Photo source: Google Earth (2016-08-17)

Review of 2024 Vedder River Gravel Removal Plan

Prepared by:

Northwest Hydraulic Consultants Ltd.
30 Gostick Place
North Vancouver, BC V7M 3G3
Tel: (604) 980-6011
www.nhcweb.com

NHC Project Contact:
Dave McLean, PhD, P.Eng.
Principal Engineer

Prepared for:

BC Ministry of Environment and Climate Change Strategy
Environmental Protection Division,
Victoria, BC

April 18, 2024
Final Report, Rev. 0

NHC Reference 3008518

Document Tracking

Date	Revision No.	Reviewer	Issued for
20240326	R0	DGM	Review Draft
20240417	R0	BC	Final Report

nhc

Report prepared by:

PROFESSIONAL ENGINEER
PROVINCE OF BRITISH COLUMBIA
D. G. McLEAN
13220

April 17, 2024

David McLean, PhD, P.Eng.
Principal Engineer
(Hydraulics and Sedimentation)

Ryan Bradley, PhD
Geomorphologist

Report reviewed by:

Barry Chilibeck, MASc, PEng
Principal Engineer

EGBC Permit to Practice Number: 1003221

DISCLAIMER

EXECUTIVE SUMMARY

The volume of sediment deposited from the November 2021 flood was exceptional, exceeding previous large sediment inflow events in 1975, 1989 and 1990 by over 50% and approximately 10 times larger than the long-term average rate. The updated (2024) design flood profile in KWL (2024) shows the dike freeboard is deficient over a length of 6 km, with freeboard reduced to less than 0.3 m over a substantial distance on both sides. The discharge (and corresponding return period) that the dikes can convey with adequate freeboard is unknown. Additional hydraulic modelling should be carried out to determine this for both present conditions and after implementation of Option D. This information would provide a better basis for assessing the benefits of the sediment removal option and would assist in planning additional short-term and long-term flood protection upgrades.

Sediment removal Option D involves excavating 243,500 m^3 of sediment from 11 sites along the river. This volume amounts to 55% of the total volume deposited in 2021. We expect this magnitude of excavation will result in some improvement to the freeboard situation in the short-term (1 to 2 years). However, the dike will remain freeboard deficient following the removal.

The feasibility of installing temporary flood protection measures (Hesco flood barriers or “Super Sacks”) should be assessed as interim measures while other longer-term solutions are implemented. Ongoing, periodic sediment removals will continue to be an important component of flood management on the Vedder River. But sediment removals alone will be insufficient to maintain adequate freeboard after extreme flood events.

In our opinion, the methods, hydraulic modelling tools, and types of monitoring used for hydraulic engineering, morphology and habitat assessment on the Vedder River should be reviewed and updated for any future sediment removal program. Significant changes in data collection and tools to assess effects have been developed and are now considered industry standard methodologies. For example, large spatial data collection, 2D hydraulic modelling and hydraulic habitat analyses using UAV photogrammetry and habitat suitability analyses have become standard tools for computing river hydraulics, assessing complex river morphologies and for habitat modelling. There has been an increased focus on using quantitative geomorphic methods to assess and monitor the physical impacts of these projects and long-term biological monitoring and evaluation to ensure project offsets ae reliable and effective. Changes to the assessment process, data and procedures will allow both the benefits and adverse impacts from the program to be evaluated more rigorously than in the past.

TABLE OF CONTENTS

LIST OF TABLES IN TEXT

LIST OF FIGURES IN TEXT

1 INTRODUCTION

1.1 Scope of Work

The BC Ministry of Environment and Climate Change Strategy (MOE) retained Northwest Hydraulic Consultants Ltd. (NHC) to review the engineering and habitat mitigation assessment for the 2024 Vedder River gravel removal plan (KWL, 2024). The project is supported by the Province's 2021 Atmospheric Event in British Columbia recovery program.

The purpose of the review is to provide independent technical opinions on the conclusions and recommended measures that have been proposed. NHC was asked to provide opinions on:

- The recommendations concerning sediment removals to increase channel conveyance and dike freeboard.
- Sediment dynamics and sediment re-distribution in response to the excavations and to future flood events.
- The conclusions and recommendations concerning effects of excavations on fish habitat.
- Other potential alternatives or additional measures to improve the security of the flood dikes and to improve fish habitat.

This report is NHC's response to that request.

1.2 Schedule of Work

NHC met with Ministry's consultants (KWL and Nova Pacific Environmental) on 11 October 2023 to discuss the purpose of the review, the type of information that was requested and the status of the sediment removal project. On 7 November 2023 NHC were informed by the Ministry that the 2024 gravel removal plan was being revised and that new reports and information would be provided at a later date. On 20 February 2024, we received notification that an updated sediment removal plan was under completion and received a PowerPoint document dated 22 February 2024, summarizing four sediment removal options. On 4 March 2024, NHC received final engineering and environmental reports (dated 29 February 2024) from KWL describing the new sediment removal plan. We did not receive a copy of the new hydraulic model that was used to evaluate the options, so we have based our comments on the information contained in the 29 February 2024 report. Our draft review report was submitted to the Ministry on 27 March 2024.

1.3 Primary Reports Reviewed

- 2024 Vedder River Hydraulic Assessment, Final Report. KWL report to Ministry of Environment and Climate Change Strategy, 29 February 2024.
- Proposed 2024 Vedder River Sediment Removal Project, Environmental Assessment Report, Nova Pacific Environmental Ltd., 29 February 2024.

- 2024 Vedder River Sediment Removal Environmental Management Plan, Version 2, Nova Pacific Environmental Ltd., 29 February 2024.

1.4 Supporting Documents

- 2023 Hydraulic Assessment Report, Proposed 2023 Vedder River Sediment Removal Project, Final Report, KWL, report to Ministry of Environment and Climate Change Strategy, 5 May 2023.
- Proposed 2023 Vedder River Sediment Removal Project: Environmental Assessment Report, Nova Pacific Environmental Ltd., 5 May 2023
- Vedder River-2023 Vedder River Sediment Removal Project, Construction Environmental Management Plan, Nova Pacific Environmental Ltd, 28 June 2023 Version 3
- Vedder River Hydraulic Profile Update 2022, Final Report. KWL report to City of Chilliwack, May 19, 2022.
- Review of the KWL 2023 Vedder River Gravel Removal Proposal, Dr Marvin Rosenau, 19 July 2023
- Information Briefing Note, Damage to fish habitat and incubating Pink Salmon eggs from a proposed MECSS summer 2023 large-scale gravel removal project on the Vedder River, Dr Marvin Rosenau, 13 June 2023

2 BACKGROUND INFORMATION

2.1 Need for Sediment Management

The Vedder River flows across a confined alluvial fan downstream of Vedder Crossing. Although the main dikes along the Vedder River are set-back from the active channel, the middle and lower reaches of the Vedder River have been channelized and narrowed by riprap “training berms” that overtop only during large floods. The river deposits virtually all of its gravel and sand sediment in the channel confined by the inner berms and Vedder Canal before joining with the Fraser River.

Estimates of the long-term average sediment deposition rate on the fan have ranged from 37,000 to 70,000 m^3/year (Bergman (1996), KWL (2024)). These deposition values also correspond to the average annual sediment inflow at Vedder Crossing. Sediment deposition has the potential to lead to bed aggradation which decreases river conveyance capacity and increases flood risk. In the Vedder River, the diking system constricts the river such that it cannot form a wide floodplain and flow around its own deposits.

The need for long-term sediment management can be demonstrated through a simple calculation. For the purpose of this example, we assume the long-term deposition rate on the Vedder River is approximately 50,000 m^3/year. Virtually all of the gravel and sand bedload deposits within the confined active channel. The surface area of this deposition zone is 900,000 m^2 (estimated from digital imagery from low water conditions in 2022). If 50,000 m^3 of sediment was uniformly deposited over the 900,000 m^2 bed area, the average thickness of sediment accumulation averages 0.06 m/year. Without long-term gravel removal, the average bed level would have aggraded by 2.4 m over the 40-year period between 1981 and 2021, which would increase water levels over this period.

In lieu of simply increasing the height of the setback dikes to reduce flood risk to the surrounding communities, a sediment removal program has been used to maintain the existing flood protection infrastructure largely as it has become a self-funding operation through sale of the excavated gravels. The need for periodic sediment removal has been acknowledged for many years (Bonham, 1980) but there are ongoing questions regarding the sediment management program including:

- how much sediment needs to be removed.
- how effective are the removals in reducing flood levels.
- what other measures could be carried to reduce the need for sediment removal, and
- what are the impacts to fish habitat.

2.2 2021 Atmospheric River Event

2.2.1 Flood Discharge

The 15 November 2021 atmospheric river event (ARE) triggered widespread flooding throughout the lower Fraser Valley. Water Survey of Canada (WSC) did not estimate the maximum instantaneous discharge during the flood because scour and deposition near the gauge site made the gauge's rating curve unreliable. The average daily discharge of 719 m^3/s on 15 November was flagged as an "estimate "only, indicating the reliability of the daily flow was also lower than standard published data. This problem has occurred several times in the past at the gauge, causing the published flood record to be incomplete. For example, the peak discharges in November 1989 and November 1990 are unknown, but caused considerable damage at the time and may have been comparable to the 2021 event.

The highest instantaneous maximum discharge in the period of record at Vedder Crossing reached 1,140 m^3/s in October 2003, followed by an event of 1,040 m^3/s in November 2006. Based on the historical data and comparison with flows measured at the upstream gauges, the peak discharge during the November 2021 event probably was of similar magnitude. The current design flood for the Vedder dikes is 1,470 m^3/s, corresponding to an estimated return period of 200 years.

The 2021 flood occurred after a 14-year period of lower than average flows between 2007 and 2020 (Figure 2.1). In comparison, the years between 1975 and 1990 were a period of sustained high flows. This cyclical variability is a commonly observed feature of long-term flood records due to multi-year climate oscillations. Similarly, there is a tendency for very high peak flows to cluster together in above-average, multi-year periods.

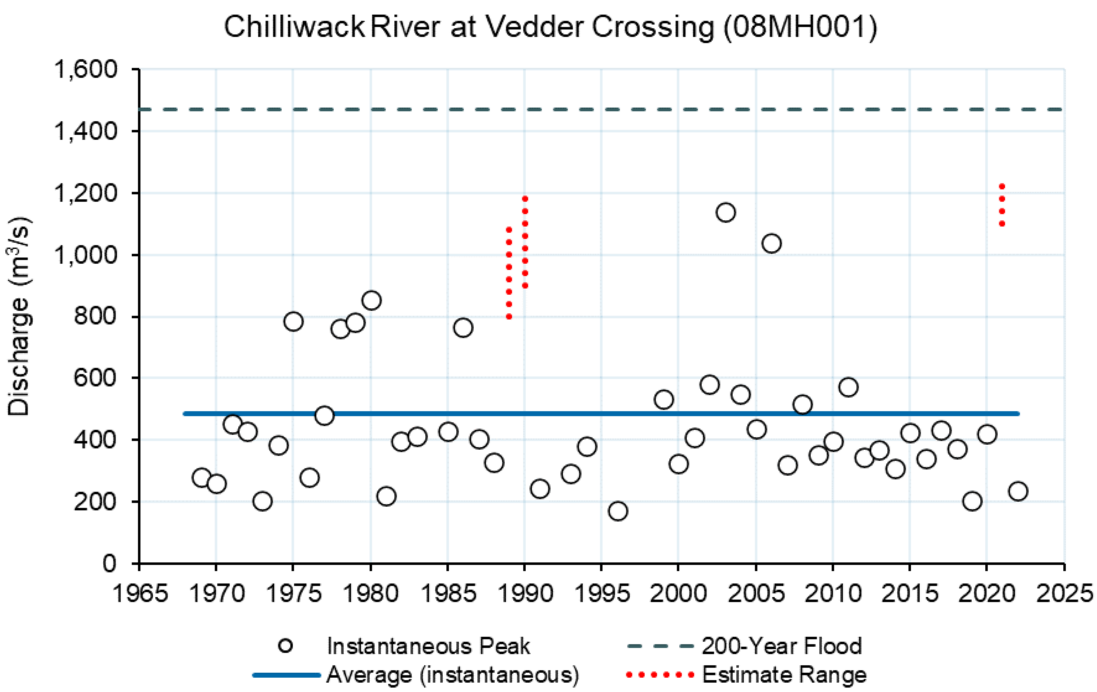


Figure 2.1 Annual maximum instantaneous (peak) discharges published by WSC along with approximate ranges of missing floods from 1989, 1990 and 2021.

2.2.2 Sediment Deposition

The volume of sediment deposited from the November 2021 flood was exceptional, amounting to over 442,000 m^3, of which 358,000 m^3 was deposited on the Vedder River and 84,000 m^3 was deposited in the Vedder Canal. Floods in December 1975, November 1989 and November 1990 also deposited large volumes of sediment on the Vedder River (248,000 m^3 in 1975 and roughly similar volumes in 1989 and 1990[1]). Deposition from the November 2021 event was approximately 50% greater than in these earlier floods and an order of magnitude greater than the long-term mean rate.

