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EFFECT OF LONGTERM NAVIGATION CHANNEL LOWERING ON SCOUR AND DEGRADATION PROCESSES ON LOWER FRASER RIVER

Andrew D. Nelson [1,5], Ilana Klinghoffer [2], Matt Gellis [3], and David McLean [4]
[1] Northwest Hydraulic Consultants, USA
[2,3,4] Northwest Hydraulic Consultants, Canada
[5] anelson@nhcweb.com

ABSTRACT

The Fraser River, which is the largest river on the west coast of Canada, terminates in a large, sand-bedded and tidally-influenced delta that extends from New Westminster to the Strait of Georgia. This lower reach of the river has been extensively modified over the last century to provide flood protection for surrounding areas and adequate draft for navigation of ocean-going vessels. Sediment removal by dredging the navigation channel below New Westminster, in combination with river training, bank hardening, and scour protection, has significantly altered the channel hydraulics, sediment transport characteristics, and morphology of the river. This paper uses the extensive historical record of bathymetric surveys that date back to the early 20th century to characterize the complex channel response that has occurred over time. The resulting bed lowering and degradation extend well beyond the limits of the localized navigation channel improvements. Importantly, bed lowering has led to increasing exposure of non-alluvial channel boundary material including riprap structures that were installed previously as scour protection measures, as well as cohesive delta foreset beds and less erodible Pleistocene deposits such as till and outwash. These hard points generate additional turbulence and plunging flow that have induced additional local scour, effectively amplifying the effect of the initial degradation. Consequently, deep local scour (over 20 m) has developed at some sections of the river.

Scour, Large river, Dredging, River training, River morphology, Channel bed facies

1. INTRODUCTION

River management activities, such as dredging, diking, and construction of river training structures and scour protection counter-measures may alter long-term channel stability and morphology. Furthermore, the presence of non-alluvial bed material —both natural and constructed engineering works— are increasingly recognized as having a significant influence on processes such as scour in lowland alluvial rivers (e.g. Nittrouer et al., 2011). Many previous studies have used historic and recent bathymetric charts to examine changes in estuary morphology (Van Der Wal and Pye, 2003) and some of these have explicitly explored estuary response to human modifications (e.g. Nichols and Howard-Strobel, 1991; Lane, 2004; Wang et al., 2013), but relatively few studies have used historical bathymetry data to evaluate long-term changes in channelized areas of the lowest reaches of large alluvial rivers.

This paper examines historical changes in channel morphology of the lower Fraser River, to characterize the complex channel response to anthropic activities over the last century. From a local perspective, this case study highlights the importance of harmonizing scour protection and navigation channel improvement activities. In the general case, it highlights the importance of understanding the local geomorphic controls and their potential interaction with intensive channel management activities on large lowland alluvial rivers.

2. THE LOWER FRASER RIVER

Geologic context

The Fraser River is the largest river on the west coast of Canada, with a basin draining about 232,000 km^2 of British Columbia. Following Pleistocene Glaciation, when glaciers scoured the Lower Mainland and left deposits of till and outwash, the river constructed an alluvial delta, which initially prograded through subaerial hills of Pleistocene glacial sediment and subsequently extended across buried glacial sediment out into the Strait of Georgia (Figure 1) to form the modern delta that extends from the channel trifurcation at New Westminster into the Strait.

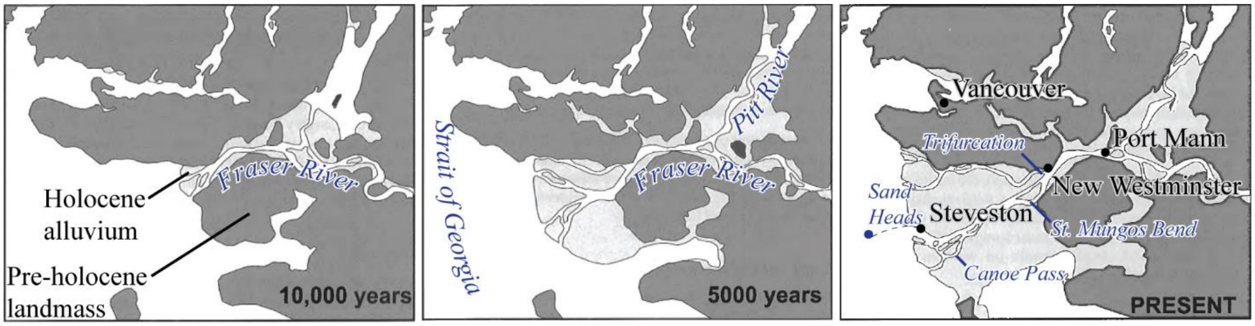

Figure 1: Holocene progradation of Fraser River into the Strait of Georgia (adapted from Clague et al., 1991) with present conditions showing key points referenced in the text.

