LILLOOET RIVER FLOOD MITIGATION PROGRAM – PRELIMINARY SEDIMENT MANAGEMENT PLAN

FINAL REPORT

Revision No. 3

Prepared for:

Pemberton Valley Dyking District Office
1381 Aster St
Pemberton, BC V0N 1B0

Prepared by:
Northwest Hydraulic Consultants Ltd.
405-495 Dunsmuir Street
Nanaimo, BC V9R 6B9

25 March 2019

NHC Ref. No. 3004580

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Report Prepared by:

Andrew Nelson
3/11/2019

W.F. HILSEN
25 March 2019

Andrew Nelson, M.Sc.
Senior Geomorphologist

Wil Hilsen, P.Geo.
Associate | Geomorphologist

Report Reviewed by:

David McLean, Ph.D., P.Eng.
Principal

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EXECUTIVE SUMMARY

This document presents a strategy and rationale for an annual sediment removal program on the Lillooet River to address increased sediment aggradation rates as a result of the 2010 Mt. Meager landslide. The Pemberton Valley Dyking District intends to adopt the approach outlined in the preliminary sediment management plan and immediately implement the recommendations described herein to carry out the necessary detailed planning and design to intensify sediment removals on the Lillooet River.

The slug of coarse sediment moving down the Lillooet River (a diffusive “sediment wave”) has increased channel instability in the upper reach, and the sand and fine gravel component has already reached the depositional zone in the lower reach, downstream of Ryan River confluence and reduced the hydraulic capacity of the channel. In 2017 the leading edge of discernable impacts of the sediment wave extended to approximately 55 km upstream of Lillooet Lake (or 14 km upstream of the FSR Bridge). It is difficult to predict the timing and magnitude of expected impacts from the sediment wave through the diked reach. However, as it diffuses downstream, some additive impact of the coarser material is expected on top of that already occurring due to the sand and fine gravel, likely promoting faster aggradation and decreased lateral channel stability. Additional disturbances in the basin could further introduce sediment to the system which could exacerbate the present sedimentation issue.

The sediment removal volumes described herein are intended to support preliminary planning sediment removal operations over the next ten to twenty years. Additional work will be required to develop a more comprehensive plan that would be used as a guiding document for future sediment removals. The sediment management plan should be updated over time following an adaptive management approach that incorporates feedback and response from the river system to refine the plan over time.

Over the next several decades, sediment removals in the order of 210,000 m^3/year to 260,000 m^3/year may be necessary to offset the anticipated incoming sediment load from the 2010 landslide. Impacts from the landslide are expected to reduce over this period, which will reduce the intensity of removals necessary to offset the incoming sediment load. Impacts may last beyond a 20-year time horizon and additional disturbances in the basin could further introduce sediment to the system, which could exacerbate the present sedimentation issue. Estimating average annual aggradation rates using less than 10 years of record can severely over or under predict the long term sediment transport rate and recurring monitoring and analyses will be necessary to refine these estimates over time.

The lower reach, between Ryan River confluence and Green River confluence, is considered to be the highest priority area for profile maintenance because a reduction of the channel’s hydraulic capacity in this area will have the largest impact on flood hazards. Sediment removals in the upper reach are considered a crucial component of the sediment management strategy to trap sediment, thereby reducing the influx of sediment to the middle and lower reaches. Sediment accumulation in Green River to Lillooet Lake reach is substantial and further assessment is necessary to evaluate potential hydraulic benefits associated with sediment removal.

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1 INTRODUCTION

Lillooet River flows through the Pemberton Valley, a broad and flat region that is bounded by steep mountains and is home to several Lil'Wat Nation settlements, the Village of Pemberton, and many rural homesteads and farms, which are vulnerable to flooding. The headwaters of the river were impacted by an extremely large landslide in August, 2010, which has increased the supply of sediment to the river and caused significant aggradation in the channel downstream. This aggradation is ongoing and expected to continue for a period of several decades.

1.1 Purpose

This document presents a strategy and rationale for an annual sediment removal program on the Lillooet River that will maintain the river's flood profile to prevent future increases due to long-term sediment aggradation. The study was conducted by Northwest Hydraulic Consultants Ltd. (NHC) for the Pemberton Valley Dyking District (the District), under an agreement dated 14 January 2019 and is based on analyses of information collected and compiled for the recent Lillooet Floodplain Mapping Project (NHC 2018).

The Pemberton Valley Dyking District intends to adopt the approach outlined in the preliminary sediment management plan and immediately implement the recommendations described herein to carry out the necessary detailed planning and design to intensify sediment removals on the Lillooet River. Future assessments will refine and expand on the strategy and rationale for sediment removals to eventually form a comprehensive, adaptive sediment management program. The sediment removal program is one component of an integrated flood management plan that will be developed to reduce the risk of flooding and erosion that have been triggered by the Capricorn Creek landslide off the slopes of Mount Meager in 2010.

1.2 Previous Sediment Removals

A gravel management plan was developed in 2007 (KWL 2007), prior to the destabilizing events triggered by the Mount Meager landslide. The annual bedload transport rate was estimated to be approximately 40,000 m^3/year, and the 2007 plan concluded the gravel component of the bedload (> 2 mm) was generally not transported beyond approximately 6 km to 8 km upstream of Lillooet Lake (near the Green River confluence). The gravel management plan recommended gravel removals of 5,000 m^3 year or 15,000 m^3 every third year, focussing on gravel bars in the Lillooet River lower reach, between the Ryan River confluence and Green River confluence.

Between 1980 and 2000, an average of 9,000 m^3/year of sediment was removed in the lower reach. No sediment was removed from the channel between 2001 and 2012 due to reasons beyond the control of the PVDD (Steve Flynn, pers. comm. 25 March 2019); however, the program was resumed in 2013 and continued in 2016 and 2017 with an average of almost 14,000 m^3/year over the 5 year period. It is noted the average annual removal rate between 2013 and 2017 was almost three times the target volume identified in the 2007 gravel management plan to address cumulative aggradation over the previous 11 years of not removing sediment, and in response to observed rapidly accumulating sediment at the channel bar excavation sites due two consecutive fall high water events in 2015 and 2016.

1.3 Mount Meager Landslide

In 2010 the Mt. Meager landslide injected approximately forty nine million cubic meters of sediment into the Lillooet River Valley (Guthrie et al., 2012). Increased sediment supply from the landslide will remain high for several decades but is expected to eventually decrease over time. The slug of coarse sediment moving down the Lillooet River (a diffusive "sediment wave") has increased channel instability in the upper reach, and the sand and fine gravel component has already reached the depositional zone in the lower reach, downstream of Ryan River confluence (NHC 2018). As a result, the original sediment budget developed in 2007 is no longer representative of sedimentation processes along the river.

The project area and reach definitions are illustrated in **Figure 1.1**.

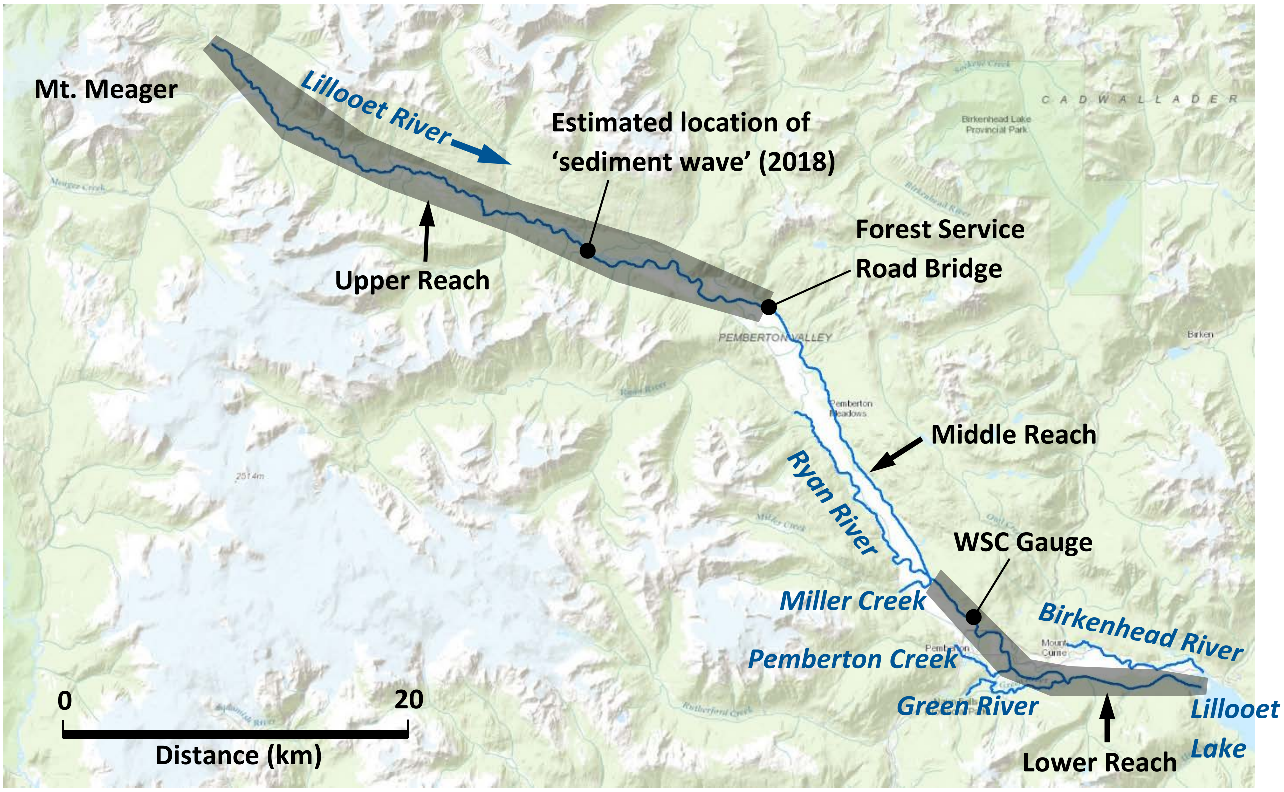

Figure 1.1. Study Area showing the Lillooet River and tributaries, simplified reach breaks, and other reference points.

