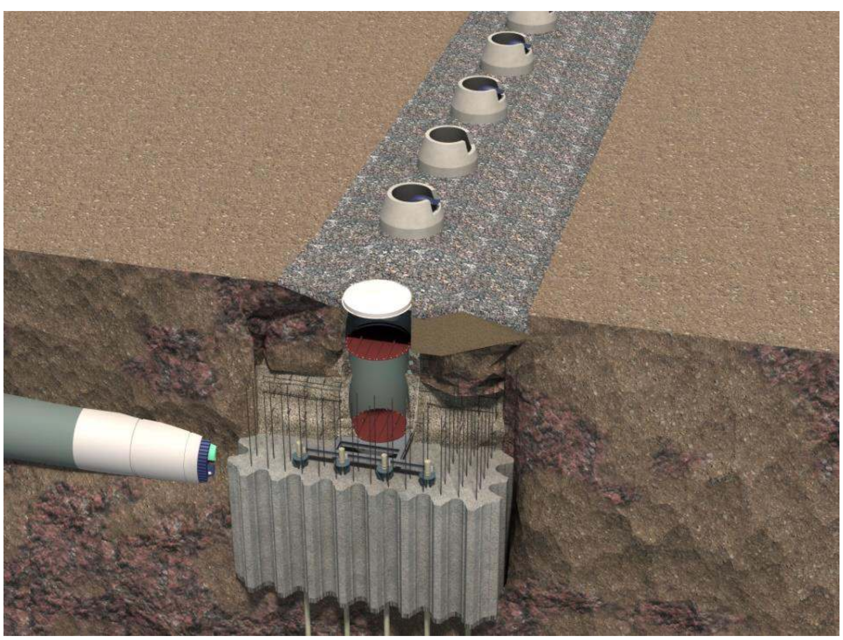
APPENDIX C
GEOMORPHOLOGICAL STUDIES

C.1: Overview of Fluvial Geomorphology

Annacis Island WWTP New Outfall System

Vancouver Fraser Port Authority
Project and Environmental Review Application



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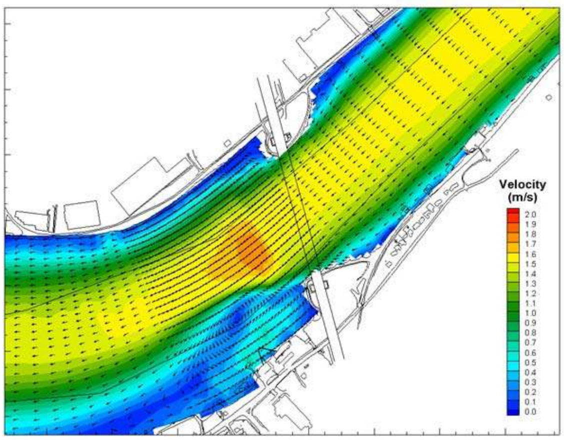
ANNACIS WWTP TRANSIENT MITIGATION AND OUTFALL PROJECT
OVERVIEW OF FLUVIAL GEOMORPHOLOGY

FINAL REPORT



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7 December 2017

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ANNACIS ISLAND WWTP TRANSIENT MITIGATION AND OUTFALL PROJECT

OVERVIEW OF FLUVIAL GEOMORPHOLOGY

FINAL REPORT

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7 December 2017

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CREDITS AND ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Northwest Hydraulic Consultants Ltd. was retained by CDM Smith to conduct a fluvial geomorphology study of the lower Fraser River as part of the Annacis Island WWTP Transient Mitigation and Outfall Project. This technical report reviews morphological changes along the Annieville Channel Reach of the Lower Fraser River over the last 50 years using historical surveys and dredging records and information compiled from past studies on hydrology and sediment transport. A one-dimensional hydrodynamic model was used to characterize the seasonal variations in water levels and mean velocities. A three dimensional hydrodynamic model was used to assess the flow patterns, velocities and shear stresses at the site for extreme flood conditions to support the scour investigations.

The river bed lowered at least 20 m near the project site over the last 40 years in response to three main factors:

- Construction of the ship collision structures at the Alex Fraser Bridge in 1984, which created a notable constriction and zone of flow separation along the south bank.
- Construction of a raised riprap apron over the South Surrey Interceptor around 1995 that has acted as a sill.
- Ongoing dredging and navigation channel improvements, which have lowered the riverbed by 2 to 3 metres upstream of the site.

The depth and geometry of the existing deep scour hole appears to be quite sensitive to the height of the riprap sill that has been formed over the South Surrey Interceptor. Raising the sill further by adding more riprap would lead to further local scour both upstream and downstream of the crossing .The effective height of the sill could also be increased if the navigation channel upstream of the crossing is deepened further.

The South Surrey Interceptor is susceptible to undermining due to progressive upstream migration of the deep scour hole that has formed. The existing scour protection apron over the crossing will need to be modified and re-constructed if the crossing is to be maintained in the long-term. This will require extending the apron further downstream as well as possibly lowering the crest height of the apron.

The planned outfalls on the north side of the navigation channel are located in a relatively stable section of the river compared to the south side. Since the mid-1980s, the bed elevation has varied by up to 2 m, with no clear association with reach-wide patterns, local infrastructure change, or flood flows. Presently, the bed in this area is near a historical low suggesting that aggradation could occur in the absence of continued reach-wide degradation (which is also possible if future navigation channel deepening is carried out).

Additional short-term periodic scour and fill caused by dunes that migrate through the reach. We recommend providing a vertical allowance of ± 2 to account for short-term scour and fill.

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1 INTRODUCTION

1.1 Purpose

Northwest Hydraulic Consultants Ltd. (NHC) was retained by CDM Smith to conduct a fluvial geomorphology study of the lower Fraser River as part of the Annacis Island WWTP Transient Mitigation and Outfall Project (the Project). This technical report reviews morphological changes along the Annieville Channel Reach of the Lower Fraser River (Figure 1) over the last 50 years using historical surveys and dredging records and information compiled from past studies on hydrology and sediment transport. .

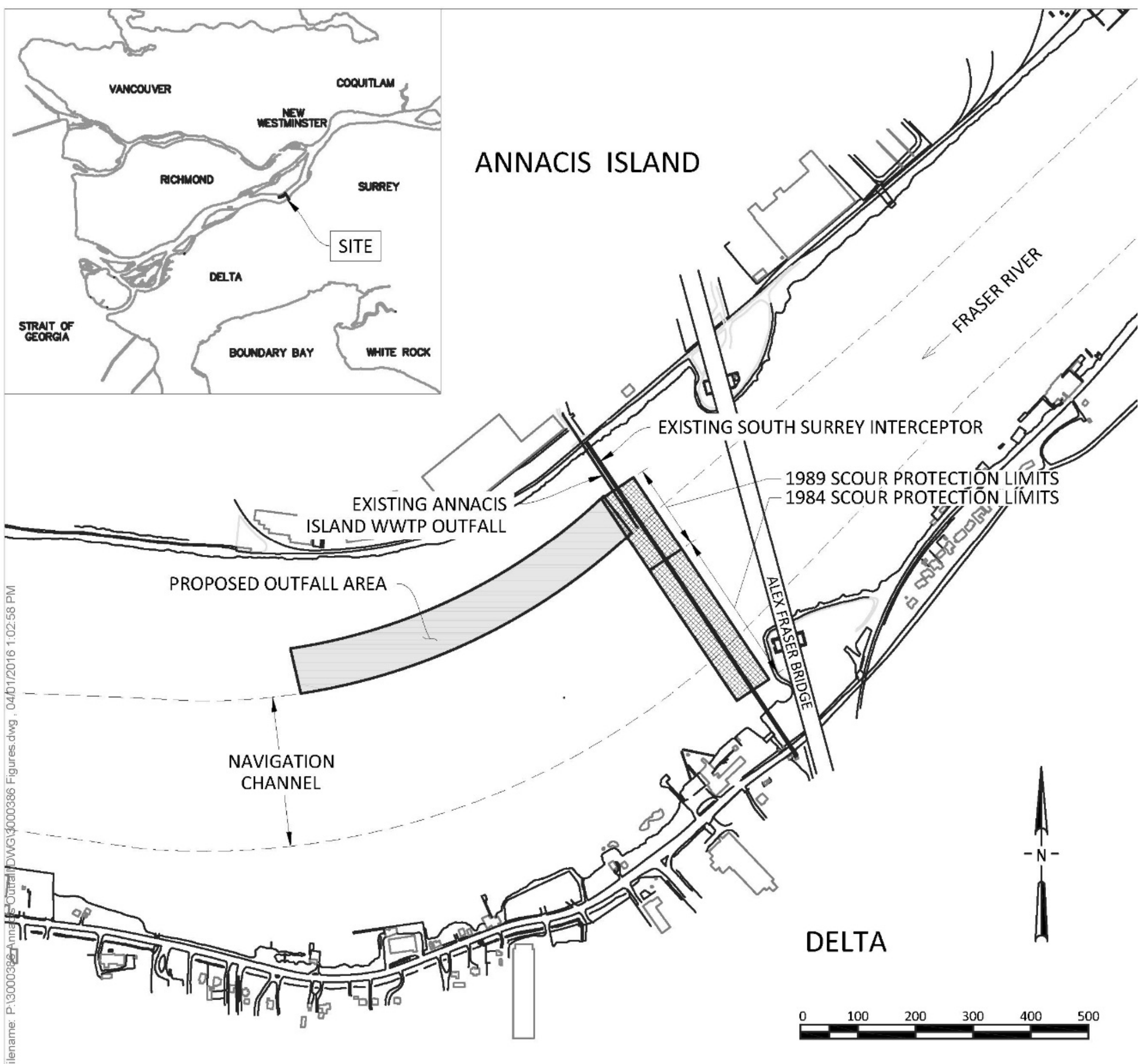


Figure 1: Site plan

1.2 Available Information

Information on the existing outfall and the South Surrey Interceptor were provided by Metro Vancouver in the form of CAD drawings showing as-built plan and profiles of the structures. Metro Vancouver also provided detailed monitoring surveys (bathymetric) in CAD format. CDM Smith supplied a multi-beam bathymetric survey of a 2.0 km reach of the Annieville Channel in digital format. This survey was conducted by Fugro Pelagos Inc. (2013) in October 2013. Historic bathymetry of the river was obtained in digital form from Public Works and Government Services Canada (PWGSC) covering the period 1988 to 2015. Earlier surveys from the period 1972 to 1988 were obtained from NHC's in-house archives and were manually digitized. Records of historic dredging volumes were available from previous studies (NHC, 2002) and were updated using information provided by Port Metro Vancouver.