The study area extends from the edge of confined flow at Steveston, upstream to the confluence of the Fraser and Pitt Rivers (Figure 1). From the Trifurcation (RK 34) east to the gravel-to-sand transition at the toe of the modern gravel fan near Sumas Mountain (RK 100), the river has a meandering, sand bedded channel with a few local flow splits around large, stable islands formed by chute cutoffs. The channel locally interacts with banks and bed substrate composed of Pleistocene glacial sediment, including overconsolidated advance outwash and pre-Vashon sediment (Quadra marine and advance outwash deposits), till (Vashon drift), glaciomarine drift (Ft. Langley formation), and gravelly recessional outwash (Capilano sediments) (Armstrong and Hicock, 1980; Armstrong and Kovachic, 1980).

The river splits into several distributary branches downstream of New Westminster as it flows through the modern delta, which extends 15 to 23 km in a broad plain. The top surface of Pleistocene sediment is typically 150 m and deeper below the delta (Figure 1) but it is irregular—ranging in elevation from approximately -300 m to -15 m (geodetic) (Clague et al., 1998). The Holocene delta is comprised of four primary facies: fine-grained bottomset beds deposited in deep water, foreset beds, medium to coarse sand river channel deposits, and floodplain and bog deposits at the surface (Clague et al., 1983, 1991). The river channel deposits form a nearly continuous 8-20 m thick sheet across the delta surface with a surface contact typically near mean sea level (Monahan et al., 1993); this sediment has very similar properties to active lower Fraser bed material. Sediment below the sand sheet was deposited on the delta foreslope and consists of fine sand and mud (Clague et al., 1983); this material has a much finer grainsize distribution than active lower Fraser bed material and will interact differently with scouring processes due to its compaction history, cohesive properties, and tendency to move into the river's wash load once eroded.

An early bathymetric chart (Richards, G.H. and Officers of the H.M.S. Plumper, 1860) provides a view of the Lower Fraser bathymetry prior to major human modification. The river ranged in width from 600 m to 1.2 km and had a general morphology like that of the present-day river, with alternating deep pools (-10 to -18 m) and shallow crossings (-2 to -6 m). The deepest observed sites occurred in the narrow channel at New Westminster (-19 m) and in a sharp bend in the area that is now Canoe Pass, with scour down to approximately -23 m.

Hydrology

Due to its large, mostly interior and high-elevation basin, the Fraser River has a snowmelt-dominated flow regime. Discharge typically rises in April, peaks between May and July (the freshet period) then recedes during the autumn and winter months. At Hope, 180 km upstream from the mouth (RK 180), the river has a mean annual discharge of about 2,800 m^3/s. Winter low flows are typically around 1,000 m^3/s, and annual freshet flood peaks typically range from about 7,000 to 15,000 m^3/s (average peak flow is about 8,700 m^3/s occurring in June). There is no secular change in peak flow intensity over the period of record for the Fraser, which extends back to 1912. Decadal-scale periodicity in flood peaks occurs on the river (NHC, 2015), which are related to Pacific Decadal Oscillation climate variability (Whitefield et al. 2010). These have been slightly higher than average for the past 10 years.

Sediment supply

Sediment flux in the lower Fraser River is wash load dominated. Most sediment flushes out to the delta front in the Strait of Georgia, but the sand component of the flux interacts with the bed. Observations of sediment loads on the Lower Fraser River were collected by Water Survey of Canada during the period 1965 to 1986, and the total suspended load averaged 17.3 million tonnes/year (range 12.3 million to 31.0 million), with the load consisting of 35% sand, 50% silt and 15% clay (McLean and Tassone, 1990; McLean et al., 1999). The suspended bed material load of sediment larger than 0.18 mm averaged 2.8 million tonnes/year (range from 1.2 to 9 million). Detailed measurements collected during 2010 are consistent with (but on the low side of) these historical observations, introducing the possibility that the load has decreased since the cessation of systematic transport measurement (Attard et al., 2014).

An estimate of the annual bed material load between Mission and the river mouth at Sand Heads was made by McLean and Tassone (1990) using a sediment budget approach based on measurements at Mission, observed channel topographic changes, and dredging removal records. That analysis indicated the annual bed material load delivered to the mouth of the river at Sand Heads was roughly 30% of the load at Mission during the period 1972 to 1997, indicating a major bed material sediment budget deficit.

Hydraulics

The river is tidally affected throughout the year as far as the gravel to sand transition at RK 100. The relative influence of the tide is governed by the fresh water inflow, magnitude of the tide, and distance from the river mouth. The lower river is subject to reversing flow during rising (flood) tides, particularly during periods of low or moderate freshwater inflows. At Port Mann (44 km upsteam from the river mouth), reversing flow occurs up until freshwater inflows exceed approximately 7,000 m^3/s. A salt water wedge can extend upstream to about RK 30 during winter when freshwater inflows are low and the tidal range is large (Ward, 1976). High freshwater discharges during the June freshet prevent the salt wedge from extending upstream of Steveston (approximately 10 km from the river mouth). The salt wedge can strongly influence near-bed hydraulics and sedimentation patterns in the lower 10 km (e.g. Kostaschuk, 2002; Dashtgard et al., 2012).