2.3 Variability of Annual Sediment Volumes

Sediment management would be relatively straightforward if the annual sediment inflows at Vedder Crossing only fluctuated over a narrow range. A sediment management program could be designed to consistently remove the long-term average sediment inflow rate such that the effect of small variations in inflows above or below the excavation rate would be attenuated over a few years of operations. Unfortunately, the sediment transport regime of the Vedder River is highly variable. Historical surveys show sediment inflows have varied over a tremendous range, with long periods of low inflows (virtually zero) punctuated by episodes of high sediment loads in excess of 200,000 m^3 during a single flood event lasting only a few days.

The annual variability in sediment deposition can be illustrated when comparing deposition volumes reported for the two periods 2018 to 2020 and 2020 to 2022 (KWL (2020), KWL (2022)). The cumulative sediment deposition along the Vedder Canal and Vedder River is illustrated in Figure 2.2. There were no sediment removals between 2018 and 2022 which simplifies the comparison between the two periods shown in Figure 2.2.

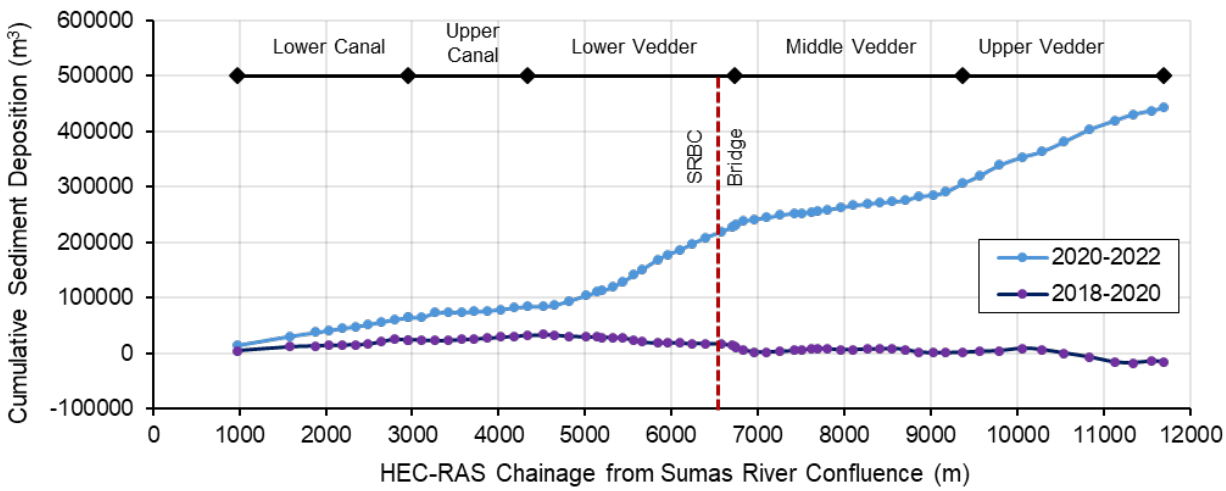


Figure 2.2 Cumulative sediment deposition along Vedder Canal and Vedder River for two periods-2018 to 2020 and 2020 to 2022. All data from KWL (2020) and KWL (2022).

In the period 2020 to 2022, the flows exceeded 300 m^3/s for four days, and the maximum daily discharge exceeded 700 m^3/s on 15 November 2021. These high discharge conditions lead to the

[1] The volumes do not include sediment deposited in the Vedder Canal since repeat surveys were not carried in the canal.

exceptional total sediment inflow volume of 442,000 m^3 at Vedder Crossing. Of this total, over 229,000 m^3 (52%) of the incoming load was deposited downstream of the SRBC railway bridge and 84,000 m^3 (19%) was deposited in the canal.

Conversely, the period 2018 to 2020 is an example when the sediment inflow at Vedder Crossing was extremely low and the Vedder River experienced net degradation even though no gravel removal occurred. During the 2018 to 2020 period, the highest daily flow was 302 m^3/s and the period of highwater lasted only one day. Approximately -49,000 m^3 of bed lowering occurred along the Vedder River and 33,000 m^3 of deposition occurred in the canal. It is likely that the actual sediment inflow at Vedder Crossing was negligible and that a relatively small quantity of sediment scoured from the Vedder River which was then re-deposited in the canal. The net difference (-16,000 m^3) suggests some of the finer sediment may have been transported through the canal into the Fraser River.

A review of surveys from 2010 to 2012, 2012 to 2014, 2014 to 2016 and 2016 to 2018 shows a similar pattern of very low sediment inflows, which is consistent with the period of unusually low flood flows in the decade between 2010 and 2020 (Figure 2.1).

2.4 Sediment Budget

A sediment budget on the Vedder River expresses the relation between the natural deposition (V_d) volume, sediment excavation volume (V_e) and the observed channel volume changes that were surveyed (V_{chan}) over a period of time:

$$V_{chan} = V_d + V_e$$

In this relation, excavation quantities are expressed as negative values. If V_{chan} is negative the channel has experienced a net loss of sediment (degraded), and positive values indicate that the bed has gained sediment (aggraded). If V_{chan} remains near zero over a long period of time, then the excavation volume has been approximately the same magnitude as the natural deposition volume. In practice, V_d cannot be measured directly, it is computed from the surveyed channel volume changes (V_{chan}) and the excavation volumes (V_e):

$$V_d = V_{chan} - V_e$$

For example, if the surveyed channel volume change over a 2-year period was 100,000 m^3 and the excavation volume was -50,000 m^3, then the actual natural deposition was 150,000 m^3.

Table 2.1 summarizes long-term estimates of surveyed channel changes, sediment removals and natural deposition volumes derived from published values (KWL, 2020) and (KWL, 2022). The starting date of the comparison (1991/1996) is based on surveys from the Vedder Canal (April 1991) and Vedder River (October 1996). Table 2.1 shows that between 1991/96 and 2020 sediment removals exceeded deposition volumes in all reaches except for the upper Vedder River. The upper Vedder River reach experienced the greatest deposition (499,100 m^3), which was offset by excavating -456,00 m^3 (corresponding to 91% of the deposition). By comparison, excavation in the Vedder Canal (-117,800 m^3) greatly exceeded the computed natural deposition volume. Overall, the total excavation exceeded the natural deposition volume in the Vedder River and Canal by -375,600 m^3 which resulted in net long-term bed lowering (degradation).

These numbers are consistent with KWL (2022) Table 6, except that KWL's table expresses the deposition as annual deposition values, which cannot be directly compared to the total bed changes and total excavation volumes. It should be noted this period included a number of large sediment removals in the 1990s, including 1996 (217,000 m^3) and 1994 (183,600 m^3) to restore the channel after earlier large floods.

Table 2.1 Comparison of long-term channel changes and sediment removals 1991/96 to 2020 based on data from KWL (2022) Table 6.

Reach	Bed Change (m^3)	Excavation (m^3)	Total Natural Deposition (m^3)	Excavation / Deposition Ratio (%)
Upper Vedder	43,100	-456,000	499,100	91%
Middle Vedder	-127,100	-256,000	128,900	199%
Lower Vedder	-139,100	-428,000	288,900	148%
Vedder Canal	-152,500	-117,800	-34,700	339%
Total	**-375,600**	**-1,257,800**	**882,200**	**143%**

A separate analysis was made by compiling the excavation volumes, bed changes and natural deposition volumes for each period between 2000 and 2020 using the data published in the hydraulic profile update reports (Bland (2002), Bland Engineering/NHC (2004), Bland (2008), Hayco (2010), Tetra Tech EBA (2014), KWL (2016), KWL (2018), KWL (2020)).

The period 2000 to 2020 experienced lower-than-average sediment inflows and lower excavation volumes (except for a removal of 212,717 m^3 after the 2006 flood). The cumulative excavation volumes (top graph) and cumulative bed volume changes (bottom graph) are shown in Figure 2.3. Excavated cumulative volume (bottom graph) through time increased from between 2000 to 2018 but then remained steady between 2018 and 2022 as no sediment was removed. The lower graph shows the bed changes between 2000 and 2010 did not show a systematic trend(natural deposition and excavation were approximately equal), then lowered consistently in all reaches between 2010 and 2020. Deposition from the November 2021 flood then re-set the bed to net aggradation of 150,000 m^3 relative to the year 2000.

In summary, during the 20 years before the 2021 flood, the Vedder River and Vedder Canal were experiencing a period of net bed lowering which was reversed by the 2021 flood.

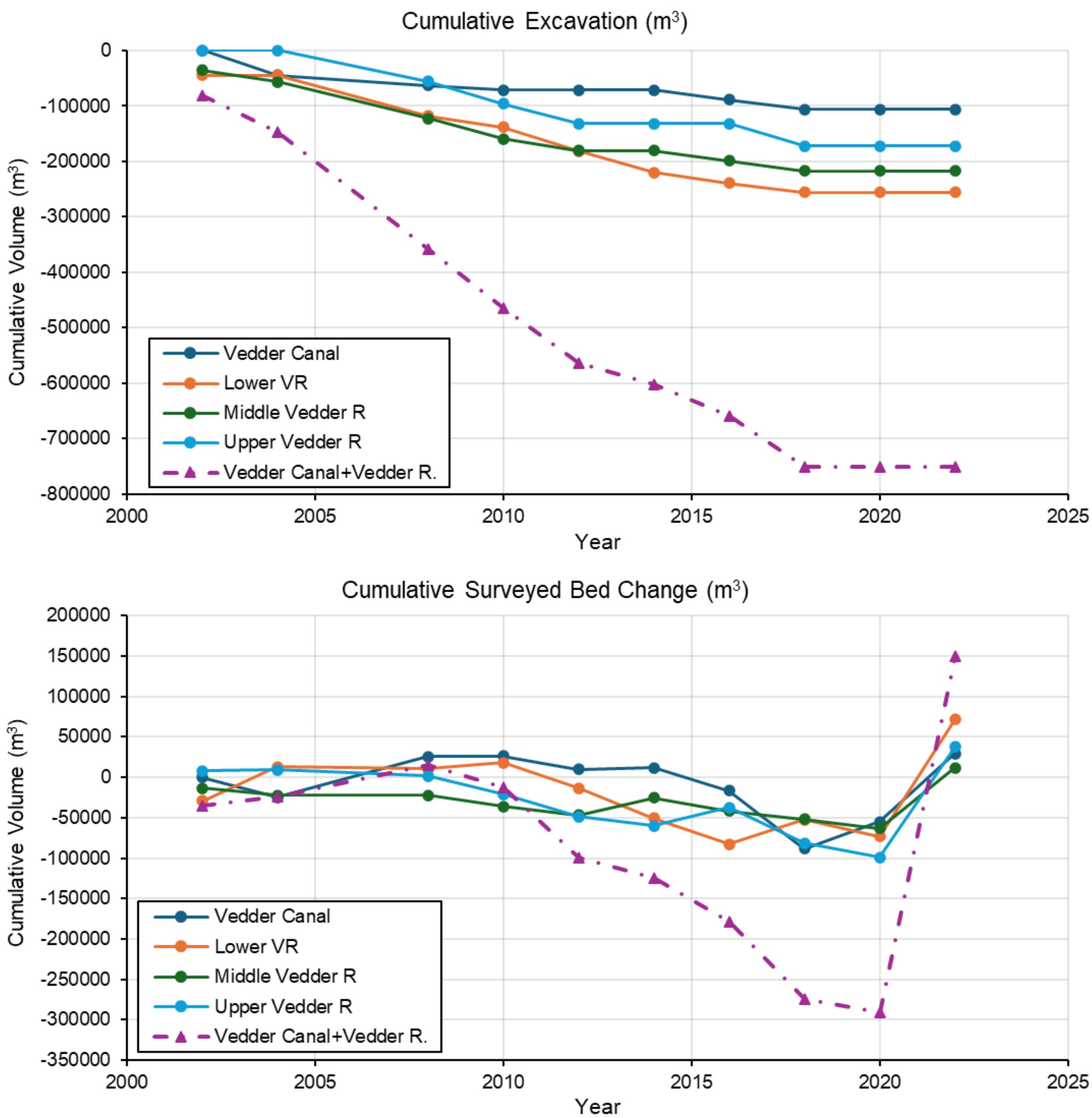


Figure 2.3 Top graph: cumulative gravel excavation volumes from 2000 to 2022. Bottom graph: cumulative bed change volumes surveyed between 2000 to 2022.

3 2024 GRAVEL REMOVAL PLAN

This section summarizes the main features of the proposed 2024 gravel removal plan, based on KWL (2024). Review comments on the plan are deferred to Section 4.

3.1 Work Carried Out Since 2021 Flood

The City of Chilliwack planned to remove 110,000 m^3 of material in 2022. However, during implementation, only 35,130 m^3 was removed from five sites. In addition, the right bank dike downstream of the SRBC railway bridge was raised by approximately 0.6 m in 2021-2022.

3.2 Proposed 2024 Gravel Removal Program (KWL, 2024)

KWL's report of 29 February 2024 provided new information on the 200-year flood profile and presented four sediment removal options for 2024. The updated hydraulic model indicated the available freeboard was substantially lower than previous post-2021 flood estimates reported in 2023 (KWL, 2023) and 2022 (KWL, 2022). Freeboard was reported to be less than 0.3 m on both banks of river along portions of the lower Vedder River and upstream of SRBC railway bridge in the channelized middle Vedder reach. Two locations were shown with freeboard < 0 m (illustrated below in Figure 3.1). The project's standard design freeboard is 0.75 m, indicating the freeboard deficiency is up to 0.5 to 0.75 m in these reaches. The report did not identify any significant flooding issues upstream of Lickman Road/Giesbrecht Road.

