounced. Boulders larger than the upper truncation value (181 mm) were present in the upstream reaches and grains less than 8 mm were present in the downstream reaches (both fractions were not represented in AGS data).

From reaches A to B to C, a downstream trend clearly exists. Reach C is finer than Reach D, which is consistent with sediment aggradation in the headpond and backwater reaches above Wilsey Dam as well as sediment starvation and bed coarsening immediately below the dam. From Reach D to E, the fining trend resumes as the river transitions from gravel-bedded riffle-pool morphology to a wider floodplain reach below the Bailey Bridge with shallower gradients. Bessette Creek appears to represent a turning point in the downstream fining trend from a coarsening trajectory upstream of the confluence to a fining trajectory downstream of the confluence. The shift in the smoothing spline trajectory is likely the result of sediment contributions from Bessette Creek and minor dam caused channel degradation (i.e., at GP51).

The presence of a downstream fining trend yields a rejection of the null hypothesis (i.e., random distribution of sizes along the length of the river) whereas the presence of outliers forces a rejection of the first alternative hypothesis (that there is a fining trend but it is not affected by tributaries, local sediment sources, or the presence of Wilsey Dam). Therefore, the second alternative hypothesis cannot be rejected, and it is reasonable to conclude that a downstream fining trend is present but that Wilsey Dam as well as certain natural features

(e.g., The Chute, Bessette Creek) interrupt this pattern and have a statistically significant influence.

4.3 OBJECTIVE 2: SALMON SPAWNING HABITAT

Prior to dam emplacement, chinook and possibly sockeye salmon were able to navigate up Shuswap Falls to the upper reaches of the MSR. Upon dam completion in 1929, salmon were cut off from access to 32 km of spawning grounds above the dam. This reduction of available spawning habitat makes existing habitat within the 8 km reach downstream of Wilsey Dam critical to returning salmon populations.

Estimates of spawning habitat from Guy and Uunila (2002) were 765,000 m² and 492,000 m² upstream and downstream of Wilsey Dam, respectively, with a total MSR spawning area of approximately 1,257,000 m². The revised estimate, completed in 2012 as a consequence of this study, for habitat upstream and downstream of Wilsey Dam are 387,265 m² and 190,906 m², respectively, giving a total spawning habitat estimate for the 28.4 km study area of 578,171 m². The 2012 estimate used up-to-date high-resolution aerial imaging (0.5 m resolution) that corrected overestimates of spawning habitat from less detailed maps used in 2002. Total spawning habitat in both 2002 and 2012 had similar upstream and downstream percentages: 77% and 33%, and 71% and 39%, respectively, although the total areas differ considerably. Both estimates show that over 70% of available spawning habitat is found above Wilsey Dam. Five maps depicting the location of salmon spawning habitat in the MSR are found in Appendix 9.

Salmon that return to the MSR tend to select the same spawning sites, and there seems to be a preference to which sites get used first (personal communication S. Wolski, Shuswap River Hatchery). Of all the preferred sites below the dam, most have been underutilized over the past 20 years due to low demand due to a small number of returning salmon (personal communication S. Wolski, Shuswap River Hatchery). However, during the large sockeye run in 2010, even sub-optimal habitat was at a premium, increasing the risk of redd superimposition and fish spawning on water margins subject to fluctuating water elevations and possibly egg desiccation (Ebner and Stueck 2010).

4.4 OBJECTIVE 3: SEDIMENT TRANSPORT MODELING

The 1.2 km salmon spawning reach of the MSR below Wilsey Dam and extending to Bessette Creek has been described as having a degraded channel bed, ostensibly because of dam emplacement (Lister 1990; Lewynsky 1997; Guy and Uunila 2002). The GSD results from this study are consistent with these assertions in the sense that the salmon spawning reach immediately below the dam is significantly coarser than most other cross-sections except those in the upper-most reaches (near Cherry Creek and upstream to Sugar Lake Dam). Sediment transport modeling was undertaken to understand what might happen to these downstream spawning gravels if the fine-grained sediment accumulating in the headpond were reintroduced downstream (e.g., by section dredging or sluicing).

For the model simulations, four GSD datasets (PAVE1, PAVE2, PAVE3, PAVE4) were used to characterize the river bed along with a combination of reintroduced material, including sand only (A runs) and sand followed by gravel augmentation (B runs). The PAVE1, PAVE2 and PAVE3 model runs did not include the very fine or very coarse grain fractions that are known to exist on the river bed. Thus, the model outputs provide insight into general trends that reveal how the river bed might reorganize itself in consequence of sediment reintroduction at the upstream boundary of the model. However, the conditions are idealized and not truly representative of real world conditions since the river retains complexities not captured by the flume-like model (e.g. sinuosity and meandering channel, eroding banks, mid side and lateral gravel bars, instream vegetation during bankfull stage, etc.). Cui et al. (2008) noted that complex channels can be modelled using a 1D model with equal width so long as average channel widths are used.

To test model performance, an initial two-week run was conducted without sand or gravel inputs and only clear-water flows (Section 3.5.1). The few bedload measurements taken from the MSR during field work did not yield any transport whatsoever so it is not unreasonable to assume that the contribution of sediment from upstream can be minimal at certain times of the year (see Section 3.2). Although sediment is transported during the freshet, based on visual assessment of water turbidity, the actual volumes of suspended and bedload rates are

unknown. Without sand or gravel inputs, the model shows that the bed coarsened (i.e., D_{50} change from 140 mm to 500 mm for some cross-sections) while bed elevation declined slightly, consistent with observations of downstream post-dam-emplacement channel response from Williams and Wolman (1984). From the model run with no sand and gravel inputs, the suggestion from the model would be that the downstream reach below the dam is not completely stable and totally adjusted to a normal spring freshet flow, which seems contrary to expectation given that the dam was emplaced in 1929 and there has been no sediment by-pass since 1971. In their assessment of 1,817 channel cross-sections immediately downstream of dams, Williams and Wolman (1984) observed rates of riverbed degradation of 0.1 to 1.0 my^{-1} for the first 5 to 10 years, after which rates of degradation slowed. Thus, the no input model results from this study are more consistent with what might happen shortly after dam closure rather than after a multi-year period of adjustment. It is not known whether this outcome is driven by the specific combination of model inputs utilized for the initial run (e.g., no large cobbles or boulders to provide frictional resistance to the flow), but the general trends shown in Figure 31 provide some confidence in the ability of the model to simulate progressive changes in a bed that is adjusting gradually to competent flows.

The reintroduction of sand alone with no gravel augmentation (PAVE 4A) causes the channel to degrade. Evidently the fine-grained fraction in transport is able to mobilize the coarse fractions on the bed, which is consistent with the observations of others (Hicken 2009; Venditti et al. 2010). After degradation during the first two weeks of the freshet, sand reintroduction causes significant changes to the bed, 0.7 m rise for the upper four cross-sections (Figure 60; see red arrows). After three days, sand begins to accumulate on the bed of the upstream cross-sections, as shown by the blue arrows. Channel aggradation, however, is short lived and from Day 25 to Day 28, all segments are degraded. The adjustments are complex, involving significant changes in surface GSD as some fractions are preferentially mobilized while others are preferentially deposited depending on upstream contributions from cross-section to cross-section. Gravel added during augmentation does not seem to result in a dynamic bed (aggradation and degradation response), similar to post-sand reintroduction.

Elevation loss in the lower eight cross-sections appears to be offset by the contribution of eroding sediment traveling downstream from the first four cross-sections. A shorter duration freshet would reduce coarsening, as would sustaining sand feed for most of the freshet.

With gravel added to the PAVE 4A model (PAVE 4B), the river bed begins to accumulate sediment thereby offsetting the trajectory of channel degradation stimulated by sand reintroduction. The lower five cross-sections that remain relatively stable during freshet experience minor degradation after gravel release. For PAVE 4B, net channel erosion after 70 days was 0.3 m averaged across the model reach. The reason for this could be the sand fraction of the augmented gravel starting to mobilize larger grains towards the end of freshet. Net channel aggradation and degradation for the PAVE 4B simulations are shown in Figure 60.

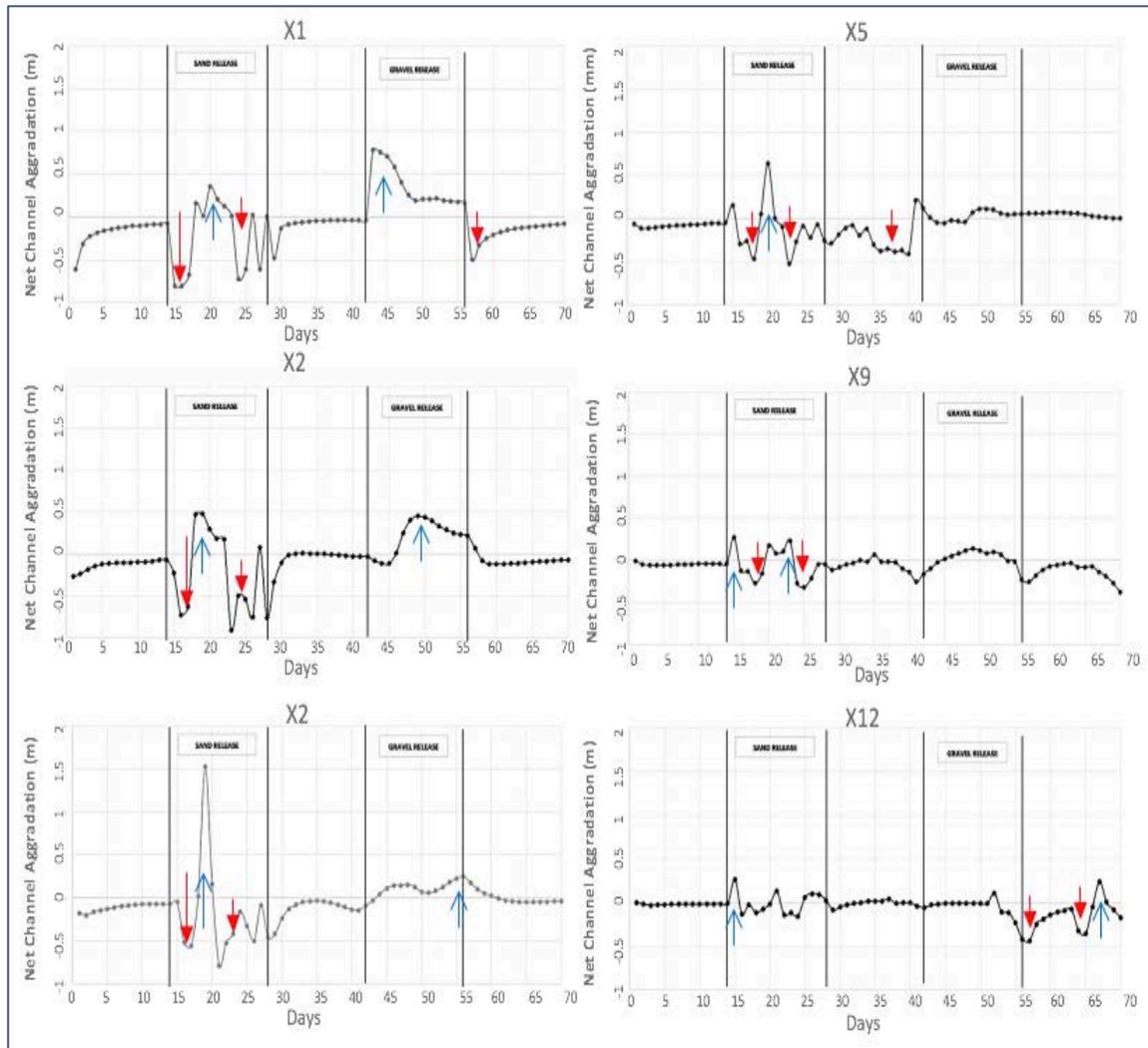


Figure 60. Net channel aggradation (+ values) and degradation (- values) for 10-week freshet for the PAVE 4B dataset simulating change in the Middle Shuswap River model reach for X1, X2, X3, X5, X9 and X12. Red arrows indicate degradation greater than 0.2 mm, blue arrows indicate aggradation greater than 0.2 mm. Black rectangle identifies weeks three and four of model. Most change in channel bed grain size distribution during sand reintroduction followed by gravel augmentation and post-gravel augmentation (X12).

Total annual sediment load in the Middle Shuswap River near Wilsey Dam is estimated to be approximately $50,000 \text{ m}^3 \text{ y}^{-1}$, with approximately $40,000 \text{ m}^3$ (80%) conveyed during the spring freshet (BC Hydro 1998). By comparison, Bessette Creek is estimated to contribute approximately $13,000 \text{ m}^3$ of bedload sediment during freshet based on field measurements of bedload transport rate at 7.12 kgs^{-1} during the 2012 spring freshet. Bedload sediment can make up to 20% of total sediment load (Hickin 1997; Czuba et al. 2011), therefore a conservative estimate of total freshet sediment contributions from Bessette Creek is $65,000 \text{ m}^3$. Given that the estimated total sediment contribution from Bessette Creek is

approximately the same as the mainstem MSR, it is possible that bed degradation resulting from dam emplacement is limited to the reach between Wilsey Dam and the confluence with Bessette Creek. Indeed, the cross-section immediately downstream of Wilsey Dam, GP51, was the only one that had a D_{50} that fell outside the 90% confidence band around the downstream fining trend. All 16 of the other sites downstream were within the 90% confidence interval, which indicates that the sediment contributions from Bessette Creek effectively mitigate the influence of the dam with regards to downstream sediment loading and salmon spawning. This does not however, suggest that reinstating the natural sediment transport regime in the MSR is either not necessary or not required for other biophysical processes.

The sediment transport model used in this study operates much like a flume in the sense that the capacity of the model is limited and the outputs oversimplified (e.g., the same GSD is used at each cross-section at the beginning of the model runs). The model does not account for grain sorting patterns, sediment patchiness, channel meanders, bank undercuts, or sediment transport pulses that are observed in natural rivers. These real world conditions, as well as limitations in friction slope, and estimates of channel roughness, are noted as being difficult challenges in sediment transport modelling as they are hard to measure in the field (Fan 1994; Ahmed, Sersawy, and Vanacker 2005). Even with the same inputs, different models can produce very different results (Fan 1994). Sediment transport modeling is inherently complex as the model attempts to simulate real world conditions, many of which vary in micro-scale and are challenging to measure (Jakeman et al. 1999; Merritt, Letcher, and Jakeman 2003). Results from this study, although providing insight into sediment transport mechanics, morphological change, and potential impacts to habitat used by anadromous salmon for spawning, are but an estimate based on a rigid set of assumptions.

PAVE 4 demonstrated that reintroduced sand will be flushed through the reach between Wilsey Dam and the Bessette Creek confluence, and therefore the alternate hypothesis (that reintroduced sediment has a limited residency time on the gravel bed within the model reach and is entrained and transported with appropriately selected flushing flows) cannot be rejected. However, the reintroduction of sand will cause changes to the river bed including

mobilization of the coarse fraction, a decrease in bed elevation, and an overall increase in D_{50} (Curran and Wilcock 2005).

CHAPTER 5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The reach of spawning habitat between Wilsey Dam and Besette Creek currently contains gravel material that supports successful spawning by anadromous salmon. Findings from this research demonstrate that downstream sand reintroduction to the MSR is a viable option for sediment management at Wilsey Dam. Sand reintroduction efforts should be trialed and monitored to see how real life conditions relate to modelled results. The limited extent of this reach—only 1.2 km—and the large contribution of sediment from Besette Creek suggest that the MSR at Wilsey Dam might be an ideal location for field-based experiments involving sand reintroduction.

The 1D sediment transport model demonstrated that when sand reintroduction is undertaken during spring freshet at flow rates of 100 cms, the sand will be flushed through the model reach quickly and that the coarse fraction residing on the bed will be mobilized. The bed however, remains well diversified and suited to the needs of spawning salmon. Fuller et al. (2016) note that change to degraded rivers downstream of small dams (< 10 m) is inversely related to pre-impoundment sediment supply rates and that for rivers like the MSR with high sediment supply rates, downstream recovery can be as quick as approximately 1 year.

Using the PAVE 4B dataset, numerous findings were obtained. During sand reintroduction, the channel bed fluctuated between periods of aggradation and degradation. The resulting channel bed at the end of the model run, although lower in elevation and coarser than the start of the modelled freshet is still well suited to the spawning needs of anadromous salmon. Using gravel immediately upstream of Wilsey Dam (from sample site GP50) in an augmentation program has the ability to reverse channel bed degradation (i.e., reducing bed elevation drop and coarsening of bed substrate D_{50}) occurring as a result of sediment reintroduction. Gravel augmentation should be considered if field trial results indicate greater bed degradation from sand reintroduction than the model predicts.