2 POTENTIAL EFFECT OF RIVER ON ANNACIS WWTP OPERATIONS

2.1 Existing Infrastructure

2.1.1 South Surrey Interceptor

The South Surrey Interceptor was constructed in 1974 and is located about 500 m downstream of the Alex Fraser Bridge (Figure 1). Details of the crossing were taken from GVSDD Drawing SF-1428. The crossing consists of two 1219 mm OD cement lined steel pipes and one 914 mm OD steel pipe in an excavated trench that was backfilled with native river bed material. The crown elevation of the pipes is -17.2 m (geodetic) near the south side of the channel, -16.6 m (geodetic) near the middle of the channel and then gradually increases on the north side. Boreholes showed the bed material consisted of dense sand or sand and gravel along the southern half of the channel. The north side of the channel consisted of fine sand. The depth of cover over the pipe varied between 6.0 and 6.4 m after construction. However, the depth of cover has decreased substantially over time (refer to Chapter 5). A scour protection apron was placed over the crossing in 1984 and was upgraded in 1989 and 1995.

- 1984: The apron extended approximately 150 m from the south bank, with the top of the apron varying from elevation -15 to -15.5 m (geodetic) based on the “as-built” line shown on the profile. The width of the apron was 67 m.
- 1989: The apron was extended a further 100 m to the north side of the channel, with the top of the apron varying from -14 to -13 m in the navigation channel.
- 1995: Additional rock was placed on the existing apron, raising its crest to elevation -13 m along its entire length.

2.1.2 Outfall

The general arrangement of the outfall is shown on GVSDD Drawing SF-1429. The outfall consists of two 1676 mm OD and one 1219 mm OD pipes that extend for a length of 235 m from an outfall control chamber that is set back 70 m from the north bank of the river. The treated effluent is discharged through seven sets of steel risers that are situated between 105 m and 165 m from the north bank. The risers consist of 450 mm diameter, 6.1 m high pipes and end approximately flush with the river bed. No scour protection was provided at these pipes.

2.2 Annacis Island WWTP Transient Mitigation and Outfall Project

There are two main components of the Project that need to consider river processes and future morphologic changes during design. These include:

- Siting and design of the planned new outfalls. CDM Smith provided NHC with a polygon showing the region on the north side of the channel that is being considered for locating a new outfall. This polygon was used in the subsequent geomorphic studies that assessed historic bed level changes.

- Potential modifications to the South Surrey Interceptor.

2.3 Hydrotechnical Design Considerations

The lower Fraser River has undergone significant changes over the last century due to river training and dredging. The river response persists for many years or decades after the changes are initiated. Factors that could affect the long-term stability of the channel near the project site include:

- Ongoing channel adjustments in response to past river training and dredging activities.
- Future improvements to the navigation channel (widening and/or deepening).
- Future increases in dredging effort upstream and downstream of the site that may be required to maintain the improved navigation channel.
- Long-term changes to the runoff and sediment supply.
- Sea level has been rising over the last century and is expected to rise at an accelerating rate in the future. An increase in ocean level would likely cause increased shoaling in the lower river. It would also cause the salt wedge to extend farther upstream.

Seasonal and daily patterns of scour and deposition also occur near the project in response to the annual freshet and effects of the tide. Natural scour occurs at sections of a channel under the influence of varying flows, sediment transport, channel shifting and other fluvial processes. There are several common types of natural scour. Bend scour generally develops near the outer bank in meandering or curved channels. It is caused by three dimensional helical flow generated by the intersection of curved streamlines with a vertical velocity gradient. Protrusion scour occurs when the main flow impinges on a bank or natural hard point protruding into the flow. Such features may result naturally from erosional exposure of a resistant geological formation. Constriction scour tends to occur across a river section that is narrower than average, usually as a result of river training works or bridge abutments (such as the ship collision structures at Alex Fraser Bridge).

Short-term cyclical patterns of scour and fill can also occur due to bed form (dune) development and downstream migration during the freshet season.

3 OVERVIEW OF LOWER FRASER RIVER

3.1 Setting

The Fraser River drains 232,000 km^2 of southern British Columbia, making it the largest river on the west coast of Canada. The contemporary Fraser River delta was formed since the most recent glaciation, beginning approximately 10,000 years ago. The modern delta of the Fraser River commences near New Westminster and extends 15 to 23 km westwards in a broad delta plain encompassing Richmond, Ladner, Delta, and Tsawwassen. The western margin of the delta extends into the Strait of Georgia approximately 27 km and includes Sturgeon Bank and Roberts Bank.

At New Westminster, the main channel splits into the North Arm and the South Arm (Figure 3). The South Arm splits again around Westham Island, with Canoe Passage along the south discharging most directly to the northern Roberts Bank tidal flats.

3.2 Hydrology

3.2.1 Available Data

Continuous discharge records are available from Water Survey of Canada (WSC) gauge “Fraser River Hope” (08MF005) for the period 1912 to 2014. Discharges have also been published intermittently during the freshet season between 1966 and 2014 from the WSC gauge “Fraser River at Mission” (08MH024). Discharges are not published during the non-freshet period at Mission due to tidal effects.

The Fraser River has a snowmelt-dominated flow regime, with the discharge typically rising in April, peaking between May and July and then receding during the autumn and winter months (Figure 4). The long-term mean flow is 2800 m^3/s at Hope and 3200 m^3/s at Mission. The flows at Mission are typically between 10% and 15% larger than at Hope due to inflows from the Harrison River and Chilliwack River.

Table 1 summarizes estimated peak discharges at the two sites (NHC, 2008), and Figure 2 shows a plot of the flow history for the River at Hope over the period of record. Inflows downstream of Mission are relatively small (the drainage area below Mission represents less than 2% of the total basin).

Table 1: Flood frequency analysis at Hope and Mission

Return Period (Years)	Annual Exceedance Probability (%)	Discharge (m^3/s)	
		Hope	Mission
10	10	11,100	12,500
20	5	12,100	13,700
50	2	13,300	15,000
100	1	14,200	16,000
200	0.5	15,300	17,300
500	0.2	17,000	19,000