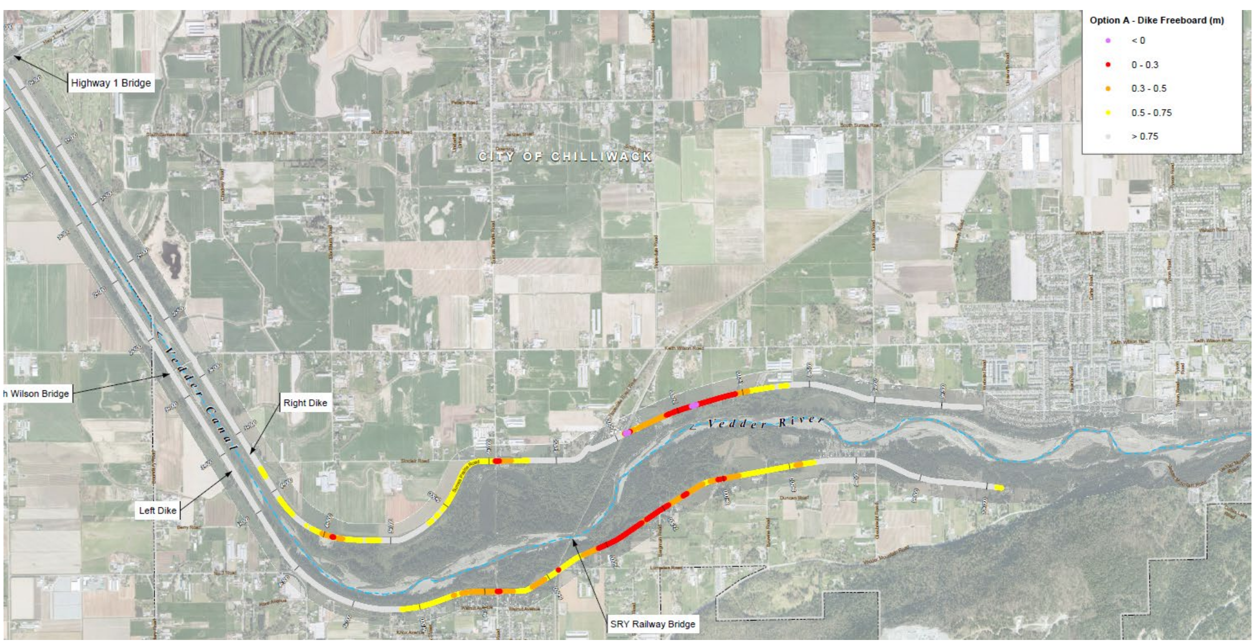


Figure 3.1 Freeboard deficiency 200-year flood condition (KWL 2024; Figure 7-3).

Sixteen potential sediment removal sites were identified and modelled. The study assessed four options, ranging from " do nothing" (Option A) to excavate 284,200 m^3 at 12 sites (Option C). The recommended option (Option D) involved excavating 243,500 m^3 from 11 sites (three on Vedder Canal, one on the lower Vedder River, four on the middle Vedder River and three on the upper Vedder River(Figure 3.2) . Individual excavation volumes ranged from 7,000 m^3 up to 34,500 m^3 at Peach Bar).

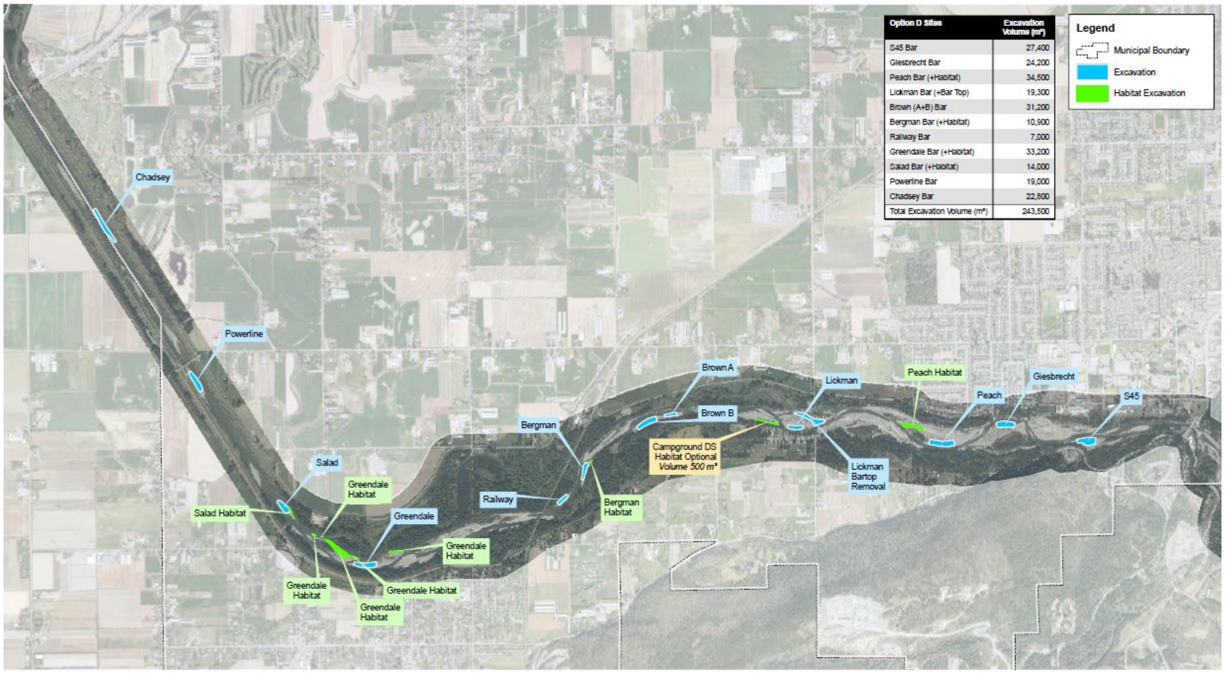


Figure 3.2 Location of gravel removal sites-Option D (KWL 2024; Figure 8-5).

The mean water surface reduction from Option D was 0.058 m (5.8 cm) over a length of 11,600 km. After implementation, the length of freeboard deficient dikes would reduce from 6,004 m to 5,144 m.

The freeboard after sediment removal is summarized in Figure 3.3. The KWL (2024) study did not assess how the morphology of the Vedder River is expected to change in response to the sediment removal options. It concluded that a notable response in channel morphology is not expected since the design and location of the sediment removal sites follow previously established guidelines.

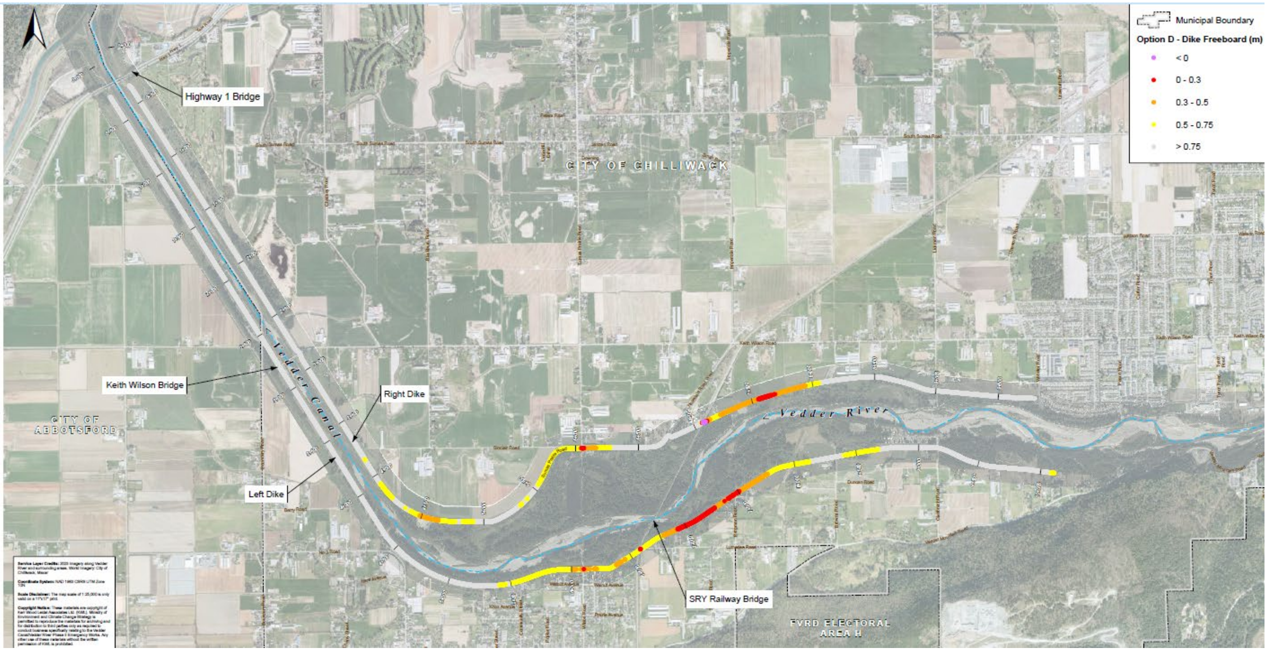


Figure 3.3 Freeboard after Option D (KWL (2024); Figure 8-10).

4 REVIEW OF 2024 SEDIMENT REMOVAL PLAN

4.1 Work Carried Out

NHC were not provided the updated hydraulic model and did not conduct independent computations to assess the effectiveness of the recommended sediment removal option. The opinions in this report are based on our interpretation of the reports provided to NHC and our past experience with sediment management and flood management in western Canada, Alaska, and Washington State.

4.2 Flood Profile Assessment

A 1D HEC-RAS hydraulic model has been used on the Vedder River for general flood modelling and floodplain mapping projects since the early 1980s by Provincial agencies and other engineering consultants. Limitations of the 1D model are described in KWL (2024, Section 6.8) and are not repeated here.

Since the early 2000s, the two-dimensional hydrodynamic version (HEC-RAS 2D) has increasingly supplanted the 1D model for many hydraulic modelling applications in BC. For example, a 2D hydraulic model was used in 2019 for developing updated floodplain maps on the Vedder/Fraser River for the City of Chilliwack (NHC, 2019) and for many different investigations on the lower Fraser River (flood profile assessment, sediment removal assessment, river engineering design and floodplain mapping).

One of the most compelling reasons that 2D models have been widely adopted in river flood modelling is that 1D models have difficulty representing complex overbank flow on floodplains and properly representing the flow distribution in the channel and floodplain when inner dikes or levees are overtopped. This is the situation that occurs along the middle reach of the Vedder River upstream of the railway bridge. In addition to its robust hydraulic characterization of flow, 2D modelling provides a tool for assessing hydraulic habitats for fish and providing context in assessing sediment transport and influences on geomorphic change.

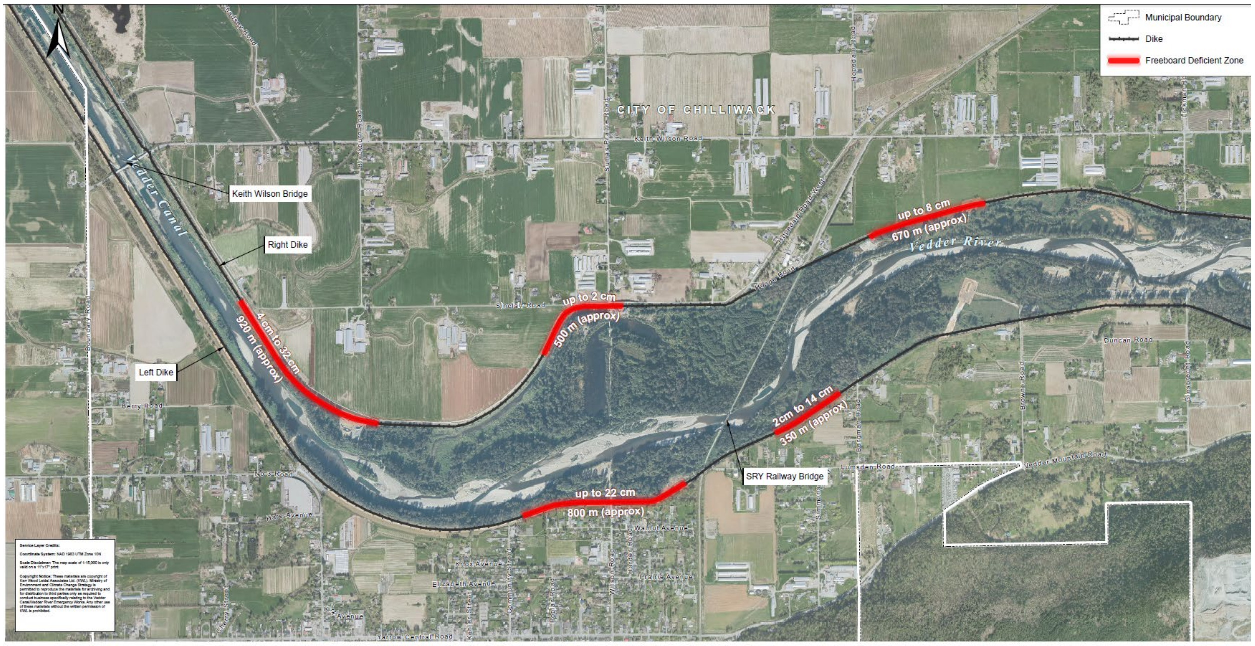
KWL (2024) identified some of the benefits of using a 2D model and recommended a 2D model be used for subsequent studies on the Vedder River, and NHC recommends that 2D modelling be used exclusively to better characterize the river and floodplain hydraulics. In our opinion, a 1D hydraulic model has limited value in assessing the effects of localized gravel removals on water levels or velocity changes, and evaluating morphologic response or impacts to fish and fish habitat.