Dredging, river training history, and consequent general channel changes

The Lower Fraser is an important commercial corridor, with the river accounting for approximately one-quarter of the total cargo tonnage handled by Port Metro Vancouver—the largest port in Canada and fourth busiest port by tonnage in North America (Richmond Chamber of Commerce, 2014). Major flood protection and river training structures control the channel, which has been dredged since the early part of the 20th Century to provide deep water navigation from New Westminster downstream. The combined effect of sediment removal from dredging and constriction of the channel has significantly altered river processes extending a considerable distance beyond the limits of the localized dredging operations (e.g. McLean et al., 2006; NHC, 2008).

Flood control dikes, constructed initially between 1913 and 1919 (Dashtgard et al., 2012) now isolate the entire historical floodplain downstream of New Westminster (except a few small mid-channel islands) and isolate 90% of the river downstream of Hope. Training structures have been built to control the flow split into distributaries, concentrate scour and increase the channel draft, and protect infrastructure along and crossing the channel as detailed by Hales (2000). Most training structures were installed prior to 1936; notable exceptions include the trifurcation project (1967-70) and Sapperton Wing Dams (1955). Scour and bank protection features have been installed more gradually through time, these include bank revetments, riprap collars around bridge piers, and riprap aprons over pipelines and tunnels.

Channel dredging has been conducted to increase the depth of a navigation channel for deep draft vessels along the river up to New Westminster. It has also included industrial borrow dredging, mostly in the period between 1976 and 1988. Dredging began in 1885 when the main channel was only 2.7 m deep at the river mouth (Dashtgard et al., 2012), but the main systematic effort began around 1945. Figure 2 illustrates the quantity of material removed from the river through time and historic change in mean bed elevation. The large removal volumes (4-6×10^6 m^3/year) between 1975 and 1992 reflect the borrow dredging activities on the river. Dredging decreased to approximately 2×10^6 m^3/year between 1997 and 2003, then increased to approximately 3×10^6 m^3/year in recent years. The total dredged volume over the last 50 years amounts to 1.5×10^8 m^3. Channel response to the dredging and river training, which have imposed a persistent bed material budget deficit, has been persistent long-term channel degradation beginning in the early 20th century and continuing to the present day (e.g. McLean and Tassone, 1990; McLean et al., 2006; NHC, 2015). Between 1965 and 1988, when sediment removals were at their peak, the bed along the navigation channel centerline lowered at an average rate of about 8 cm/year. Comparison of change in bed elevation between 1988 and 2014 shows that that the pattern of channel degradation has continued through the past two and a half decades, but notably slowed to an average rate of about 2 cm/year since the late 1980s or early 1990s.

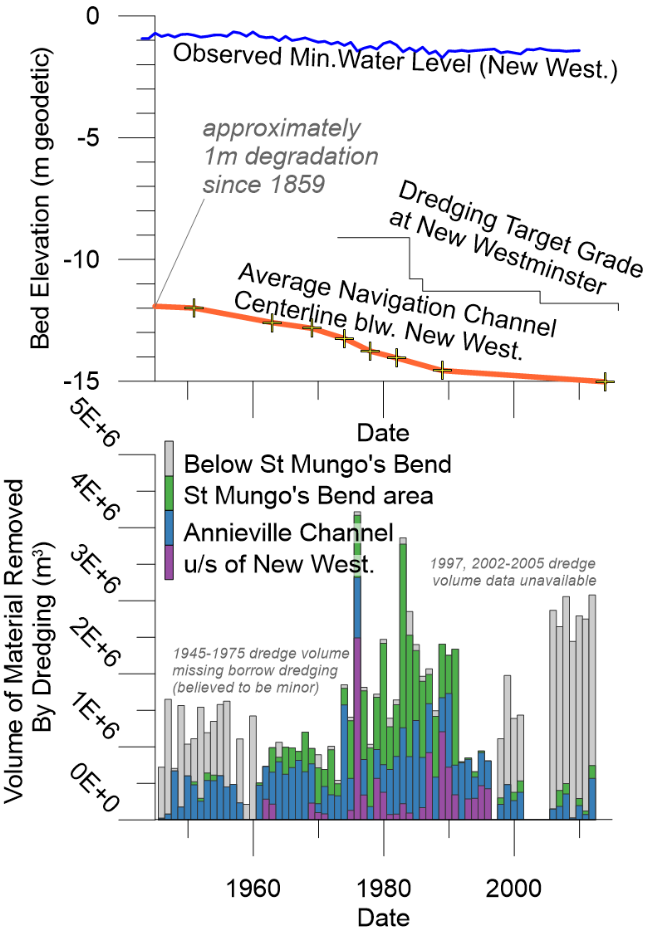

Figure 2: Historic changes in general bed elevation (top) and pattern of channel dredging activity (bottom).