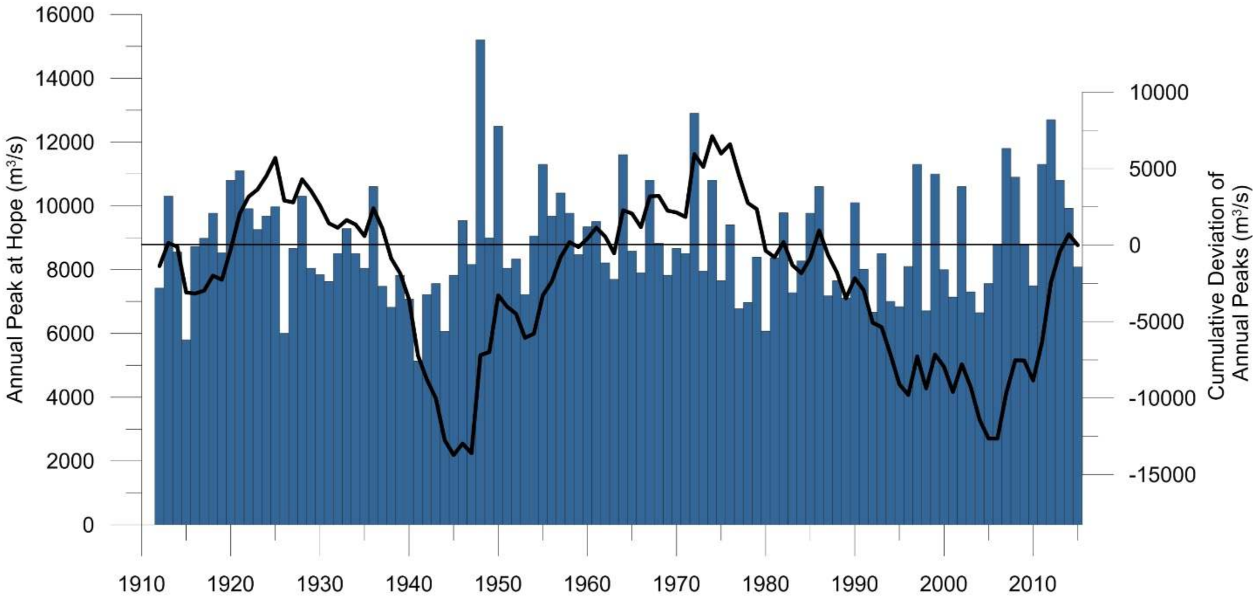


Figure 2: Fraser River flow history at Hope

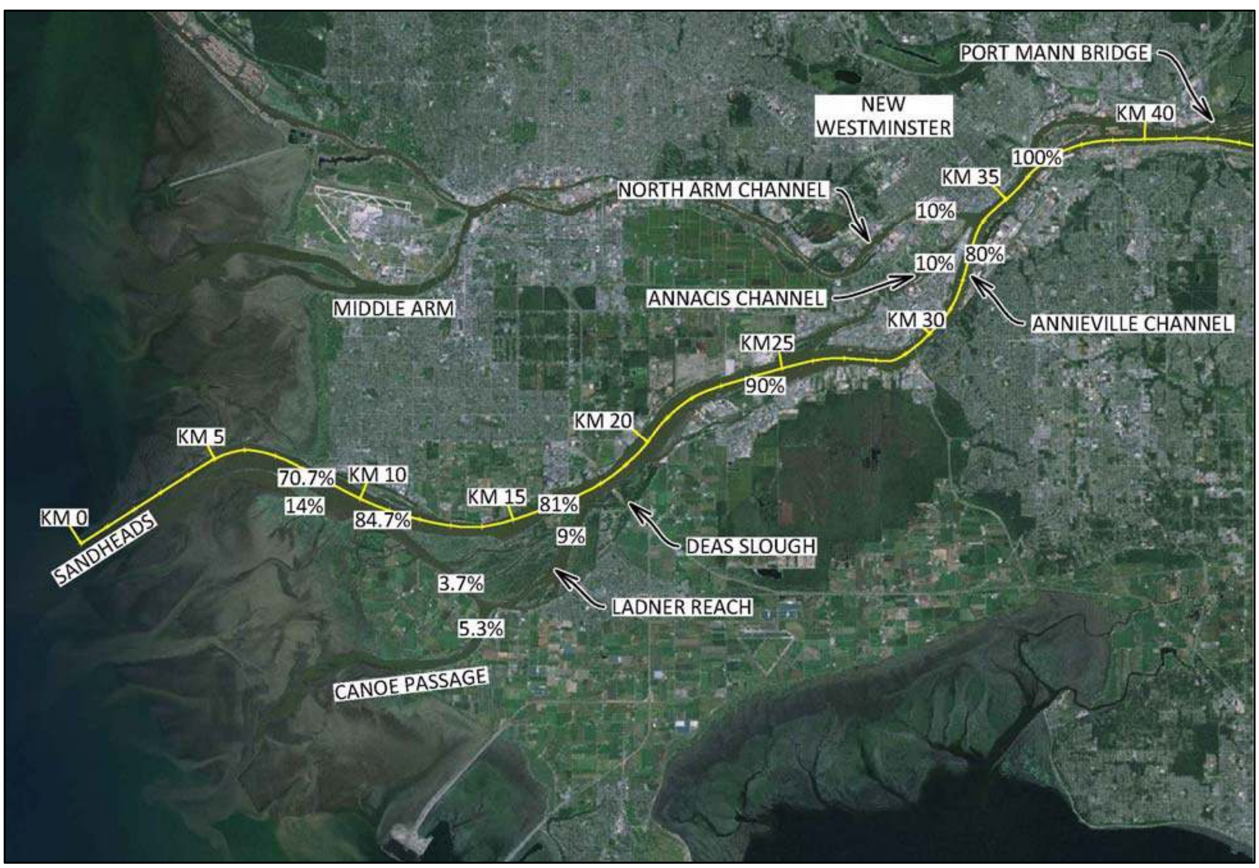


Figure 3: Approximate distribution of flow in distributary channels during freshet conditions

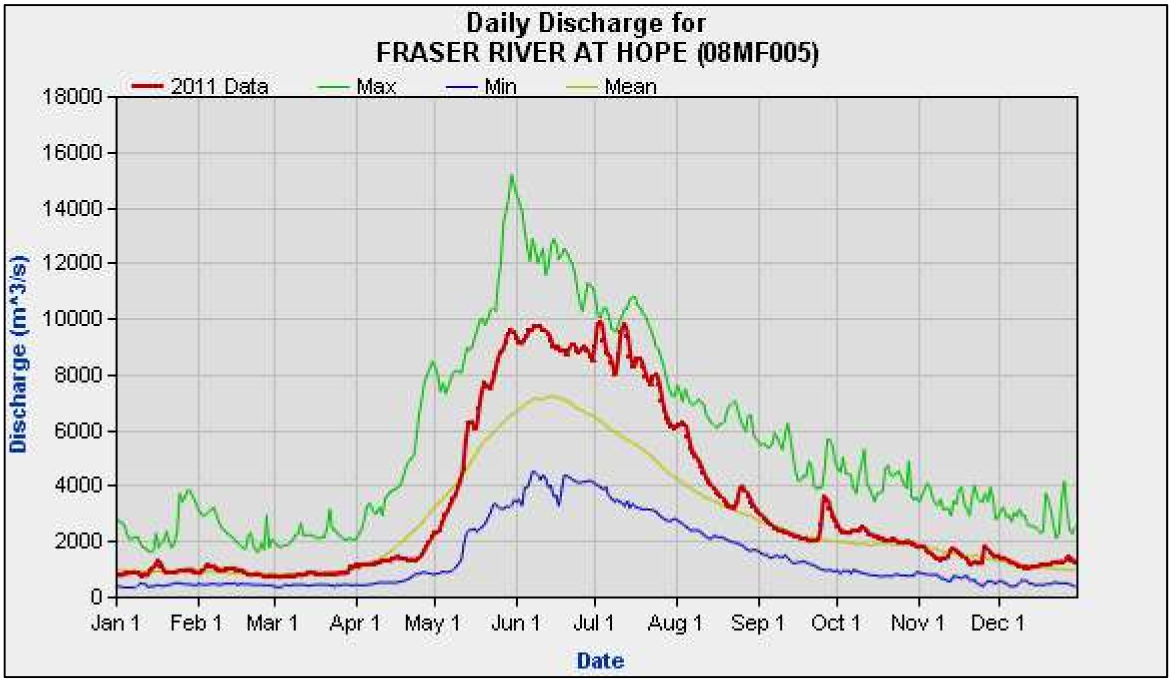


Figure 4: Annual Hydrograph of Fraser River

Estimates of the flow splits in the various branches have changed over time due to effects of river training and dredging. Accurate estimation of the flow splits is complicated by the tidal varying nature of the flow. Early results (Keane 1957) were reported in Water Survey of Canada (1970) and indicated the South Arm conveyed 90% of the flow below New Westminster, 10% of the flow into Ladner Reach and 5% of the flow through Canoe Passage.

In May-June 2002, PWGSC conducted ADCP discharge measurements at several branches of the river in support of flood modelling investigations (NHC 2006). The measurements indicated Annieville Channel carried 80% of the flow measured at New Westminster, while the North Arm and Annacis Channel each carried 10% (Figure 3). Repeat measurements during the 2007 freshet indicated the Annieville Channel carried 78% of the total flow near New Westminster.

3.3 Sediment Loads

Sediment loads on the Lower Fraser River were measured by Water Survey of Canada during the period 1965 to 1986. Based on that data, 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 1988, McLean et al. 1999). The suspended bed material load averaged 2.8 million tonnes/year (range from 9.0 million to 1.2 million). A grain size of 0.18 mm was used to distinguish the bed material load from the wash load. Bed load sampling measurements at Mission and Port Mann indicate that the bed load was less than 5% of the total bed material load.

There are no reliable, long-term sediment transport measurements in the estuary, although considerable effort was made to measure loads at Port Mann during the 1960s (the tidally varying flow conditions made it impractical to determine transport rates reliably). An estimate of the annual bed material load between Mission and the river mouth at Sand Heads was made by McLean and Tassone (1988) 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.

Water Survey of Canada discontinued its program of systematic sediment transport measurements on the Lower Fraser River over 25 years ago, and so it is unclear whether these estimates are representative of present or future conditions. Detailed measurements collected during 2010 are consistent with (but on the low side of) these historical observations (Attard et al. 2014).

3.4 Site Geology

The project site is located where the Fraser River leaves a valley confined between uplands composed of Pleistocene marine, glacial and glaciofluvial sediment and enters its delta. Clague et al. (1983, 1991) have described the evolution of the delta. After the Cordilleran Ice Sheet receded from the area (approximately 11,000 years ago) a saltwater fjord extended inland between the Surrey and Burnaby uplands to approximately the present day location of Maple Ridge. The Fraser then deposited sediment into this embayment, resulting in delta progradation between the confining uplands. The delta front reached the project location at the edge of the confining uplands approximately 10,000 years ago and has pushed out the remaining 20 km to its present location since then (occasionally avulsing between Boundary Bay and the Strait of Georgia).

At the project site, the left (south) bank of the Annieville Channel abuts the Surrey Uplands, which consist of over consolidated Pleistocene Age glacial and interglacial deposits underlying the Capilano unit of the Sumas Drift (Armstrong et al. 1990). Upstream of the Alex Fraser Bridge, the channel parallels the topographic edge of the uplands. At the bridge, the boundary between the uplands and delta curves away from the channel towards the south. Thus, the channel boundary would be expected to transition between alluvial material on the right bank to non-alluvial Pleistocene sediment on the left bank. The non-alluvial material on the left bank would, furthermore, be expected to transition to alluvial material moving downstream from the project site.