2 OVERVIEW OF SEDIMENTATION PROCESSES

2.1 Pre-Landslide Conditions

In the 1940's and 50's, the Prairie Farm Rehabilitation Administration introduced measures to reduce flooding in the Valley. The Lillooet River was straightened, bypassing natural bends in several locations; some dikes were constructed and Lillooet Lake was lowered by modifying the lake outlet (Weatherly and Jakob 2014). Since the 1940's the channel had been degrading in response to these channel modifications. Degrading channels will have an increased channel conveyance capacity, meaning the measured water level for a given flow condition will be lower than the pre-degrading condition. Conversely, aggrading channels will have a decreased conveyance capacity, meaning the measured water level for the same flow will be relatively higher.

Figure 2.1 highlights the how the measured water levels for a 100 m^3/s flow condition have changed over time at Water Survey of Canada gauge 08MG005 *Lillooet River near Pemberton*. These water level records highlight a period of degradation lasting approximately 50 years before abruptly shifting to a rapidly aggrading channel bed following the 2010 landslide.

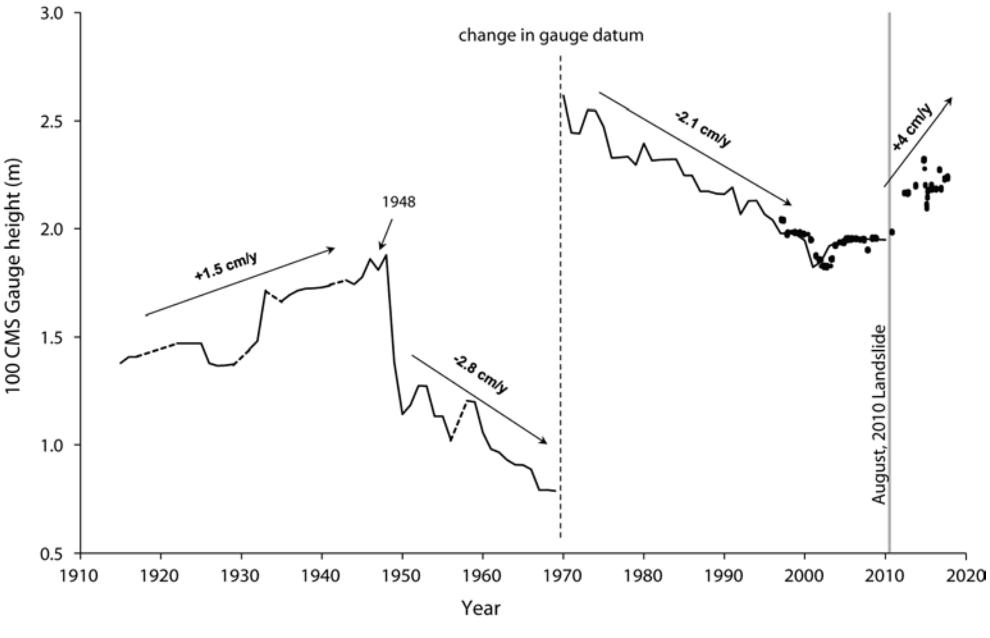

Figure 2.1. Specific gauge analysis for WSC Gauge 08MG005, modified from Weatherly and Jakob (2014) with addition of recent data (NHC 2018). The specific gauge analysis shows how water level at a specific discharge has changed at a constant discharge in the river, indicating average bed level change in the reach.

2.2 Overview of Impacts From Capricorn Creek Landslide

2.2.1 Channel aggradation

Since the landslide occurred a substantial portion of the lower reach has aggraded in the order of 0.4 m (~0.07 m/year), with aggradation in the order of between 0.5 m to more than 2.0 m (0.08 to 0.3 m/year) in the middle channel reach (NHC 2018). **Figure 2.2** to **Figure 2.6** illustrate the changes in the channel bed profile along the Lillooet River, based on a comparison of the cross sectional averaged channel bed elevation between 2001, 2011, and 2017. This information is based on an analysis of repeated bathymetric channel survey data, and long term average annual channel aggradation rates can be estimated by comparing measured channel changes at each cross section and accounting for sediment removals. Estimating average annual aggradation rates using less than 10 years of record can severely over or under predict the long term sediment transport rate and recurring monitoring and analyses will be necessary to refine these estimates over time.

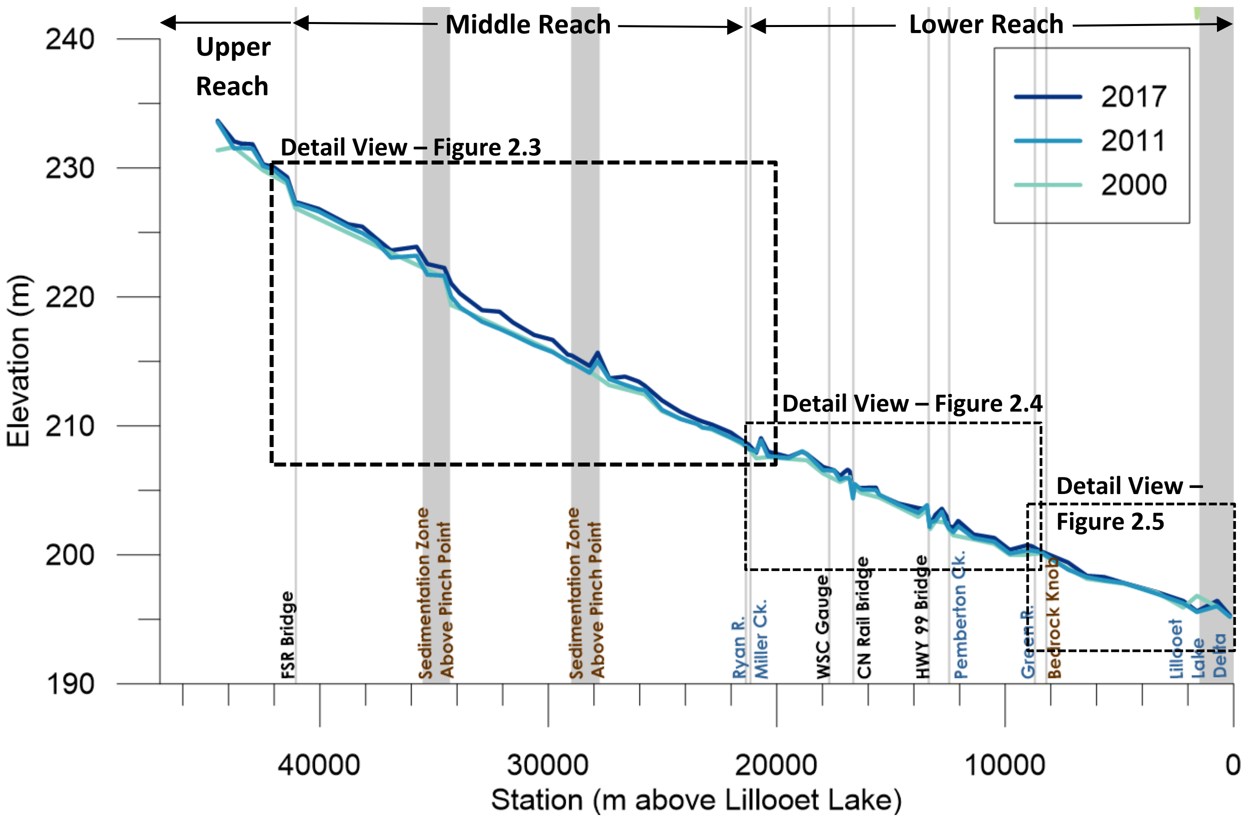

Figure 2.2. Comparison of surveyed Lillooet River profiles (2001-2017): change in average bed elevation.

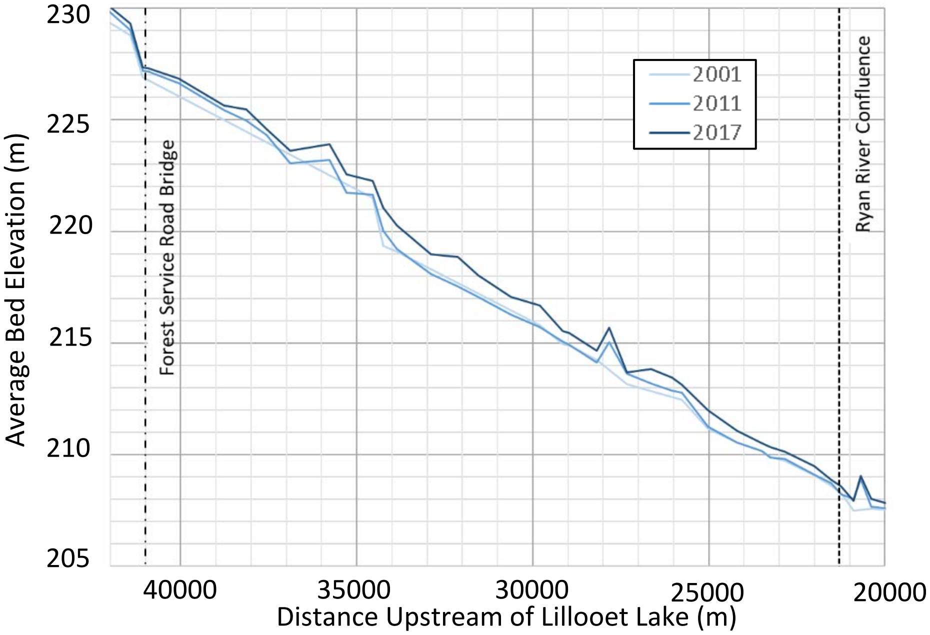

Figure 2.3. Comparison of surveyed Lillooet River profiles between FSR Bridge and Ryan River Confluence (2001-2017): change in average bed elevation.