Figure 2 also shows how the river bed lowering at and downstream of the project site has caused the minimum observed water level to systematically drop at New Westminster, as well as how the average channel grade has typically been 3 to 4 m below the target grade through time. This offset between the target grade and average channel centerline grade reflects the fact that the target grade is the maximum allowed elevation at shallow current crossover locations and that deeper pool areas are common along the channel.

3. METHODS

Bathymetric changes in time have been evaluated by compiling, digitizing, registering, and differencing historic sounding information at two distinct scales along the river. General channel changes have been evaluated at the reach-scale from Steveston (RK 9) to the Pitt River confluence (RK 44), as summarized in Table 1. In order to better understand the processes responsible for the observed reach-scale changes in channel morphology, bathymetric data were analyzed in detailed annual or semi-annual temporal resolution at two sites; St Mungo's Bend (RK 28-32) and in the area of New Westminster from the channel Trifurcation upstream to the Pattulo Bridge (RK -34-38). Local data from 1898 to 1955 were digitized from bathymetric charts included in the UBC Library Fraser River Model Project fonds (Jarlan, 1956); from printed navigation charts published by Public Works Canada from 1962 through 1985; and digital data provided by Public Works and General Services Canada (PWGSC) from 1989 through the present. Prior to 1999, the digital dataset consisted of surveyed cross-sections—typically with a spacing of 75-100 m— of about one fifth of the navigation channel width. From 1999 to 2011, multi-track surveys were conducted by producing grid coverage with an average spacing of around 1 m. Since 2011, extremely detailed multi-beam bathymetric data are available. These data were transformed from point data into a grid format with a common vertical reference.

Bathymetric changes at the reach-scale were analyzed by dividing the channel into 100 m segments and evaluating the pattern of elevation change—with emphasis on the relation between change in mean channel depth and maximum scour depth. In addition, the comparison between late 1980s and 2014/15 mosaics was stratified by the initial depth of the channel and overall changes in each 100 m segment. Results of this comparison at the reach-scale were plotted both spatially (to illustrate patterns along the channel) and as cumulative distributions in order to show the magnitude and relationships between bathymetric parameters along the channel.

Areas of non-alluvial channel boundary material exposed at the present (2014/15) time were mapped based on the surface texture visible in multi-beam bathymetry data (see for example Nittrouer et al., 2011). This is possible because recently acquired sub-metre topography can reveal bedforms indicating some depth of alluvial material coverage, erosional features such as flutes or kettles, slopes higher than the angle-of repose indicating exposed cohesive material, and high local roughness and a blocky texture which suggests riprap cover. Because only recent data show these features, the timing of initial non-alluvial material exposure is generally unknown. Therefore, analysis of the relationship between scour amplification and non-alluvial material focuses on the period between the late 1980s and 2014/15.

Table 1: Summary of data sources used in river-scale bathymetric comparison.

Period	Year	Extent	Mosaic Extent	Mosaic Comparison
1953	1953	RK 34 to RK 44	RK 34 to RK 44	NA
Early 1970s	1971 1972 1974	RK 9.7 to RK 20.3 RK31.6 to RK 44.6 RK 20.2 to RK 31.4	RK 9 to RK 44	Change between 1953 and 1974 from RK 34 to RK 44
Late 1980s	1988 1989 1992	RK9 to RK 44 with gaps fill gaps in 1988 dataset	RK 9 to RK 44	Change between 1974 and 1988 from RK 9 to RK 44
2014/15	2014 2015	RK 9 to RK 35 RK 35 to RK 46	RK 9 to RK 44	Change between 1988 and 2015 from RK 9 to RK 44

Data sources: 1953 through 1974 PWGSC Charts; 1988-1992 PWGSC single beam soundings; 2014-2015 PWGSC multi-beam soundings. The source data are referenced to a local low water datum, which is a stepped datum along the lower river that has changed through time as hydraulic conditions have responded to the general bed lowering. For the purposes of this study, data were reduced to geodetic datum.

4. RESULTS

Reach scale changes

The spatial and temporal patterns of bathymetric change along the Lower Fraser River support the hypothesis that human-forced channel bed lowering is increasingly exposing non-alluvial channel boundary material with the consequence of increasing heterogeneity in channel bed elevation through time, which is dominantly expressed through scour depths increasing faster than average channel depth (Figure 3, Figure 4, and Table 2).

Comparison of bathymetry between 1953 (approximately the beginning of major channel lowering) and the early 1970s is restricted to RK 34 to 44 due to the spatially limited extent of the 1953 dataset. During this period, the average bed elevation in individual segments lowered by 1.1 m and the median maximum local depth increased by 1.9 m in this area. Over the whole study reach between 1859 and the early 1970s, the average bed elevation lowered by about 3 m, and median maximum local depth increased by about 2 m, probably mostly between 1945 and 1974 given the known history of navigation centerline channel lowering (Figure 2). Between the early 1970s and late 1980s, a tremendous volume of sediment was evacuated from the Lower Fraser, with a cumulative bed material deficit of around 30 million m^3 between RK 44 and RK 9. The average bed elevation dropped by 2.5 m and the median maximum local depth increased by 3.5 m.