Sediment fluctuations from the model output appear lower than calculated for the volume of sediment being released, an unexplainable occurrence. The model is an oversimplification of site conditions and should be field tested during fine-sediment release trials. Nevertheless, the model and the data collected to drive the model was used to test a series of hypotheses that lead to the following conclusions for the thesis:

Conclusion 1: Underwater Automated Grain Sizing is a potentially useful tool for rapid collection of river grain size distributions but requires further calibration and refinement before it can be considered a reliable sampling method.

As noted by Graham et al. (2012), characterizing the distribution of grains in a river is very challenging. Others have documented this challenge (Williams and Wolman 1984; Bunte and Abt 2001, Adams 2013). Manual pebble counts (i.e., Wolman counts), while a standard method for collecting data on substrate material size in gravel and cobble rivers, are considered insufficient to properly characterize the entire GSD (Bunte and Abt 2001). Pebble counts tend to bias the sample toward large grain sizes because collection of fine material is difficult (e.g., an inherent operator bias against picking up and measuring a grain less than 15 mm). Grains less than 8 mm are not sampled effectively, whereas the largest boulders on the bed are often purposely avoided during sampling (Bunte and Abt 2001). Furthermore, the riverbed can be altered during long in-situ sampling times, and time per sample can be lengthy, averaging 0.5 to 2 hours (Bunte and Abt 2001). Underwater Automated Grain Sizing is a useful tool in rapid collection of grain size distribution. Clear water and low flow conditions are required. Advantages include no need to transport heavy samples, less time sampling in the swiftwater environment, relatively little sampler training and samples can be pooled, compared against adjoining years and held as a permanent record. The method is limited by water depth which limits the height above the channel bed required to capture a large surface area, and texturized grains, which when processed using DG ©, can result in over-segmentation of individual grains. Image correction, while somewhat effective, can require significant time spent correcting texturized images (Adams 2013). There is still a need for standardized method for measuring all grain sizes in a river for multiple sites in which rock collection and counting occurs rapidly. The underwater AGS method requires refinement before it can be used and considered as a standard method. Procedures for AGS on dry land have been established (Ibbeken 1986, Verdú et al. 2005, Graham et al. 2012).

Sampling dry gravel (e.g., bar top) using AGS is encouraged until underwater methods are further refined.

Conclusion 2: The downstream fining trend in the Middle Shuswap River indicates that:

(a) Cherry Creek and Ferry Creek have a spatially limited influence on the mainstem GSD;

(b) that the headpond and backwaters facilitate the settling of fine sediment, leading to aggradation upstream of Wilsey Dam;

(c) that the 1.2 km salmon spawning reach between Wilsey Dam and the Bessette Creek confluence is degraded and coarse-grained but still functional as spawning habitat for salmon; and

(d) that Bessette Creek contributes sufficient sediment to the MSR mainstem that mitigates to a degree the coarsening effect of the dam on reaches below the creek.

The presence of a downstream fining trend, albeit with large variance, is an important finding. Since there is currently no rapid GSD collection method that captures the entire distribution of grains from silts to cobbles, knowing that a truncated GSD (8 to 181 mm range) can detect the presence of a downstream fining trend will help others studying long river sections. It is appropriate to select one morphological facie, as recommended by Bunte and Abt (2001), to limit between facie hydraulic and grain size changes and sediment patchiness. This allowed for a direct comparison from one sampled morphological facie to the next.

For the most part, the MSR is a healthy river system with a near natural discharge regime (i.e., substantial spring freshet; periods of low flows), a myriad of opportunities for shifting sedimentological and aquatic habitat changes, and relatively few anthropogenic influences (relative to other rivers in the region). Sediment recruitment in the mainstem MSR is sourced from several large tributaries (Cherry Creek, Ferry Creek, Bessette Creek) as well as bank erosion, channel bed-level fluctuations, and colluvial inputs. The influence of Wilsey Dam appears relatively limited upstream (the aggrading headpond and backwaters) and downstream (to the Bessette Creek confluence). The aggrading headpond has the greatest potential to influence sediment transport dynamics because of the reduced transfer of sediment to the river below Wilsey Dam.

Preserving physical habitat below dams is critical to the preservation of aquatic diversity and abundance (Ligon et al. 1995). The best way for maintaining rich and diverse physical habitats is to allow the natural sediment transport and flow regimes to persist. Ligon et al. (1995) presents ways for dam owners and operators to maintain natural systems through estimating pre- and post-dam water sediment budgets, monitoring water and sediment discharge, modeling downstream impacts from dam emplacement and endeavoring to predict channel response. With appropriate infrastructure (e.g., low level outlet gates, hydraulic gates, in-situ dredge equipment, inflatable dams) and management techniques (e.g., annual sediment releases, gravel augmentation, high flow releases) dam managers can limit the impacts of dams on the river's natural sediment transport regime (Williams and Wolman 1984; Bunte et al. 2007; Kondolf 2014; Wild et al. 2015).

Conclusion 3: There is sufficient salmon habitat upstream of Wilsey Dam to support salmon repatriation.

Estimates of available salmon spawning habitat detailed in this research will assist decision makers in prioritizing conservation efforts and assessing the feasibility of reintroducing salmon above Wilsey Dam. Hanrahan (2004) reports that in some cases, only 5% to 30% of total estimated spawning habitat is utilized. This is especially true when one considers factors such as redd size, redd spacing, annual fluctuations in returning salmon, and other numerous and emerging determinates of spawning site selection (Hanrahan et al. 2004). Although other methods exist to refine estimates of available salmon spawning habitat, the maps presented in this paper (Appendix 9) are well suited for decision-making and detailed examinations of polygons specifying salmon spawning grounds. Available salmon spawning habitat is not considered a limiting factor in salmon reintroduction efforts since there is more than twice the amount of habitat available above Wilsey Dam as there is below.

The emplacement of dams on alluvial rivers can cause un-natural biophysical responses. These research findings will help understand how to restore natural processes in terms of fluvial sediment transport, channel morphodynamics and biological productivity to ensure that the biophysical riverscape upstream and downstream of dams are productive. There are numerous dam operators and environmental scientists worldwide that endeavor to manage

accumulating sediment and increase ecological productivity around dams for which the outcome of this research may be of interest.

Conclusion 4: Sediment transport modelling suggests that sand and gravel reintroduction from the headpond to the channel reach below Wilsey Dam will not negatively impact conditions for salmon spawning based on median grain size.

Sand reintroduction past Wilsey Dam should be timed with flushing flows in May or June of each year. Removal and reintroduction of sand from the headpond to the downstream reach can be accomplished using a large suction pump, clam shell crane or by reinstating the existing low-level outlet gates. Under insufficient flow conditions, sand can accumulate in gravel interstices which can lead to reduction in surface roughness and increases in the shear stress that may initiate erosion and transport of finer material (Station 2009).

The model simulations indicate that sand reintroduction may cause mobilization of coarse bed materials leading to channel degradation (riverbed elevation loss) and an increase in D_{50} . However, after one full freshet, the resulting D_{50} from model results is still suitable for the needs of spawning coho and chinook salmon. Gravel augmentation appears to reverse the effect of riverbed degradation and may be a suitable mitigation strategy to observed riverbed degradation should a GSD monitoring program be implemented. Since salmon have successfully spawned below the dam for the past 44 years, year-to-year fluvial morphological changes are no longer significant, largely because the system should have approached a new equilibrium bed configuration that is adjusted to the absence of natural sediment contributions from upstream.

Conclusions apply to glide facies under specific flow conditions; no conclusions are drawn on changes to the river at other fluvial geomorphic facies or under differing flow conditions. Nevertheless, the thesis results are useful as they demonstrate the localized impacts of small dams, considerations that need to be considered in preparation for dam pre-construction and during management operations. This thesis provides valuable information to decision makers on how to start addresses sediment management at small dams, provides key insights into underwater AGS, a new rapid data collection method that shows promise provided further

method and software refinement continue to be undertaken by others, and it demonstrates empirically how small dams can interrupt a river's natural sediment transport processes and how dam emplacement can become one of many factors in the downstream fining trend of the river.

5.2 RECOMMENDATIONS

The following is a list of recommendations based on findings from this research that could be explored for the purposes of study refinement and reinstating interrupted sediment transport processes at dams.

1. A field trial presents a good opportunity to calibrate findings from the model. A field trial should be undertaken in which a known volume of fine sediment (e.g., 5,000 to 10,000 m³ of fine sediment from the Wilsey Headpond) is released from the dam using a suction pump similar to what was done at Aberfeldie Dam to the downstream receiving environment. Headpond sediment from the release should undergo grain size distribution and GP sites between Wilsey should be sampled before and after dredging.
2. A preliminary investigation of the effort and cost required to reinstate the Wilsey Dam low level outlets gates should be undertaken to determine a long-term means for releasing aggraded sediment from the headpond, or alternatively, de-commissioning the dam and returning the MSR system to its natural condition.
3. Based on model results, gravel augmentation might be effective at preventing coarsening and channel bed degradation that arise in consequence of sand reintroduction.
4. A more sophisticated 2D sediment transport model should be run to compare results to the 1D modeling simulations undertaken in this study.

Future model simulations should examine reintroduction of fine-grained sediment at a range of flow discharges and across different temporal scales in order to find an optimal sequence of conditions for creating the least amount of net change to bed GSDs. Sediment transport modeling could further explore how D_{84} and D_{max} factor into suitable spawning conditions for salmon.

5. Explore the option of using active and passive hydro-acoustic techniques on the model reach of the MSR during flood events to map bedload patterns during sediment releases (Lorang and Tonolla 2014).

5.3 STUDY LIMITATIONS

This study has the following limitations:

- Findings are specific to the Middle Shuswap River.
- Findings are specific to glide morphological facies and are not intended to describe transport dynamics or shifts in GSD in morphological units (e.g., riffles, pools)
- Substrate GSD and grain sizes included the model data sets less than 8 mm and greater than 181 mm are estimates; therefore, additional sampling could be undertaken to improve model outputs as they apply to the model reach.
- Model calibration will inform limitations of the model and further inform model outputs as they relate to the model reach.

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Appendices

APPENDIX 1: HEADPOND SEDIMENT SIEVE ANALYSIS REPORT



**OKANAGAN TESTING
LABORATORIES LTD**

#100 - 1516 Keehn Road, Kelowna, B.C. V1X 5T3
Ph: (250) 860-9955 Fax: (250) 860-9918

SIEVE ANALYSIS REPORT
8 16 30 50 SERIES

PROJECT NO. 001599

CLIENT BC HYDRO REVELSTOKE GENERAL
C.C.

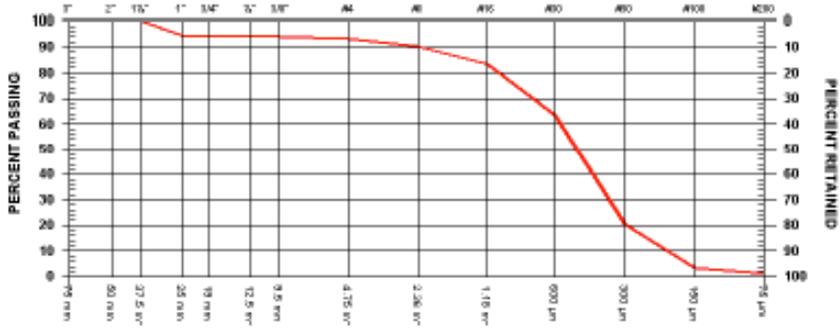
TO [BC HYDRO REVELSTOKE GENERAL STATION
WESTSIDE RD
REVELSTOKE, BRITISH COLUMBI
V0E 2S0

ATTN: ADRIENNE SHAW

PROJECT GRADATION SAMPLE REVELSTOKE
MATERIALS TESTING
CONTRACTOR

SIEVE TEST NO. 1 DATE RECEIVED 2009.Nov.26 DATE TESTED 2009.Nov.26 DATE SAMPLED 2009.Nov.26

SUPPLIER BC HYDRO	SAMPLED BY CLIENT
SOURCE REVELSTOKE	TESTED BY JH
SPECIFICATION	TEST METHOD WASHED
MATERIAL TYPE SAND WITH SOME ROCK	



GRAVEL SIZES		PERCENT PASSING	GRADATION LIMITS
3"	75 mm		
2"	50 mm		
1 1/2"	37.5 mm	100.0	
1"	25 mm	94.7	
3/4"	19 mm		
1/2"	12.5 mm		
3/8"	9.5 mm	94.3	

SAND SIZES AND FINES		PERCENT PASSING	GRADATION LIMITS
No. 4	4.75 mm	93.4	
No. 8	2.36 mm	90.1	
No. 16	1.18 mm	83.3	
No. 30	600 µm	63.5	
No. 50	300 µm	20.6	
No. 100	150 µm	3.4	
No. 200	75 µm	1.3	

MOISTURE CONTENT 5.6%

COMMENTS

Page 1 of 1 2009.Dec.15 OKANAGAN TESTING LABORATORIES PER. _____

Reporting of these test results constitutes a testing service only. Engineering interpretation or evaluation of test results is provided only on written request.

APPENDIX 2: TIMELINE OF THE SHUSWAP RIVER HYDRO PROJECT

1910 TO 2011

Author's note:

The proceeding appendix lists important moments in the history of Wilsey Dam from 1910 to 2011 inclusive and was not originally scheduled for inclusion in this paper because of the informal note-like quality of the information presented. However, in the absence of another similar record, I have decided to include it. This is a history of the Shuswap River hydroelectric system as I understand it and have researched it and it likely contains omissions and some errors. Please source check all information contained within this Appendix before reference and citation.

2011

MSR Terrestrial Sensitive Habitat Inventory Mapping (SHIM) (Iverson 2012)

2009

Aug. 7 to 31 – Dredge Wilsey Dam headpond (Shearing, 2010)

2007

SHIM report - 06.SHU.03 (Minor 2007):

- 73 ha (vs. 76.5 ha in Summit report; stated considered “13 mm to 102 mm gravel substrate without considering water depth) of spawning-size gravel/cobble covered by at least 0.3 m of water at low flow was found in the study area above Wilsey Dam (between Wilsey and Sugar Lake dams)
- 27.8 km of side channels between Wilsey and Peers with good diversity of habitat
- Lower 20 km of MSR have slope (not sure if channel or water) less than 0.3%
- Side channels were only counted if there was connectivity at moderate to low flows with the mainstem; “25.1 kms were wetted at the time of survey and 1.4 kms were seasonally wet”
- Spawning habitat identified by hydraulic type, simple visual (confirm) substrate classification of differing dominance and sub-dominance of gravel, cobble complexes, water depths between 0.4 and 1 m and side channel depths of 0.1 - 0.4 m. Rearing habitat total side channel area with depths >0.2 m at the time of survey
- States that if spawning gravel is a limiting factor below Wilsey, then there is more than double above Wilsey.
- Available holding pools a limiting factor upstream (personal communication S. Wolski) (Minor 2007)
- 6 restored/constructed channels total 15.6 ha
- Conserving natural channels more cost effective than reconstructing or rebuilding

Table 3: Lengths and areas of channel of the Shuswap River between Wilsey and Peers Dams with predominantly spawning size gravel/cobble substrate. All side and main channels are included that have a wetted depth between 0.2 and 1.5 m.

% Gravel (2-64 mm)	% Cobble (64-256 mm)	Length (m)	Area (ha)
70 - 90	0-25	2,110	1.21
50 - 69	25-45	2,960	7.57
40 - 49	30-60	7,190	22.13
30 - 39	70 - 50	7,940	32.66

Table 6: Comparison of the results of three studies done on the middle Shuswap River between Shuswap Falls and Sugar Lake. Segments of the SHIM were grouped to correspond to the reaches used in the earlier studies for comparison purposes.