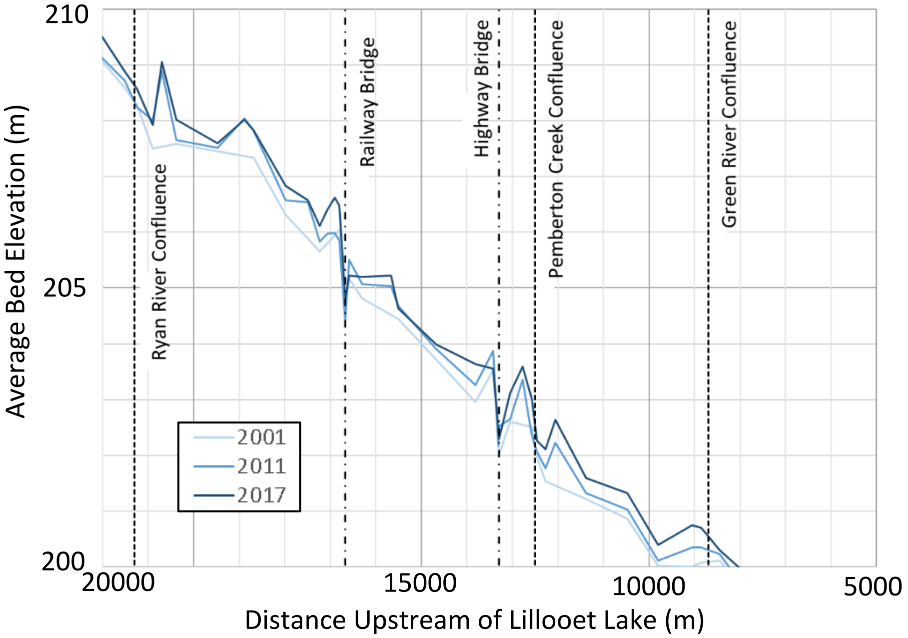

Figure 2.4. Comparison of surveyed Lillooet River profiles between Ryan River Confluence and Green River Confluence (2001-2017): change in average bed elevation.

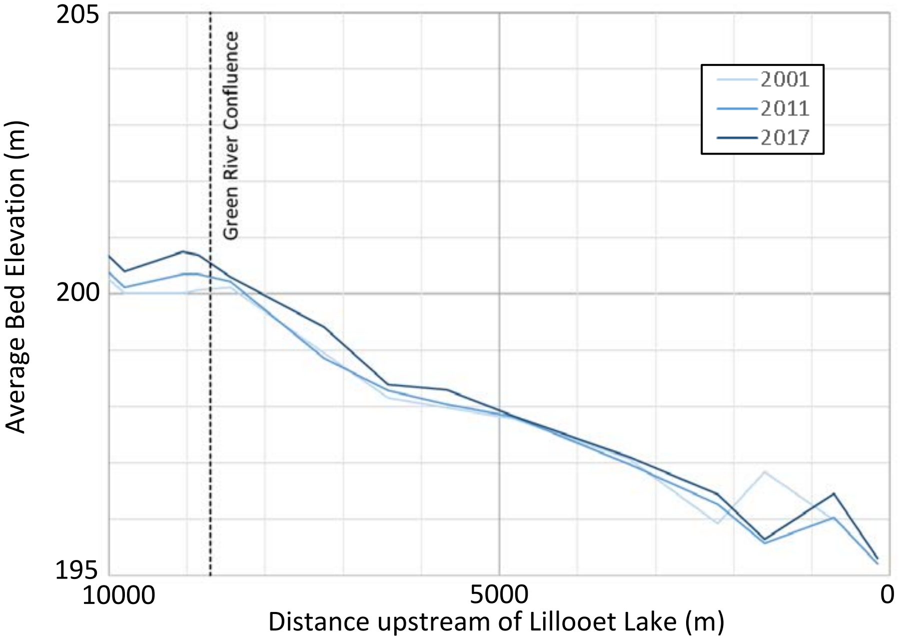

Figure 2.5. Comparison of surveyed Lillooet River profiles between Green River Confluence and Lillooet Lake (2001-2017): change in average bed elevation.

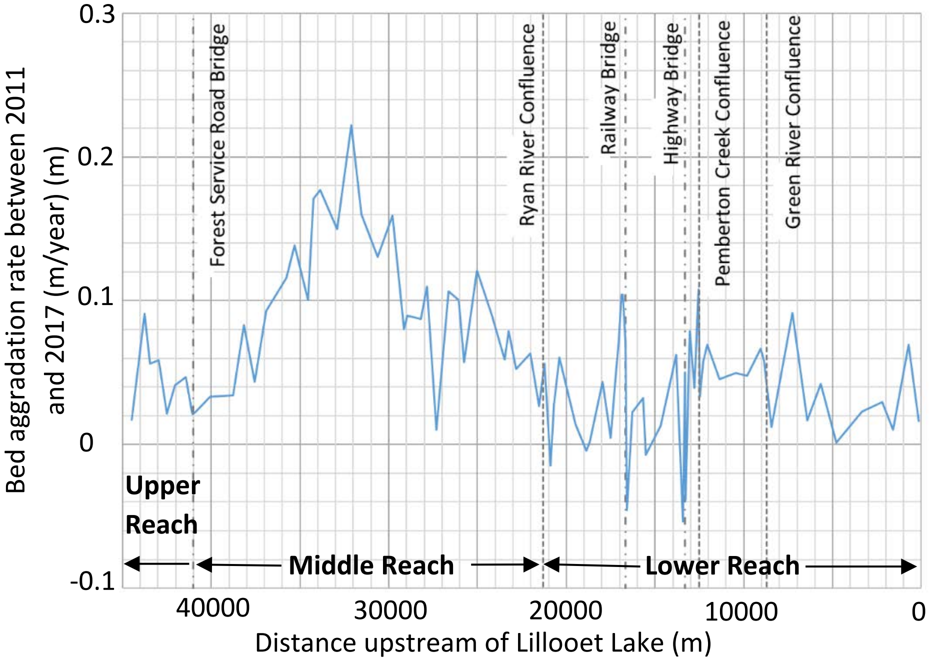

Figure 2.6. Estimated bed aggradation rate between 2011 and 2017, based on cross section comparison.

2.2.2 Reduced hydraulic channel capacity

Between 2011 and 2017 the hydraulic capacity was reduced by between 15% and 20% in the lower reach and as much as 35% in the middle reach. **Figure 2.7** presents the measured change in cross sectional area; negative values indicate a reduced cross sectional area and positive values indicate an increased cross sectional area. It should be noted that two locations show an apparent increase in cross sectional area that is unrepresentative of the general trend: the railway bridge and highway bridge. Both of these sites are located where the channel is artificially narrowed by each bridge structure and therefore the cross sectional geometry at these locations can fluctuate considerably depending on the timing of the survey with respect to flow conditions.

Based on the present rate of infilling, the reach upstream of the highway bridge could aggrade by up to 0.5 m by 2025, reducing the effectiveness of the dikes to contain floods. A model simulation for the recent Lillooet Floodplain Mapping project computed a corresponding 0.3 m increase in water level during the 200-year flood event, which underscores the impacts of future sedimentation on flood levels (NHC 2018).

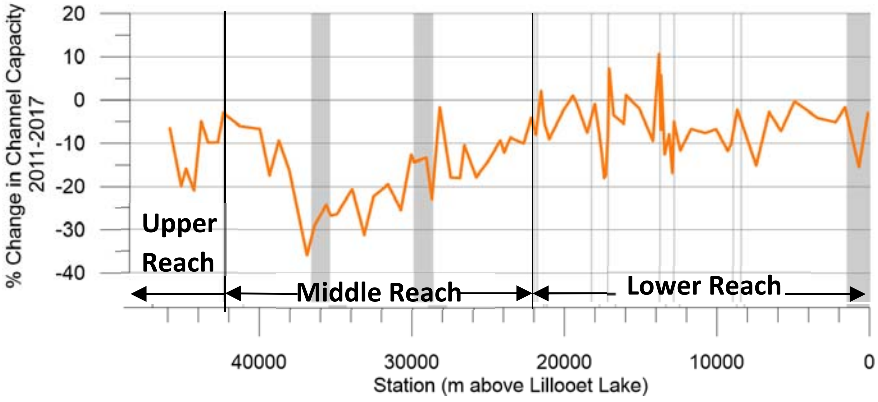

Figure 2.7. Comparison of surveyed Lillooet River profiles (2011-2017): percent change in channel hydraulic capacity.

2.2.3 Altered sedimentation pattern following the 2010 landslide

Between 2010 and 2017, approximately 7.5 million cubic metres of sediment was eroded from the landslide deposit altering the volume and grain size distribution of sediment supplied to the river (NHC 2018). Relative to 2011, sediment samples collected from the channel in 2017 generally contain a much higher proportion of coarse sand and granules, and these sediments have rapidly accumulated in the channel. The effects observed to date in the middle and lower reaches represent the initial response of the channel due to the arrival of the fine gravel and sand component of the sediment slug. The impacts from the coarse fraction of the sediment load will become increasingly apparent over the next several decades.

Figure 2.8 illustrates the change in sediment grain size distribution from 2011 to 2017 and compares the estimated cumulative average annual aggradation rate[1] between 2001 to 2011 and 2011 to 2017. This figure does not account for sediment removal volumes and uses the Green River confluence as the baseline location for measuring cumulative aggradation. Accounting for sediment removals, the cumulative average annual aggradation rate between the Forest Service Road (FSR) Bridge and Green River confluence has increased from about 40,000 m^3/year to 210,000 m^3/year. This calculation has considerable uncertainty (+/-50%); however it indicates in the order of a fivefold increase since 2011.

As described in **Section 2.2.1** and **2.2.2**, the reach between Green River and Lillooet Lake has substantially aggraded since the landslide, and the annual aggradation rate in this sub-reach between 2011 and 2017 is estimated to be in the order of 40,000 m^3/year. Additional investigations (described in **Section 4**) are warranted to better understand bed material transport processes downstream of the Green River confluence.

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[1] The cumulative average annual aggradation rate is the time-averaged estimate of the volume of accumulated channel bed sediment based on a comparison of successive channel cross section surveys, measured cumulatively upstream from the lake.