The mean bed elevation change has been about -0.37 m between the late 1980s and 2014/15, resulting in a cumulative bed material deficit of about 4.5 million m^3 from RK 44 to RK 9. The average bed elevation changes were relatively modest; however, local maximum depths continued to rapidly lower. The maximum depths (observed during non-flood conditions) increased by 1 to 3 m along most of the lower river, with some areas experiencing up to an additional 13 m of bed lowering (Figure 3).

Figure 4 shows how scour holes have increasingly become more sensitive to channel lowering than the general bed level. Scour hole depth and morphology has become exaggerated in areas where the deepest portion of the channel is reaching below -20 m—the approximate bottom of the Fraser Delta sand sheet and corresponding historic maximum scour depth. Figure 5 shows the characteristic relation of these areas of bed lowering in deep channel areas to the presence of non-alluvial channel boundary materials.

Cumulative distribution plots of changes in the maximum, mean, and minimum bed elevation calculated for each 100 m segment are a way to summarize the magnitude of bed changes that have occurred along the representative reach of the lower river (Figure 6). These illustrate the magnitude of possible bed changes to be expected with moderate lowering of the average channel grade and show that the scour amplification ratio has increased through time. Most recently, between the late 1980s and 2014/15, minimum bed elevations have been very sensitive to the modest general bed lowering: 50% of sites experienced more than a 1.4 m increase in maximum depth (about triple the median change in mean bed elevation), and 16% of sites experienced more than 2.8 m increase in maximum depth. In comparison, between 1974 and 1988, 50% of sites experienced more than 3.5 m increase in maximum depth (about 1.2 times the median change in mean bed elevation), and 16% of sites experienced more than 5.2 m increase in maximum depth. Between 1953 and 1974, 50% of sites experienced more than 1.9 m increase in maximum depth (about 1.3 times the median change in mean bed elevation), and 16% of sites experienced more than 4.1 m increase in maximum depth.

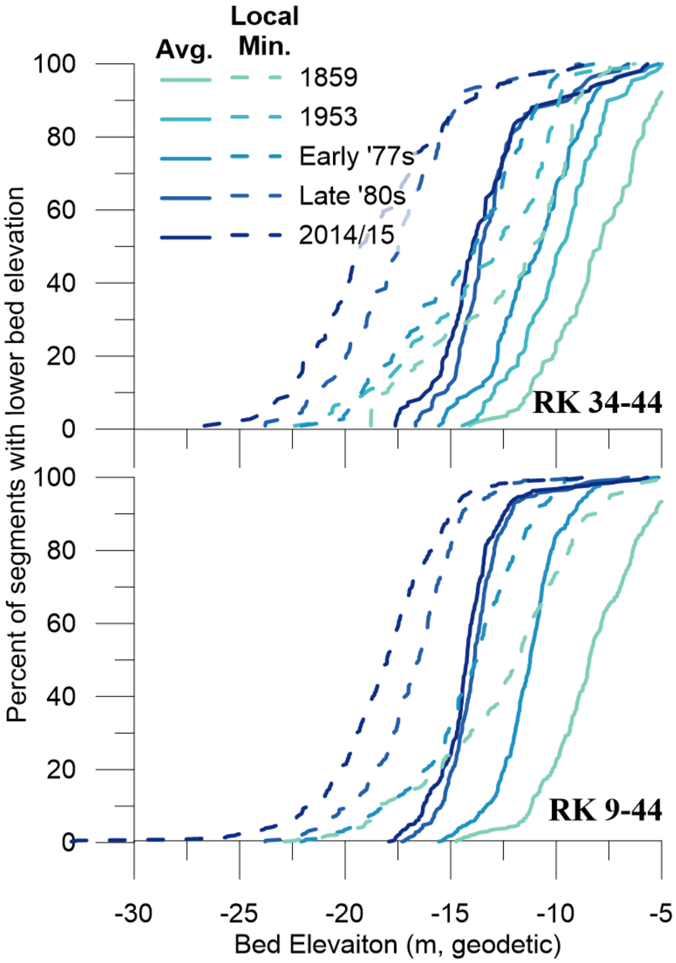

Figure 3: Cumulative bed elevation distribution plots for portions of the lower Fraser River showing much faster lowering of minimum bed elevations than mean bed elevations.

Table 2: Average bed elevation change and cumulative bed material deficit from RK 9 to RK 45.

Period of Comparison	Average Bed Elevation Change (m)	Cumulative Volumetric Bed Change (m^3), by RK 44 to 34	44 to 9	Change in Maximum Local Depth (m), by percentile 16th	50th	84th	Scour Amplification Ratio**
1953 to 1970*	-1.06*	-4,376,000	n/a*	*-0.45	-1.9*	-4.1*	2.7*
1974 to 1988	-2.5	-8,404,000	-29,637,700	-2.2	-3.5	-5.2	1.4
1988 to 2015	-0.37	-1,394,000	-4,495,700	-1.0	-2.3	-3.6	6.2

* Available data to evaluate changes for the period 1953 to 1974 restricted to RK 34-44.