Detailed geologic and geophysical investigations were conducted associated with the construction of the Alex Fraser Bridge, which document the geologic composition of the uplands where they intersect the channel (described by Bazett and McCammon 1986). A gravelly Pleistocene-age deposit is present at the channel boundary. It is described as “hard and very dense to openwork, poorly sized, sandy gravel” ranging in size from pebbles to boulders. It is interpreted to be ice-contact deposits that are a part of the Semiahmoo drift. The D_{50} of this material ranges from sand size to 20 mm and the D_{90} from 1 mm to 70 mm. During the design of the Alex Fraser Bridge, this material was considered to be essentially inerodable, but no tests quantifying its erodibility have been conducted. Abrasion by transported sand, severe hydraulic conditions, and heterogeneity of the deposit could all allow local erosion to occur. Similar over consolidated gravelly material is also described in the left bank and under the left portion of the river channel from boreholes along the alignment of the South Surrey Interceptor.

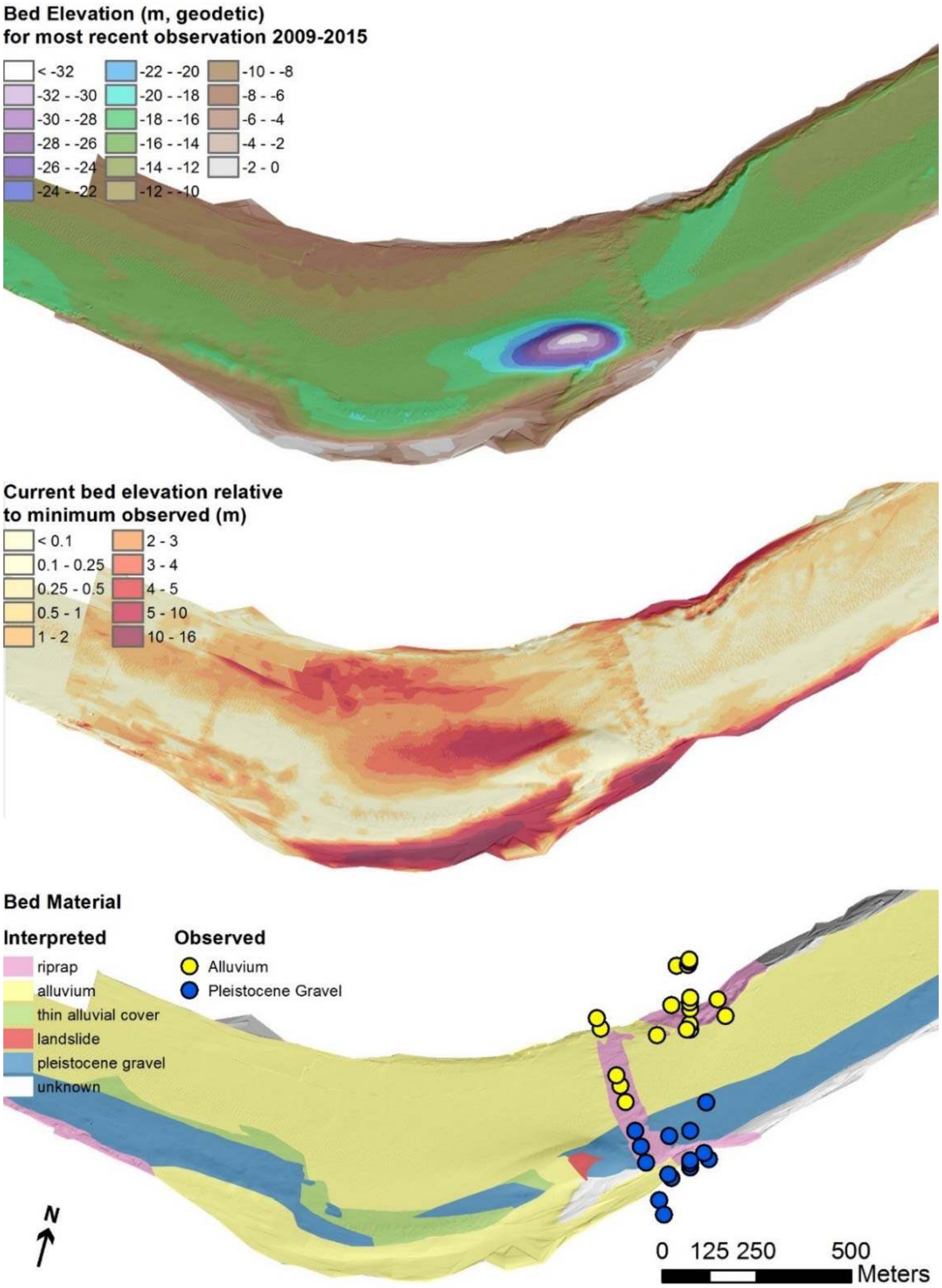


Figure 5: Bed material in the project reach

In addition to the geotechnical observations of the Pleistocene deposit, topographic characteristics observable in high-resolution survey data and historic changes in bathymetry of the river bed can also be used to differentiate between alluvial and non-alluvial channel boundary material (see for example Nittrouer et al. 2011). The current extent of non-alluvial material must lie below the minimum observed historical scour depth. The surface texture of alluvial and non-alluvial material is also distinguishable. For example, the presence of bedforms indicates some depth of alluvial material coverage, while the presence of features such as erosional flutes or kettles indicates eroding non-alluvial material. High local roughness caused by individual pieces of riprap and boulders visible in high-resolution bed topography indicates riprap cover. Figure 5 shows observed and interpreted material at the channel boundary in the vicinity of the project site on the basis of past geotechnical investigations and topographic characteristics of the river bed.

3.5 Navigation and Dredging

3.5.1 Navigation Channel

The navigation channel on the lower Fraser River extends approximately 35 km from Sand Heads to New Westminster. The channel has been deepened and widened over the years to improve navigation. In the 1980s, the channel was used by vessels having a draft of 7.5 m and was deepened further in the 1990s to accommodate vessels having a draft of 10.7m. Between 2004 and 2007, the channel was deepened by dredging to accommodate vessels having a draft of up to 11.5 m. During low tides, the available depths are too low in some sections to allow the vessels to use the channel. Therefore, some degree of tidal assist is required, particularly near the mouth of the river. Table 2 summarizes the navigation channel depths through the St. Mungo's Bend Reach and Annieville Channel Reach that were adopted by in 2010 by Port Metro Vancouver. The design grade through these reaches varies between 10.1 m and 10. 4 m below reference Lowest Low Water (LLW).

Table 2: Fraser River Navigation Channel Design Grades near Project

Reach	Kilometre	Design Grade Below LLW (m)	Underkeel Clearance (m)	Depth Required (m)	Tidal Assist Required (m)
St. Mungo's Bend	27 to 28	10.1	0.9	12.4	2.3
	28 to 29	10.1	0.9	12.4	2.3
	29 to 30	10.1	0.9	12.4	2.3
Annieville Channel	30 to 31	10.2	0.9	12.4	2.2
	31 to 32	10.2	0.9	12.4	2.2
	32 to 33	10.3	0.9	12.4	2.1
	33 to 34	10.4	0.9	12.4	2.0
	34 to 35	10.4	0.9	12.4	2.0

Recent sounding charts (2014) published by PWGSC indicate the design grade was increased to between 10.4 and 10.5 m below LLW. However, a review of the annual navigation surveys from 2014 and 2015 indicate that the actual bed levels in the St. Mungo's Bend and Annieville Channel Reaches are well below the design grade. Figure 6 shows the actual bed levels on the centreline of the navigation channel in 2015 and the channel design grade. The bed levels are below the design grade by more than 2 m in most locations and locally by up to 20 m in the deep scour hole downstream of the Alex Fraser Bridge. The one exception is along the South Surrey Interceptor where a mound of riprap has been placed to protect the pipe. The depths at the crossing are typically about 1 m below the design grade, which means it does not limit vessel operations at the present time.