The updated model was based on 2022 bed topography with additional topography derived from 2023 Lidar surveys made during low water (KWL, 2024). A Digital Elevation Model (DEM) was then developed to represent the terrain. The model was calibrated using a water surface profile surveyed water level on 1 December 2021 at discharges ranging between 300 to 400 m^3/s. A review of previous flood profile update studies including previous hydraulic update reports from KWL (2022) through to Hay and Company Consultants (2010) shows this was the first re-calibration of the model since 2010, when the model was calibrated with highwater marks surveyed during the 2006 flood. Other improvements to the 2024 model were made by adding blockages, ineffective flow areas and accounting for skewness of the railway bridge.

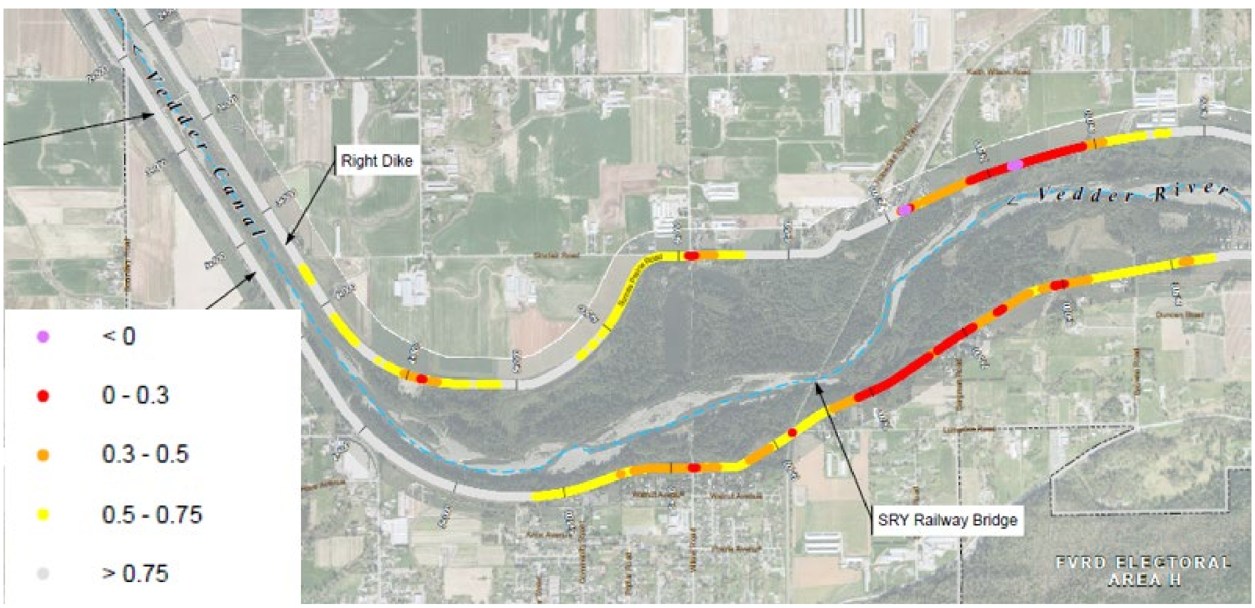
The updated flood profile in KWL (2024) produced substantially higher water levels along the Vedder River in comparison to flood levels reported in KWL (2022) and KWL (2023). The differences are illustrated by comparing the KWL (2023) (top) and KWL (2024) (bottom) freeboard deficient areas in Figure 4.1[2]. KWL (2023) reported that the minimum freeboard was between 0.50 m and 0.67 m along the right dike and between 0.43 m and 0.57 m along the left dike. The freeboard deficiency varied from 0.08 m to 0.25 m along the right dike and 0.18 m to 0.32 m along the left dike. It was also stated that the freeboard prior to the 2021 flood was greater than 0.70 m at all sections.

The updated 2024 flood profile in KWL (2024) shows long sections of the dikes on both sides where the freeboard is less than 0.3 m and two locations on the right bank with freeboard less than 0 m (shaded purple). Although the most serious deficiencies occur upstream of the SRBC railway bridge, there are four locations downstream with freeboard less than 0.3 m.

[2] Note that the values shown on the top map from KWL (2023) are freeboard deficiencies while the legend on the bottom map shows absolute freeboard values.



Top: Baseline freeboard deficiency locations from KWL (2023-Figure 6-3). Red lines indicate locations where the freeboard is less than 0.75.



Bottom: Baseline freeboard locations from KWL (2024-Figure 7-3)

Figure 4.1 Comparison of baseline freeboard conditions from 2023 to 2024 flood profiles.

Figure 4.2 compares the computed flood levels from 2020, 2022 and 2024 to illustrate the sensitivity of the water levels to differences in bed topography (2022 and 2020) and model calibration (2024 and 2022). The flood profiles rise nearly 2 m through the SRBC railway bridge due to the severe constriction and backwater from the bridge. The comparison shows that the reported reduction in freeboard along the dikes is due to changes (i) sediment deposition from the 2021 flood as well as (ii) changes due to the revised hydraulic model.

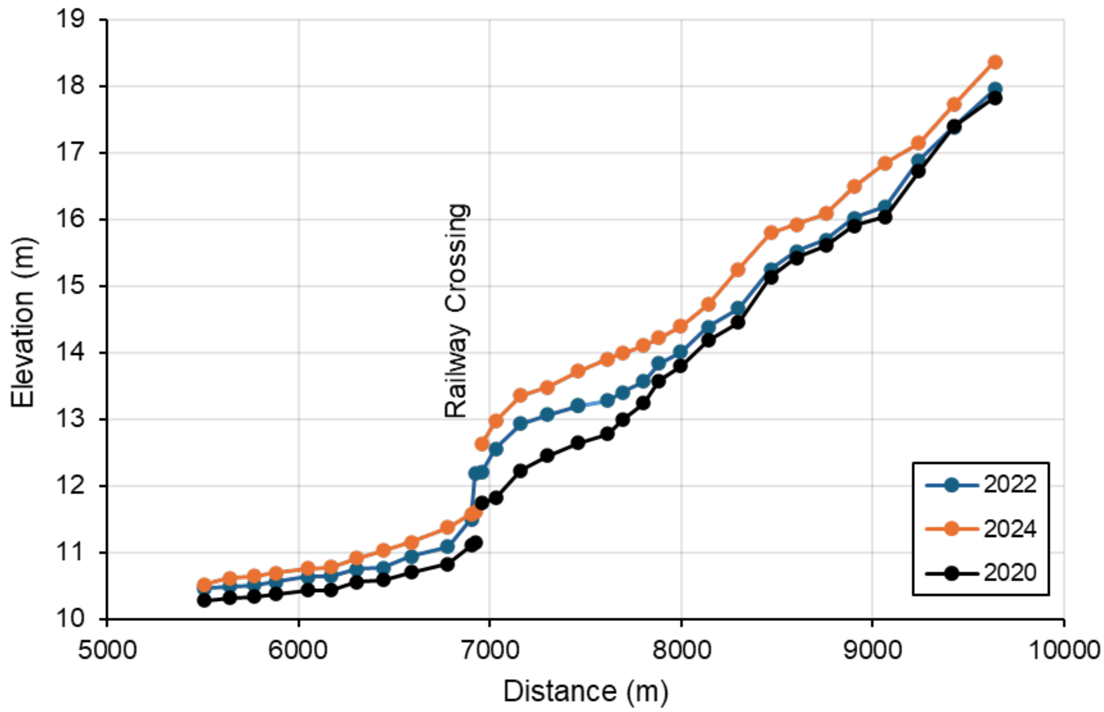


Figure 4.2 Water surface profiles near railway bridge from three hydraulic model runs showing the effect of sediment deposition from the 2021 flood event (2022 versus 2020) and the effect of model calibration (2024 and 2022). All results from KWL (2020), KWL (2022) and KWL (2024).

Figure 4.2 shows that water levels are sensitive to the local constriction at the bridge. At present, all models assume 200 m^3/s of flow leaves the main channel on the right bank upstream of the bride and passes through the relief channel and culvert at the railway embankment. They also assume 150 m^3/s of flow leaves the main channel on the left bank and flows through the trestle at the rail embankment. These assumptions are based on an analysis from Bland (2008). Actual flow splits could be very different, particularly if debris and log jams occur (as in the November 1990 flood). Given these uncertainties, it is not unreasonable to assume that the predicted flood levels could be within ± 0.5 m of actual levels during a design flood event in this reach. This alone justifies the need for attempting to maintain at least 0.75 m of freeboard at all times.

4.3 Effect of Sediment Removals on Flood Profile

Figure 3.2 shows the location of the 11 sediment removal sites in KWL's (2024) recommended Option D. Figure 4.3 compares the removals with the 2021 deposition volumes. The three sites in the upper reach (S45, Giesbrecht, Peach) total 86,100 m^3 and make up 35% of the total excavated volume. All of these sites are located upstream of the freeboard deficit reach. We assume these excavations will function as sediment traps to reduce the rate of infilling in the middle and lower reaches, but it is difficult to assess how efficient the traps will be without additional analysis and monitoring. The remaining excavations should increase the flow conveyance in the freeboard deficit reach to varying degrees until they re-fill with sediment.

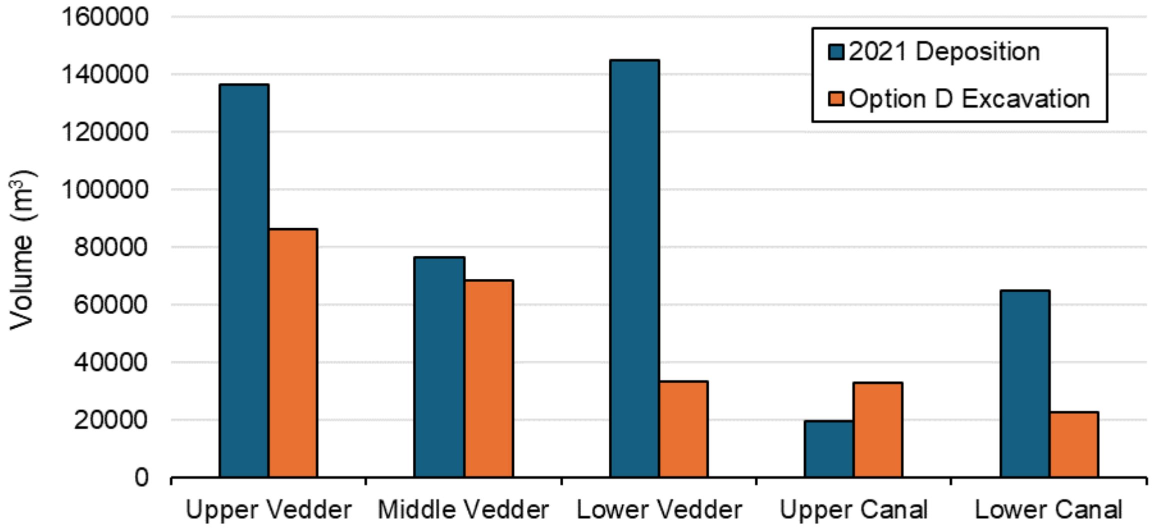


Figure 4.3 Comparison of 2021 sediment deposition and Option D removals by reach.

The usefulness and accuracy of the 1D model for assessing the water level reduction from a series of relatively localized, excavated pits has not been evaluated and would require comparing the results with other types of models that can simulate two dimensional (such as HEC-RAS 2D) or three dimensional flow processes (Delft-3D, Telemac-3D). In general terms, the limitations from 1D models include:

- Friction losses and water levels are averaged between discrete cross sections. It is difficult to simulate the impacts on water level from a relatively short, localized excavation with a limited number of cross sections, particularly when the underwater bathymetry has been interpolated.
- Flow paths must be prescribed ahead of time and do not account for the local effects of the excavation. An excavation may alter flow paths and divert flow into it, eventually resulting in other morphological effects.
- The model assumes the bed is fixed and cannot represent sediment deposition, scour, or bank erosion. The computed water level reductions represent a “snapshot” in time before the excavations begin to refill with sediment. This problem is inherent in all “fixed bed” models.