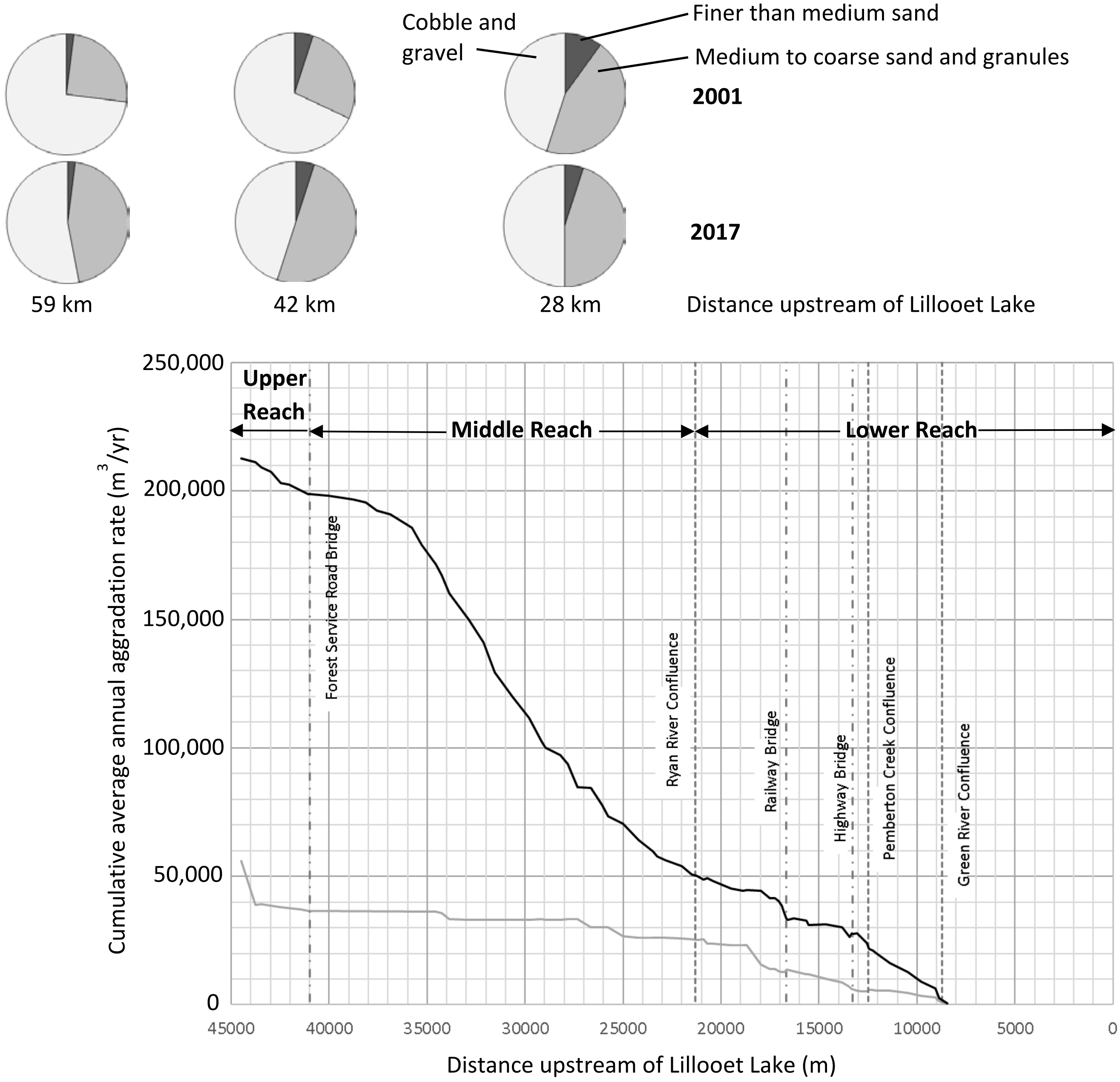

Figure 2.8. Upper: 2011 and 2017 grain size distribution (from bulk samples). Lower: Estimated cumulative average annual aggradation between 2011 and 2017 (black line) and 2001 and 2011 (grey line) based on cross section comparison and measured cumulatively upstream of Green River confluence (not accounting for sediment removals which average 11,650 m^3/year between 2011 and 2017).

Observations of the patterns of downstream geomorphic change in summer 2017 suggest that fluvially-remobilized sediment from the landslide could be divided into four components based on grainsize and sediment transport mechanism:

1) Finer than medium sand (0.25 mm)
    - Approximately 30% of the remobilized landslide material
    - Transported as wash load to the rivers delta and deep portions of Lillooet Lake, exerting little geomorphic affect on the river.
2) Medium to coarse sand and granules (0.25-8 mm)
    - Approximately 40% of the remobilized landslide material
    - Interacted with the bed material through braided and wandering channel reaches, located above 49 km upstream and between 41 and 49 km upstream of Lillooet Lake respectively, dramatically reducing subsurface grain size distribution thereby decreasing the stability of the bed sediment (**Figure 2.8**).
    - Becomes suspended in the water column during high flows and is flushed rapidly through the steep upper reach and transported farther downstream to the confined and lower gradient middle and lower reaches where shear stress is lower.
    - In the middle and lower reaches, reduced transport capacity causes these sediment sizes to move as bed material load, resulting in substantial bed aggradation.
3) Cobble and gravel material (8-256 mm)
    - Approximately 25-30% of the of the remobilized landslide material
    - Largely comprises a sediment slug that is slowly dispersing downstream, with the largest geomorphic impacts close to the landslide deposit.
    - Leading edge of impacts from these sediment sizes was interpreted to be about 25 km downstream of the landslide, or approximately 55 km upstream of Lillooet Lake.
4) Boulder sized sediment (>256 mm)
    - Less than 5% of the landslide mass
    - Not present in the remobilized sediment and has remained at and in the vicinity of the landslide.

2.3 Post-Landslide Sediment Budget

For any given reach of river the bed material sediment budget is defined by the relation of three terms, and the budget can be solved mathematically so long as two of the three terms are known (Church 2006). The mathematical relationship is defined below:

$$\frac{\Delta S}{\Delta t} = Q_{bi} - Q_{bo}$$

where ΔS represents the change in sediment storage over a given period of time (Δt) and Q_{bi} and Q_{bo} represent the flux of bed material sediment into, and out of the reach (respectively) for that same period of time.

A conceptual post-landslide sediment budget was developed for the Lillooet River from Lillooet Lake to the FSR Bridge by integrating grainsize data, estimates of the quantity of material eroded from the landslide, and comparison of cross sections from 2011 and 2017. **Figure 2.9** presents the conceptual sediment budget and illustrates some of the key relationships between the sediment bodies and sources of material impacting the middle and lower reaches. From the perspective of flood hazard management through these reaches, three key concerns become apparent:

1) Medium to coarse sand eroded from the landslide, transported through the upper reach, and deposited in the middle and lower reaches is impacting the channel profile and flood hydraulics.

2) Gravel recruited from the upper reach floodplain due to channel widening in the braided reach is entering the middle and lower reach and contributing to channel aggradation.

3) The leading edge of the coarse cobble and gravel bed material (sediment wave) diffusing downstream from the landslide is expected to reach the middle and lower reaches sometime in the next decade.

The rate of export of these grainsize fractions to the river’s delta is less certain, and a better understanding of sediment grainsize distribution in the lower reach will be required to estimate the sediment flux through the system with any degree of certainty.

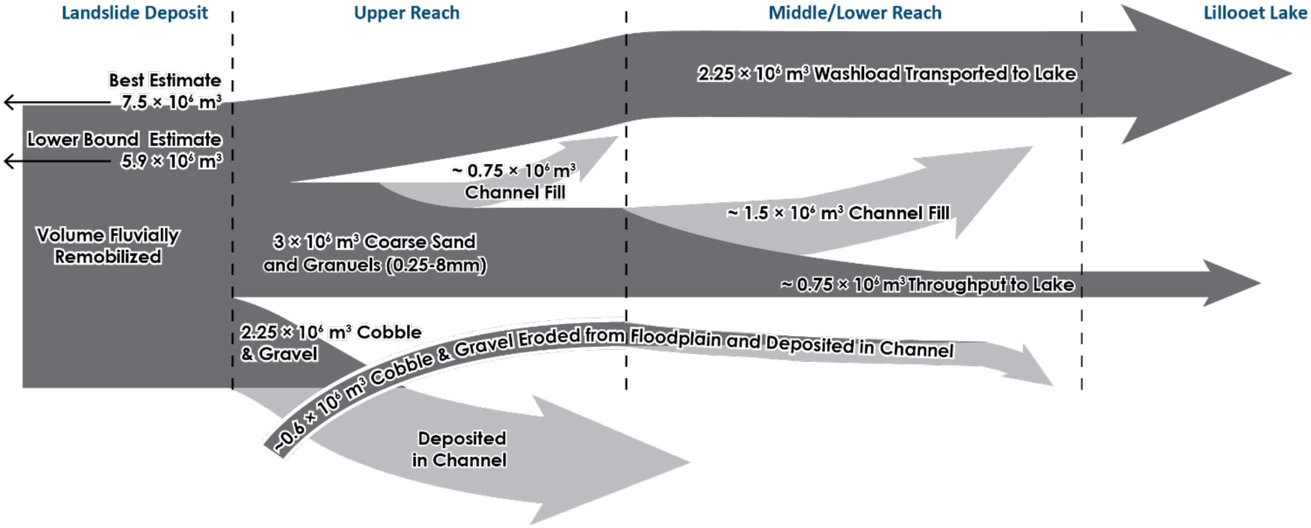

Figure 2.9. Conceptual sediment budget for the period between the landslide in 2010 and 2017 illustrating key sediment exchanges interpreted from available evidence. Volume estimates are subject to substantial uncertainty, ranging from ± 20% for the best constrained to order-of-magnitude for the least well known.

2.4 Future Sedimentation Rates

This section provides a preliminary estimate of future sedimentation rates based on information collected, compiled, and analyzed for the recent Lillooet Floodplain Mapping project (NHC 2018).