Study	Reach	Q ¹ (m ³ /s)	Wetted Width ² (m)	Reach Length (m)	Wetted Area (ha)	Riffle Depth (cm)	Gradient (%)	Pool (%)	Run (%)	Riffle (%)	Total Cover (%)	Fines (%)	Gravel (%)	Cobble (%)	Boulder (%)	Bedrock (%)	
Fee & Jong (1984)	3	25 - 30	43.0	3,700	15.9	-	0.2	35	55 ³	10	-	20	30	50 ⁴	22.0	3.0	
	4		39.1	13,100	51.2	-	0.26	5	80	15	-	5	41				54
	5		39.0	15,200	59.3	-	0.63	4	42	53	-	4	4				62
Trident (1995)	3	15.5 - 27	17.3	3,700	10.73	70	-	5.0	80.0	15.0	3.0	8.0	17.0	50.0	22.0	3.0	
	4		31.0	13,100	40.61	52	-	3.4	68.3	28.3	2.6	3.0	17.0	60.7	18.6	0.7	
	5		29.8	15,200	45.36	69	2.0	0.9	40.1	59.0	2.9	2.7	15.5	55.0	25.0	0.7	
SHIM (2006)	3	16 - 30	49.2	3,280	16.13	200	0.07 ⁵	4.3	18.4	73.8	52	4.8 ⁶	28.6	33.2	10	23.4	
	4		56.74	13,810	74.99	60	0.36	9.7	34.4	56.0	11	10.0	23.3	52.9	13.6	0.1	
	5		49.4	16,070	75.43	73	0.58	11.5	33.2	55.3	22	6.0	22.1	51.9	19.8	0.2	

¹ Range of flow at the time of survey

² Main channel and side channels

³ Fee and Jong distinguished between run and glide. These two have been combined for comparison purposes.

⁴ Fee and Jong categorized substrate >10 cm as "Larges"

⁵ Gradients for the reaches was determined using distances from the SHIM and spot elevations from the B.C. Water Resources Atlas web map,

<http://srmapps.gov.bc.ca/apps/wrbc/>

⁶ Organics and fines are grouped together for this comparison. Percentages are weighted by fraction of total wetted area. Side channels are included in the total wetted area.

2005

March 31 – Release of Phase 2 Wilsey Fishway Feasibility Study

March – Dam Safety Surveillance Annual Report (Stewart 2005)

- Assigned high consequence category as per BC Hydro Dam Safety Management Manual, Attachment 1.2-1, 15 November 2001.
- Low-level outlets closed in 1991 by bolting stainless steel plates over sluice inlets.
- A concrete arch dam at the downstream toe of Wilsey Dam was constructed in 1929 and upgraded in 1992.
- Powerhouse 140 m downstream of Wilsey Dam.
- Free-crest spillway conveys excess flow for approx. 6 months.
- Area Dam Safety Engineer inspects headpond slopes twice annually between the dam and the highway bridge.
- Dam Safety Issue Number WIL03-1 indicates sediment levels upstream of the dam should be checked against 1992 levels to determine if sediment loads are acceptable or require dredging. (has dredging occurred immediately upstream of the Wilsey Dam?)

(Heidstra 2005) notes that LLOGs decommissioned and valves removed in 1990. Downstream ends of LLOGs are open and can be reinstated if required.

2004

June 14 – BCRP Open house with 60 area residents (Phase 2, p. 12)

Oct. 28 – Wilsey Dam Fishway Concept Meeting (Phase 2, p. 12)

2005

Channel along right bank upstream of spillway deepened during construction (Heidstra 2005)

2003

Steering committee formed. Included Ministry of Water, Land and Air Protection, BC Hydro, Okanagan Indian Band, ONFC, DFO, Spallumcheen Indian Band, Secwepemc Indian Band (Phase 2)

BCRP report lists fertilization experiments as a low priority (BCRP 2003). In addition, the same report identified future research projects to include examination of reduced habitat potential caused by insufficient recruitment of sediment and wood.

2002

- Summit Environmental report estimates 492,000 m³ of spawning gravel downstream of Wilsey. Spawning gravel area upstream of Wilsey to Sugar estimated at 765,000 m³. **Report suggests sediment trapped behind Wilsey is degrading spawning habitat 1.5 km downstream of the dam** (Phase 2, p. 14)

2001

February. Arc Environmental Report: Shuswap River Fish/Aquatic Information Review (ARC 2001a):

- Threats to MSR below Wilsey: channelization, agriculture, removal of riparian vegetation, non-point source pollution, stream bank trampling
- MSR is nitrogen limited
- Sediment discharges can impact spawning grounds; however, flushing flows should be suitable to mobilize fine sediment. Note that Bessette sediment loading enough to possibly impact spawning sites below confluence (big influx with 1997 flood).
- Remark that gravel recruitment and quality of gravel [I assume them mean size] could decline overtime.
- State there is a need to monitor important MSR habitat over time, including gravel recruitment and quality upstream and downstream of Bessette (rated moderate to high priority in report).
- Recommends conducting modeled tests of substrate change at cms: 28.3, 25.5, 22.7, 19.8 and 15.6 for fall and winter period.
- Habitat productivity in MSR is low and stock information in 2001 suggested the system was under capacity, the result of which was unknown.
- 359 water licenses exist on the Shuswap River system; however, in 2001, their location was unknown.

2001

October 8th week – 2 tripping incidents in which Summit Environmental was contracted to ID risks to kokanee and chinook – impacts to spawners not observed (MacLean 2000).

June: Bengeyfield, et al. 2001:

- This report identifies dam height and biological interactions as the only minor impediments to fish passage at Wilsey. (Bengeyfield et al. 2001)

2000

- Letter from I. MacLean to H. Stalberg (DFO) regarding fisheries issues on the Middle Shuswap System (MacLean 2000)
- DFO concerned with forced outages altering water levels
- MacLean notes the difficulty of monitoring flow disruption on small time scales.
- Report mentions possible future installation of rubber spillway gates, automatic trash-rack cleaner for G2 and G1 auto-synchronizing after a forced outage.

2000

- Fall and winter flow regimes established for the Shuswap River (MacLean 2000).
- Gate position sensors installed to better control the headpond (MacLean 2000).
- Permanent-Sequence-of-Event indicator installed to assist with “troubleshooting problems” (90% complete this year) (MacLean 2000).
- As of 2000, Shuswap Falls Generating station generates on average 37,00 MWH annually or ~1.6 million in revenue (BC Hydro 2003)
- BC Hydro begins work with independent facilitator on Water Use Plan process (BC Hydro 2003)
- (Algar 2000) lists “gravel recruitment/quality/transport/scouring” as a fisheries issue and the continued challenge of Wilsey Headpond forebay dredging as a water quality and supply issue.

1999

- G2 gate control system installed “enabling removal of cross-tripping scheme.” (MacLean 2000)
- Water Use Plan for Shuswap Generating System started (MacLean 2000).

1998

- “Headpond silt removal program completed without compromising water quality downstream.” (MacLean 2000) – *Must have year wrong since none of the other dredge documents refer to a dredge this year*
- Chinook transplanting above Wilsey recommended to continue by DFO (DFO 1998)

1997

- (Quamme, Clarke, and Slaney 1997) study details flow ramping related to fish production
- High water year potentially resulted in morphological changes to channel form (ARC 2001a)

- Significant agricultural losses documented in (BC Hydro 2003)
- G1 gate control system installed allowing for “faster response to outages” (MacLean 2000)
- Vic Lewynsky’s EMP for Dredge references degrading habitat below Wilsey Dam (Lewynsky 1997). Remarks that “knowledge of downstream substrate condition and tolerance to a shift in timing” is required to make informed long-term decisions.
- Water License 15230 permits storage of water in Sugar Lake ($123.3 \times 10^6 \text{ m}^3$) and Water License 14507 allows for $20.7 \times 10^3 \text{ m}^3$ behind Wilsey. Powerhouse licensed to divert 31.1 cms comprised of WL 9756 (9.9 cms), WL 11057 (7.07 cms) and WL 15074 (14.15 cms) (BC Hydro 1997)

1996

- Oil containment installed inside powerhouse (MacLean 2000).
- Letter from AGRA Earth and Environmental to Dave Purcell regarding limited dredge stockpile options (Hawson 1996)

1995

- Aug. 21-Sept. 7 Chinook transplant above Wilsey Dam (153 female, 140 male, 7 jacks) (ARC 2001a), (Triton 1995) – spawning and rearing successful (ARC 2001a)
- Oil containment installed in substation (MacLean 2000)
- “Major” upgrade to powerhouse and operating reliability (MacLean 2000).
- BC MOE expresses concerns about salmon transplants on resident salmonids [I guess rainbow, brook and bull trout?] (Jantz 1995) (Bengeyfield et al. 2001)
- DFO tested feasibility of re-introducing chinook above Wilsey; results were fry reading above the dam ((Bengeyfield et al. 2001), Triton)
- French report on historical fish passage (French 1995)
- Evidence suggests Chinook above Shuswap Falls, possibly above Brenda Falls. sockeye might have passed Shuswap Falls
- Installation of water gauge below powerhouse.

1994

Substrate Size of reaches between Wilsey and Sugar from (Triton 1995)

Size	Reach 3 (to Chute)	Reach 4 (below Cherry)	Reach 5(to Sugar)
% fines (0-10 mm)	20	5	4
% gravels (10-100 mm)	30	41	34
% cobbles (>100 mm)	50	54	62

1993

- Dec. 22 – BC Hydro starts using WSC Telemark system to receive spot measurements of discharge (Triton 1994b)
- November – Acres International Ltd. prepared report H2706 on alternatives to dredging.
- Aug. 10-20. Chinook transplant above Wilsey (144 female, 144 male, 5 jacks) (ARC 2001a)

- First bypass valve (Howell Bunger Valve) installed on G2 to mitigate flow interruption caused by an outage (MacLean 2000),(ARC 2001a) (D. Gordon 1994) Cost \$800k (BC Hydro 2003)
- Maximum turbidity recorded during bypass valve was 3.06 NTU (background ~0.39 NTU)
- DFO tested feasibility of re-introducing Chinook above Wilsey; results were fry rearing above the dam (Benneyfield et al. 2001), (Triton 1995)

1992

- Foundation drain installed in Wilsey Dam and post-tensioned anchors added to improve plug stability (Stewart 2005)
- 1991-1992 fisheries flow release trials at Wilsey Dam (Sigma Engineering Ltd)
- (Cornish et al. 1992) found that economic loss to fisheries from a dam failure would be \$1.6-32 M depending on the season of loss.

1991

- BC Hydro staff observe flows of 28.3 cms as being able to facilitate passage for all fish species (Sigma 1993a).
- 2,000-3,000 sockeye escapement (Sigma 1993a)
- LLOGs closed by bolting stainless steel bell-mouth plates over inlet passages in the arch dam during full-pool (Stewart 2005) (Hodge, Gygax, and Muir 2005) (Cornish et al. 1992). Drawing for steel plates found in (Cornish et al. 1992).
- (BC Hydro 1991) provides a detailed description of LLOG condition in 1989. This report also describes the following benefits of reinstating the LLOGs:
 - In an emergency, gates could be used to relieve loading from the dam.
 - Restore downstream flow during unplanned event if upstream side free of sediment.
 - Estimated discharge capacity of 16 cms could reduce water overtopping the dam during flood events
 - Allow for headpond drawdown for inspection of intakes and other submerged infrastructure.
 - To remove accumulated sediment from the headpond.
- From (BC Hydro 1991):
 - 25 m of sediment in places within the headpond
 - Existing wood debris measures sufficient

1990

Cornish et al. (1992) technical report provides the following insights:

- Head drop from Sugar Lake to Mable Lake is 208 m of which Wilsey represents 28 m
- Sugar to Mable diversion has potential for 60 MW of power generation but would require 22 m of additional reservoir storage (raising the lake)
- Installation of a 3rd unit at SHU discussed
- Minimum flows presented as 25 cms Sept. 15 to Nov. 15 and 15 cms all other times. 5 cms release from Sugar Lake at all other times (appears to be first mention of min. flows in the literature reviewed). This recommendation accompanied conceptual plans for the Sugar to Mable diversion in which case MSR flows would be severely

disrupted. The Montana Method from Tennant 1976 suggests that “30% of mean annual flow is a generally adequate base flow for fish habitat.” It was noted that such a loss would result in long-term fluvial morphological changes and decreases in channel complexity and therefore habitat types.

- States that: “a major factor affecting the operation of the Shuswap Project is the sediment deposits which have accumulated” in the headpond. Estimates that headpond was then filled with 400,000 m³ of sediment with annual loading rate of 25,000 m³ although it’s noted that loading rate could vary.
- Dredging cost estimated in 1988 at \$40,00 per year.
- Was then believed that removing 100,000 m³ would be required to reduce frazil ice and sediment-related equipment wear.
- It was written later that realized costs derived after 1988 and 1989 dredging made annual costs closer to \$250,000 annually (for removal of ~25,000 m³).
- Two options presented include reinstating the LLOGs or constructing a dividing wall. Also stated is that headpond sediment removal and LLOG refurbishment were “major items that require attention in the near future.”
- Discusses a plan for reinstating the LLOGs

LLOGs decommissioned and valves removed in 1990. Downstream ends of LLOGs are open and can be reinstated if required (Heidstra 2005).

April

- DB Lister and Associates Ltd. report on “An Assessment of Fisheries Enhancement Potential of BC Hydro Operations at Shuswap River” (Lister 1990)
- Noted in the report that insufficient sand and gravel recruitment “could lead to degradation of the channel and possibly, some reduction in fish spawning bed quality.” Using the LLOGs is recommended as a way to maintain sediment equilibrium
- A discussion on hatchery expansion is presented
- Outmigration of Chinook and coho salmon past Wilsey is discussed. Downstream fry migration would occur April to May (peak between April 20 and May 10); smolt migration April 20 to May 10
- Fish entrainment mortality rate using “Eicher Associates” review suggest 17% (range of 1% to 28% with hydraulic heads of 30 m; SHU is 28 m head)
- Suggests entrainment mortality limited by downstream migration peaking after freshet spilling has commenced, most salmonids are “surface oriented” and would likely avoid deeper water leading to the intakes (Intake building 448.52 m, spillway crest: 444.52 m, top of G2 trash-rack: 437.56 m, bottom of G2 trash-rack: 435.16 m, river-bottom: 427 m, water level at 17 cms: 445 m – from low water level to top of trash-rack ~5 m. Lister notes 7 m from freshet elevation to trash-rack, but he probably is referring to the bottom).
- Also, the fishway intake could provide an alternative for pre-freshet migrators before spilling occurs (no discussion on when spilling occurs and water level is lower relative to watered penstocks).
- Concluded winter flow augmentation beneficial to salmon(Lister 1990).

LLOG plugged with steel bulkheads to prevent sediment flushing (from report to DFO mentioned as positive mitigation) (MacLean 2000)

- sockeye escapement 96000 (Sigma 1993a)
- Chinook escapement to Middle Shuswap increased to an average of approx. 4000, 5 times greater than estimates of 420 in Fee and Jong study of 1984 (Phase 2, p. 13). Although lower Shuswap escapement has increased past 1990, Middle Shuswap has not.
- Arc 2001 data suggests 95% of Chinook in Shuswap exhibit Ocean-type life history – (Phase 2, p. 13)

Cornish, L. J. 1990. *Shuswap Project Rehabilitation/Redevelopment Overview Study*. H2159. Vancouver, BC: BC Hydro.

1989

- Shuswap Hatchery reports water drop of 0.3 m resulting in juv. salmon stranding and mortality ~1 km DS of Powerhouse resulting from stop-log removal (Lister 1990)
- April 10 – flow release from Sugar Lake was reduced from 17.6 cms to 9.6 cms to facilitate dredging operations (release in 2009 was 600 cfs of 16.9 cms). Clamshell for wet, 1 Excavator for dry material. TSS monitored by Hatchery Contractors Ova Tech (TSS sampling methods and results presented in report) (Lister 1990)
- March 28 - DFO and MOE permit dredging operations at Wilsey Headpond (BC Hydro 1989)
- BC Hydro and DFO agree that a long-term plan for Wilsey Headpond dredging should be undertaken, and to include MOE (Smith 1989b)

1988

- 1988-1999 Average 1700 Chinook escapement and 80,000 sockeye, 500-1200 coho (Sigma 1993a)
- Photos suggest rock outcrop was removed in 1988 (BC Hydro 1989) Also stated in (BC Hydro 1991)
- Study modeled sediment movement if a “long-wall” structure was constructed in headpond to divide thalweg from headpond (Lewynsky 1997)
- Study referred to by Lewynsky (1997) was (Margolis 1988)
 - Recommended rock projection (~4000 m³ bedrock; 3000 m³ overburden) be excavated and dividing wall between headpond and thalweg.
 - As of 1988, 8 to 14 m of sediment had accumulated in the headpond depending on location (Margolis 1988)
 - Agree that annual sediment load is 22,000 m³/yr. (Margolis 1988)
 - Dredge material found to have D80 percent-finer-than = 0.5 mm and D5 of 0.1 mm
 - Daily discharge records: 1913, 1917-1924, 19-26-1935, 1946-1973, 1984-1986
 - Note that WSC records extrapolated above 265 cms, therefore not as reliable.
 - Note that a pre-dam construction survey exists.