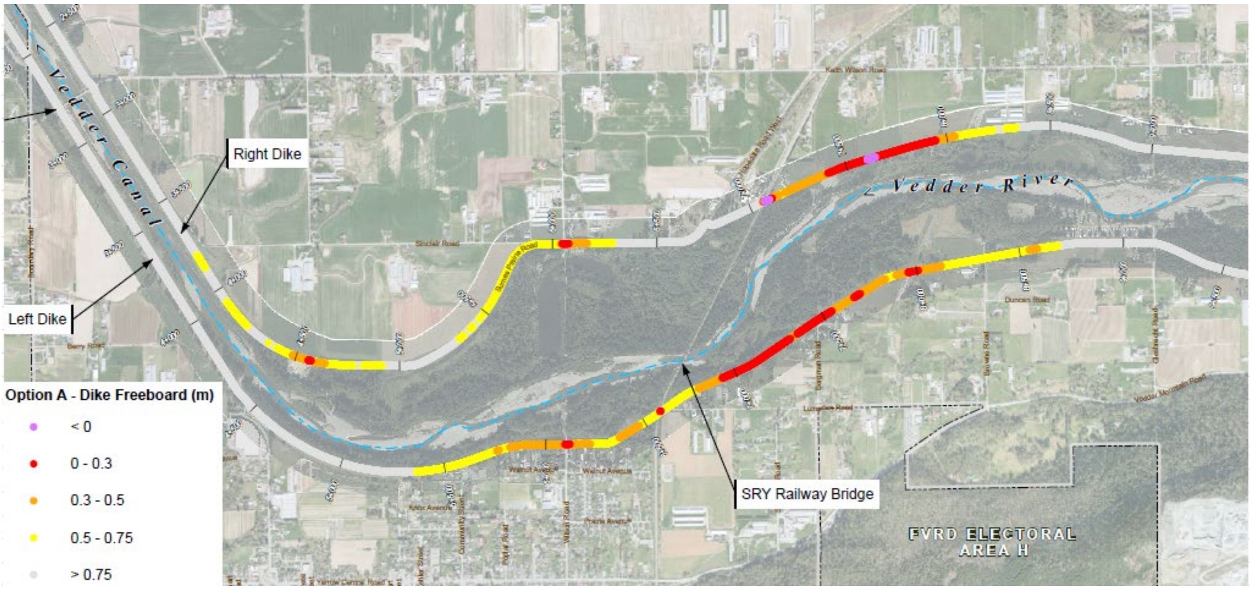
Now that detailed bathymetric data is available which allow generation of a 2D DEM, a 2D model would be a much better choice for attempting to estimate the hydraulic effectiveness of localized bar excavations.

The computed water level reductions from the 11 individual excavation sites in Option D ranged from 0.015 m at Chadsey Bar in the Vedder Canal to 0.215 m at bar S45 near Vedder Crossing. The excavations were selected on the basis of their “effectiveness”, a parameter that compares the magnitude of the reduction and the length of reduction to the volume of excavation. This approach justifies including a number of excavations that produce very small water level reduction benefits (some less than 0.03 m).

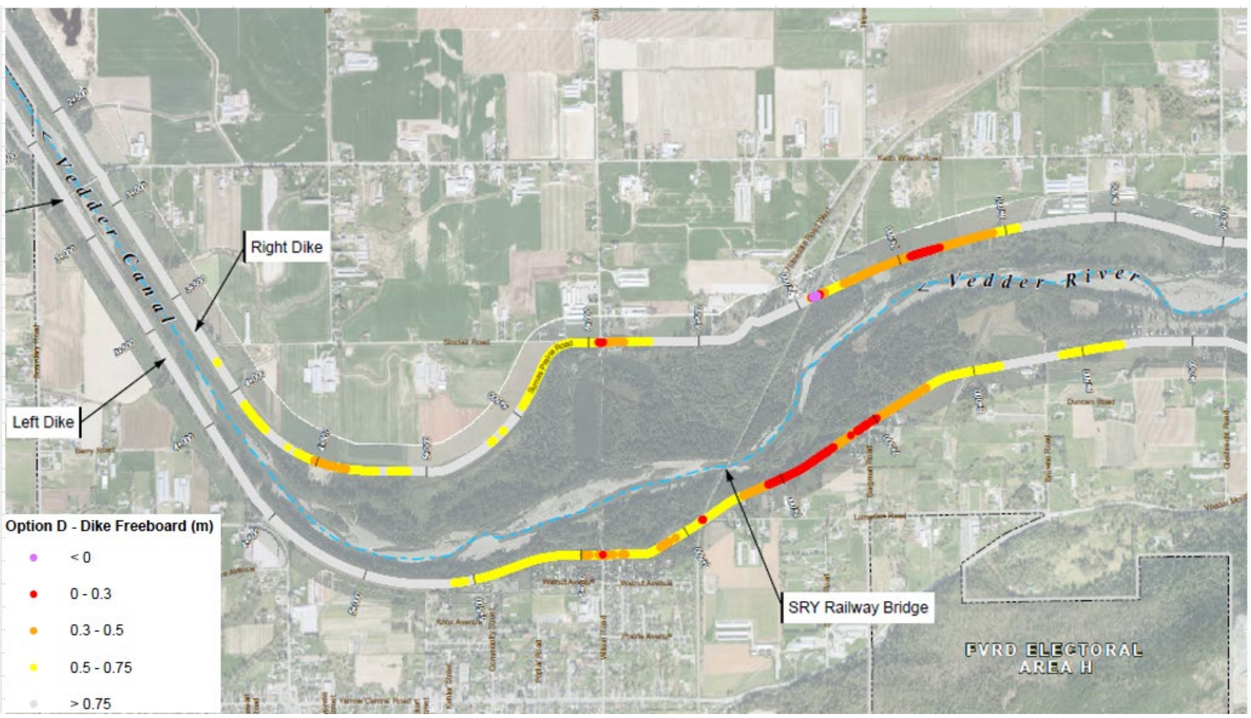
In our opinion, the real effectiveness of a removal site is measured by its reduction compared to the freeboard deficiency in the reach affected by the excavation. Ultimately, the actual benefit of excavating Chadsey bar in the Vedder Canal (average reduction of 0.015 m) is negligible, when the freeboard deficiency in the lower Vedder River is in the range of 0.6 m. Given the overall uncertainty in the flood level predictions (both for the baseline conditions and the localized effect of the removal), this magnitude of lowering is not a significant improvement. The low gradient and relatively short length of the excavations ultimately limit the potential water level reduction of excavations in the canal. The effectiveness of the excavations generally increases upstream of the canal.

The average combined water surface reduction from Option D was reported to be 0.058 m (5.8 cm) over a length of 11.6 km. The minimum freeboard increased to 0.19 m at station 7+161 on the left bank just upstream from the railway bridge, and 0.32 m at station 8+296 on the right bank. The location of the greatest water level lowering was located close to the sections with the lowest existing freeboard. It was reported the length of the freeboard deficient dike was reduced from 6,004 m to 5,144 m.

Figure 4.4 compares the freeboard conditions along the dike without any sediment removal (top) and after 248,500 m^3 of sediment is removed (bottom). Although there is an incremental improvement to the freeboard, other additional measures are still necessary to improve the security against overtopping or breaching. The feasibility of installing temporary flood protection measures (Hesco flood barriers or "Super Sacks") should be assessed as interim measures while other longer-term solutions are implemented. If additional structural measures (dike raising, floodway improvement) are not carried out then presumably another large removal will be required in 2026.



Top: Freeboard with Option A (no sediment removal)



Bottom: Freeboard after Option D (243,500 m3 sediment removal from 11 sites)

Figure 4.4 Comparison of recommended project (Option D) with no excavation (Option A).

5 MORPHOLOGICAL RESPONSE TO GRAVEL REMOVALS

The morphological effects from the planned sediment removals were not directly assessed in KWL (2024). This type of assessment is important because a “fixed bed” one-dimensional hydraulic analysis alone cannot adequately describe or assess how the planned excavations will function after they are constructed. For example, the excavations will induce morphological changes to the river cross section that will modify the channel’s hydraulic characteristics (potentially improving overall conveyance in comparison to the fixed-bed model predictions). Alternately, if excavations in the lower river and canal fill-in rapidly after construction their effectiveness in lowering water levels may be reduced during a flood event. Also, any impacts to fish and fish habitat will depend on how the morphology of the bars and channels respond to the excavations. This section provides a brief overview of the physical processes involved and the potential morphological effects that can occur.

Studies to predict the effects of sediment excavations on river morphology have been carried out for several decades (de Vries, 1985). The main sediment transport processes in an idealized excavation are illustrated qualitatively in Figure 5.1. In this case, the incoming sediment is trapped in the deepened channel, reducing the supply to the channel downstream. This results in a downstream progressing wave of bed lowering or degradation. The excavation will gradually fill-in from upstream to downstream, restoring the sediment balance downstream. At the upstream end, the process is different. The deeper flow in the excavation creates lower velocities, which flattens the water surface slope through it, resulting in a local steepening of the water surface upstream. This “draw-down” effect will induce upstream progressing degradation (head cutting).

The magnitude of degradation depends on the water level lowering at the upstream end of the excavation and on the coarseness of the riverbed material. If the magnitude of water level lowering is small and the riverbed is coarse, degradation is likely to be small. On gravel bed rivers with complex planforms a range of other potential impacts have been documented by (Rempel, 2004) and Church et al. (2001). One impact that is particularly relevant to the Vedder River, is the observation that gravel removal from the river channel may accelerate erosion and sediment transport locally in the short term.

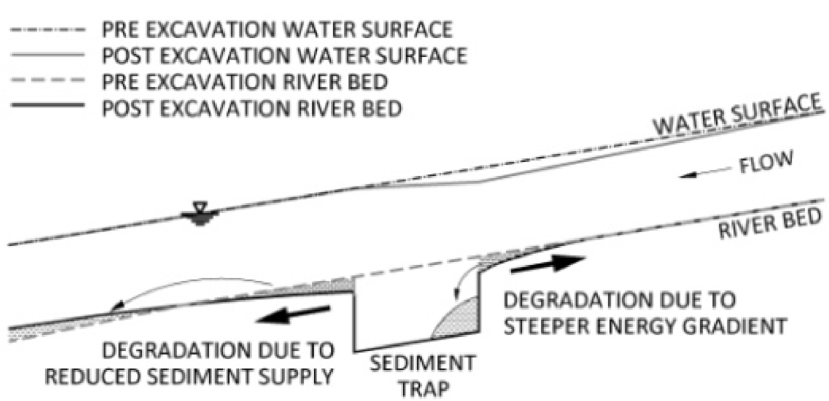


Figure 5.1 Effect of sediment removals on stream profiles (from McLean et al. (2013)).

NHC undertook a high-level desktop review of how bars responded to the 2016 sediment removals using information from Nova Pacific Environmental Ltd. (2016) and satellite imagery from Google Earth (Appendix A). NHC examined imagery from two to three years following the removal to qualitatively assess changes to the bar where sediment was removed. Between 2016 and 2019 there were no large channel-altering floods (the maximum instantaneous discharge was 433 m^3/s on 23 November 2017) which allowed for an examination of how the bars respond under low flows. Such an assessment using aerial imagery is not possible following a flood like the November 2021 event because the channel undergoes such substantial rearrangement.

The bar-scale morphological response varied at the 2016 sediment removal sites, but in all the cases the impact of the excavation area was visible in the latter half of the 2017 freshet (July 2017) (Appendix A). The 2016 removal at Giesbrecht bar appears to be responsible for some substantial morphological change. An avulsion occurred between August 2016 and July 2018, as the main channel shifted its position and occupied the area of sediment removal (Figure 5.2).

At Yarrow Bar, the pit left behind from the 2016 removal left a wetted area on the bar that was still present in August 2019, suggesting that infill in this location was limited (Appendix A, Figure A5). Other locations, such as Railway Bar (Appendix A, Figure A4), appear to return to a similar morphology as the pre-2016 removal through infilling after a couple of years. However, the pit of the removal remained exposed through the winter and 2017 freshet, so normal sediment transport processes were affected for at least one year.

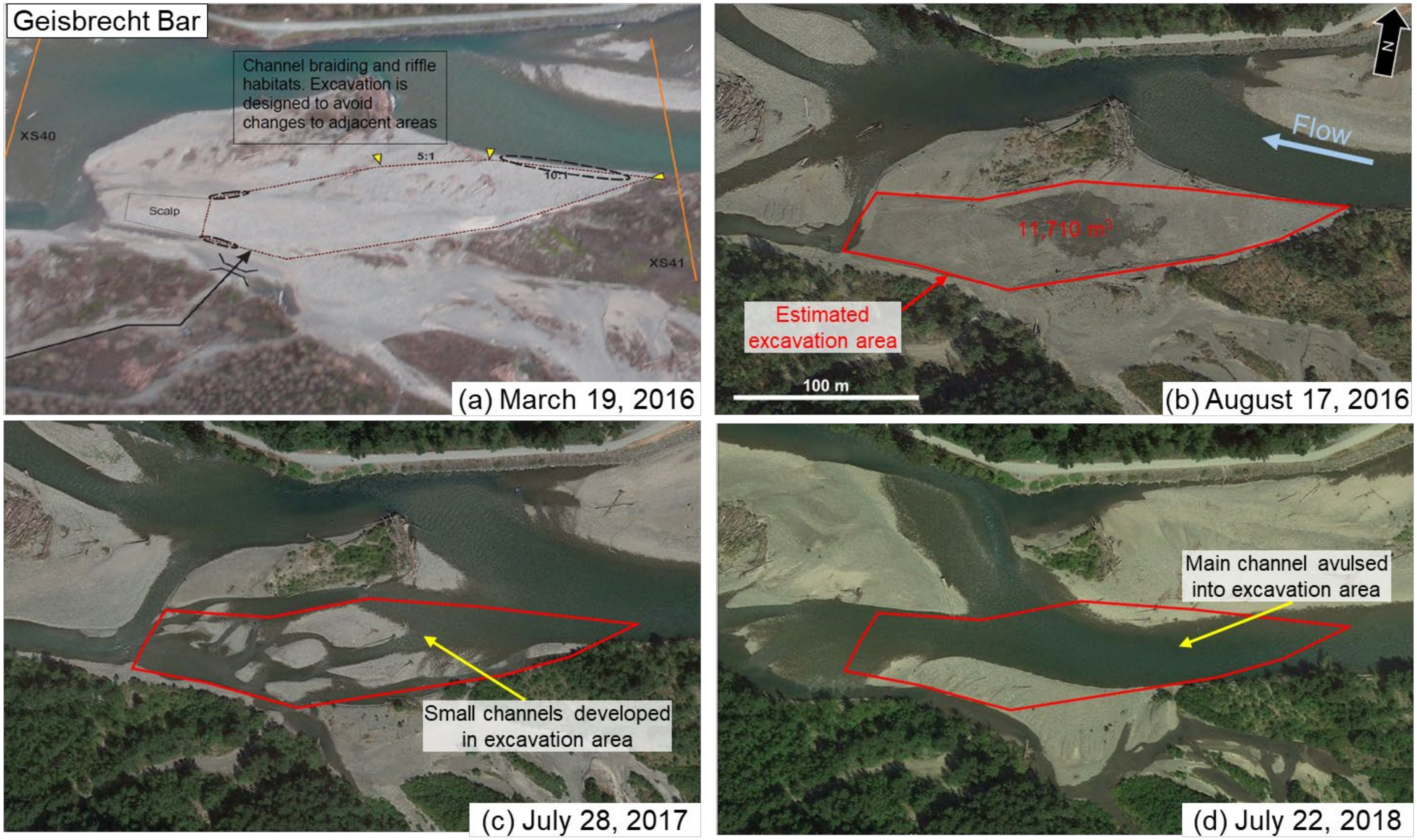


Figure 5.2 Giesbrecht Bar on (a) March 19, 2016, (b) August 17, 2016, (c) July 28, 2017, and (d) July 22, 2018. Aerial imagery in (a) is from Nova Pacific (2016) while satellite images in (b) to (d) are from Google Earth. Sediment removal here occurred between August 10 and August 17, 2016. The extent of the removal can be seen in panel (b).