2.4.1 Sediment Inflows From 2010 Landslide Deposits

A large amount of deposited landslide sediment remains available for future river remobilization. By comparing 2010 satellite photogrammetry with LiDAR elevation data from 2015 and aerial photos from 2017, it is estimated only about 10% of the landslide deposit volume was eroded between 2010 and 2017. Impacts from the landslide will continue for several decades, and will reduce over time assuming the rate of landslide sediment re-mobilization follows an exponential decay rate. Additional disturbances in the basin could further introduce sediment to the system, which could exacerbate the present sedimentation issue.

Sediment yield is expected to remain higher than pre 2010 landslide conditions for a time frame in the order of several decades. **Figure 2.10** shows the projected remaining landslide deposit volume on the left axis and estimated annual sediment remobilization rate on the right axis. The average annual background sediment yield is plotted on the figure to illustrate the present-day sediment yield since the Mt. Meager landslide relative to historical conditions, which are based on the estimated sediment volume supplied from debris flows, landslides, and glaciers in the watershed over a time scale on the order of a thousand years (Jordan and Slaymaker 1991).

The estimated exponential decay rate of sediment remobilization is uncertain. It is based on a commonly observed pattern of exponential decay in landslide-sediment remobilization rates (Adams, 1980; Pearce and Watson, 1986; Major et al., 2000; Dadson et al., 2004; Koi et al., 2008; Hovius et al., 2011; Huang and Montgomery, 2012; Nelson and Dubé, 2016; Croissant et al., 2017) calibrated to a single point. Management of the sediment influx should be expected to continue beyond the project time frame for sediment remobilization from the landslide to match historical background levels because it will take several years for the sediment to be transported to the middle and lower reaches.

An exponential decay pattern is expected to occurs because:

- It becomes more difficult to erode slide deposits as the most accessible material is washed away;
- Channel gradient over the deposit slug decreases over time thereby becomes more resistant to mobilization; and
- Landslide deposits become stabilized as the finer material is washed away and coarser lag material is left behind and forms an armor surface layer, and as vegetation becomes established.

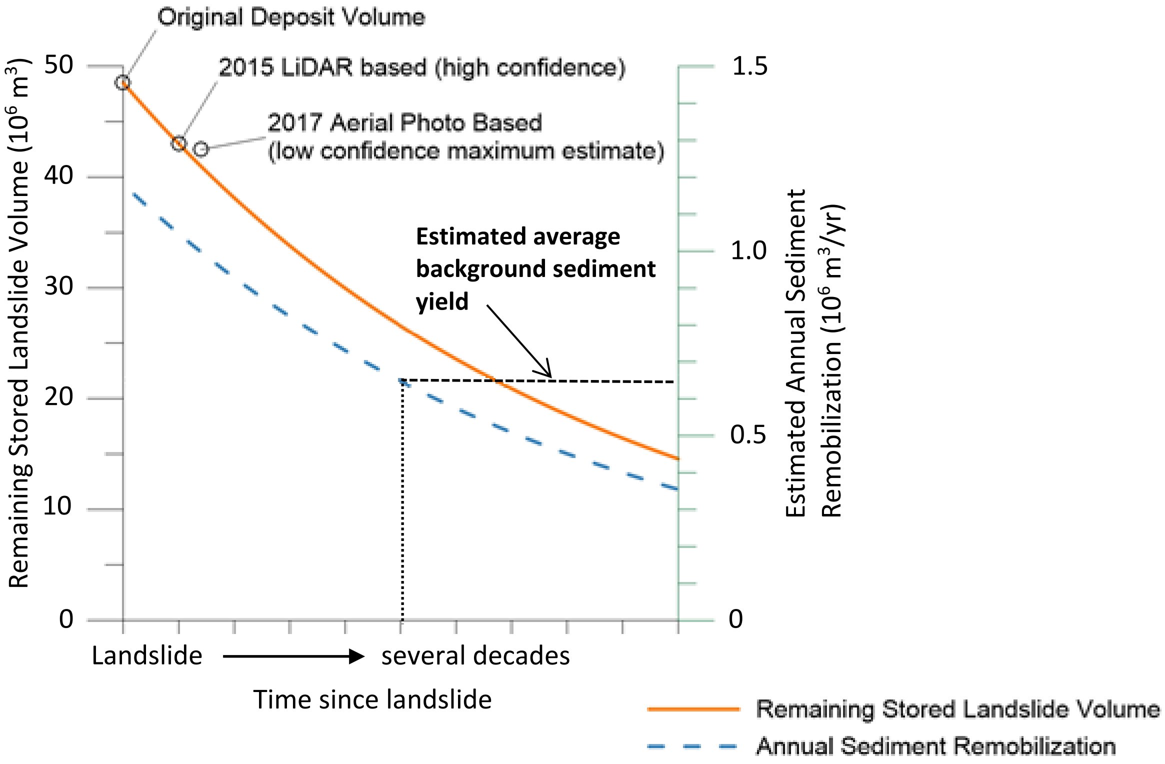

Figure 2.10. Estimate of change in landslide deposit volume and annual sediment remobilization through time. This figure assumes simple exponential decay in the landslide volume with a half-life of 28.8 years (calibrated to the volume removed between 2010 and 2015).

2.4.2 Impact of "Sediment Wave" on Middle and Lower Reaches

In 2017 the main slug of cobble and gravel material injected by the landslide ("sediment wave") appeared to be moving diffusively through the system, with most significant impacts occurring close to the landslide and the leading edge of discernable impacts extending to approximately 55 km upstream of Lillooet Lake (or 14 km upstream of the FSR Bridge). It is difficult to predict the timing and magnitude of expected impacts from the sediment wave through the diked reach. However, as the "sediment wave" travels downstream, higher concentrations of gravel and cobble will be supplied and deposited in the middle and lower reaches.

Channel confinement patterns in the middle and lower reaches create alternating zones of relatively high and low shear stress, with areas of lower shear stress becoming localized gravel deposition zones that will be increasingly prone to lateral instability (NHC 2018). Computed shear stresses indicate the most pronounced impacts will occur in the following sedimentation zones:

- Middle Reach: 28 km and 35 km upstream of Lillooet Lake.
- Lower Reach: 8 km, 13 to 17 km, and 20 km upstream of Lillooet Lake.

3 SEDIMENT MANAGEMENT PROGRAM

This section describes a proposed sediment management program for the Lillooet River that is intended to maintain hydraulic conveyance for floodwater in the most cost-effective and environmentally sensitive way feasible. Prior to preparing the plan we conducted a brief review of sediment management strategies and projects on several other river systems in BC and Washington State. **Appendix A** summarizes the key lessons learned from these projects.

3.1 Adaptive Management Strategy

One of the guiding principles of the sediment management program will be to follow an adaptive management strategy, incorporating feedback and response from the river system to refine the plan over time. It is proposed the program will be built on a framework that includes four main components (**Figure 3.1**). The time period for the program is in the order of 3 to 5 years, following which the program would be re-assessed to determine the effectiveness of the program and refine it as deemed necessary. Key indicators would be identified during the program development phase and would be used to gauge the performance of the program. The four components program include:

- Implementation – Sediment removal plans based on the latest information and assessments.
- Monitoring – Systematic observation of channel response, performance of sediment management sites, and effects on key indicators.
- Evaluation – Assessing results of monitoring, obtaining feedback from stakeholders and regulators.
- Adaptation – Revising plans and designs based on results of the evaluation process.

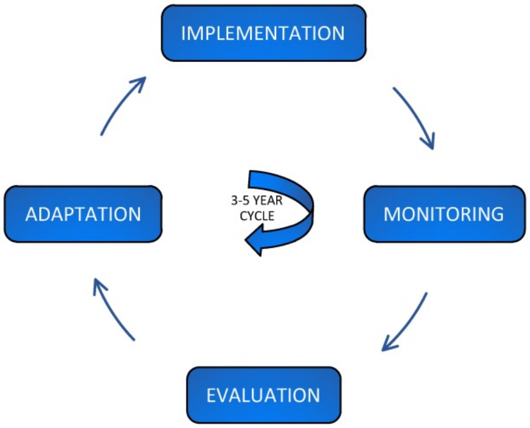

Figure 3.1. Program Outline.

3.2 Predicting Morphological Effects of Sediment Removals

Construction of a sediment trap or in-stream channel excavation in any alluvial river has the potential to induce upstream and downstream changes to the channel pattern, channel geometry, gradient, and sediment characteristics. The degree of morphological impact will vary from river to river, primarily depending on the removal volume relative to the rate of bed material movement along the channel.

The Lillooet River middle and lower reaches are clearly aggrading. Morphological impacts on the Lillooet River from sediment removals are expected to be relatively lower than in non-aggrading river systems because sediment loads are relatively high, and reduced sediment supply downstream of an excavation would help offset the increased deposition patterns that have been observed since the landslide.

By applying the adaptive approach described in **Section 3.1**, it is possible to achieve a balance between the rate of aggradation and the rate of sediment removal to maintain a stable profile over time. This principle of 'profile maintenance' provides a basis for developing a sustainable, long term sediment management program.

From sediment transport perspective, Lillooet Lake is considered to be a depositional zone and a geomorphological barrier to downstream progression of sediment that is supplied from the reach upstream of Lillooet Lake. Therefore, no impacts are expected in the reach downstream of Lillooet Lake as a result of sediment removals in the reach upstream of Lillooet Lake.

3.3 Preliminary (Phase 1) Sediment Management Plan

Flood profile maintenance has been applied on several aggrading river systems in BC, and typically target removals of 100% or more of the annual average sediment aggradation rate (**Appendix A**).For preliminary planning purposes, flood profile maintenance on the Lillooet River may require annual sediment removals in the order of 210,000 m^3/year to 260,000 m^3/year (100% to 125% of the annual bed material influx) over the next ten to twenty years to offset incoming sediment load from the 2010 landslide. Impacts from the landslide are expected to reduce over this period, which will reduce the intensity of removals necessary to offset the incoming sediment load. Impacts may last beyond a 20-year time horizon and additional disturbances in the basin could further introduce sediment to the system, which could exacerbate the present sedimentation issue.