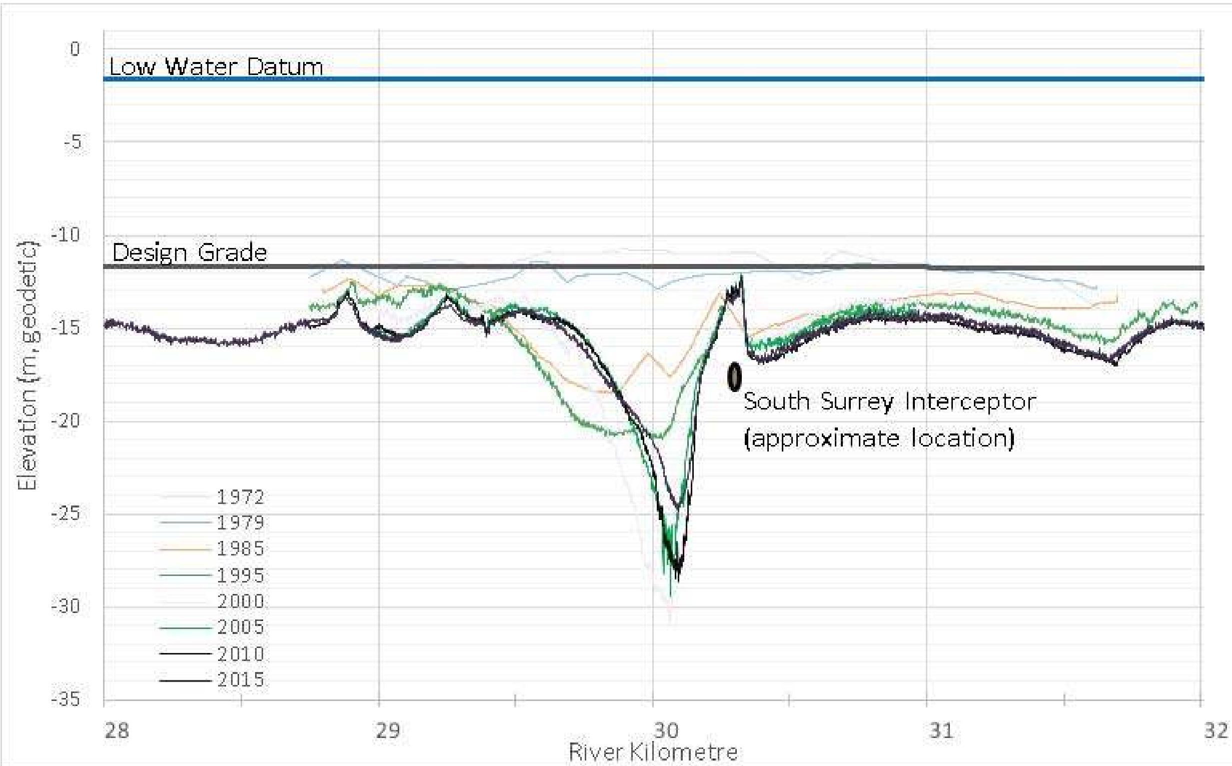


Figure 6: Longitudinal profile showing actual bed levels through time and navigation channel design grade

3.5.2 Dredging and River Training

Dredging on the Fraser River began in 1885 when the main channel was only 2.7 m deep at the river mouth. Documentation of dredging quantities, locations and other details has gradually become more systematic over time due to the efforts of the Canadian Coast Guard and Fraser Port. This has provided a means for reviewing trends and changes to the program over the last 40 years.

Prior to 1957, most dredging was carried out exclusively by Public Works Canada (PWC). Approximately 1.4 million m^3/year of material was dredged from the main arm in the period between 1946 and 1956 (NHC, 2002). In addition to dredging for navigation, industrial borrow dredging has also been carried out by private contractors along the river. Borrow dredging volumes were small prior to 1975. Between 1976 and 1988, industrial borrow dredging often exceeded the navigation dredging volumes. The spoil was used for raising land, as pre-load material or in the construction industry. Canadian Coast Guard maintained responsibility for dredging the river until 1998, at which time they withdrew their program. The Fraser River Port Authority took over the program on the South Arm in 1999. Most dredging on the primary navigation channels is carried out by a trailing suction hopper dredge. The sand is either disposed in an approved ocean disposal site or else is deposited in an underwater transfer pit. In other areas, such as adjacent to the Fraser Surrey Docks, a cutter suction dredge is used to pump sand to an upland disposal site (NHC, 2002). Clamshell dredges are usually used alongside berths.

Figure 7 shows the total dredging (maintenance and borrow) on the main channel, excluding the North Arm. The large removal volumes (4 to 6 million m^3/year) between 1975 and 1992 reflect the borrow dredging activities on the river. Dredging decreased to approximately 2 million m^3/year between 1997 and 2003, then increased to approximately 3 million m^3/year in recent years. The total dredged volume over the last 50 years amounts to 150 million m^3.

Figure 8 shows the dredging effort near the Project site, in the St. Mungo's Bend reach (Km 25 to 30) and in the Annieville Channel (Km 30 to 35). This plot shows dredging in St. Mungo's Bend reached up to 1.4 million m^3/year in the early 1980s, then reduced drastically. Dredging upstream in Annieville Channel was typically 200,000 m^3/year in the 1970s and 1980s and increased in the 1990s to 300,000 to 400,000 m^3/year.

Figure 9 shows the trend in the annual minimum water levels at New Westminster (Km 25) and further upstream at Mission (Km 84) as well as the ocean level at Point Atkinson. At New Westminster, the minimum water level decreased consistently over the period 1960 to 1990, then remained approximately constant. Further upstream at Mission, the water also decreased, particularly over the period 1970 to 2000. A review of discharge data at Hope showed there is no systematic trend in decreasing flows during this period. Therefore, the trend of lower water levels reflects the effect of bed lowering caused by the navigation channel improvements and dredging activity on the lower river.

The main river training near the site took place near the New Westminster trifurcation to control the division of flow between the North Arm, Annacis Channel and Annieville Channel. The main work involved constructing two weirs to limit flow into the Annacis Channel and was completed around 1970.

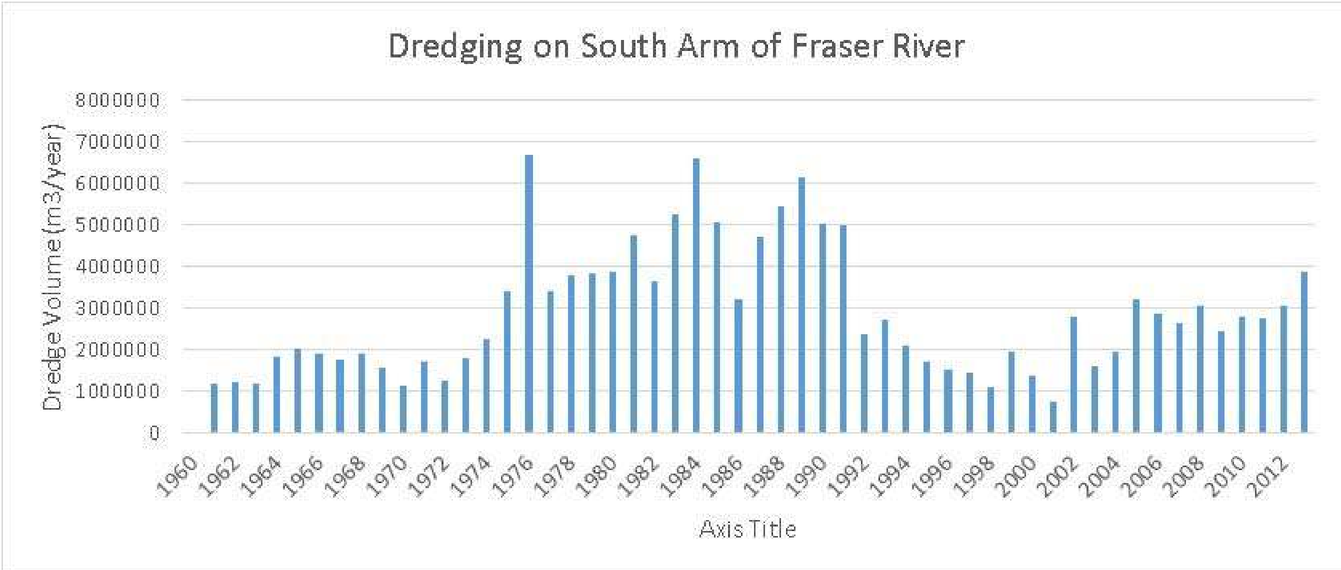


Figure 7: Total Dredging on Lower Fraser River, New Westminster to Sand Heads, excluding North Arm