** Sour amplification ratio defined as the ratio of 50th percentile change in local maximum depth to average bed elevation change.

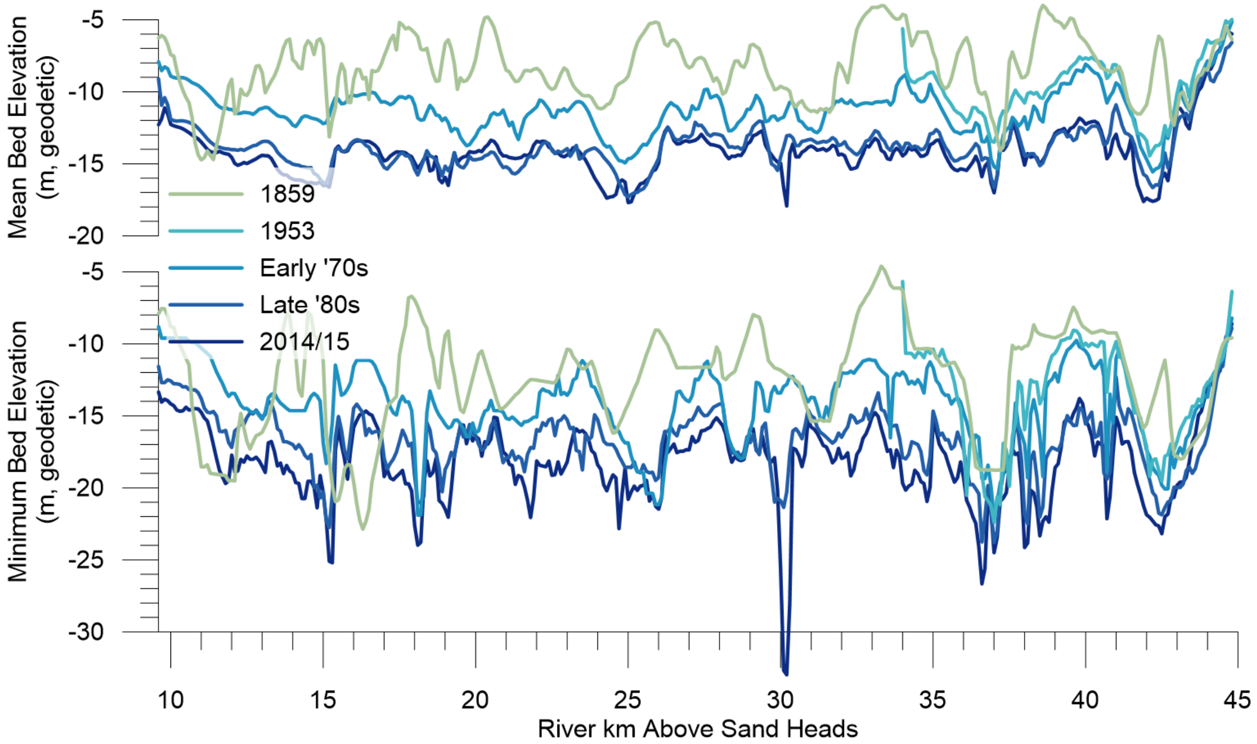

Figure 4: Profiles showing historical change of bed elevation summarized by 100 m segments along the study reach. Downstream of RK 19.3, the 1859 alignment diverges from the present alignment; bed elevation shown correlated to the nearest segments of the present alignment.

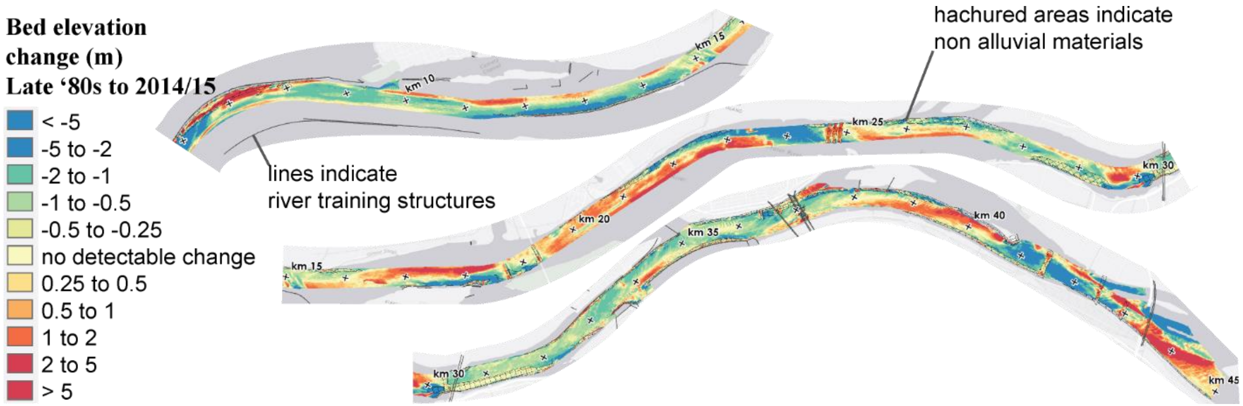

Figure 5: Map view of recent (late 1980s to 2014/15) bathymetric changes showing relationship to areas with non alluvial materials mapped from the 2014/15 multi-beam bathymetry.