With limited data, it is infeasible to estimate bed material load with certainty and annual removal volumes presented herein conservatively assume cumulative annual average aggradation rates between Green River confluence and FSR bridge can be used as a proxy for estimating bed material load to the middle and lower reaches[2]. Cumulative annual aggradation rates since the 2010 landslide are presented in **Figure 2.8** and discussed in **Section 2.2.3**.

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[2] Assuming bed material is not transported downstream of the Green River confluence, the estimated cumulative average annual bed aggradation rate serve as a lower bound estimate of bed material load.

For preliminary planning purposes **Table 3.1** presents target annual sediment removal volumes that may be necessary to maintain the flood profile over the next several years to decades, summarized by reach and assuming removals focus on the upper and lower reaches where accumulated sediment can most feasibly be removed from the channel. These are preliminary estimates that will need to be refined after further observations and analyses are completed to help verify how the rate of sediment remobilization from the landslide deposit is changing over time, better define the bed material load transport rate, and monitor for changes in the grain size distribution. Over time, target sediment removal volumes in the lower or middle reach will need to be refined to account for concurrent sediment removals in other channel reaches and to accommodate changing sediment influx rates. The proposed sediment management approach for the middle and lower reaches are described in **Section 3.3.1** and described for the upper reach in **Section 3.3.2**.

Table 3.1 Preliminary target annual sediment removal volumes for flood profile maintenance over the next several years to decades.

Reach	Preliminary Target Annual Removal Volume (m^3/year)[1,2]
Upper	150,000 to 200,000
Middle	Refer to Section 3.3.1
Lower	60,000
Total	**210,000 to 260,000**

Notes:

1. Annual removal volumes are preliminary estimates intended for preliminary planning purposes. Target removal volumes will be refined in future studies and it is expected these values will be updated over time following the adaptive management approach.
2. The values presented assume no sediment is removed from the middle reach.

3.3.1 Hydraulic Profile Maintenance in the Lower and Middle Reaches

Aggradation has already occurred in response to the 2010 landslide, increasing flood water levels and reducing the discharge required to overtop the Lillooet River diking system below the FSR Bridge. Targeted sediment removals in the middle and lower reach are intended to maintain the channel profile, and if funding is available removals could possibly be intensified to attempt to match the pre-landslide condition. Once sediment budget management removals upstream of the Forest Service Road Bridge (described in **Section 3.3.2**) begin to become effective, profile maintenance removals in the lower reach should become less intensive.

As discussed in **Section 2.1**, for several years prior to the 2010 landslide the channel bed at the WSC gauge station was starting to show signs of relative stabilisation after many decades of bed degradation. Reductions in bed levels below the pre-landslide profile could potentially negatively impact channel morphology, habitat connectivity, and increase vulnerability of dikes to scour. The 2011 channel bed survey is considered indicative of the pre-landslide channel profile.

Middle Reach

This reach has experienced the largest degree of aggradation and greatest losses in channel capacity since the 2010 landslide. In the order of 150,000 m^3/year of sediment aggraded in the reach between the FSR Bridge and Ryan River confluence during the period 2011 to 2017. Sediment removals in this reach will be challenging due to limited accessibility of channel bars; however, removals could improve hydraulic capacity in this reach and reduce the influx of sediment to the lower reach. The 2007 gravel management plan identified Erikson Bar as a candidate for sediment removals; accessed through private property located at the end of Erikson Road (KWL 2007).

Lower Reach between Ryan River confluence and Green River confluence

The sub-reach between Ryan River confluence and Green River confluence is considered to be the highest priority area for profile maintenance because a reduction of the channel's hydraulic capacity in this area will have the largest impact on flood hazards. Annual sediment removal rates in the lower reach of somewhere in the order of 60,000 m^3/year may be necessary to balance the rate of sediment removal and sediment influx over the next two decades for this sub-reach, depending on the remobilization rate of the landslide material over time and the intensity of sediment removals farther upstream. For the same time horizon, substantially larger annual removals – possibly in the order of an additional 30% or more sediment by volume – would likely be necessary to return the channel profile in this sub-reach to the pre-landslide condition.

Table 3.2 illustrates the impacts of past, proposed 2019, and potential future sediment removals on net aggradation volumes for this sub-reach. Values presented in this table are uncertain and intended to provide an order of magnitude understanding of preliminary sediment removal targets over the next twenty years. Heightened sediment removals will likely be required beyond 2038. In context, between 2010 and 2018 approximately 70,000 m^3 of sediment was removed from this sub-reach which is less than 20% of the total sediment deposited in this reach for this period.

Table 3.2 Lower Reach between Ryan River confluence and Green River confluence: estimated total channel aggradation, recorded sediment removal volumes between 2010 and 2018, proposed sediment removal volume for 2019, and preliminary target sediment removal volumes between 2019 and 2038.

Time Period	Estimated cumulative aggradation since landslide (cu. m) without management[1]	Estimated cumulative aggradation since landslide (cu. m) with management[1]	Sediment removal volume (cu. m)
2010 – 2011	60,000	60,000	-
2011 – 2012	120,000	120,000	-
2012 – 2013	180,000	140,000	38,000[2]
2013 – 2014	240,000	200,000	-
2014 – 2015	300,000	260,000	-
2015 – 2016	360,000	300,000	18,100[2]
2016 – 2017	420,000	350,000	13,800[2]
2017 – 2018	480,000	410,000	-
2018 – 2019	540,000	450,000	15,000[3]
2019 – 2038	1,670,000	~450,000	~60,000/year [4]

Notes:

1. Assumes a long term average aggradation rate of 60,000 m^3/year for the reach between Ryan River confluence and Green River confluence. Estimates rounded to the nearest ten thousand.
2. Recorded removal volumes.
3. Estimated 2019 pre-freshet removal volume.
4. Preliminary target annual future removal volume to balance the estimated incoming sediment load and the estimated net aggradation between 2019 and 2038.

Sediment removals since 2010 have focussed on four bars: Voyageur, Beem, Belkin, and Big Sky; however, it is unlikely the target annual removal volume for this reach can be excavated from these bars alone. **Figure 3.2** shows the location of these four bars and identifies several other gravel bars that could potentially be targeted for sediment removals in the reach between Ryan River confluence and Green River confluence.

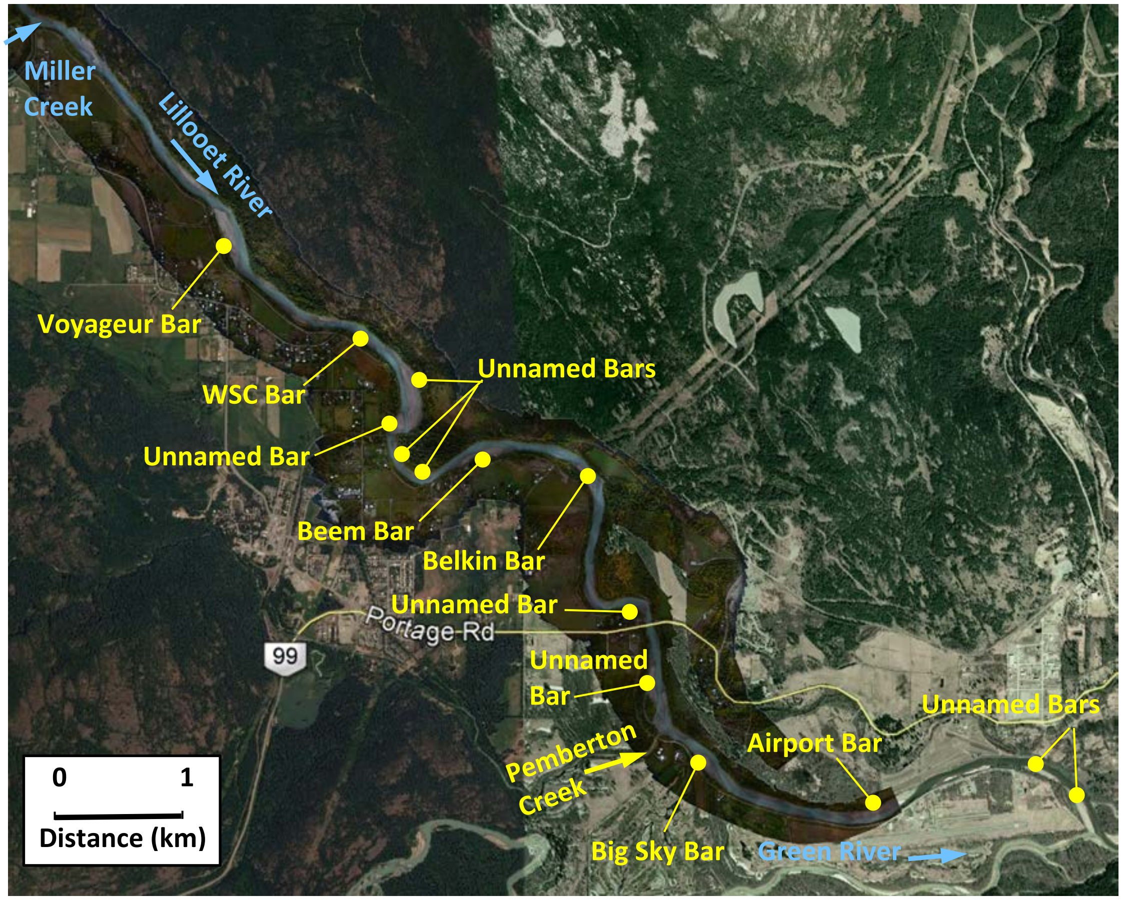

Figure 3.2. Gravel bars located in the lower reach between Ryan River confluence and Green River confluence.

Lower Reach between Green River confluence and Lillooet Lake

Approximately 40,000 m^3/year of sediment aggraded in the sub-reach downstream of Green River confluence between 2011 and 2017. The reach downstream of Green River is not diked and flooding in this part of the channel could impact key infrastructure, such as a Provincial fire fighting station and sewage treatment plant located just upstream of the Green River confluence, and could affect First Nations settlements and other landowners (Steve Flynn, pers. comm. 31 January 2019). Further assessment is necessary to determine the degree of sediment management that is feasible and practical considering access constraints, and to carry out a cost-benefit analysis of flood reduction in this sub-reach in context of the substantial hydraulic control imposed by Lillooet Lake.