These images illustrate how the bars and channel have responded to excavations during a period of low floods and low sediment inflows. During larger floods the channel changes will occur more rapidly with increased sediment transport. If the excavations fill relatively quickly, their effect on the flood profile will be less than the “fixed bed” hydraulic models indicate.

In the event Option D is implemented in the summer of 2024 then NHC recommends systematic, multi-year monitoring be carried out using available imagery and drone coverage to assess the morphologic response from the excavations. This should be combined with geomorphic field studies and local topographic surveys to document how bed elevations and morphology change at a reach scale and how bars downstream or upstream of the removal sites are impacted. Bed material samples should be collected at each excavation site during the first one or two years of infilling to document the sizes of sediments that are re-filling the excavations. In our opinion, systematic morphological monitoring of effects of the gravel removals has not been undertaken to the detail required to is forecast possible changes to the channel bed, sections and overall planform on a local and reach-wide basis. A geomorphic-focused assessment would provide a much stronger basis for determining:

- the relative depth and extent of gravel removals to limit large-scale changes.
- developing geomorphic analogs that yield hydraulic benefits while limiting possible residual effects, and
- possible short and long-term changes to the river channel that affect fish and fish habitat.

6 MITIGATION AND OFFSETTING OF EFFECTS ON FISH AND FISH HABITAT

Project documentation specific to the assessment, mitigation and offsetting of impacts to fish and fish habitat were reviewed by NHC professionals familiar with similar works, regulatory processes, and approvals. The primary reporting reviewed includes NPE (2024a) and NPE (2024b).

The first document summarizes the construction-related environmental practices and procedures to be implemented with the work, generally procedural and mitigative in nature and common to most large-scale instream construction works. The second document provides site-project context, description of works and site-specific details. This document also outlines potential effects to fish and fish habitat, mitigation, residual effects and habitat offsetting.

In the second document, NHCs review comments are limited to the proposed rationale used to assess and define residual effects, and implications in terms of the habitat offsets suggested. Review of the suggested effectiveness monitoring, and suggestions for additional approaches to be considered in future monitoring are also provided.

6.1 Project Mitigation

Project mitigation is described in NPE (2024a), which includes site descriptions, activities, personnel and a general construction environmental management plan for the proposed work. The plan is generalized for application at all proposed sites with further mitigation identified in NPE (2024b). General comments include:

- Site-specific criteria related to environmental monitoring needs to be defined. For example, rainfall criteria referenced should include gauge location, data source and availability (Section 5.5).
- *Fisheries Act* reference sections should be updated to the current legislation. Fish habitat offsetting related to placement of LWD should be detailed in other documentation (Section 5.6).
- Site-specific water quality monitoring should include sampling methodology, sediment regressions (e.g. NTU to TSS) and description of relative location to excavations. No exceptions in data recording and compliance related to pit opening should be allowed in NTU/TSS reporting (Section 5.10).
- Downstream SEV (Severity-of-Ill Effects) monitoring for the duration of the project should be included to assess cumulative effects of fish and fish habitat. See Courtice *et al.* (2022), Newcombe and Jensen (1996). SEV modelling should be included in the assessment of effects to determine possible limits of the proposed work.
- Casting of materials during pit opening should be removed, with excavation and hauling of materials and control of rate-of-work to limit sediment generation. Pit opening plan at each site and TSS record should be included in as-built documentation (Section 5.13).
- Draft incident reports are included, but incident reporting timeframes and criteria are not documented and agency contacts are not provided (Section 6.3). The final CEMP should include a flow chart of responsibilities, communications and actions related to project-specific incidents (Section 6.4).

6.2 Project Offsetting

The review of NPE (2024b) was limited to the sections relevant to assessment of effects on fish and fish habitat, mitigation and offsetting included in Sections 5 though 7. General comments include:

- Actions incorporated to avoid impact or effect to fish and fish habitat should be identified. This would include re-location of gravel extractions that have unmitigable impacts, impacts to SARA-listed species or impact critical habitat. Alternatively, gravel removals that are hydraulically ineffective and provide no reduction of the flood risk should be avoided.
- Potential effects of the gravel removals screened under Section 5.2 do not reference the most recent DFO pathway-of-effects document. A more project-specific POE framework is provided here[3], which identifies activities not considered in the NPE review of effects on fish and fish habitat. The review should consider POE guidance in Brownscombe and Smokorowski (2021) in the development of a tabular reference to cross-reference mitigation outlined in the report with the effect identified.

[3] https://www.dfo-mpo.gc.ca/pnw-ppe/pathways-sequences/dredging-dragage-eng.html , accessed March 20, 2024.

- Pre-project site surveys should incorporate a geodetically-referenced control survey and site survey conducted with RTK survey and RTK UAV techniques at an appropriate scale (Section 5.3.1).
- Compliance monitoring should follow parameters, characteristics and criteria developed in the effects assessment and POE analysis. Importantly, the monitoring should separate those elements related to the construction EMP (NPE, 2024b) from those related to effects monitoring. Following this rationale, items in Section 5.3 should be restructured.
- Site-specific plans identified in Section 5.5 do not include estimates of quantities (area) and types (mesohabitat) of fish habitat affected by the work, and a habitat balance sheet has not been developed for the site or the project in total. The proposed site-specific mitigation and offsetting do not follow the DFO policy framework[4] and information requirements (pg. 24).
- Assessment and quantification of fish habitat and the subsequent rating and anticipated outcome are not supported by metrics, data or information common to those used in the assessment of fish habitat. If so, then references should be made to those methodologies, data and standard methods (e.g. Ward and Slaney, 1996). The proposed anticipated outcomes identified in the site-specific assessment are not quantitative and are subjective.
- The commentary provided in the site assessments with respect to infilling are subject to change and do not accurately reflect the recovery trajectory of the bar complexes or refilling of the excavations. Information provided in Appendix A illustrates that several gravels removals have effects on the river channel and habitat over several years:

Removal Site	Outcome from Previous Removal (Date)	Anticipated Outcome (2024)
Giesbrecht Bar	Channel avulsion (2016)	“pit will refill quickly”, pg 34
Lickman Bar	Channel avulsion (2016)	“The deep pit excavation is expected to refill without significantly changing the habitat configuration in the vicinity”, pg 40
Bergman bar	Multi-year refill (2016)	“The pit is expected to refill with sediment”, pg 45
Railway Bar	Multi-year refill (2016)	“refill to a similar configuration within one to two years after the excavation”, pg 48
Yarrow Bar	Multi-year refill (2016)	Not proposed
Railway Bar	Multi-year refill (2016)	Not proposed

[4] Policy for Applying Measures to Offset Adverse Effects on Fish and Fish Habitat Under the *Fisheries Act*, Published by: Fish and Fish Habitat Protection Program, Fisheries and Oceans Canada, 2019.

- Table 4 in Section 6 outlines the application of the DFO policy on the project work. It does not include critical elements like changes to the channel morphology and relies on application of the guidelines and monitoring (e.g. internal CEMP guidelines) as mitigation. The POE analysis with respect to impacts to river behaviour and influence on existing habitats is poorly described as outlined in Section 5 of this report.
- The offsetting plan in Section 7 correctly identifies "shallow rearing habitat" as a key residual effect (Section 7.1), and Table 5 outlines the habitat losses. The offsetting ratio suggested (0.1) is not supported by typical industry-standard modelling and assessment procedures and is considered subjective.
- The loss and alteration of potential fish habitat at each site are not quantified and depend on flow. In NHC's opinion, 2D hydraulic modelling and a weighted-usable area (WUA) fish habitat analysis is likely required to provide quantifiable results in terms of habitat changes and offsetting requirements.
- Calculation of offset amounts (Section 7.1) does not account for the documented uncertainty and temporal lag in the impacts to fish habitat. Typical offsetting rations for instream habitat in similar project types are 2:1 such that 19,230 m^2 of offsetting would be required.
- Section 7.3 and Table 6 summarizes the proposed project offsetting. The proposed offsetting relies on rewatering a large area of excavate works as a means to achieve the required offset areas. These offsets are not like-for-like in terms of replacing shallow rearing habitat identified in Section 7.1.
- The plans provided in Section 7.3.2 and Section 7.5 are conceptual (10% design) and would not likely provide the reliability and certainty required for an offsetting plan accepted as part of a project *FAA*. Further detail in terms of engineered drawings, hydraulic analysis and assessment of habitat types and quantities are required to document the offset design and effectiveness.

6.3 Effectiveness Monitoring

Comments on effectiveness monitoring (Section. 7.6) and general monitoring of the Vedder River related to gravel removal has been included together. NHC's opinion is that biological and physical data collection and monitoring is a key element to better assess the efficacy and effects of current and future gravel removals on the Vedder River and Vedder Canal. Specific comments are as follows:

- Past NPE reporting and assessment frameworks should be reviewed in the context of requirements related to the current *FAA* and DFO FFHP Branch policy. Past information provided to date does not indicate a consistent effectiveness monitoring framework and data collection process has been developed. For example, assessment information documenting habitat values at these sites since 1994 is not referenced or provided.
- The issue of the duration of project effects versus offset service life is questioned. The long term effects of gravel removals are not well documented or studied. A more structured approach in terms of monitoring the removals and documenting the duration of impacts to fish habitat is required to better assess offsetting requirements.

- The NPE document does not consider the cumulative effects of construction effects (e.g. SEV modelling), short-term habitat alterations and long term morphological effects are not assessed in the NPE document.
- It is outside the professional expertise of the NHC reviewers, but additional biological monitoring would be important to understand the fisheries values of existing and modified fish habitats. We suggest that the monitors in Table 6 be refined and expanded to include more comprehensive work. For example, fish sampling that provides measure of relative abundance and assessment techniques that evaluate habitat area and suitability are valuable over a through time to support offset effectiveness monitoring and evaluation.
- Additional geomorphic monitoring is also recommended, as suggested in Section 5 of this report. This would include scaled UAV surveys of the gravel removal areas and adjacent river channels to document change over a longer assessment period than proposed. Other sediment and channel characteristics are suggested in Section 5.
- The duration of monitoring should follow the period in which impacts are observed and/or the duration of the offset effective evaluation. Biological and physical monitors could be developed according to biological criteria (e.g. Pink salmon abundance) or flow based criteria (e.g. flood return periods) for physical assessments.

7 CONCLUSIONS

The volume of sediment deposited from the November 2021 flood was exceptional, exceeding previous large sediment inflow events in 1975, 1989 and 1990 by over 50% and approximately 10 times larger than the long-term average rate.

The updated (2024) design flood profile shows the dike freeboard is deficient over a length of 6km, with freeboard reduced to less than 0.3 m over a substantial distance on both sides. The revised hydraulic model results show significantly higher water levels than results published in 2023, 2022 and 2020. The higher water levels reflect changes to the model calibration and other modifications to the model as well as from sediment deposition in the channel.

Sediment removal Option D involves excavating 243,500 m^3 of sediment from 11 sites along the river. This volume amounts to 55% of the total volume deposited in 2021. We expect this magnitude of excavation will result in some improvement to the freeboard situation in the short-term (1 year).

The 1D hydraulic model indicates Option D will reduce the length of the freeboard deficient zone from approximately 6 km to 5.1 km. Given the present risk of overtopping, this improvement is beneficial from a flood control/public safety concern. However, a substantial length of dike will remain freeboard deficient following the removal.