Case studies

Two local case studies (Figure 7) that motivated the preceding reach-scale analysis provide helpful insight regarding some of the processes governing scour depth amplification along the lower Fraser River. The first of these is St. Mungo's Hole (RK 30 Figure 4), which has scoured to a depth of -33 m (geodetic), about 10 m below the historic maximum scour depth for the reach.

The Annieville Channel upstream of the hydraulic influence of Alex Fraser Bridge has been persistently degrading as it tracks general bed lowering. From the 1972 survey to the present, the channel has degraded by approximately 5 m. The reach-wide pattern of bed lowering upstream of Alex Fraser Bridge must be kept in mind when interpreting bed-level changes at and downstream of the bridge, as it may compound or otherwise interact with local hydraulic perturbations in those areas. One particularly important change through the whole project reach has been increasing exposure of non-alluvial bed material along the left bank toe area, which has increased the hydraulic complexity of the channel through this reach.

The dominant change in the channel configuration downstream of Alex Fraser Bridge has been the initial development and subsequent metamorphosis of the St. Mungo's scour hole near the centre of the channel downstream of the bridge. Interaction of shear layer flow shedding from the Alex Fraser Bridge's left abutment in the horizontal plane and diving flows downstream of the submerged apron protection of South Surrey Interceptor in the vertical plane are believed to have created the hole. The initial development tracked the predicted morphology (Western Canada Hydraulic Laboratories Ltd, 1982) for the feature following installation of the bridge abutments. Around 1994, the prominence of riprap apron protection over a sewer line upstream increased as the channel degraded (and likely, additional riprap placed), forming a 1.5 m high sill on the bed. Immediate deepening of the hole followed this perturbation. Continued channel degradation upstream has increased the effective height of the sill and generated continued scour hole deepening.

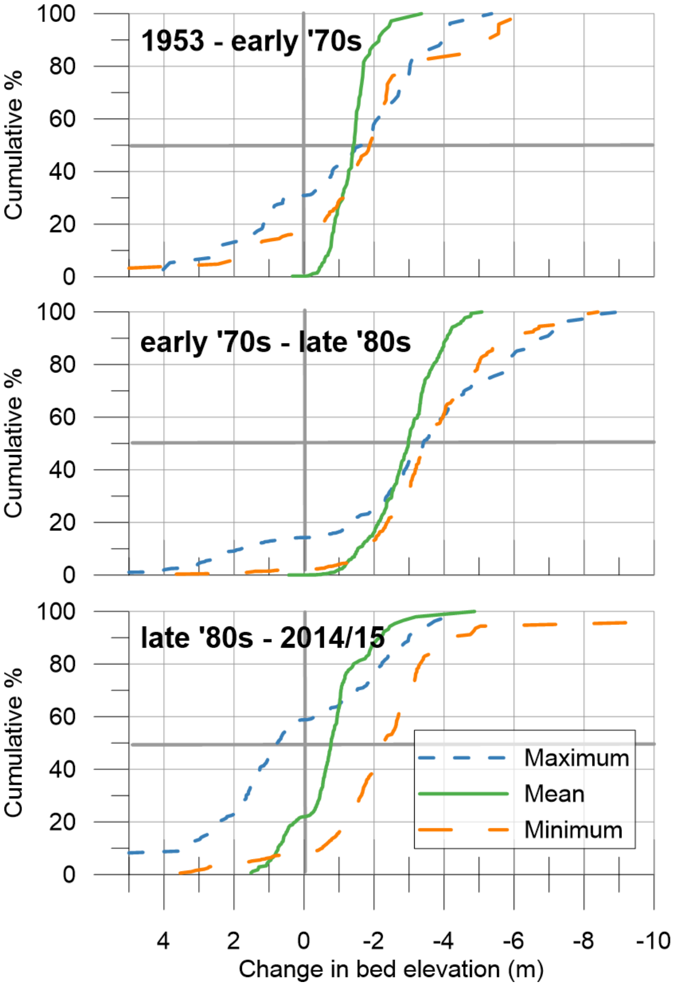

Figure 6: Cumulative distribution plots illustrating the changes in maximum, mean, and minimum bed elevation (max. scour depth) that have occurred along the Lower Fraser. 1953-early 70s comparison restricted to RK 34 to RK 44.