- For dredging, (Margolis 1988) recommend pumping 5 hours per day for 4 weeks during May and June (which they note DFO would allow) to remove 6000 m³ at 70 m³ per hour.

1987

- Drilling investigations in the headpond to depths 19.5 m near the G2 intake and 16.1 m near the middle of the headpond found “very loose to loose, clean, medium to fine sand over[lying] dense sandy gravel.” (Margolis 1988)
- Hydraulic model study to assess headpond siltation mitigation (Heidstra 2005)
- February - Rock outcrop excavation completed (Margolis 1988)
- ~4000 m³ rock jetty blasted upstream of dam to straighten thalweg.
- (BC Hydro 1987) report describes the barge mounted suction dredge. Says silt is cleared annually over the spillway for a month over freshet. It’s noted that Fisheries are consulted beforehand. This report also describes the exact operation of the LLOGs.

1986

- Memo from I. C. Dirom to K. Epp suggesting 10,000 cubic meters needs to be removed annually from in front of the intakes (Margolis 1988) (note that removal of the rock outcrop was theorized to reduce the annual dredge volume from 10k to 6k m³ (Margolis 1988)
- Shuswap hatchery starts to release hatchery fish (Phase 2, p. 13)
- DFO reopened commercial Chinook fishery on Shuswap River system (Lister 1990)

1985

- Bengeyfield writes: Shuswap Falls Hatchery began enhancing the Middle Shuswap chinook stock in 1985 after earlier escapements dropped to 500 fish per year ((Bengeyfield et al. 2001).
- Shuswap River Hatchery construction – Oct. 23, 1985 (see PDF historical photos)
- LLOG concrete buttress strengthened and new LLOG gate hoists installed (Donaldson 1987)

1984

- Lister notes that the Shuswap Hatchery has operated since 1984 (Lister 1990) Photo evidence suggests hatchery was still under construction in 1985. (Lister 1990) provides further comment that a trail hatchery existed starting in 1984.
- Fee and Jong report on Chinook transplant above Wilsey Dam (Fee and Jong 1984)
- Stream area decreased from 336 ha in July to 237 ha in October
- Note that wood cover found less beneficial to juv. Coho in 2003 study (Giannico and Hinch 2003) although is used in this study to quantify rearing habitat.
- Carrying capacity of Shuswap River was 740 adult salmon, as per Fee and Jong study (Phase 2, p. 13)

1983

1983-91 – reasonably accurate outflow data (Sigma 1993a)

1982

- Acres Consulting Service Ltd. estimated annual sediment accumulation rate of 22,000 m³ per year. Grains sampled averaged 0.1 to 1.0 mm (Margolis 1988)
- (Wardle 1982) recommends reopening discussion with DFO regarding use of LLOGs, such as annual sluicing

1979

1979-1982 – relatively poor hydrologic data, although good enough for inclusion (Sigma 1993a)

R.P. Griffith report (Griffith 1979)

- Griffith divides Wilsey to Peers into 3 reaches: 3) Wilsey to 3.7 km upstream 2) 3.7 km upstream of Wilsey to Cherry Creek and 1) Cheery Creek to Peers Dam.
- Reach 1 has slope greater than 0.63% with confined channel, larger substrate
- Reach 2 has slopes less than 0.6%, small substrate and less confined channel (more backwaters and side channels)
- ID mountain whitefish as most abundant species.
- During Oct. 18-23, 1978 survey, most rainbow trout and whitefish found in Reach 1
- Found “prime habitat” not used by any fish species, suggesting underutilization.
- Although invertebrate production rated as reasonable (by who?) suggest Brenda Falls limiting detrital conveyance and therefore primary production.
- Suggest removing whitefish to enhance rainbow trout.
- Suggest gravel augmentation scheme in Reach 1.
- Further study on food availability in Reach’s 1-3
- Reach 2 not as good for rainbow trout but good for Chinook
- Good information is provided on channel length
- Found substrate in Reach 2 to be a majority of 5-10 cm in diameter, too large for the small RBT found in the MSR
- Stated that size differences between RBT and Chinook preclude direct competition

1978

- BC Hydro begins measuring daily discharge below the powerhouse and spillway (Margolis 1988)
- Another transplant occurred within only 12 fish, many of whom swam back down over the spillway (Griffith 1979).

1977

- DFO tested feasibility of re-introducing Chinook above Wilsey by releasing 75 adults (in Aug-Sept, 38 f and 33 m were captured below Wilsey and released 10 km above. ((Bengeyfield et al. 2001),(Triton 1995), (Griffith 1979) (BCRP 2003)

1974

- (Mulherin 1974) makes the following remarks:
- Sediment accumulation from 1961 (although I think he meant 1966, the last sluice) had too greatly accumulated that use of the LLOGs was prohibited by DFO.
- Estimate of annual sediment loading estimated to be 15,000 cubic yards (~11,500 m³)
- Reference depth soundings in 1966 and 1970 that estimate total sediment accumulation at 115,000 m³
- DFO requirement for first suction dredge discharge was 150 yards/he max at 4000 cfs flows.
- This report documents the exact pumps used for early 1970's dredging.

1973

- A submersible pump used to dredge had problems with wood plugging the pump (Mulherin 1974)

1972

- LLOG gates abandoned – on drawing from (Stewart 2005) and (Heidstra 2005) – See Evernote note.
- (Heidstra 2005) notes ceasing use attributes to DFO concerns and “poor condition of the downstream slide gates.”
- LLOGs were blocked with a tree stump and would not close. Dynamite used to remove the stump and once the gate was closed, use of the LLOGs ceased (BC Hydro 1991)

1971

- Depth soundings of the forebay between September 1970 and April 1971 showed no increase in sediment, consistent with the theory that most sediment deposition occurs during the Spring freshet (Margolis 1988).
- BC Hydro discontinues use of LLOGs in response to DFO concerns (not described) (Lister 1990)
- Meeting minutes of Feb. 10, 1971 between DFO and BC Hydro regarding sediment management (Edgeworth 1971)

1970

- DFO instructs BC Hydro not to use sluice gates; no reason given in cited report (Margolis 1988); (BC Hydro 1987)
- BC Hydro “restrained” by DFO to stop using LLOGs, sluicing occurred every 5 years or so. (Wardle 1982)
- LLOGs abandoned because of “serious fisheries concerns” (BC Hydro 1997)

1966

- Last hull headpond flush using sluice gates (Margolis 1988) (NOTE: incorrect, last flush in 1970)
- Sluicing described in (Battram 1966):
- “Sluicing of the forebay started March 13 and finished on March 31. Gravel to a depth of over 5 feet was deposited immediately below the power house completely

covering the exits to both draft tubes. Silt was cleaned away from the penstock intake areas. Some trouble was experienced with plugging of the sluice openings with stumps and logs and on one occasion the drag line clam shell bucket went through the opening to the downstream side. Such troubles were minimized by altering sluices and marking the drag line cable so that the operator knew at all times the position of the bucket in relation to the sluice gate opening. Equipment used for the sluicing operations included one dragline, a D7 caterpillar tractor and a D2 size tractor.”

1962

- Wilsey and Sugar Lake dams acquired by BC Hydro (ARC 2001a)

1954

- Shuswap generating system taken over by Water Rights Board, Province of BC (French 1995)

1952

- Gate house constructed over LLOG valves (Heidstra 2005) and steel liners added in sluice-ways “to transmit the gate forces to the upstream face of the dam and to reduce water entry into the construction joints between the dam and the gatehouse.” (BC Hydro 1987)

1947

- Pacific Salmon Commission constructs second fish ladder at Hells Gate (BCRP 2003)

1946

- Shuswap generating system taken over by BC Power Commission (French 1995)

1945

- Wilsey and Peers acquired by B.C. Power Commission (predecessor of BC Hydro) ((Benneyfield et al. 2001))

1944

- Pacific Salmon Commission constructs first fishway at Hells Gate (BCRP 2003)

1942

- Significant flow regulation occurred this year (Sigma 1993a)
- Sugar Lake Dam raised to 6.2 m, original sluice gates decommissioned and a LLOGs added (Donaldson 1987). (Heidstra 2005) states that dam raised to 13 m.

1941

- Second generator added at Wilsey Dam (Triton 1995) (Donaldson 1987)
- Upstream LLOGs replaced with downstream gates (BC Hydro 1987)
- Sugar Lake Dam increases in size (Sigma 1993a)

1929

- Concrete gravity plug installed at base on Wilsey Dam after reservoir filling caused a washout of material at the base of the dam (Stewart 2005) (Donaldson 1987)
- June 15 – plaque date that indicates the formal start of facility operation (Bengeyfield et al. 2001)
- Project in 1928/1929 consisted of: (Donaldson 1987)
 - Sugar Lake Dam at 5.2 m tall
 - Wilsey Dam at 30 m tall with spillway and LLOGs
 - Intake on L. bank with twin intakes; one used, one terminated before daylighting through the rock tunnel
 - 2.4 m diameter penstock
 - 1 - 3 MW unit
- Peers Dam completed at Brenda Falls (Triton 1995)
- Canada Fisheries Branch Annual Report from 1928-29 states: “Shuswap River Falls – Investigation was made into the feasibility of providing a fishway for a dam seventy feet in height at this point. As a result of these investigations it was ascertained that the passage of salmon could not be assured and under the circumstances it was recommended that the construction of a fishway was not required. (Bengeyfield et al. 2001)

1928

- Wilsey and Peers constructed by West Canadian Hydroelectric Company. Wilsey only had one unit (Bengeyfield et al. 2001))
- Last year spawners could get above Wilsey Dam (Sigma 1993a))

1927

- 1927-1934 – No significant flow regulation identified on WSC Sugar Lake outflow records (Sigma 1993a)

1926

- WSC Gauging Record begins again for 08LC003

1920

- West Canadian Hydro Electric Company (US owned, Water Use Plan) prepared a conceptual engineering plan of the proposed Wilsey Dam that showed a short fish ladder leading into the lower end of the spillway channel. (Bengeyfield et al. 2001)

1915

- March – Rock removed from Hells Gate
- R. Bailey said the rock would not have prevented Chinook from passing into the interior.

1914

- February – a second rock slide at Hell’s Gate that further reduced upstream migration of salmon (Bengeyfield et al. 2001)

1913

- October – Babcock visits Shuswap Falls and saw no fish and was “of the opinion that the area of spawning grounds above the falls is not sufficient consequences to oppose the construction of a dam or the necessity upon the construction of a fishway, in the event that the dam is placed there.” (Benneyfield et al. 2001)
- June or July - Within 2 months after 1913 correspondence between F. Cunningham and H. Shotton – rock slide at Hell’s Gate in Fraser Canyon [significantly – i.e. because Babcock could not see fish at SHU in Oct. 1913] reduced fish passage (Benneyfield et al. 2001)
- May – Chief Inspector F. H. Cunningham passed [H. Shotton’s?] notes to the Provincial Commissioner of Fisheries J.P. Babcock and added the following comment: I am very strongly of the opinion no effective fish ladder could be constructed in a dam of this height” (Benneyfield et al. 2001)
- April – H. Shotton recommends to Chief Inspector that a fishway be required at this dam. (Benneyfield et al. 2001)
- February – Couteau Power Company submits application to Chief Inspector of Dominion Fisheries in New Westminster to not construct the fish ladder; application includes two photos of pre-project river, a pre-project hydrograph and a map of the river with a note [describing] of 38 foot sheer falls at Sugar Lake outlet (Mackenzie 1913) (Benneyfield et al. 2001).
- WSC Gauging Record begins for 08LC003

1912

- March - Kamloops fisheries officer H. Shotton was sent to region and relayed various notes from local residents about fish presence and good spawning grounds above the lower (Shuswap) falls and in their opinions as to the necessity of a fish ladder at Shuswap Falls. ((Benneyfield et al. 2001)
- Couteau Power Company from Vancouver plans to develop hydroelectric facility at Shuswap Falls (Benneyfield et al. 2001) and was unsuccessful (French 1995)

1900

- BC Lieutenant Governor pronounced Shuswap falls to be “one of the best water powers for electrical manufacturing purposes in the province” (French 1995)
- Max height without flashboards: 444.52 m or with flashboards: 445.49 m (BC Hydro 1987)
- Discharges into main spillway channel and saddle dam into historical channel

APPENDIX 3: HISTORY OF DREDGE OPERATIONS AT WILSEY DAM

Table A.1. Timeline of sediment management techniques by year at Wilsey Dam, BC (1929-2009).

Year	Removal Method	Volume Removed (m ³)	Reference
1929-late 1960s	Sluice Gate Operation	Unknown	BC Hydro Dredge History Binder
1951	Sluice Gate Operation Bull dozer	Unknown	(BC Hydro 1989)
1961 (Started March 15 for 2 weeks)	Sluice Gate Operation (2-week sluice) Crane to remove wood debris Bulldozer to push sediment into the river flow 2.8 to 4.2 cms flow at time of sluice	293,589	(Lauga 1961)
1966	Last record of sluice gate being used to flush entire headpond of accumulated material	Entire Headpond	(Sigma 1993b)
1970	Partial headpond sluice	Partial headpond sluice	Personal communication O. Langer
6 wks. from May-June 1971	Suction dredge (dredgeate discharged over spillway)	Unknown	(Sigma 1993b)
6 wks. from May to June 1972 - 1988 (except 1975)	Suction dredge (dredgeate discharged over spillway)	Unknown	BC Hydro Photo (Sigma 1993b)
Sept. 18, 1975	Suction dredge (dredgeate discharged over spillway)	Unknown	BC Hydro Archive Photo
June 22-23, 1988	Suction dredge (dredgeate discharged over spillway) Flow 75 cms	5400	BC Hydro Archive Photo
March, May, June/July & Nov. / Dec. 1989	Clamshell 1 Excavator Reference to flow discharge reduction at Sugar Lake Dam for dredging. (stockpiled at old townsite)	16,362	(Lister 1990) (BC Hydro 1989)
1991	2 Excavators used	Unknown	BC Hydro Photo
1992	Method unknown	Unknown	(Guy and Uunila 2002)
1993	Method unknown	Unknown	(Guy and Uunila 2002)
1994	Suction dredging (spoil piped to near-by gravel pit)	Unknown	BC Hydro Dredge History Binder (Lewynsky 1997)
Aug. 25-29, 1997	1 Excavator: Hitachi EX270LC (stockpiled at old townsite)	~4357	BC Hydro Dredge History Binder (Guy and Uunila 2002)
1998	“Headpond silt removal program completed without compromising water quality downstream.”		(MacLean 2000)
Aug.29 - Sept. 10, 1999	2 Excavators: Hitachi EX270LC w/ Extended boom Komatsu PC200LC-6 Vacuum Truck and Divers (stockpiled at old townsite)	12,690	BC Hydro Dredge History Binder BC Hydro Photo (MacLean 2000, Guy and Uunila 2002))
August 2003	2 Excavators: EX200LC EX300LC (stockpiled at old townsite)	18,456	BC Hydro Dredge History Binder (BC Hydro 2001)
Aug. 15 – Sept. 11 2006	Long-reach excavator (stockpiled at old townsite)	Est. 10,000 - 15,000	BC Hydro Dredge History Binder
Aug. 9-30 2009	Manitowoc Crane Clamshell Dredge 1 Excavator (stockpile adj. to headpond)	~20,000	(Shearing, 2009)