The excavation volume in Option D is approximately 2.5 times larger than typical removals (90,000 m^3) but is comparable to other large excavations in 1989 (186,600 m^3), 1990 (187,500 m^3), 1996 (217,000 m^3) and 2006 (212,717 m^3). We have insufficient information to assess how the river was impacted by those removals or how the removals improved the flood capacity of the river, and this was not addressed in the KWL (2024) report.

KWL (2024) recommended that other options such as dike raising, modification to the railway embankment relief structures also be evaluated but did not indicate a time frame for this work. We concur with this recommendation. The feasibility of installing temporary flood protection measures (Hesco flood barriers or "Super Sacks") should be assessed as interim measures while other longer-term solutions are implemented. Periodic sediment removals will continue to be an important component of flood management on the Vedder River. But sediment removals alone will be insufficient to maintain adequate freeboard after extreme flood events.

NPE (2024a and 2024b) provide environmental management and impact assessment information related to the project. In the terms of current assessment and offsetting requirements, NHC considers the physical information incomplete relative to other similar projects undertaken in BC. There has been an increase in both the amount, type and detail of information required for assessment of instream works that affect fish and fish habitat. Given the potential spatial and temporal scale of this project and possible impacts, additional due diligence is likely required for development of a comprehensive habitat effects assessment and complementation offsetting works.

In our opinion, the methodology, tools and procedures used for hydraulic engineering, river morphology and habitat assessment should be reviewed and updated for any future sediment removal program. Significant changes in data collection and tools to assess effects have been developed and are now considered industry standard methodologies. For example, large spatial data collection, 2D hydraulic modelling and hydraulic habitat analyses using UAV photogrammetry and habitat suitability analyses have become standard tools for computing river hydraulics, assessing complex river morphologies and for habitat modelling. There has been an increased focus on using quantitative geomorphic methods to assess and monitor the physical impacts of these projects and long-term biological monitoring and evaluation to ensure project offsets ae reliable and effective.

Changes to the assessment process, data and procedures will allow both the benefits and adverse impacts from the program to be evaluated more rigorously than in the past.

8 REFERENCES

Bergman, L. (1996). *Vedder River Gravel Management Plan*. BC Ministry of Environment.

Bland Engineering Ltd. (2008). *Vedder River Hydraulic Profile 2008 Update*. BC Ministry of Environment.

Bland Engineering Ltd., and NHC (2004). *Vedder River Hydraulic Profile Update*. For Ministry of Water, Land, and Air Protection; City of Abbotsford; City of Chilliwack.

Bonham, E. (1980). Resolving the Fish vs Flood Control Controversy on the Vedder River. *Canadian Water Resources Journal*, 5:2, 38–53.

Church, M., Ham, D., and Weatherly, H. (2001). *Gravel management in lower Fraser River*. Department of Geography, UBC, Vancouver, BC.

Courtice, G., Bauer, B., Cahill, C., Naser, G., Paul, A., (2022). *Suspended sediment releases in rivers: Toward establishing a safe sediment dose for construction projects*, Science of The Total Environment, Volume 848, 2022, 157685, ISSN 0048-9697,

Hay and Company Consultants (2010). *Vedder River Hydraulic Profile Update 2010*. City of Chilliwack.

KWL (2018). *Vedder River Hydraulic Profile Update 2018*. City of Chilliwack.

KWL (2020). *Vedder River Hydraulic Profile Update 2020*. City of Chilliwack.

KWL (2023). *2023 Hydraulic Assessment Report, Final Report, Proposed 2023 Vedder River Sediment Removal Project, May 5, 2023*. Ministry of Environment and Climate Change Strategy.

KWL (2024). *2024 Vedder River Hydraulic Assessment Final Report, Vedder Canal/Vedder River Phase II Emergency Works*. Ministry of Environment and Climate Change Strategy.

KWL Kerr Wood Leidal (2016). *Vedder River Hydraulic Profile Update 2016*. Report to City of Chilliwack. 62 pp.

KWL Kerr Wood Leidal (2022). *Vedder River Hydraulic Profile Update 2022*. Prepared for City of Chilliwack.

Newcombe, C.P., and J.O.T. Jensen. (1996). *Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact*. North American Fisheries Management 16: 693-727.

NHC (2019). *City of Chilliwack Floodplain Mapping Project 2018/2019*. Prepared by Northwest Hydraulic Consultants Ltd. for the City of Chilliwack.

Nova Pacific Environmental Ltd. (2024a). 2024 *Vedder River Sediment Removal Project, Environmental Management Plan V2*, February 29th 2024. 75 pp.

Nova Pacific Environmental Ltd. (2024b). *Proposed 2024 Vedder River Sediment Removal Project, Environmental Assessment Report*, February 29th 2024. 134 pp.

Nova Pacific Environmental Ltd. (2016). *Proposed 2016 Vedder River Sediment Removal Project*. Ministry of Forests, Lands and Natural Resource Operations. 46 pp.

Rempel, L. (2004). *Physical and Ecological Organization in a Large, Gravel-Bed River and Response to Disturbance*. University of British Columbia.

Brownscombe, J.W., Smokorowski, K.E. (2021). *Review of Pathways of Effects (PoE) diagrams in support of FFHPP risk assessment*. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/079. iv + 55 p.

Tetra Tech EBA (2014). *Vedder River Hydraulic Profile Update 2014*. City of Chilliwack, City of Abbotsford.

de Vries, M. (1985). *Engineering Potamology*. International Institute for Hydraulic and Environmental Engineering, Delft, Netherlands.

Table 1	Table caption

Table 2	Table caption

Table 3	Table caption

APPENDIX A

DESKTOP ASSESSMENT OF 2016 SEDIMENT REMOVALS

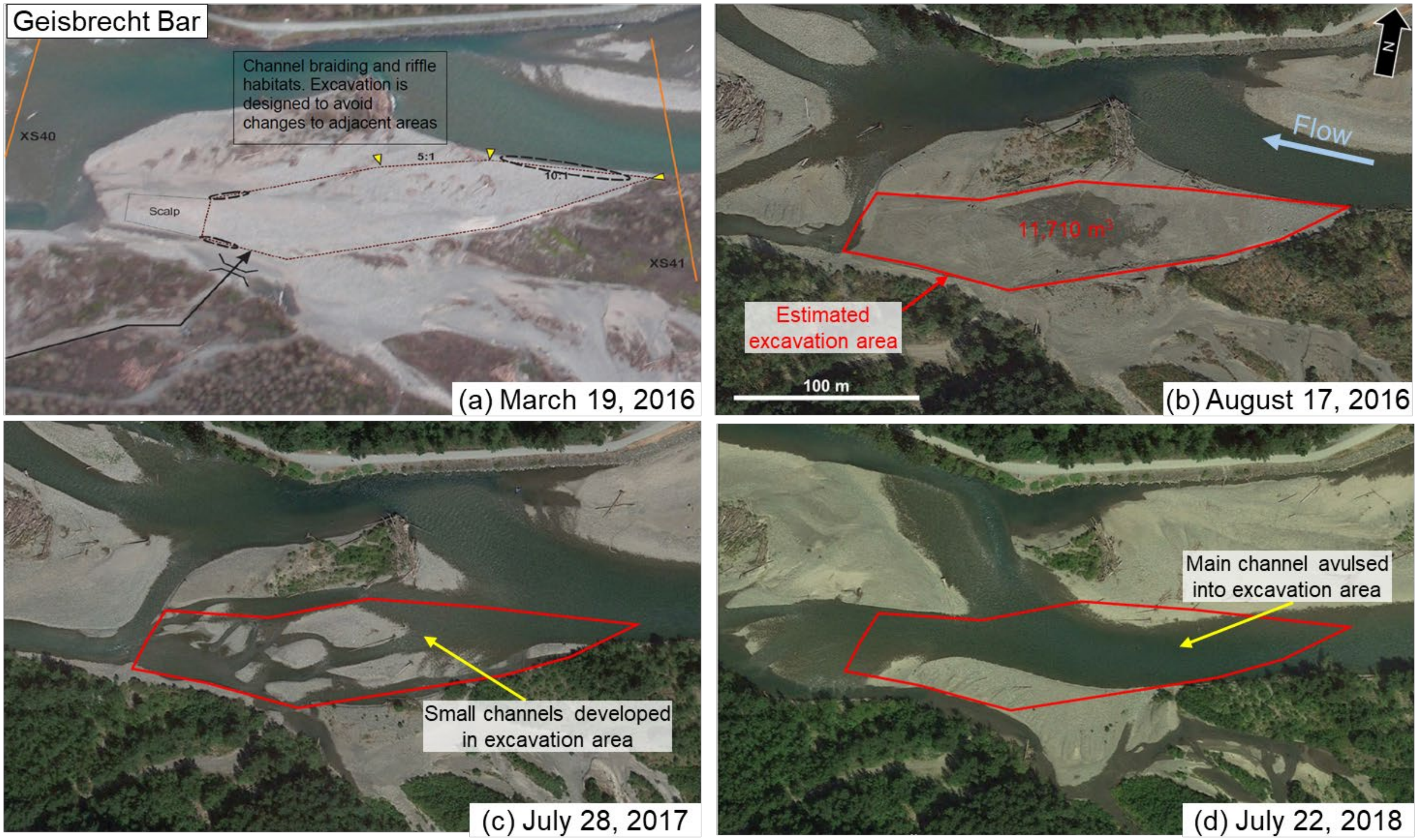


Figure A.1 **Giesbrecht Bar on (a) March 19, 2016, (b) August 17, 2016, (c) July 28, 2017, and (d) July 22, 2018. Aerial imagery in (a) is from Nova Pacific (2016) while satellite images in (b) to (d) are from Google Earth. Sediment removal here occurred between August 10 and August 17, 2016. The extent of the removal can be seen in panel (b).**

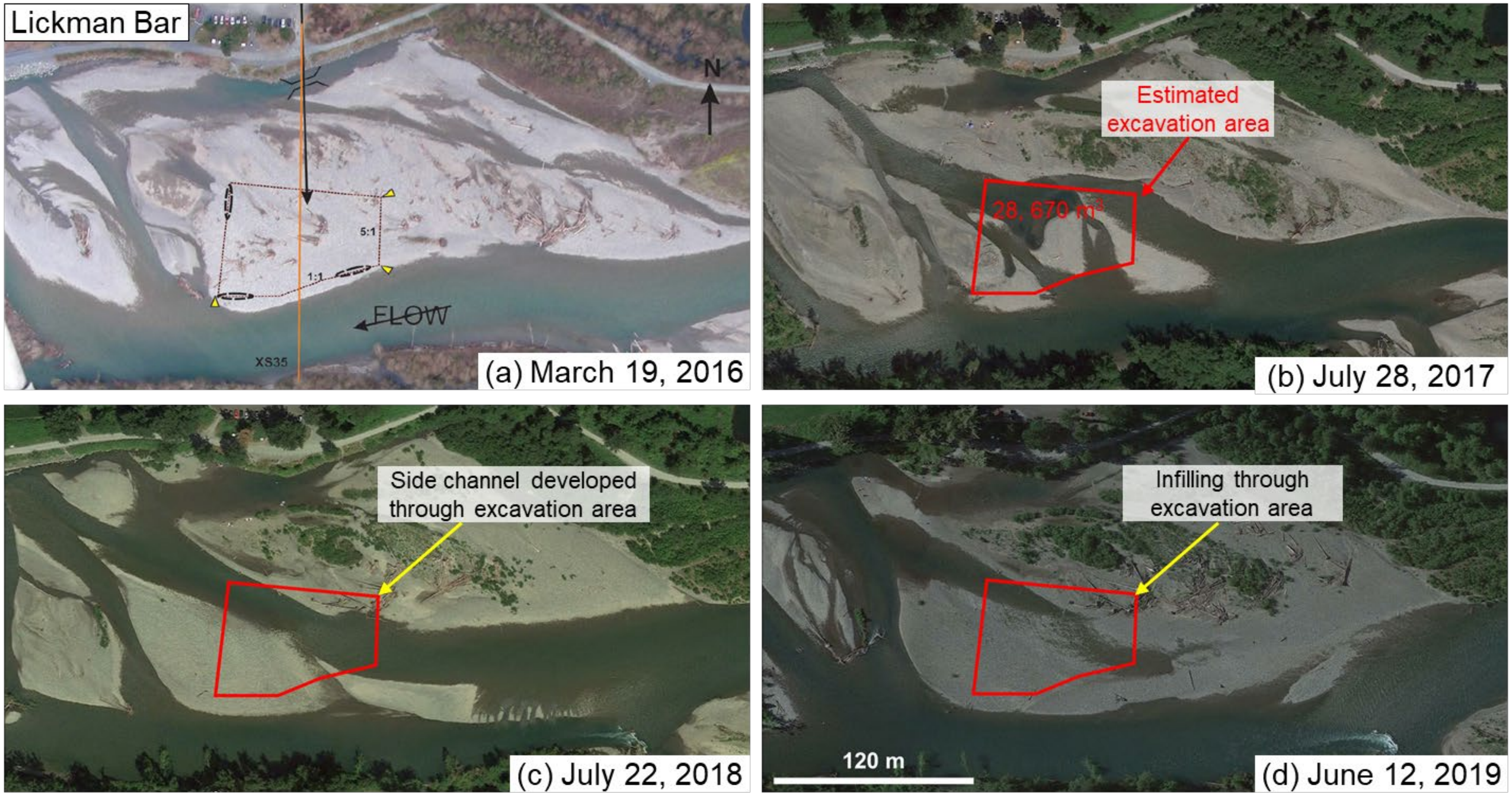


Figure A.2 Lickman Bar on (a) March 19, 2016, (b) July 28, 2017, (c) July 22, 2018, and (d) June 12, 2019. Aerial imagery in (a) is from Nova Pacific (2016) while satellite images in (b) to (d) are from Google Earth. Sediment removal here occurred between September 9 and September 27, 2016. There is no imagery available directly following the removal