3.3.2 Upper Reach Sediment Trap

Sediment removals in the upper reach are considered a crucial component of the sediment management strategy to reduce the influx of sediment to the middle and lower reaches. For preliminary planning purposes, a sediment trap in the upper reach may need to target somewhere in the order of 150,000 m^3/year to 200,000 m^3/year to effectively maintain the flood profile; based on annual removal volumes for the entire reach between Meager Creek confluence and Lillooet Lake that are limited on average to 100% to 125% of the estimated total bed material influx and assuming annually recurring sediment removals in the lower reach as described in **Section 3.3.1**.

Figure 3.3 and **Figure 3.4** show two potential sediment trap locations that could potentially be targeted, based on accessibility and channel characteristics. Each figure shows the location of the site relative to the FSR bridge, with inset maps showing a more detailed view of the channel in 2013 and 2017 to show the change in morphology over this period. Channel morphology is expected to further change over time and therefore sediment trapping efforts in the upper reach will likely need to target other locations.

Initially, the sediment trap should be designed to optimize trapping of sand and granule sized sediment to target the primary type of material that is being transported and deposited in the middle and lower reaches. Over time, the trap design will need to be modified as the “sediment wave” progresses farther downstream to target larger proportions of gravel (and cobble) and removal volumes may need to be increased to accommodate higher sediment transport rates.

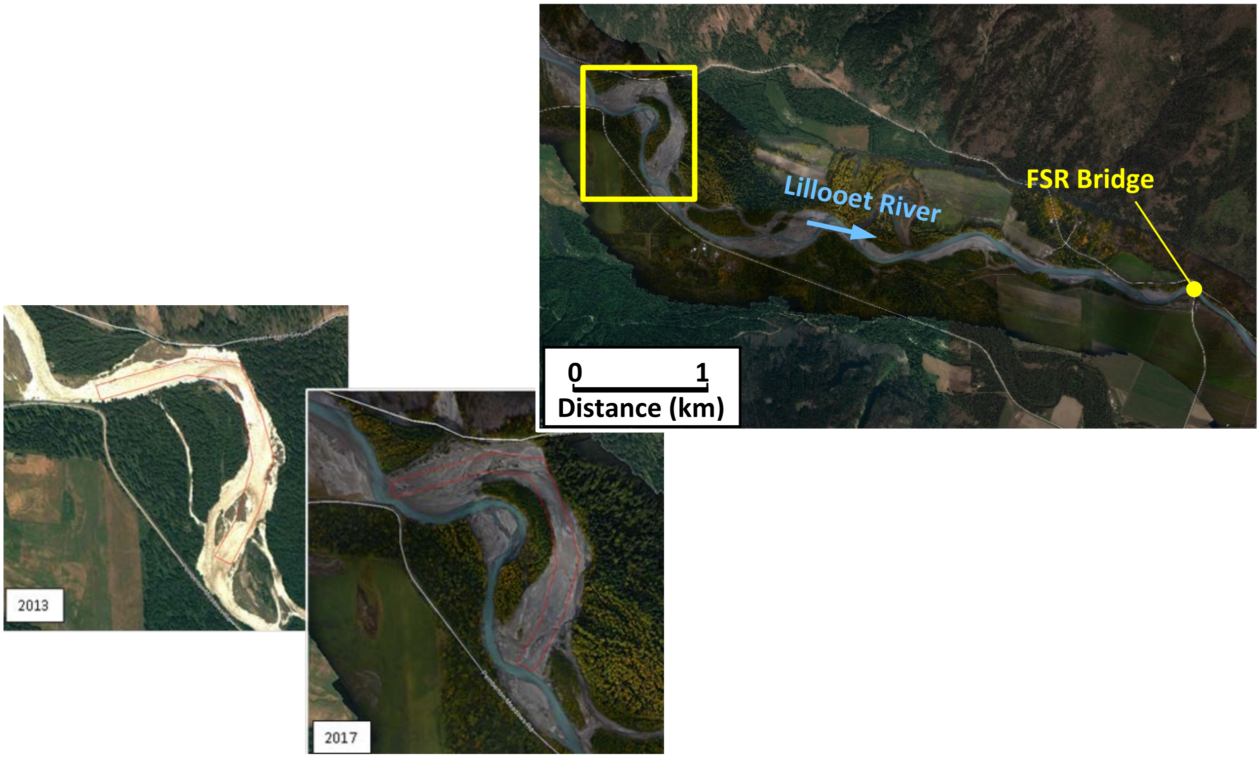

Figure 3.3. Potential upper reach sediment trap – infilled and abandoned channel.

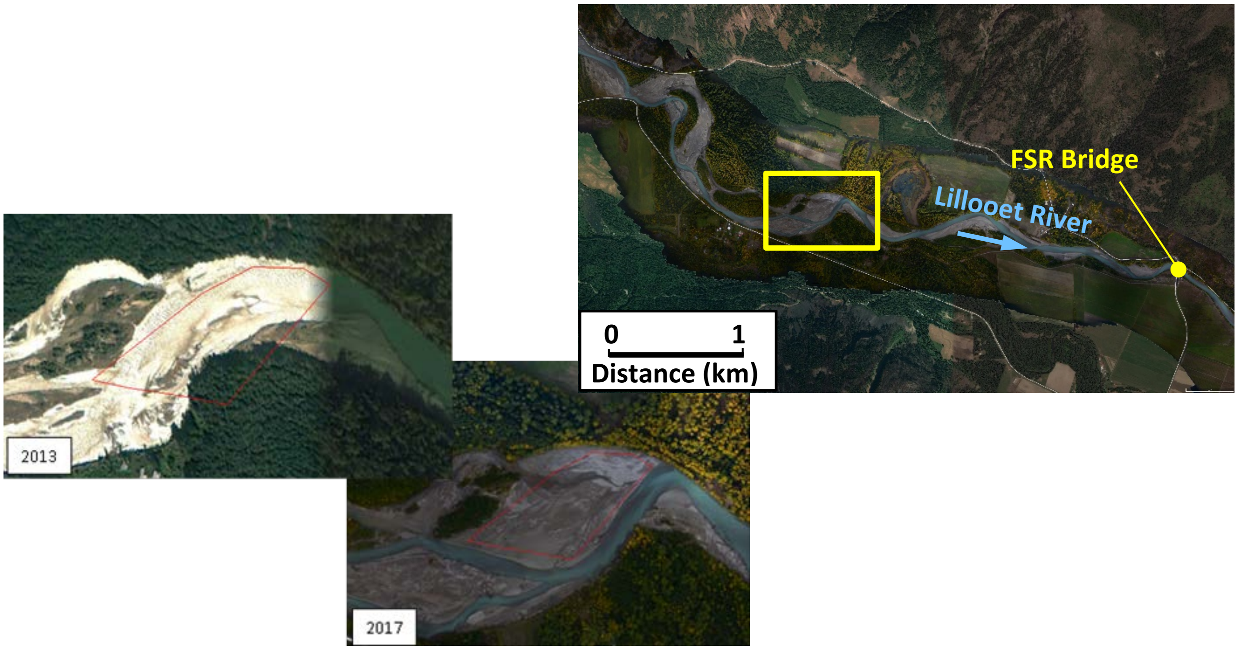

Figure 3.4. Potential upper reach sediment trap – channel bar formation.

4 CONCLUSIONS AND RECOMMENDATIONS

The sediment removal program is one component of an integrated flood management plan that will be developed to reduce the risk of flooding and erosion that have been triggered by the Capricorn Creek landslide off the slopes of Mount Meager in 2010.

The objective of the sediment management plan is to maintain the flood profile. This approach has been applied in several other rapidly aggrading river systems in BC and Washington State and typically includes a sediment removal intensity that matches or sometimes exceeds the incoming bed material load. Sediment removal volumes described in this report are preliminary and are intended to identify potential funding requirements over a ten to twenty-year time frame.

Over the next several decades, sediment removals in the order of 210,000 m^3/year to 260,000 m^3/year may be necessary to offset the anticipated incoming sediment load from the 2010 landslide. Impacts from the landslide are expected to reduce over this period, which will reduce the intensity of removals necessary to offset the incoming sediment load. Impacts may last beyond a 20-year time horizon and additional disturbances in the basin could further introduce sediment to the system, which could exacerbate the present sedimentation issue. Estimating average annual aggradation rates using less than 10 years of record can severely over or under predict the long term sediment transport rate and recurring monitoring and analyses will be necessary to refine these estimates over time.

The lower reach, between Ryan River confluence and Green River confluence is considered to be the highest priority area for profile maintenance. Annual sediment removal rates in the lower reach of somewhere in the order of 60,000 m^3/year may be necessary, depending on the remobilization rate of the landslide material over time and the intensity of sediment removals farther upstream. For the same time horizon, substantially larger annual removals – possibly in the order of an additional 30% or more sediment by volume – would likely be necessary to return the channel profile in this sub-reach to the pre-landslide condition. Sediment removals in the upper reach are considered a crucial component of the sediment management strategy to trap sediment, thereby reducing the influx of sediment to the middle and lower reaches. A preliminary target removal volume for the upper reach is estimated to be somewhere in the order of 150,000 m^3/year to 200,000 m^3/year.

The results of more detailed analyses, conclusions, and recommendations would form a more comprehensive plan that would be used as a guiding document for future sediment removals and target sediment removals would be continuously refined over time to adaptive to observed channel responses and changing conditions. Additional work will be required for the sediment management plan:

- Target sediment removal volumes should be refined by collecting additional sediment data, and by collecting additional LiDAR data and ortho-imagery for comparison with existing datasets. Additional sediment data will improve the present understanding of the bed material flux through the system and grain size distribution in the middle and lower reaches. The estimate of the duration and acuteness of the landslides impact on downstream sedimentation processes are both very sensitive to the estimate of the half life period, which based on a theoretical relationship and therefore is relatively uncertain.