APPENDIX 4: WENTWORTH SCALE

Φ	PHI - mm CONVERSION $\phi = \log_2 (d \text{ in mm})$ $1 \mu\text{m} = 0.001 \text{mm}$		Fractional mm and Decimal inches	SIZE TERMS (after Wentworth, 1922)	SIEVE SIZES		Intermediate diameters of natural grains equivalent to sieve size	Number of grains per mg		Settling Velocity (Quartz, 20°C)		Threshold Velocity for traction cm/sec		
	mm	mm			ASTM No. (U.S. Standard)	Tyler Mesh No.		Quartz spheres	Natural sand	Spheres (Gibbs, 1971) cm/sec	Crushed	(Nevin, 1946)	(modified from Huston, 1909)	
-8	200	256	10.1"	BOULDERS (> -8φ) COBBLES								200	1 m above bottom	
-7	100	128	5.04"											
-6	50	64.0	2.52"	PEBBLES	2 1/2"	2.12"								
-5	30	45.3	1.26"		very coarse	1 1/2"	1.12"						150	
-4	20	32.0	0.63"		coarse	1 1/4"	1.06"						100	
-3	10	26.9	0.32"		medium	3/4"	.742"				100	50	100	
-2	5	17.0	0.16"		fine	5/8"	.525"				90	40	90	
-1	2	11.3	0.08"		Granules	1/2"	.371"				80	30	80	
0	1	9.52	0.08"		very coarse	3/8"	.265"				70	20	70	
1	.5	8.00	0.08"		coarse	4		1.2	.72	.6		10	40	40
2	.25	6.73	0.08"		medium	5		.86	2.0	1.5	10	7	30	
3	.125	5.66	0.08"		fine	6		.59	5.6	4.5	6	5	30	
4	.0625	4.76	0.08"	very fine	7		.42	15	13	4	4	20		
5	.03125	4.00	0.08"	SAND	8		.30	43	35	3	3	20	26	
6	.015625	3.36	0.08"		coarse	10		.215	120	91	2	2	20	26
7	.0078125	2.83	0.08"		medium	12		.155	350	240	1	1.0	20	26
8	.00390625	2.38	0.08"		fine	14		.115	1000	580	0.5	0.5	20	26
9	.001953125	2.00	0.08"		very fine	16		.080	2900	1700	0.329	0.329	20	26
10	.0009765625	1.63	0.08"		coarse	18								
11	.00048828125	1.41	0.08"		medium	20								
12	.000244140625	1.19	0.08"		fine	25								
13	.0001220703125	1.00	0.08"		very fine	30								
14	.00006103515625	.840	0.08"		SILT	35								
15	.000030517578125	.707	0.08"	coarse		40								
16	.0000152587890625	.545	0.08"	medium		45								
17	.00000762939453125	.420	0.08"	fine		50								
18	.000003814697265625	.354	0.08"	CLAY	60									
19	.0000019073486328125	.297	0.08"		coarse	70								
20	.00000095367431640625	.250	0.08"		medium	80								
21	.000000476837158203125	.210	0.08"		fine	100								
22	.0000002384185791015625	.177	0.08"	CLAY	120									
23	.00000011920928955078125	.149	0.08"		coarse	140								
24	.000000059604644775390625	.125	0.08"		medium	170								
25	.0000000298023223876953125	.105	0.08"		fine	200								
26	.00000001490116119384765625	.088	0.08"	CLAY	230									
27	.000000007450580596923828125	.074	0.08"		coarse	270								
28	.0000000037252902984619140625	.062	0.08"		medium	325								
29	.00000000186264514923095703125	.053	0.08"		fine	400								
30	.000000000931322574615478515625	.044	0.08"	CLAY										
31	.0000000004656612873077392578125	.037	0.08"		coarse									
32	.00000000023283064365386962890625	.031	0.08"		medium									
33	.000000000116415321826934814453125	.026	0.08"		fine									
34	.0000000000582076609134674072265625	.022	0.08"	CLAY										
35	.00000000002910383045673370361328125	.018	0.08"		coarse									
36	.000000000014551915228366851806640625	.016	0.08"		medium									
37	.0000000000072759576141834259033203125	.0128	0.08"		fine									
38	.00000000000363797880709171245166015625	.008	0.08"	CLAY										
39	.00000000000181898940354585622727265625	.00625	0.08"		coarse									
40	.000000000000909494701772928113636328125	.004	0.08"		medium									
41	.0000000000004547473508864640568181640625	.002	0.08"		fine									
42	.00000000000022737367544323202840908203125	.001	0.08"	CLAY										
43	.000000000000113686837721616014204541015625	.0005	0.08"		coarse									
44	.0000000000000568434188608007102022705078125	.00025	0.08"		medium									
45	.00000000000002842170943040035510113525390625	.000125	0.08"		fine									

APPENDIX 5: GRAIN-SIZE DISTRIBUTIONS: RAW DATA

Table A.2. Raw grain size distribution data (number of photos/site, n_{grains} , site elevation, distance from start of survey, D_{84} , D_{50} and D_{max}) from Underwater Automated Grain Sizing in the 28.4 km study area within the Middle Shuswap River, British Columbia. 2012. Black values were included in analysis. Red values were not processed and included in analysis because they contained less than 3 photos /site.

Site GP#	Photos/site	n_{grains}	Elevation (m)	Distance DS (m)	D_{84} (mm)	D_{50} (mm)	D_{max} (mm)
1	5	550	512	0	27.16	11.74	144.48
2	3	246	511	420	27.56	11.60	121.65
3	2	89			32.17	16.25	141.68
4	3	219	511	1190	23.40	12.73	243.44
5	4	324	507	1440	26.00	10.95	121.83
6	2	62			38.47	12.68	67.94
7	4	276	506	2070	18.46	11.46	96.00
8	3	142	505	2530	19.25	10.47	99.03
9	3	79			17.79	1.56	68.78
10	3	105	503	3000	19.71	9.09	86.97
11	3	52			14.10	0.85	77.07
12	3	58			14.13	1.39	131.03
13	4	152	502	3790	29.32	13.90	78.68
14	2	94			19.38	8.69	101.07
15	3	102	495	4570	17.40	8.94	113.90
16	5	401	495	4800	27.18	12.75	112.06
17	4	229	494	4890	26.90	12.64	153.10
18	4	116	494	5050	26.57	10.69	75.04
19	5	464	494	5340	27.85	13.16	178.95
20	3	142	493	5580	24.36	12.35	98.29
21	2	42			15.04	0.99	76.27
22	2	55			17.58	1.50	148.33
23	4	142	485	7000	22.28	11.85	115.36
24	2	166	485	7310	22.99	12.01	129.34
25	Unable to process						
26	1	32			9.66	0.83	78.37
27	1	56			13.30	1.38	74.05

Site GP#	Photos/site	n_{grains}	Elevation (m)	Distance DS (m)	D_{84} (mm)	D_{50} (mm)	D_{max} (mm)
28	3	222	481	9660	22.44	12.73	54.99
29	2	43			17.96	1.57	140.72
30	4	188	479	10520	30.05	14.64	78.07
31	4	217	476	11270	30.91	12.41	146.33
32	1	14			0.55	0.54	61.32
33	2	47			12.48	1.11	81.05
34	4	372	472	12600	30.55	12.59	131.69
35	2	201	470	13150	27.92	13.67	133.38
36	4	183	469	13360	34.19	14.86	116.14
37	5	664	468	13940	27.94	14.53	78.13
38	2	45			10.63	1.34	121.47
39	3	214	466	14640	28.31	13.54	91.42
40	2	109	460	15230	23.50	10.23	59.60
41	5	466	457	15540	19.33	12.00	48.29
42	5	201	454	15968	19.75	12.36	76.77
43	1	32			9.11	1.23	98.32
44	Unable to process						
45	Unable to process						
46	4	399	451	17700	26.90	13.75	88.90
47	3	75			14.90	0.91	43.45
48	5	144	450	18300	24.10	12.58	68.11
49	3	140	450	18600	24.90	11.26	119.87
50	5	327	450	19300	24.64	14.07	76.36
51	4	201	419	20400	32.51	14.65	135.79
52	4	342	418	20500	28.57	13.36	99.41
53	1	24			0.70	0.68	58.49
54	4	228	418	20900	28.37	13.46	113.95
55	3	169	418	21060	32.22	14.79	97.75
56	3	36			10.51	1.14	79.99
57	5	171	415	21530	30.51	13.39	87.24
58	5	601	414	21800	22.55	11.66	116.26
59	4	145	414	21940	25.26	11.13	73.10
60	5	209	414	22500	33.89	14.90	138.92
61	Unable to process						
62	Unable to process						
63	5	300	414	22900	32.19	13.80	97.24

Site GP#	Photos/site	n_{grains}	Elevation (m)	Distance DS (m)	D_{84} (mm)	D_{50} (mm)	D_{max} (mm)
64	5	288	413	23200	23.27	12.83	97.84
65	5	277	413	23500	28.59	13.53	122.38
66	3	128	413	23950	24.12	11.16	93.65
67	4	278	412	24100	31.31	13.63	80.66
68	4	316	411	24360	18.20	11.91	84.86
69	5	867	411	24700	18.86	11.53	55.25
70	1	29			8.33	1.02	75.43
71	4	246	411	25500	33.00	16.01	89.02
72	4	138	411	25800	24.82	12.07	91.54
73	5	416	411	26600	20.43	11.64	52.15
74	5	199	411	26880	29.77	13.13	80.56
75	3	272	411	27000	24.25	13.23	88.67
76	5	569	409	27400	19.22	11.46	57.69
77	2	78			15.66	1.03	84.54
78	3	370	406	27830	25.42	13.28	114.07

APPENDIX 6: GRAIN-SIZE DISTRIBUTIONS

Table A.3. Processed grain size distribution data (number of photos/site, n_{grains} , site elevation, distance from start of survey, D_{84} (mm), D_{50} (mm), D_{84} (Psi), D_{50} (Psi) D_{max} (mm) and site latitude and longitude) from Underwater Automated Grain Sizing in the 28.4 km study area within the Middle Shuswap River, British Columbia. 2012. All sites that were not processed have been excluded.

Site GP#	Photos per site	n_{grains}	Elevation (m)	Distance DS (m)	D_{max} (mm)	D_{84} (mm)	D_{50} (mm)	D_{50_Psi}	D_{84_Psi}	LATITUDE	LONGITUDE
1	5	550	512	0	144.48	27.16	11.74	6.09	6.95	50.274219	-118.608574
2	3	246	511	420	121.65	27.56	11.60	6.14	6.65	50.270886	-118.610903
4	3	219	511	1190	243.44	23.40	12.73	6.87	7.52	50.266129	-118.616622
5	4	324	507	1440	121.83	26.00	10.95	6.11	6.73	50.264372	-118.618780
7	4	276	506	2070	96.00	18.46	11.46	4.84	6.56	50.262061	-118.625198
8	3	142	505	2530	99.03	19.25	10.47	5.91	6.15	50.260631	-118.630972
10	3	105	503	3000	86.97	19.71	9.09	5.77	6.29	50.259126	-118.636953
13	4	152	502	3790	78.68	29.32	13.90	5.30	6.02	50.254979	-118.645902
15	3	102	495	4570	113.90	17.40	8.94	6.17	6.63	50.251508	-118.654690
16	5	401	495	4800	112.06	27.18	12.75	5.26	6.49	50.250418	-118.657359
17	4	229	494	4890	153.10	26.90	12.64	5.61	6.94	50.250059	-118.658539
18	4	116	494	5050	75.04	26.57	10.69	5.18	6.11	50.249092	-118.660133
19	5	464	494	5340	178.95	27.85	13.16	5.95	6.87	50.247633	-118.663167
20	3	142	493	5580	98.29	24.36	12.35	5.06	5.90	50.247667	-118.666517
23	4	142	485	7000	115.36	22.28	11.85	5.06	6.80	50.245320	-118.682303
24	2	166	485	7310	129.34	22.99	12.01	5.58	6.55	50.246320	-118.686476
28	3	222	481	9660	54.99	22.44	12.73	4.51	5.33	50.256345	-118.712560
30	4	188	479	10520	78.07	30.05	14.64	5.18	5.99	50.256872	-118.724377
31	4	217	476	11270	146.33	30.91	12.41	5.99	6.86	50.260653	-118.732651
34	4	372	472	12600	131.69	30.55	12.59	5.60	6.21	50.260222	-118.748196
35	2	201	470	13150	133.38	27.92	13.67	5.17	6.61	50.260312	-118.755354
36	4	183	469	13360	116.14	34.19	14.86	5.74	6.49	50.261879	-118.756970
37	5	664	468	13940	78.13	27.94	14.53	4.93	5.66	50.264271	-118.762376
39	3	214	466	14640	91.42	28.31	13.54	5.43	6.02	50.267422	-118.770462
40	2	109	460	15230	59.60	23.50	10.23	5.05	5.61	50.269477	-118.777878
41	5	466	457	15540	48.29	19.33	12.00	4.21	4.95	50.270865	-118.781747
42	5	201	454	15968	76.77	19.75	12.36	4.31	5.35	50.272039	-118.787306

Site GP#	Photos per site	n _{grains}	Elevation (m)	Distance DS (m)	D _{max} (mm)	D ₈₄ (mm)	D ₅₀ (mm)	D _{50_Psi}	D _{84_Psi}	LATITUDE	LONGITUDE
46	4	399	451	17700	88.90	26.90	13.75	5.00	5.72	50.282324	-118.800423
48	5	144	450	18300	68.11	24.10	12.58	4.88	5.72	50.287093	-118.803186
49	3	140	450	18600	119.87	24.90	11.26	5.31	6.38	50.289064	-118.804847
50	5	327	450	19300	76.36	24.64	14.07	4.75	5.37	50.294400	-118.807014
51	4	201	419	20400	135.79	32.51	14.65	6.02	6.89	50.297489	-118.817157
52	4	342	418	20500	99.41	28.57	13.36	5.37	6.14	50.298817	-118.817404
54	4	228	418	20900	113.95	28.37	13.46	5.58	6.47	50.301558	-118.816399
55	3	169	418	21060	97.75	32.22	14.79	5.62	5.93	50.302873	-118.817966
57	5	171	415	21530	87.24	30.51	13.39	5.85	6.28	50.306182	-118.821477
58	5	601	414	21800	116.26	22.55	11.66	5.40	6.61	50.308591	-118.819884
59	4	145	414	21940	73.10	25.26	11.13	5.07	5.66	50.308921	-118.818309
60	5	209	414	22500	138.92	33.89	14.90	5.68	6.32	50.312786	-118.817319
63	5	300	414	22900	97.24	32.19	13.80	5.43	5.88	50.315908	-118.814376
64	5	288	413	23200	97.84	23.27	12.83	5.40	6.34	50.318775	-118.814499
65	5	277	413	23500	122.38	28.59	13.53	5.36	6.45	50.322444	-118.814554
66	3	128	413	23950	93.65	24.12	11.16	5.33	6.47	50.324985	-118.815466
67	4	278	412	24100	80.66	31.31	13.63	5.35	6.07	50.326506	-118.815931
68	4	316	411	24360	84.86	18.20	11.91	4.80	5.73	50.328630	-118.815268
69	5	867	411	24700	55.25	18.86	11.53	4.24	5.13	50.330908	-118.812811
71	4	246	411	25500	89.02	33.00	16.01	5.27	5.83	50.336601	-118.809992
72	4	138	411	25800	91.54	24.82	12.07	5.14	5.89	50.339208	-118.807154
73	5	416	411	26600	52.15	20.43	11.64	4.48	5.22	50.344772	-118.802727
74	5	199	411	26880	80.56	29.77	13.13	5.23	5.97	50.345345	-118.800598
75	3	272	411	27000	88.67	24.25	13.23	4.97	5.93	50.346295	-118.798484
76	5	569	409	27400	57.69	19.22	11.46	4.21	4.94	50.349364	-118.796646
78	3	370	406	27830	114.07	25.42	13.28	5.20	6.06	50.352875	-118.796399

APPENDIX 7: SALMON SPAWNING HABITAT UPSTREAM OF WILSEY DAM

Table A.4. The spawning habitat polygons (Reaches 1 and 2) areas for chinook and coho salmon in the Middle Shuswap River upstream of Wilsey Dam, British Columbia. 2012.

Polygon No.	Area (m2)	Corresponding AGS Site	Location Reference
REACH 1			
US8	1083	GP41	Chute US
US9	10480	GP40	
US10	8914	GP39	
US11	33347	(Guy and Uunila 2002)	
US12	5407	GP38	
US13	13856	GP37	
US14	14568	GP36	
US14	0	GP35	
US15	26490	GP34	
US16	8629	GP33	
US17	7900	GP32	
US18	17424	GP31	
US19	8156	GP30	
US20	8282	GP29	
US21	6698	GP28	
US22	9186	GP27	
US23	8573	GP26	
US24	14924	(Guy and Uunila 2002)	
US25	5087	GP24	
US26	19374	GP23	
US26		GP22	
US27	15850	GP21	
US28	9912	GP20	
US29	19565	GP19	
US29	0	GP18	
US29	0	GP17	
US29	0	GP16	Ferry Creek DS
US30	6846	GP14	Ferry Creek US
US31	10101	GP13	Cherry Creek DS
US32	17639	GP9	Cherry Creek US
US32	0	GP8	
US33	39271	GP7	
US33	0	GP6	
REACH 2			
US1	8653	GP50	Wilsey Dam US
US2	3043	GP49	
US3	3471	GP48	
US4	3200	GP47	
US5	5075	GP46	
US6	13814	GP43	
US7	2447	GP42	Chute DS
Total Area:	387,265		

APPENDIX 8: SALMON SPAWNING HABITAT DOWNSTREAM OF WILSEY DAM

Table A.5. The spawning habitat polygon (Reach 3) areas for chinook and coho salmon in the Middle Shuswap River upstream of Wilsey Dam, British Columbia. 2012.