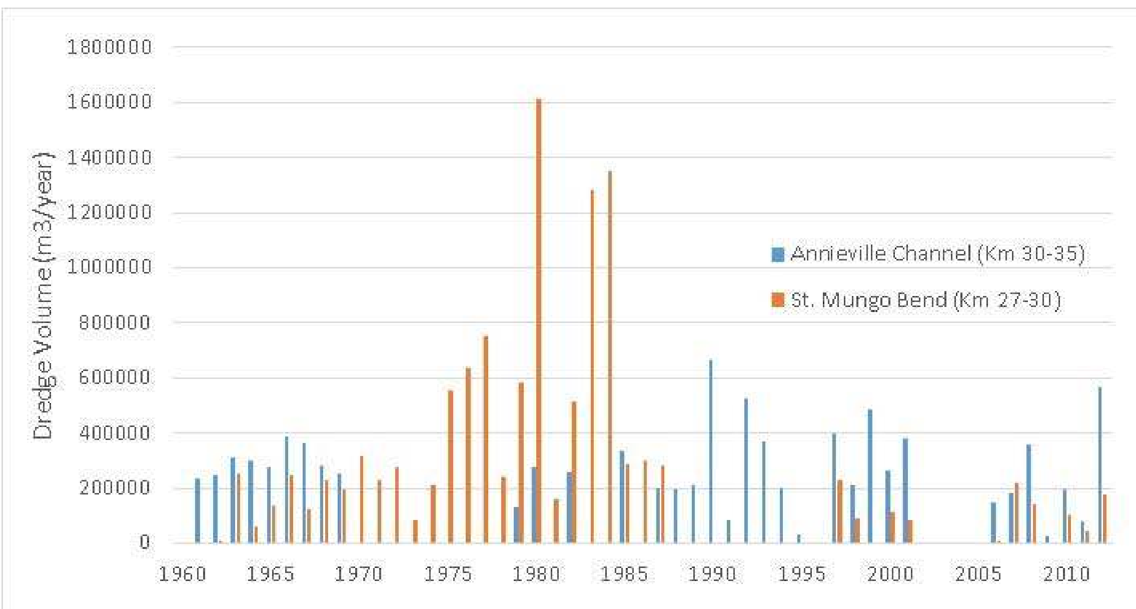


Figure 8: Dredging in Annieville Channel and St. Mungo's Bend

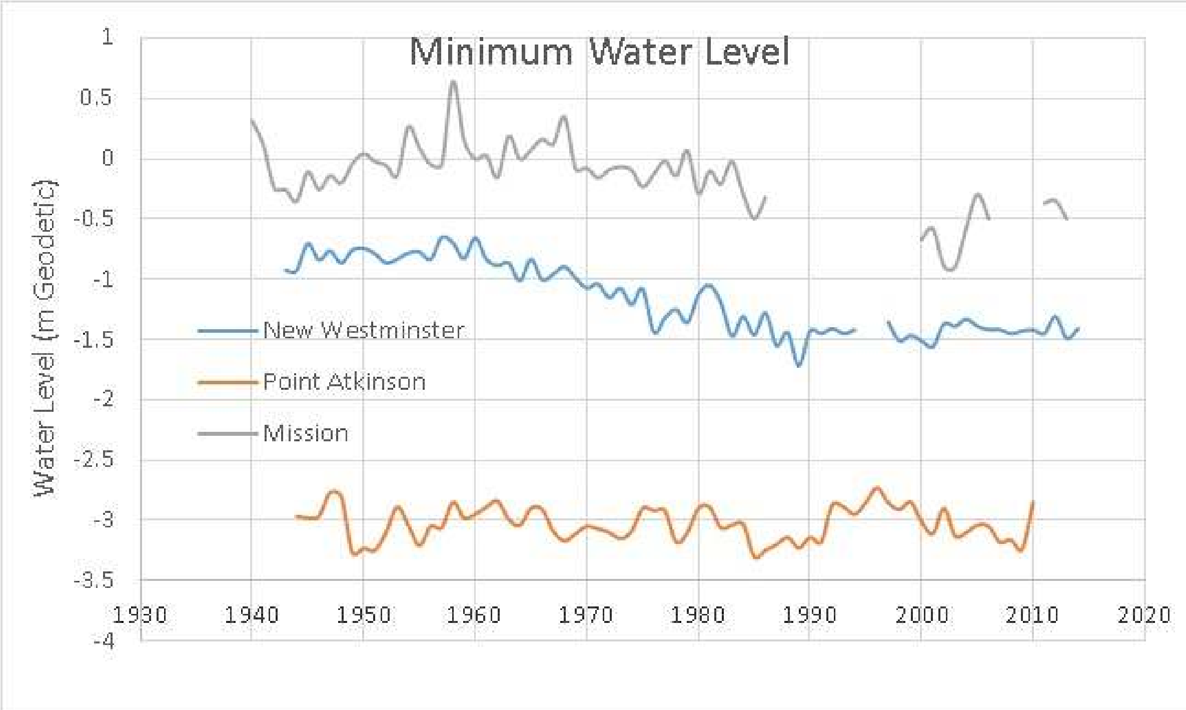


Figure 9: Trends in minimum water levels on Lower Fraser River

3.6 Alex Fraser Bridge

The Alex Fraser Bridge (Photo 1) was constructed in 1984 and has a span of 464 m. The bridge is skewed approximately 30 degrees to the flow (Figure 1), making the effective waterway opening 370 m. The top width of the channel varies between 450 m upstream of the bridge and 800 m downstream. As a result, the bridge forms a significant constriction to the flow. The two main bridge towers are protected against ship collisions with large sand islands that project into the flow forming short guide banks. The south sand island is located on the outside of a gentle bend and creates a prominent back eddy and zone of flow separation downstream of the bridge along the southern third of the channel. The north sand island is more sheltered and has less impact on the approach flows.

Photo 1: Aerial view of Alex Fraser Bridge, viewed from the northwest

4 HYDRAULICS

4.1 Available Information

Background information on general river hydraulic characteristics of the Fraser River was based primarily on results from NHC's one-dimensional hydrodynamic model (Mike-11) of the Lower Fraser River (NHC 2008). This model extends approximately 170 km from the town of Hope to the Strait of Georgia. Discharges are specified at the upstream boundary using the discharge data at the Hope hydrometric station (08MF005). The downstream boundary is set using tide levels at the mouth of the three main distributary branches: South Arm, North Arm and Canoe Pass.

A detailed three-dimensional hydrodynamic model of the Annieville Channel was developed between km 27 and km 35 in order to simulate the local hydraulic conditions and to aid the fluvial geomorphology assessment.

4.2 1 D Model Results

Peak water levels at the site occur during two times of the year:

- During the freshet season (May to July) when high river discharges coincide with high tides.
- During the winter months (December and January), when large astronomical tides coincide with storm surge events in the Strait of Georgia. At these times, the flow in the river is much less than during freshet conditions.

Downstream of Alex Fraser Bridge, the highest water levels are governed by winter high tides and storm surges. Upstream of the bridge, the highest water levels occur during the freshet period (NHC 2006). Table 3 summarizes information on various flood events. These values do not include any provision for future sea level rise or climate change.

The daily range in water levels due to the tide depends on the magnitude of the river discharge and the tidal range in the Strait of Georgia. During freshet floods, the daily variation may be as low as 1.0 m. During winter months, the diurnal tidal range can exceed 2.5 m. The lowest water levels generally occur in the months of January to March, during times of low river inflow and low tides.

Figure 10 shows the frequency distribution of water levels at the site from a one year simulation of water levels over the period January 1 to December 31, 2012.

Table 3: Key water levels near project site

Condition	Water Level (m Geodetic)
500-Year Freshet Flood	3.3
2012 Flood (approximately 20-year event)	2.4
Lowest Low Water	-1.58

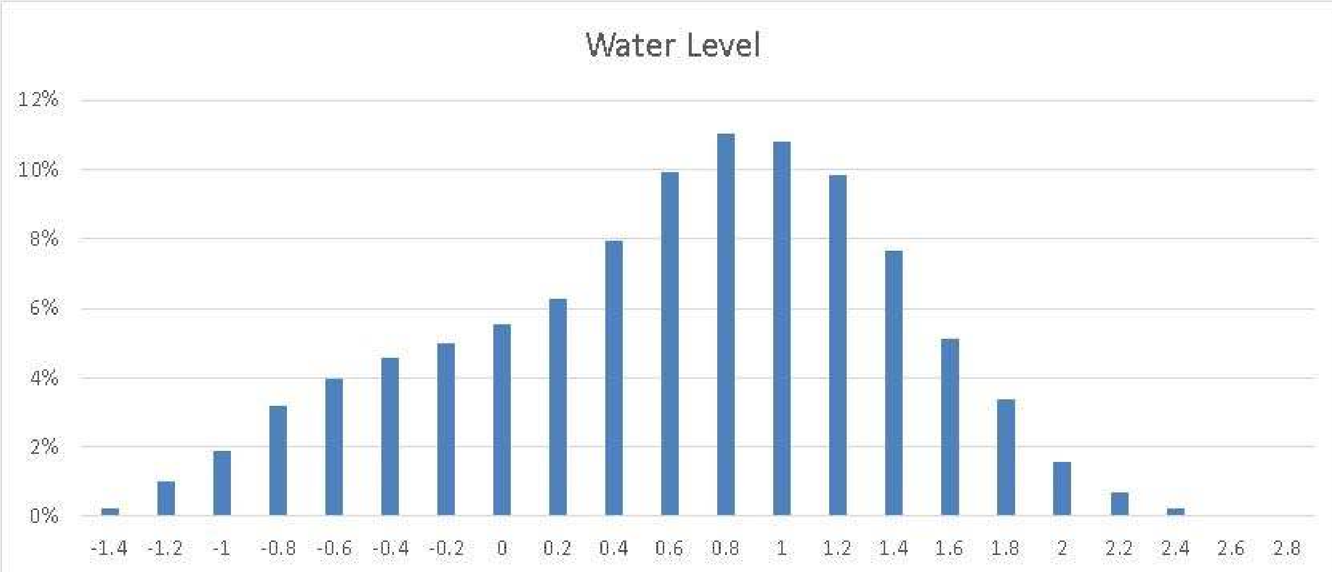


Figure 10: Frequency of water levels over the period January 1 to December 31, 2012 at project site

The highest velocities at the site occur during the freshet season when high river discharges coincide with large tidal swings during ebb tide conditions. Figure 11 illustrates the variations in water levels and mean velocities over two days during two simulated flood conditions:

- 1894 flood, coinciding to a 500-year return period
- 2012 flood, coinciding to a 20-year return period event.

This plot shows that the velocity ranged from 2.8 m/s to 2.1 m/s during the 1894 event and from 2.5 m/s to 1.2 m/s during the 2012 event.

Figure 12 shows a frequency histogram of mean channel velocity over the 12 month period in 2012. During freshet season (typically May through July), the river flow does not reverse over a tidal cycle and the salt wedge remains downstream of the site, near the river mouth. In 2012, upstream (reversing) flow occurred 22% of the time. Periods of reversing flow first occurred in early August, when the discharge at Hope was below 5000 m^3/s. The tidal range and river discharge both influence when the river is subject to reversing flows.