While changes at St. Mungo's Bend illustrate an extreme response to increased relative prominence of non-alluvial features (glacial sediment and riprap), changes near New Westminster (RK 34-38), illustrate a more typical channel degradation pattern. Initial channel-narrowing efforts (1900-1970) caused typical regime-type response of general channel lowering in response to constriction. Intensive dredging beginning in the mid-1970s has been focused on the left bank, where persistent deposition of material on a point bar causes shoaling; maintenance is required to facilitate shipping access to the Fraser Surrey Docks. In contrast, deeper portions of the channel have persistently and monotonically degraded through time, which is interpreted to be a result of the reach-scale sediment

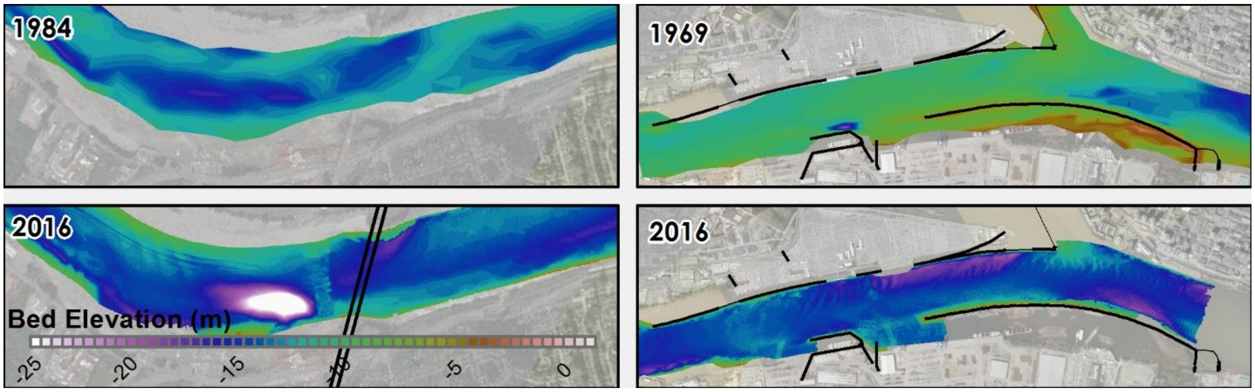

Figure 7: Overview of bed-level changes at Mungo's Bend (left) and the Trifurcation (right).

budget deficit. The historic persistent deposition of material on a point bar causes shoaling and maintenance is required to facilitate shipping access to the Fraser Surrey Docks. In contrast, deeper portions of the channel have persistently and monotonically degraded through time, which is interpreted to be a result of the reach-scale sediment budget deficit. The historic bathymetry also shows persistent scour associated with the natural constriction formed by Pleistocene sediment at Pattullo Bridge, and local scour associated with bridge piers (including scour formation following construction of the Skytrain Bridge).

5. DISCUSSION

Combining observations from the detailed case studies and morphodynamic history with understanding of the geologic context and river management history suggests that human activities have caused a fundamental change in the factors governing channel topography and scour along the Lower Fraser River. Over the last several decades, maximum depths along the channel have been increasing at a faster rate than general (average) bed lowering. Today, general channel levels approach the historic maximum "natural" scour depth, which corresponds to the typical stratigraphic boundary between alluvial sand with similar characteristics to the active bed material in the river, and Pleistocene glacial sediment or Holocene delta foreset beds with contrasting properties. Thus, the channel boundary has shifted from one underlain by deep alluvial cover, to one with intermittent alluvial cover over much finer grained, partially cohesive delta foreslope deposits over the delta, and intermittent alluvial cover over Pleistocene glacial sediments from New Westminster upstream. Furthermore, scour protection features that were once buried or only exposed during high-flow now form prominent sills above the channel bed. These sills, in conjunction with other river training features and increasingly exposed Pleistocene deposits, have caused strong secondary currents to locally develop. Such localized currents are responsible for the deepest observed scour—which presently exceed comparable historic scour depths by 10 to 15 m.

This interpretation raises important considerations regarding the strategy for long-term management of the river. Continued aggressive navigation channel dredging to maintain or increase the available draft in the channel may be expected to trigger disproportionate increases in scour depths along the river. If past trends continue—which is not guaranteed considering the inference of a fundamental change in the typical channel boundary materials—increasing the navigation channel draft by 1-2 m may trigger a disproportionate increase in scour depths of 2 to 6 m. At many sites, scour protection measures are, ironically, one of the principal factors driving intense local channel deepening. Future construction of such features should be designed to minimize hydraulic obstruction, assuming that channel degradation will continue into the future—otherwise feedback between the structures and channel degradation may result in a self-defeating dynamic.

In the general case, these observations from the Fraser River highlight the importance of understanding the local geomorphic context and predicting long-term geomorphic processes interaction with intensive channel management of large lowland alluvial rivers. Such studies need to consider potential perturbations to the sediment budget balance through altered hydraulics, sediment supply, or storage (e.g. dredging); the geologic history and stratigraphic context of the channel boundary; and —crucially— the cumulative impact of diverse management activities over a reasonable management timeframe of decades to centuries.

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