Polygon No.	Area (m2)	Corresponding AGS Site	Location Reference
REACH 3			
DS1	42310	GP51	Wilsey Dam DS
DS1	0	GP52	
DS1	0	GP53	
DS1	0	GP54	
DS1	0	GP55	
DS1	0	GP56	
DS1	0	GP57	Bessette Creek US
DS2	2041	(Guy and Uunila 2002)	
DS3	12684	GP59	Bessette Creek DS
DS4	6643	(Guy and Uunila 2002)	
DS5	10045	GP60	
DS6	13481	GP63	
DS7	12914	GP64	
DS7	0	GP65	
DS8	10776	GP66	
DS8	0	GP67	
DS9	15814	GP68	
DS9	0	GP69	
DS10	13719	GP71	
DS11	16740	GP72	
DS12	7007	GP73	
DS12	0	GP74	
DS13	14176	GP75	
DS13	0	GP76	
DS14	12556	GP77	
DS14	0	GP78	
Total Area:	190,906		

APPENDIX 9: MAPS OF SALMON SPAWNING HABITAT IN THE MIDDLE SHUSWAP RIVER

Figure A.1. MAP SHEET 1 (Reach 3)
N.T.S.

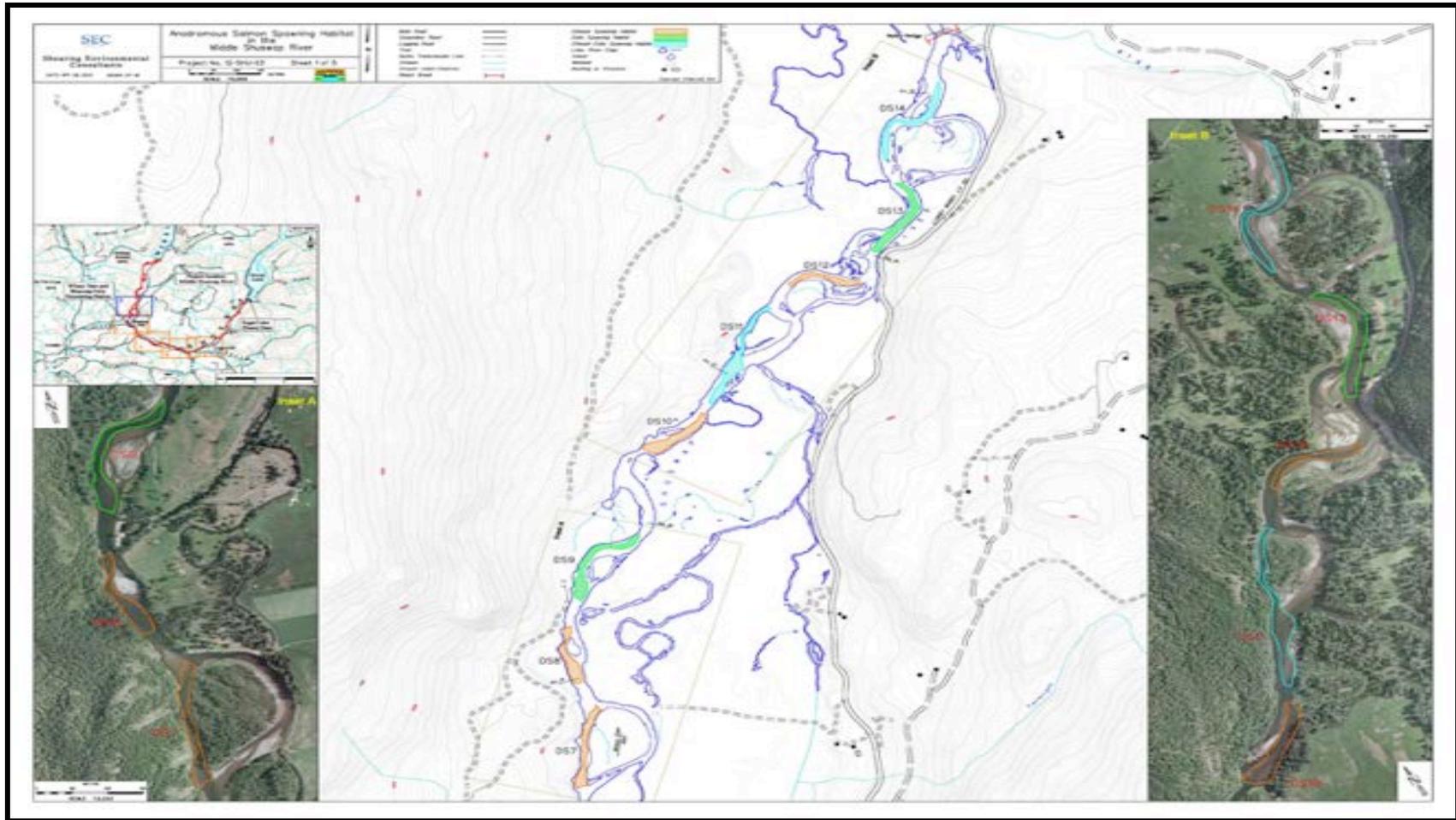


Figure A.2. MAP SHEET 2 (Reaches 2 & 3)
N.T.S.

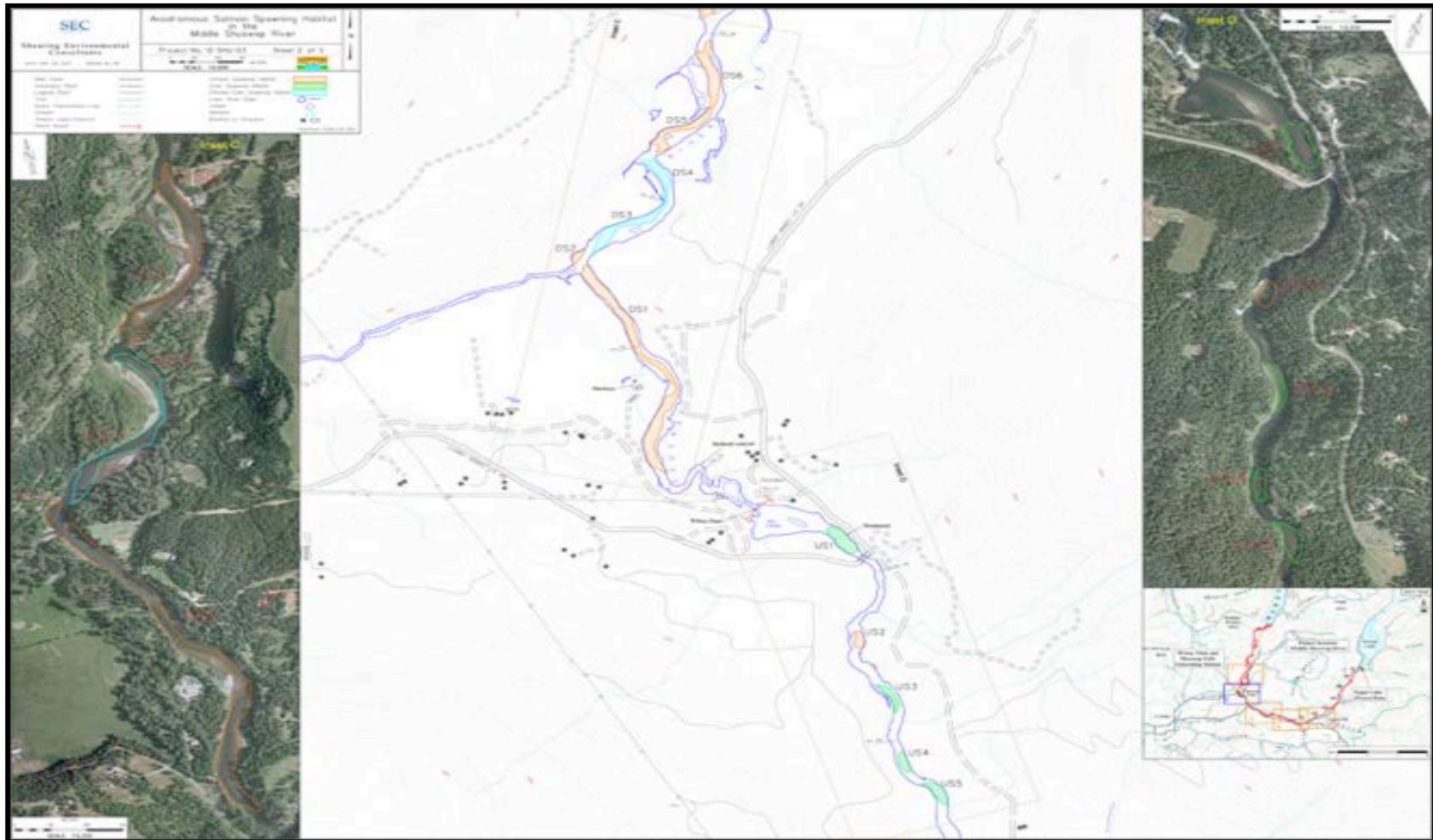


Figure A.3. MAP SHEET 3 (Reaches 1 & 2)
N.T.S.

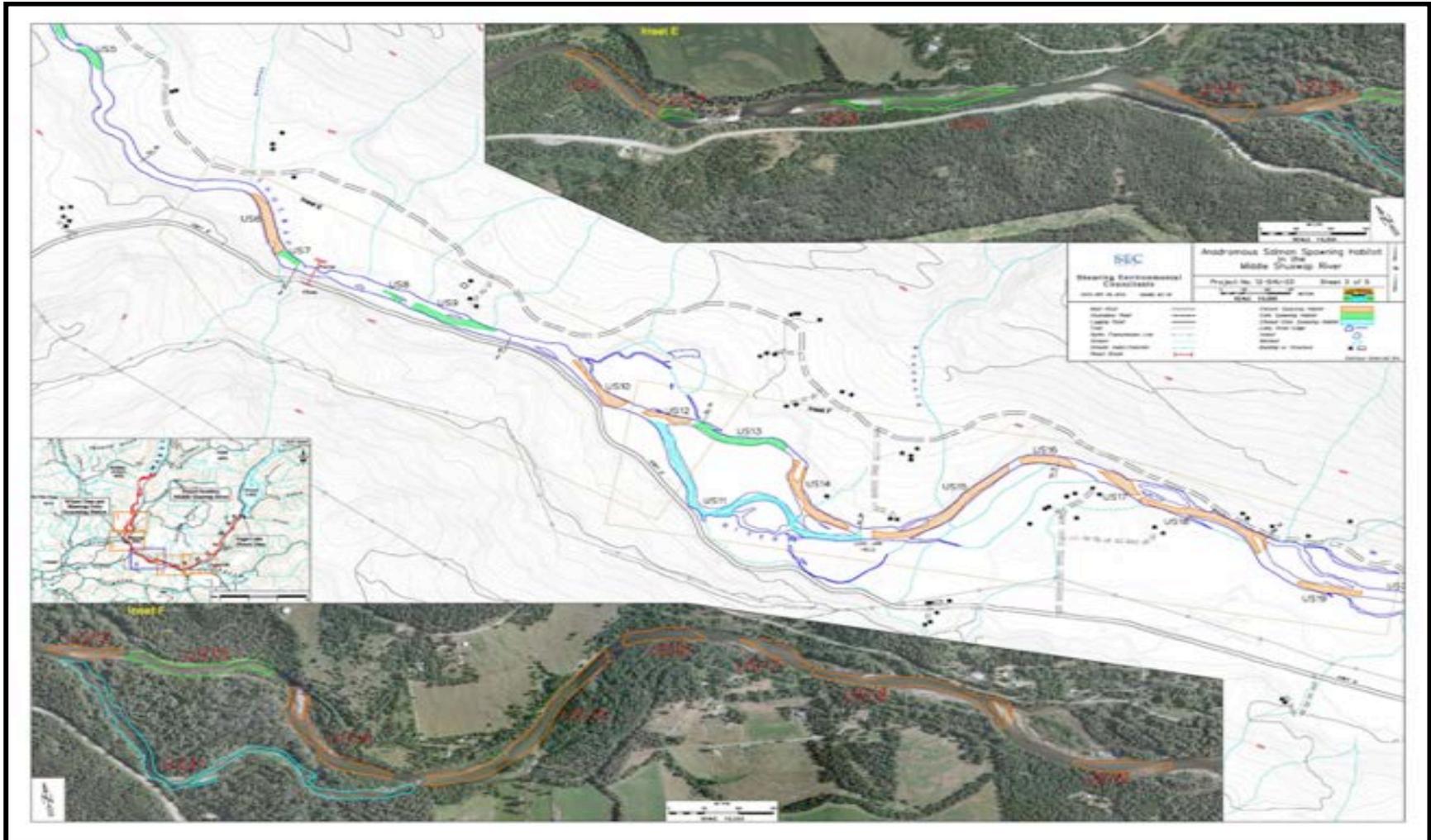
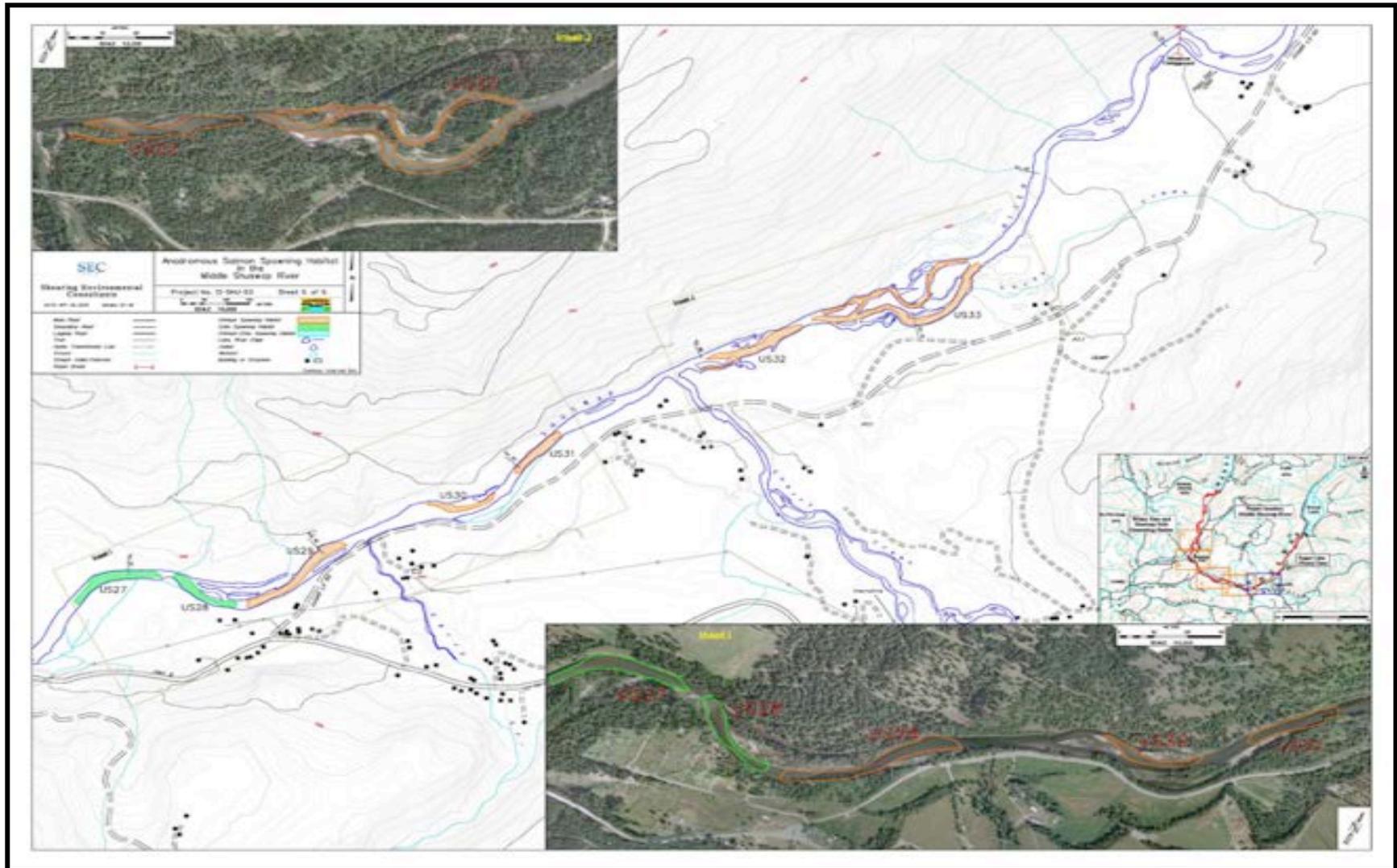
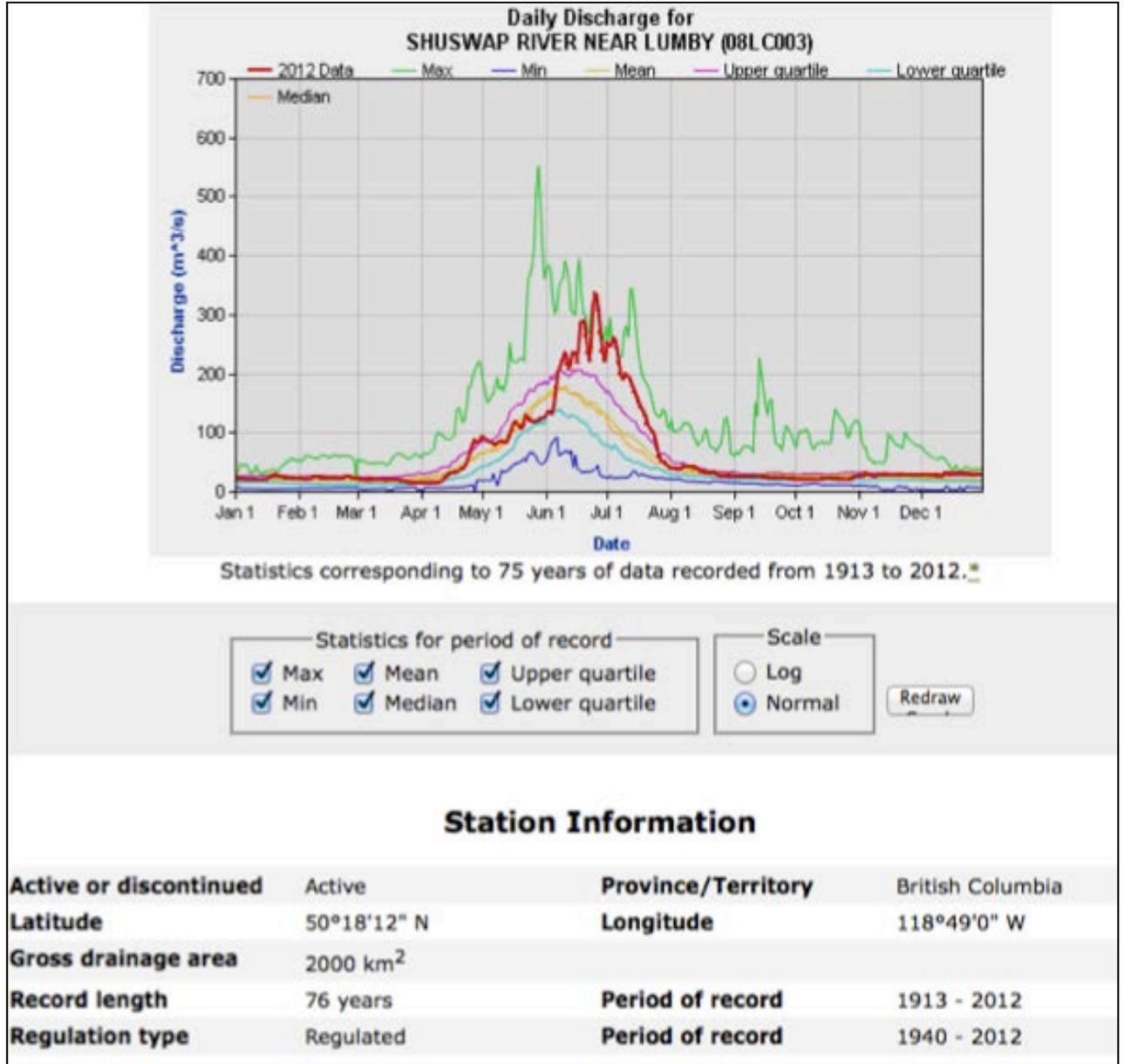