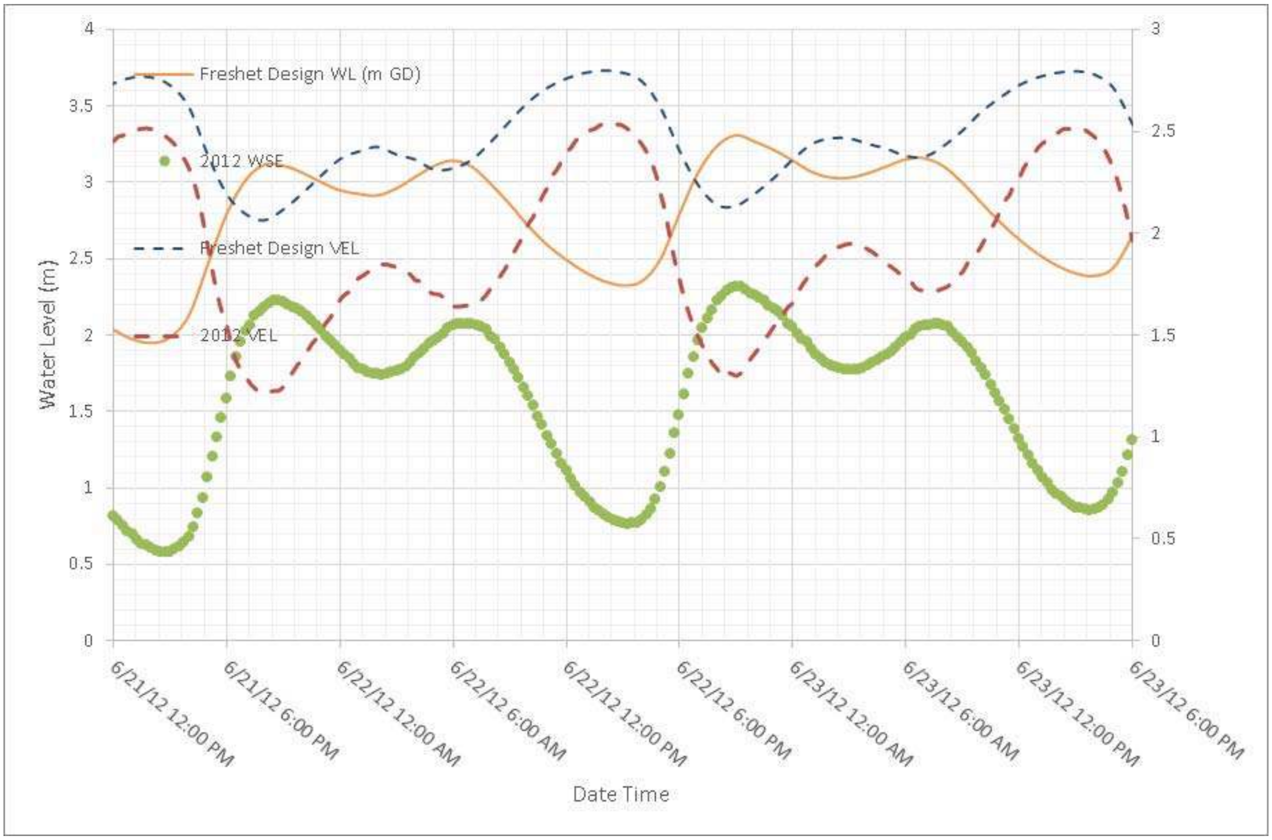


Figure 11: Tidally varying water level and mean velocity during two freshet flood conditions

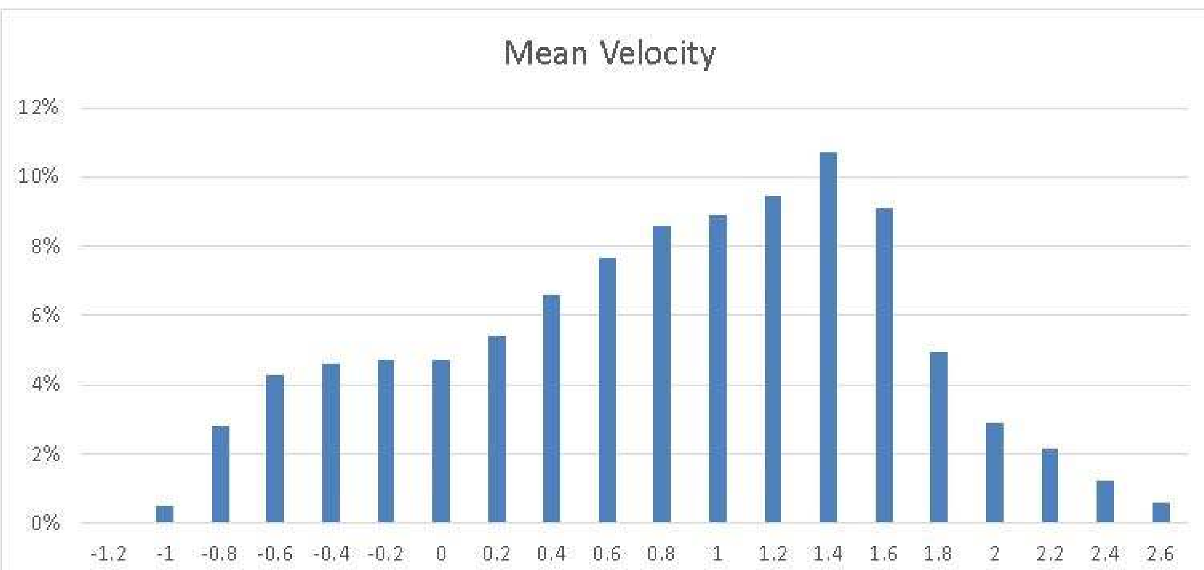


Figure 12: Frequency of channel velocity over the period January 1 to December 31, 2012 at project site

4.3 Detailed Three-Dimensional Hydrodynamic Model

4.3.1 Model Development

A three-dimensional hydrodynamic model was developed to simulate the detailed local hydraulic condition in the project site under design flood events. The resulting bed shear stress map is used to aid the fluvial geomorphology assessment. The model used for the study is Delft3D, a 3D hydrodynamic model which calculates non-steady flow and transport phenomena that result from tidal and river flow forcing on a rectilinear or a curvilinear grid. Delft3D uses a finite difference scheme that numerically solves the horizontal momentum equation and includes discharge sources. The equations and model description are provided in detail in Lesser et al. (2014).

The curvilinear model grid extends from New Westminster (km 30) to just downstream of the Annacis Island (km 27) as shown in Figure 13. The model consists of a variable horizontal grid spacing with the finest grid resolution in the vicinity of the South Surrey Interceptor crossing where it is approximately 5 m. In the vertical direction, the model grid consists of 50 fixed z-layers with uniform layer thickness of 0.5 m. At the upstream and downstream ends of the model, river flows and water levels were computed using the Fraser River Mike-11 model.

The model bathymetry for the model is derived using the following datasets:

- 2013 Fugro Pelagos bathymetry survey; and
- 2014 PWGSC (Public Works and Government Services Canada) bathymetric surveys.

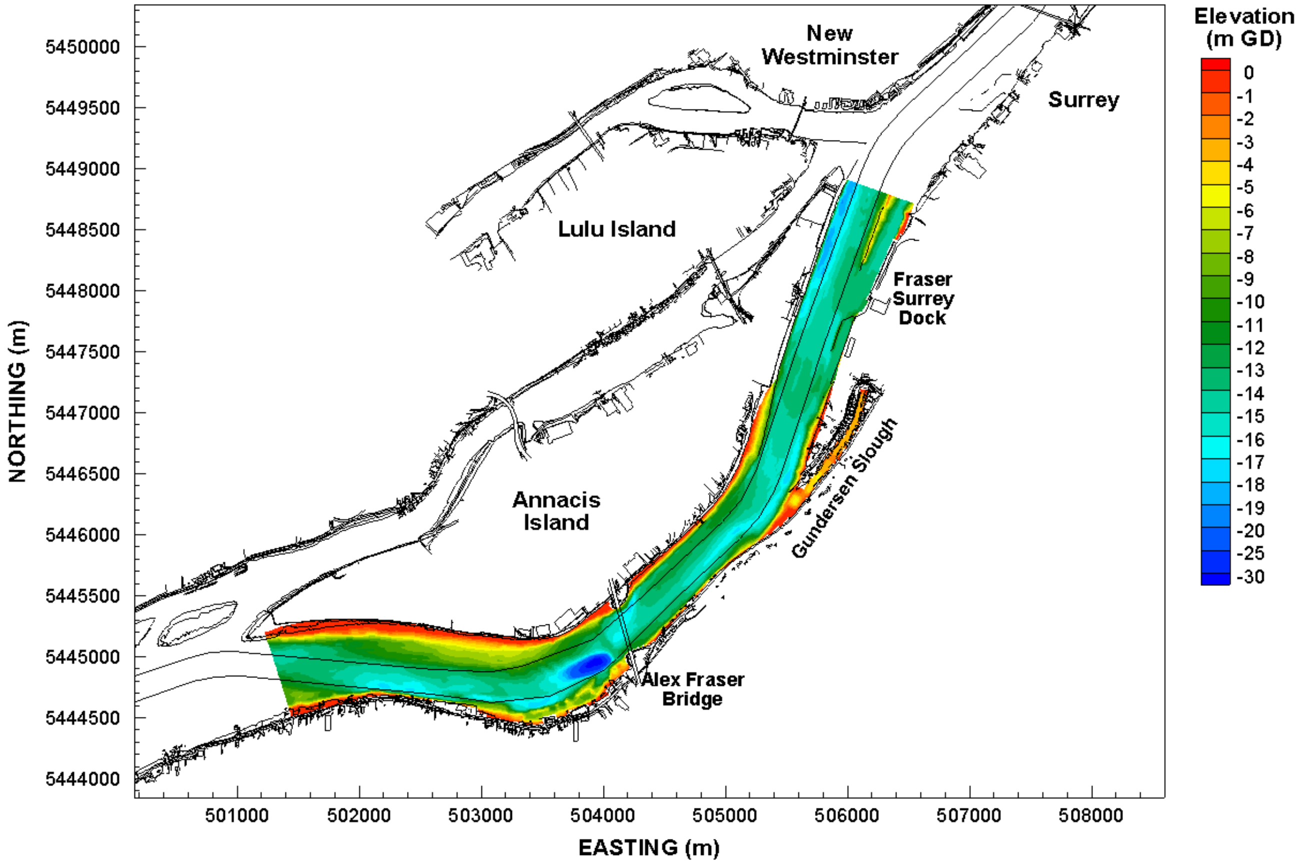


Figure 13: Numerical model spatial extent and elevation

4.3.2 Model Validation

The hydrodynamic model was validated by comparing the model results to the velocity measurements from the March 15th, 2013 acoustic Doppler current profiler (ADCP) survey. Figure 14 shows the survey transect conducted across the project site around noon on Marcth 15th, 2013. The measured flow discharge was approximately 7,000 m^3/s. The background GoogleEarth image was taken on June 19th, 2012 which illustrates the eddies along the left bank immediately downstream of the southern ship collision structure.