- Acquisition of new LiDAR topography data for the landslide deposit will provide additional calibration or validation data on the supply of landslide derived material to the reaches farther downstream.
- LiDAR data of the downstream channel reaches will better constrain the sediment budget terms for the upper reach, which will in turn allow higher confidence in the interpreted flux of sediment into the middle and lower reaches.
- A reconnaissance site visit will be necessary to identify optimal locations for sediment removals.
- An overview level assessment is recommended to determine fish habitat value that may impact site selection, to assess channel conditions, and to consider logistical aspects of the program. More detailed fish habitat studies are anticipated and would be carried out by others.
- Select sites should be surveyed in more detail to collect bathymetric and topographic information that will support the design development phase and form the basis for future channel cross section monitoring.
- Numerical modelling is recommended to support design of the upper reach sediment trap, initially to optimize trapping of sand and granules and to eventually modify the design to trap coarser material as the “sediment wave” advances farther downstream. The numerical model developed for the recent Lillooet Floodplain Mapping project (NHC 2018) should be utilized to assess for flood benefits for possible sediment removals in the lower reach downstream of the Green River confluence. The existing numerical model could also be utilized to assess for hydraulic impacts associated with larger scale removals in other parts of the lower (or middle) reach.

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Appendix A: Lessens learned from recent sediment management projects on other river systems

Several examples of sediment management programs from rivers in BC and Washington were reviewed to assess the key lessons learned from these projects. Brief descriptions of the projects are summarized below. All of the sites have experienced long-term aggradation; however, none at the rate presently occurring on the Lillooet River. The objectives of the projects were primarily to maintain the design flood profile in order to avoid having to continually raise or rebuild dikes. The main findings relevant to Lillooet River are as follows:

- Sediment removal at a rate that approximates gravel influx has no major adverse effect on river processes and channel morphology
- Church (2010) concluded that for the Fraser River gravel-bed reach (Hope to Sumas Mountain) the bed material removal rate should not exceed 1.5 times the gravel recruitment over the most recent 5-year period. Later on this was ammended to a ratio of 1.25 times, averaged over a 10 year period. These results are consistent with observations and findings from the Cowichan River near Duncan.
- Sediment removals can be carried out to maintain the flood profile while preserving fish habitat. The programs need to be implemented adaptively and should include monitoring, evaluation, plan updating as components of the works.

Removing gravel from alluvial rivers that are utilized by fish has been controversial in the past, since in-stream excavations may induce changes to aquatic habitat. Prior to 2000, most studies to assess the effects of gravel removal on stream morphology and habitat were conducted on industrial-scale gravel mining operations, where the rate of extraction far exceeded the rate of supply (Kondolf 1995). For example Sutek (1989) described a number of industrial gravel mining projects in Alaska where the annual removals were between 10x and 100x the incoming sediment loads. These examples are not representative sediment management programs, which aim to maintain the long-term stability of a channel by conducting targeted removals and monitoring programs.

Vedder River Near Chilliwack, BC

The Chilliwack drains 1,230 km^2 of steep, mountainous terrain and flows through a narrow valley to the head of its alluvial fan near Vedder Crossing. The long-term average annual gravel inflow rate at Vedder Crossing ranges from 50,000 to 75,000 m^3/year. During large floods the gravel transport rate exceeds 250,000 m^3. Downstream of Vedder Crossing, the river is referred to as “Vedder River”, after it avulsed across its fan into Vedder Creek in the early 1900’s (**Figure 1**). The transport capacity decreases downstream from Vedder Crossing in response to the decrease in slope. The zone of greatest deposition occurs near the head of the Vedder Canal.

Attempts at flood control during the 1970s produced strong criticism from environmental groups and fisheries agencies due to concerns about destruction of spawning and rearing areas for salmon and steelhead trout. In 1983 the Vedder River Management Plan proposed a system of flood control works including setback dikes on the floodplain, bank protection along both sides of the main channel to maintain a stable alignment, a series of groynes to protect the setback dikes and a program of ongoing sediment removal.

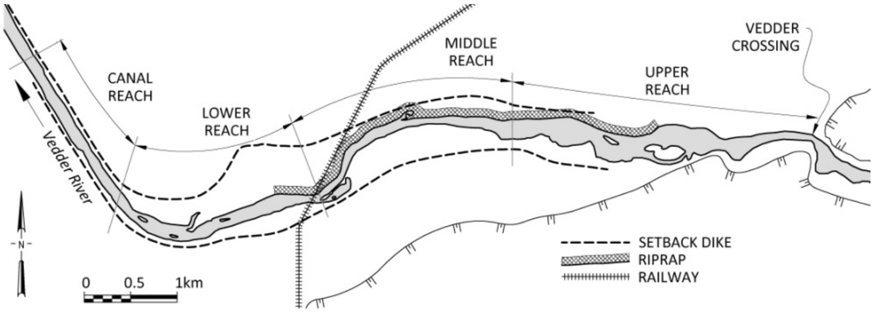

Figure 1: Vedder River management area.

Maintaining a stable 200 year flood profile has required an annual average gravel removal rate of about 75,000 m^3/year since 1983 (Bergman, 1996). The removals were not always carried out each year, depending on the sediment inflow rate. Several distinctly different gravel removal strategies have been tried over the years. Commencing in 1994, a program of excavating deep pits was adopted, replacing the "bar scalping" approach which had been used previously. This program effectively limited the rate of gravel accumulation in the Vedder River.

Physical habitat inventory of the river has found that the excavations improved habitat conditions at most sites, but that habitat impacts were small and difficult to distinguish from normal river changes (McLean et al., 2013).

Fraser River Gravel Bed Reach, BC

The Fraser River exits its narrow bedrock canyon near the town of Yale and spreads across a broad alluvial plain downstream from the town of Hope. The alluvial, gravel-bed reach of the Lower Fraser River extends approximately 70 km from Hope to near Sumas Mountain. Due to the decrease in slope through this reach, the incoming gravel load is deposited and the river changes abruptly to a sand-bed channel below Sumas Mountain. Estimates of gravel inflow rates have varied widely. Church (2010) recommended using 230,000 m^3/year as a current estimate of average annual bed material recruitment.

Hydraulic studies (NHC, 2006) indicated that many sections of the existing flood dikes were not adequate to contain a recurrence of the 1894 flood of record. It was hypothesized by some agencies that gravel deposition had contributed to a reduction in flood conveyance along the river. Pilot gravel removals were carried out between 2000 and 2009, averaging 113,000 m^3/year and reaching up to 274,000 m^3/year in 2006. A review of the program was carried out in 2010 (Church, 2010). It was concluded for an aggrading river system such as the Fraser:

- Sediment removal at a rate that approximates gravel influx has no major effect on river processes and morphology.

- The bed material extraction rate should not exceed 1.5 in comparison with the best estimate of gravel recruitment over the most recent 5-year period. Later on this was ammended to a ratio of 1.25 averaged over 10 years.

Cowichan River, Vancouver Island, BC

The Cowichan River conveys approximately 25,000 m^3/year of bedload sourced from a 826 km^2 basin. Much of this accumulates along the lowest 7 km of the river near the City of Duncan, BC, where aggrading bed levels have increased the 200 year flood level by a rate of about 5 cm/year since 1981 (McLean et al., 2013). A sediment management program was implemented in 2012-2013 by the Cowichan Valley Regional District and its partners, the Municipality of North Cowichan, City of Duncan, and Cowichan Tribes. The project has three main objectives: maintain the 200-year flood profile, reduce the risk of channel instability, and maintain or enhance fisheries habitat. The gravel excavations have been carried out annually since 2013, with the excavations alternating between two preferred sites.

The Cowichan is an internationally designated Heritage River that supports seven species of salmon including a Chinook run that is a key indicator in the Canada/US Pacific Salmon Treaty. Through close collaboration with the project biologists, design elements of the sediment removal were specifically incorporated to optimize the likelihood of achieving the habitat targets. Monitoring results indicate the project provided a net benefit to habitat and increase in salmonid productivity (Current Environmental, 2013).

Fitzsimmons Creek, Whistler, BC

Based on 52-years of delta progradation into Green Lake near Whistler, BC the annual average bed load transport rate on Fitzsimmons Creek is estimated to be in the order of 10,000 m^3/year (Pelpola et al. 2004). Gravel removals have recurred on the channel since 1992, with 7,994 m^3 of sediment removed in August 2018 (KWL 2018), which is approximately 80% of the estimated average annual sediment load. Sediment removals on Fitzsimmons Creek is part of a flood management program for the Resort Municipality of Whistler, BC and is intended to reduce water surface elevations during the 200-year return period flood event.

Toutle, Cowlitz and Columbia River, Washington, USA

Experience on the rivers below Mount St. Helens in Washington State provides helpful context for understanding sediment removal in unstable volcanic landscapes. The disturbance associated with the 1980 eruption was orders of magnitude larger than the 2010 landslide on Mt. Meager, but the response illustrates the range of sediment management challenges and responses possible following an extreme sediment injection. Aggradation in the Toutle and downstream Cowlitz river put adjacent communities at risk of flooding (even during normal flows) and created a navigation hazard in the Columbia River. A sediment retention structure (dam) was constructed across the channel to promote upstream aggradation, levee crest elevations were raised at vulnerable locations, and the beds of the Toutle, Cowltz, and Columbia Rivers were all dredged to remove accumulating sediment (Willingham, 2005).

Nearly four decades after the eruption, management of fluvially remobilized sediment remains a costly challenge (Major et al., 2000; Major, 2004; Sclafani et al., 2018), but increasing the sediment trapping efficiency and storage volume of the sediment retention structure with only targeted removals of sediment from the channel downstream appears to be the most cost-effective option, particularly because in channel sediment management is complicated by interactions with ESA listed species (Sclafani et al., 2018).

Cedar River, Washington, USA

The Cedar River transports a fairly modest bed material load (about 5,500 m^3/yr from a 487 km^2 basin) across an alluvial fan and into a very low-slope canal that connects the toe of the fan into Lake Washington. It flows through downtown Renton, WA (a suburb of Seattle), where there is dense commercial and industrial use of the river's floodplain. Aggradation in the canal periodically results in the modeled 100 year flood water surface profile exceeding the crests of dikes along the river, necessitating dredging of the canal to remove 100% of the accumulated sediment about every 10 to 15 years (NHC, 2014).

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