Figure A.5. MAP SHEET 5 (Reach 1)
N.T.S.



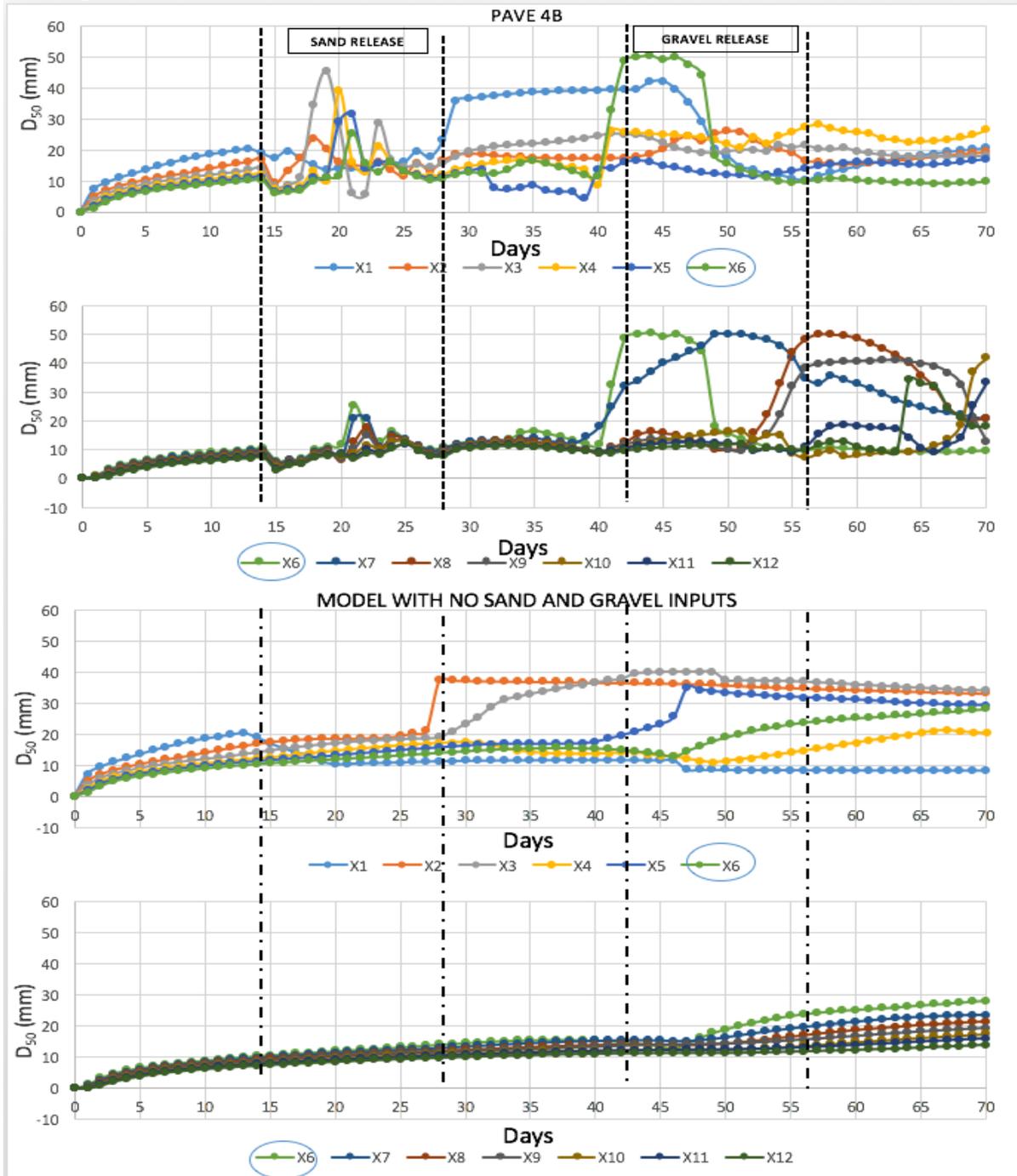
APPENDIX 10: MIDDLE SHUSWAP RIVER HISTORICAL HYDROGRAPH

Figure A.6. Middle Shuswap River Water Survey of Canada Station 08LC003 Below Wilsey Dam 1913 to 2012. Courtesy of the Water Survey of Canada.



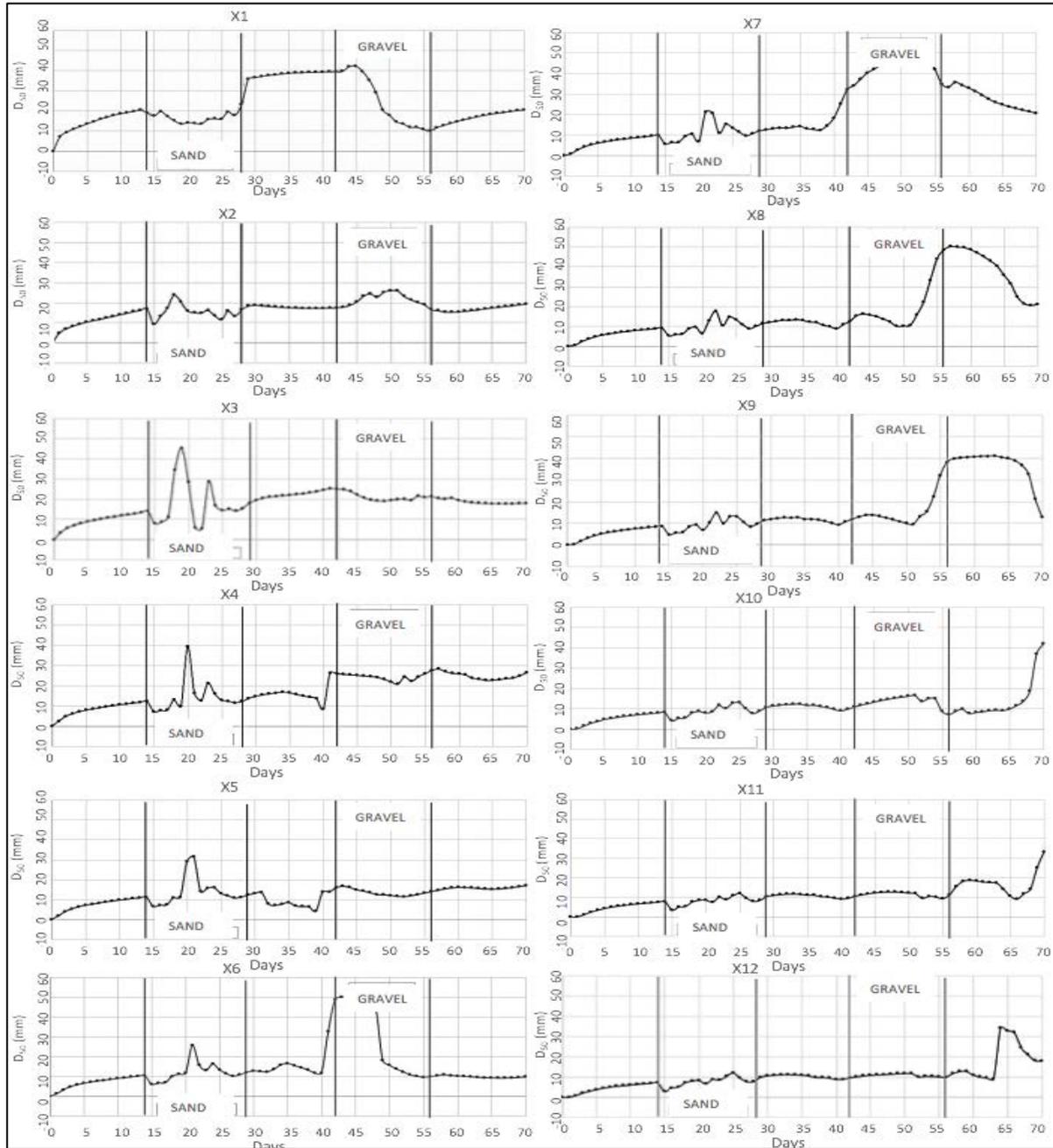
APPENDIX 11: CUMULATIVE CHANGE IN D_{50}

Figure A.7. Cumulative change in D_{50} (mm) derived from sediment transport model output using PAVE 4B dataset and no sediment input dataset during 70-day freshet on the Middle Shuswap River, British Columbia. For the PAVE 4B model run, 10,000 m³ of sand is introduced equally between weeks three and four and 5000 m³ of gravel is introduced equally between weeks seven and eight and flows equal mean (100 cms).



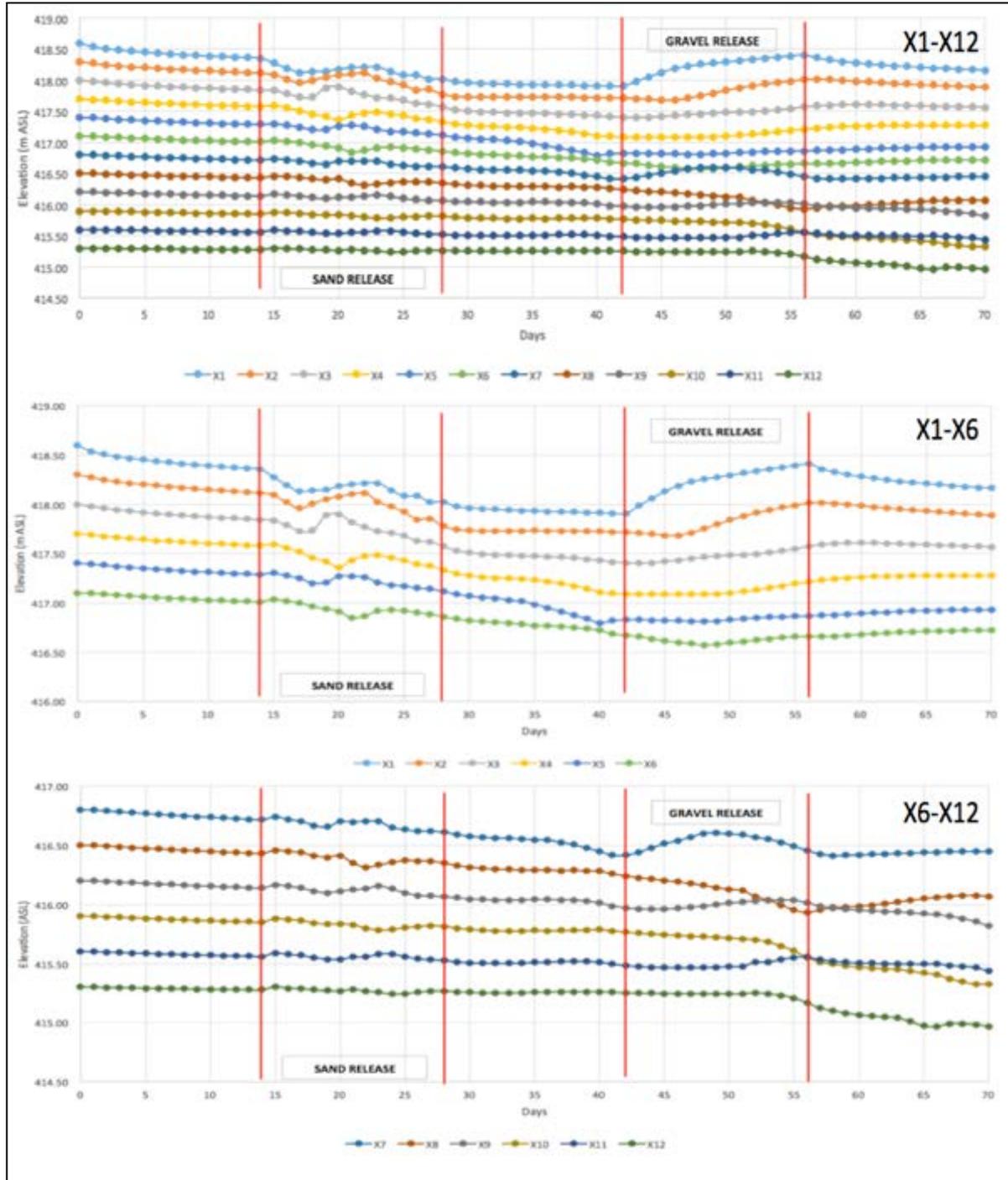
APPENDIX 12: CUMULATIVE CHANGE IN D_{50} BY CROSS-SECTION

Figure A.8. Cross-section cumulative change in D_{50} (mm) derived from sediment transport model output using PAVE 4B dataset during 70-day freshet on the Middle Shuswap River, British Columbia. 10,000 m³ of sand is introduced equally between weeks three and four and 5000 m³ of gravel is introduced equally between weeks seven and eight and flows equal mean discharge (100 cms).