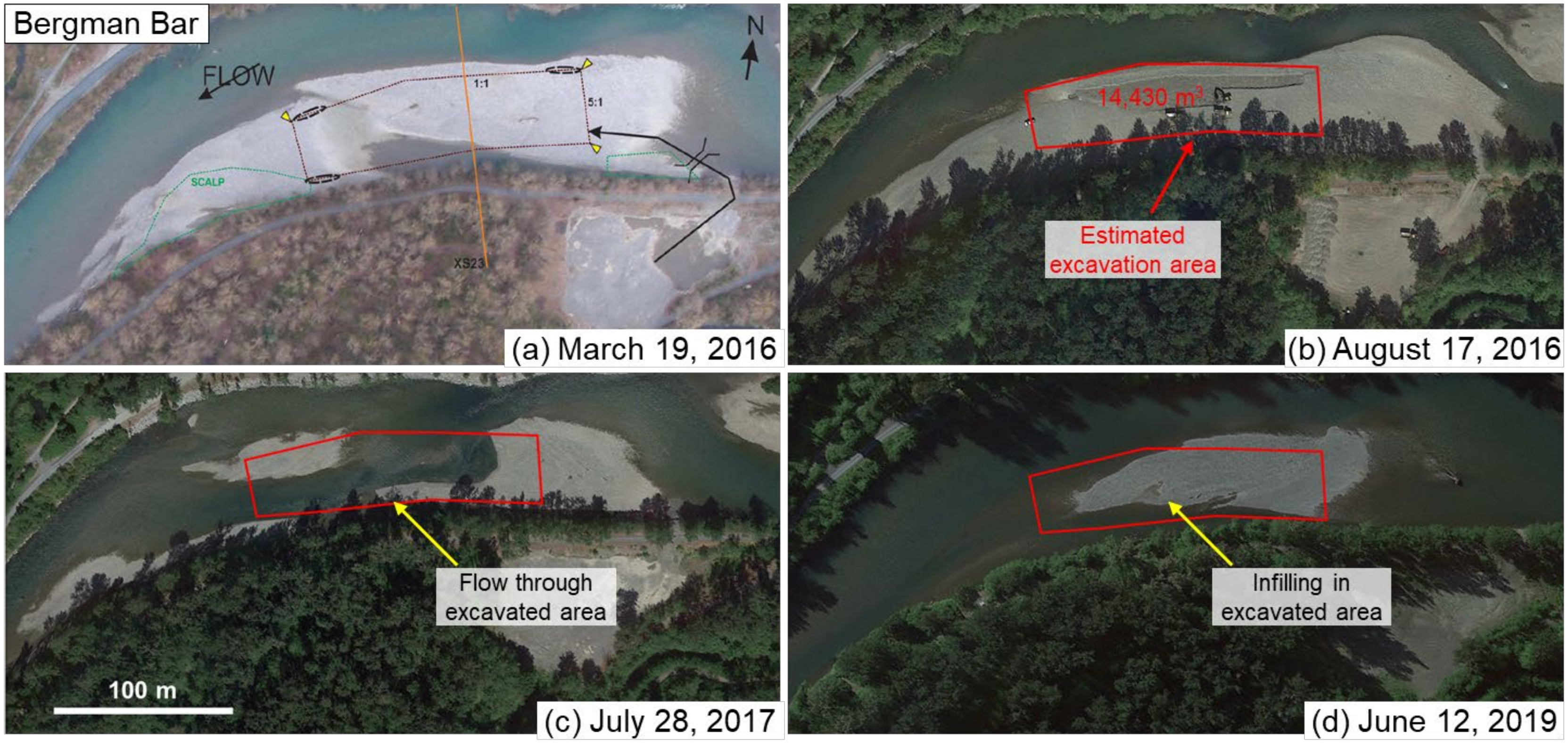


Figure A.3 **Bergman Bar on (a) March 19, 2016, (b) August 17, 2016, (c) July 28, 2017, and (d) June 12, 2019. Aerial imagery in (a) is from Nova Pacific (2016) while satellite images in (b) to (d) are from Google Earth. Sediment removal here occurred between August 17 and August 26, 2016. The image in (b) occurred during the sediment removal.**

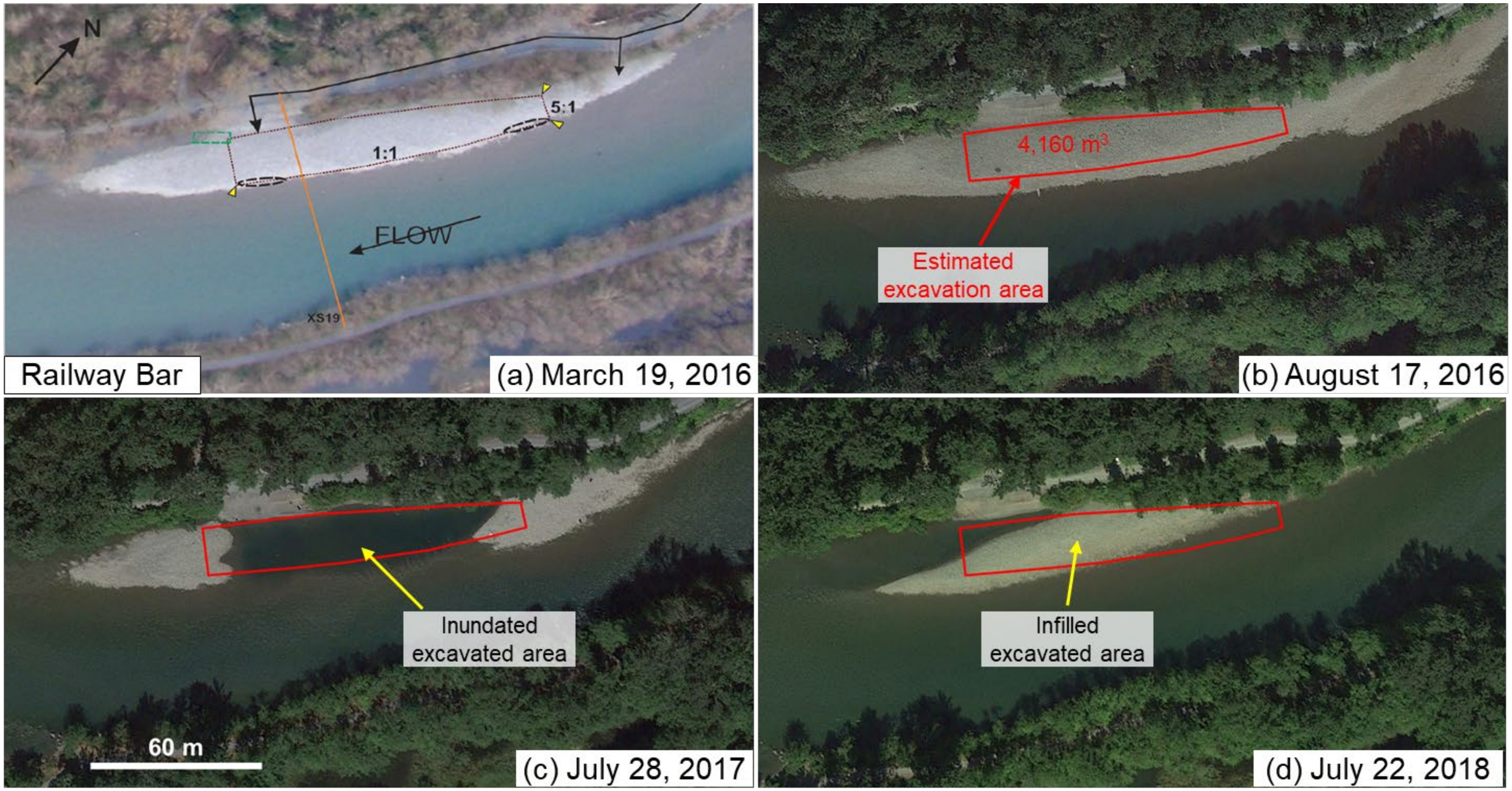


Figure A.4 Railway Bar on (a) March 19, 2016, (b) August 17, 2016, (c) July 28, 2017, and (d) July 22, 2018. Aerial imagery in (a) is from Nova Pacific (2016) while satellite images in (b) to (d) are from Google Earth. Sediment removal occurred between September 9 and September 13, 2016. The image in (b) is before the sediment removal.

Figure A.5 Yarrow Bar on (a) March 19, 2016, (b) August 17, 2016, (c) July 28, 2017, and (d) August 13, 2019. Aerial imagery in (a) is from Nova Pacific (2016) while satellite images in (b) to (d) are from Google Earth. Sediment removal here occurred between August 27 and September 8, 2016. The image in (b) is before the sediment removal.

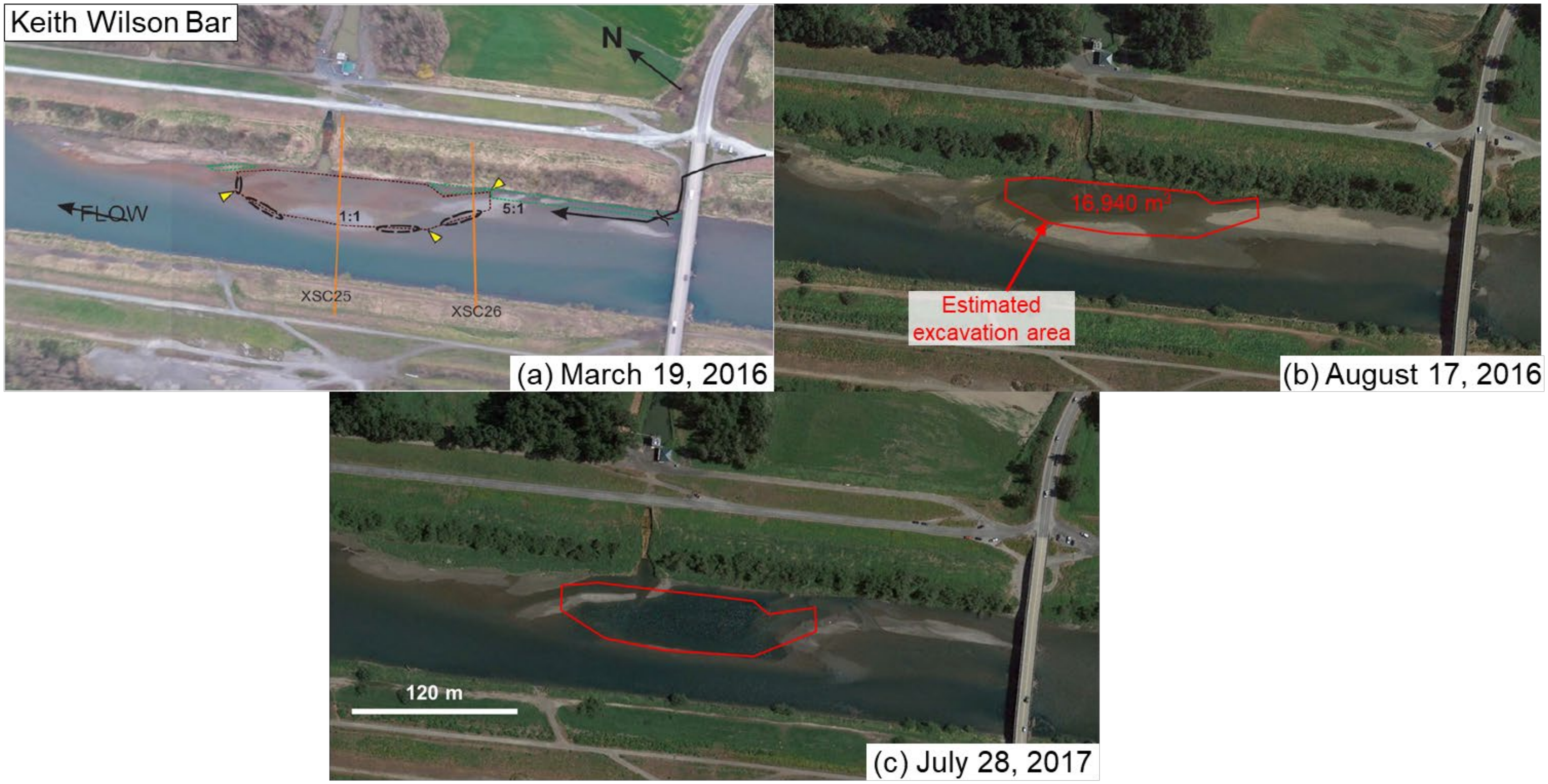


Figure A.6 Keith Wilson Bar on (a) March 19, 2016, (b) August 17, 2016, and (c) July 28, 2017. Aerial imagery in (a) is from Nova Pacific (2016) while satellite images in (b) and (c) are from Google Earth. Sediment removal here occurred between September 6 and September 29, 2016. The image in (b) occurred before the sediment removal. There is no imagery of the exposed bar in the years following 2017 due to high water levels.