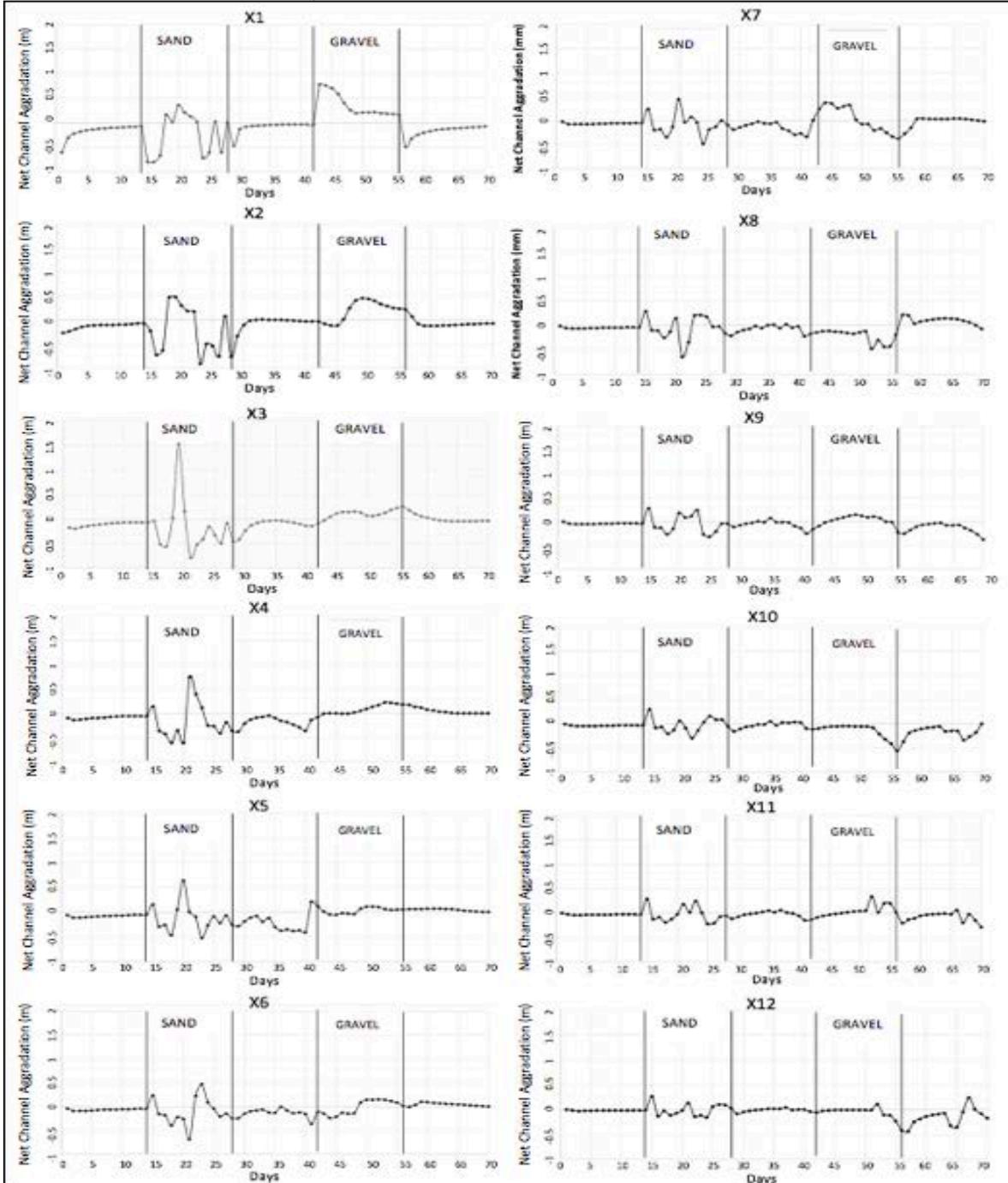
APPENDIX 13: CHANGE IN RIVERBED ELEVATION

Figure A.9. Change in riverbed elevation for weeks three and four for the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Test conducted with customized 1D sediment transport created by G. Parker (University of Illinois), P. Nelson (Colorado State) and T. Fuller (Simon Fraser University); model run in MATLAB ©.



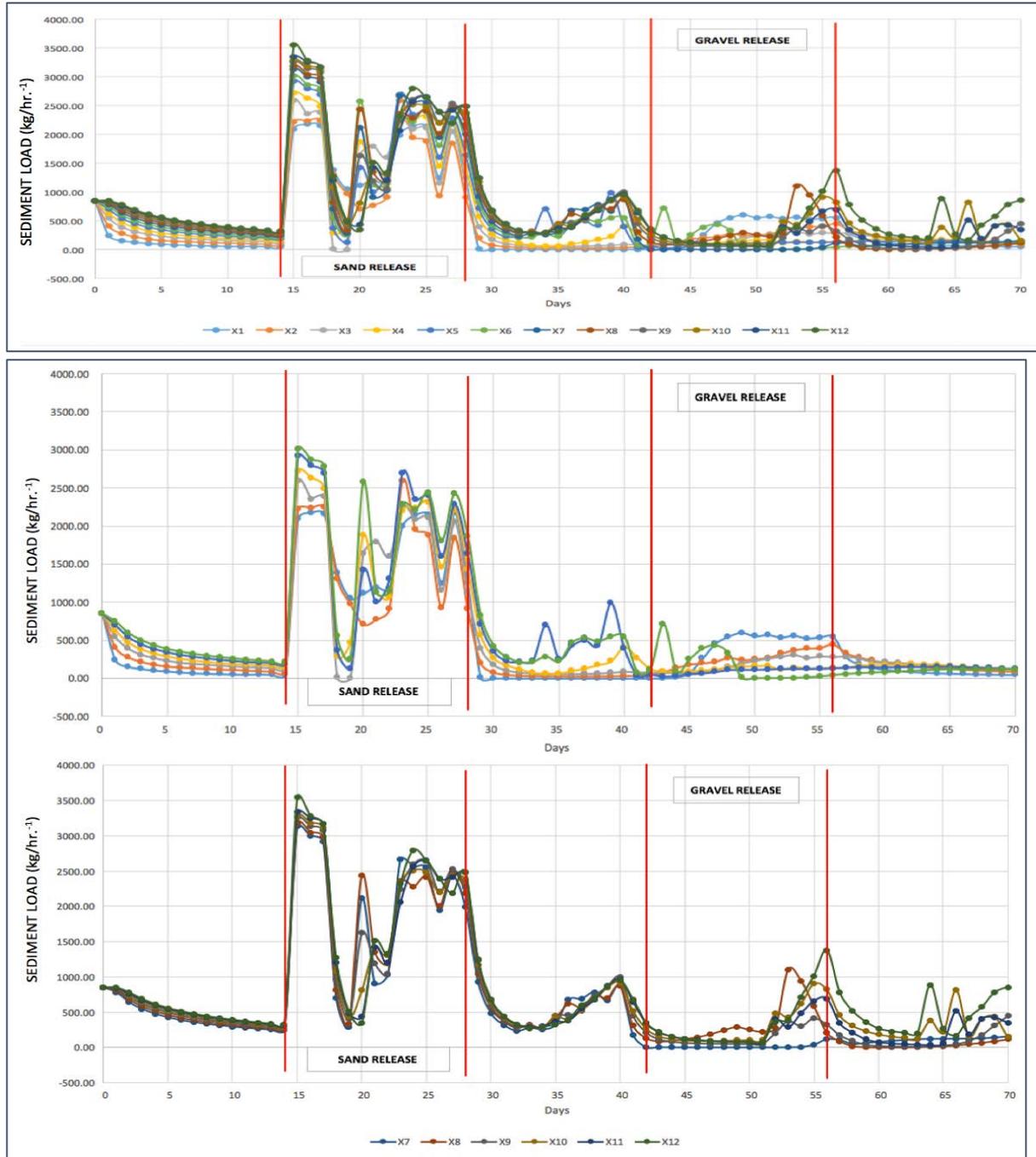
APPENDIX 14: AGGRADATION AND DEGRADATION OF THE RIVERBED

Figure A.10. Net channel aggradation and degradation over a 70-day freshet using the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Test conducted with customized 1D sediment transport created by G. Parker (University of Illinois), P. Nelson (Colorado State) and T. Fuller (Simon Fraser University); model run in MATLAB ©.



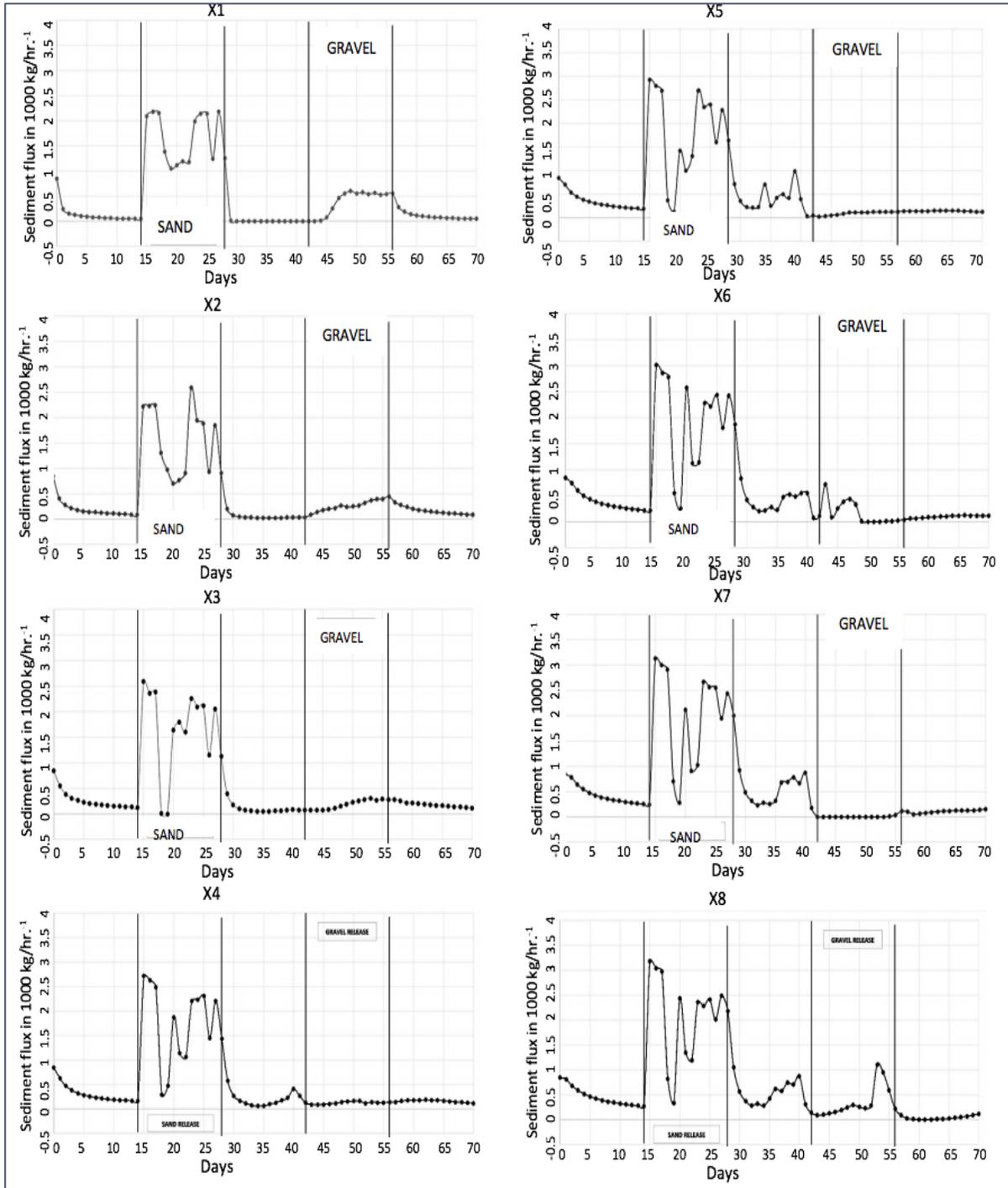
APPENDIX 15: SUMMARY OF SEDIMENT FLUCTUATION

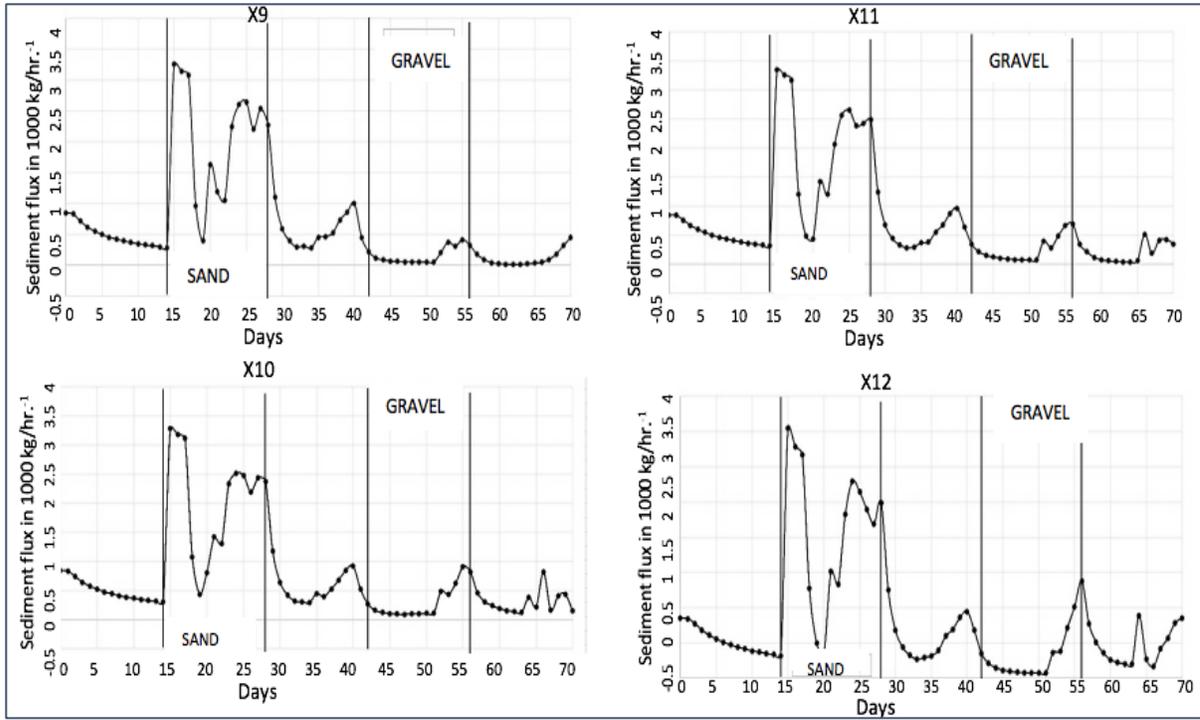
Figure A.11. Sediment fluctuation in kg/hr^{-1} , for all 12 cross-sections in the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Test conducted with customized 1D sediment transport created by G. Parker (University of Illinois), P. Nelson (Colorado State) and T. Fuller (Simon Fraser University); model run in MATLAB ©.



APPENDIX 16: SEDIMENT FLUCTUATION BY CROSS-SECTION

Figure A.12. Sediment fluctuation in $\text{kg/hr}^{-1} / 55 \text{ m}$ channel width for each cross-section in the PAVE 4B dataset simulating change in the Middle Shuswap River model reach.





APPENDIX 17: SEDIMENT TRANSPORT RATE DISTRIBUTION IN PSI

Figure A.13. Change in transport probability distribution function for days 0 to 69 for the PAVE 4B dataset simulating change in the Middle Shuswap River model reach. Test conducted with customized 1D sediment transport created by G. Parker (University of Illinois), P. Nelson (Colorado State) and T. Fuller (Simon Fraser University) model run in MATLAB ©.