Figure 14: March 15th, 2013 ADCP survey transect location

Measured and modelled velocities are shown in Figure 15 and Figure 16.

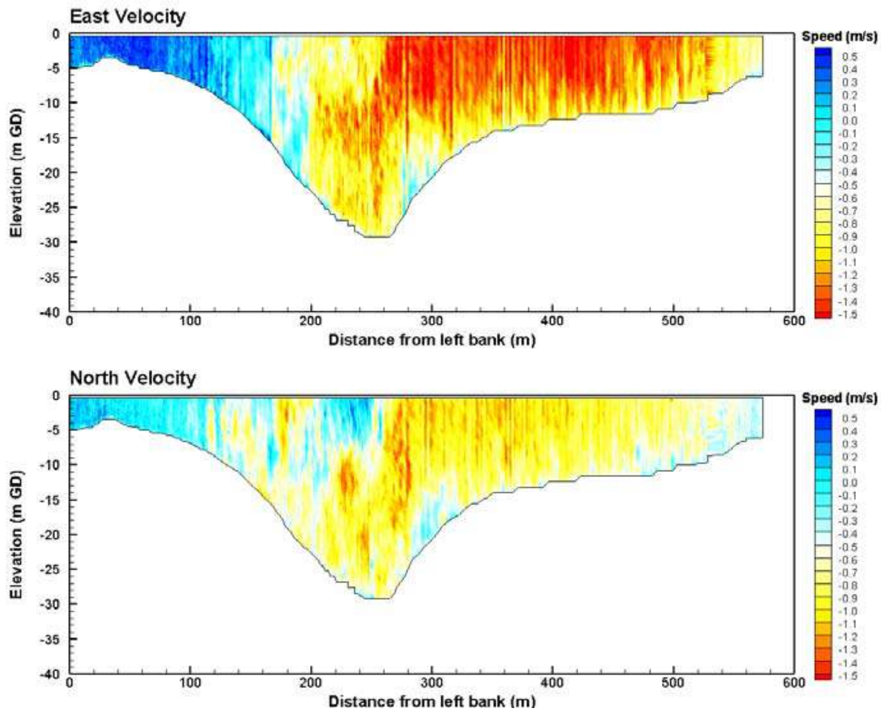


Figure 15: March 15th, 2013 ADCP survey EAST and NORTH velocities

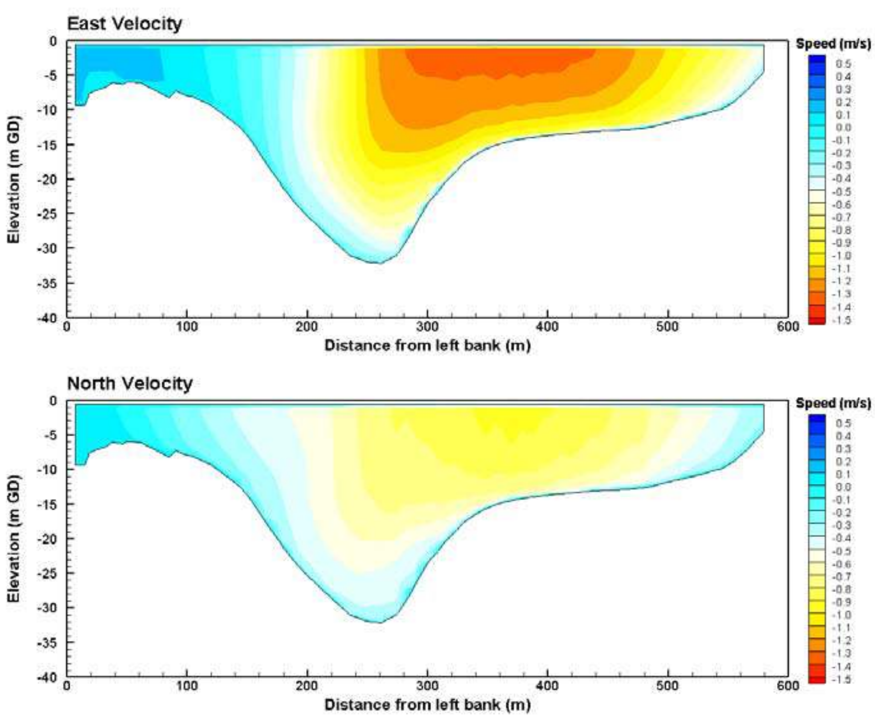


Figure 16: March 15th, 2013 Modelled EAST and NORTH velocities

The computed results capture the same general features observed in the ADCP survey, particularly the region of higher velocity on the right (north) part of the channel as well as the location of the back eddy and zone of flow separation on the left bank downstream of the bridge. Modelled surface velocities are shown in Figure 17. A uniform velocity vector is shown for every two model grid points to illustrate the flow pattern. Surface velocities in the middle of the navigation channel upstream, on top of, and downstream of the blanket are 1.5, 1.7, and 1.6 m/s, respectively.

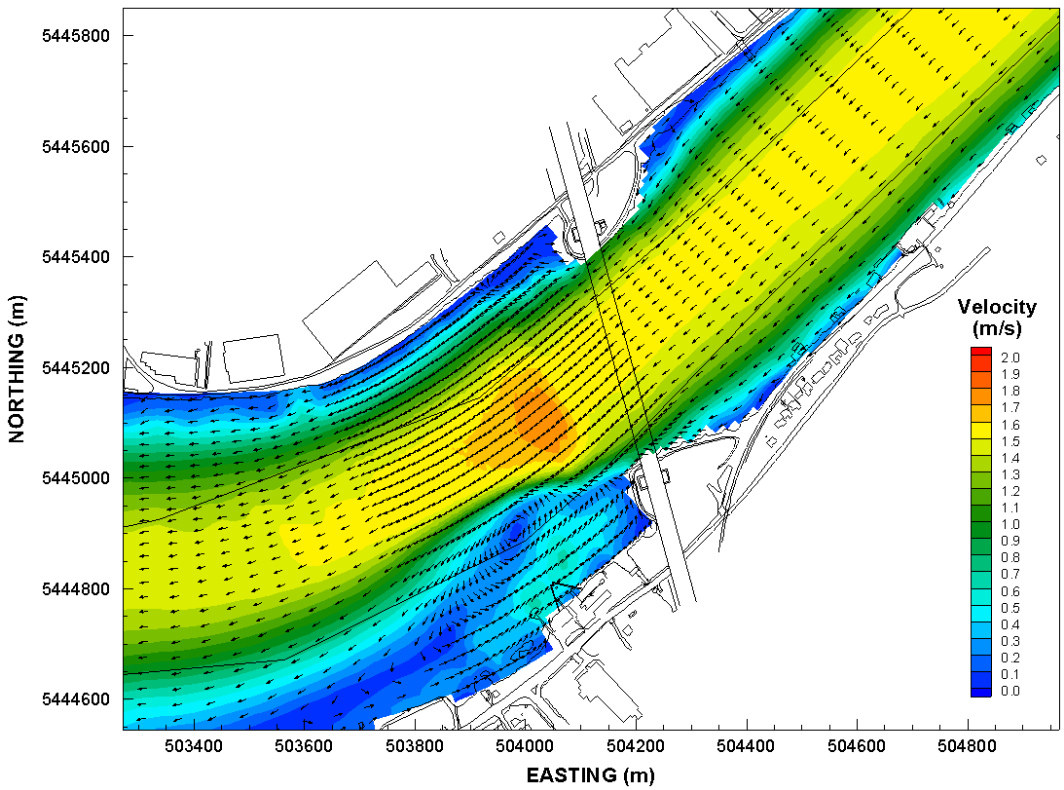


Figure 17: March 15th, 2013 Modelled surface velocity

4.4 Simulated Flood Events

Two design events were simulated and the corresponding hydraulic information such as flow pattern and bed shear stresses are used to assist with the geomorphological assessment to determine the potential scour. These two design events are:

- 200-yr event – upstream discharge of 13,287 m^3/s and downstream elevation of 0.32 m.
- 1894 event (500-yr event) – upstream discharge of 14,985 m^3/s and downstream elevation of 1.83 m.

Modelled bed shear stress maps for the 200-yr event and 1894 event are shown in Figure 18 and Figure 19.

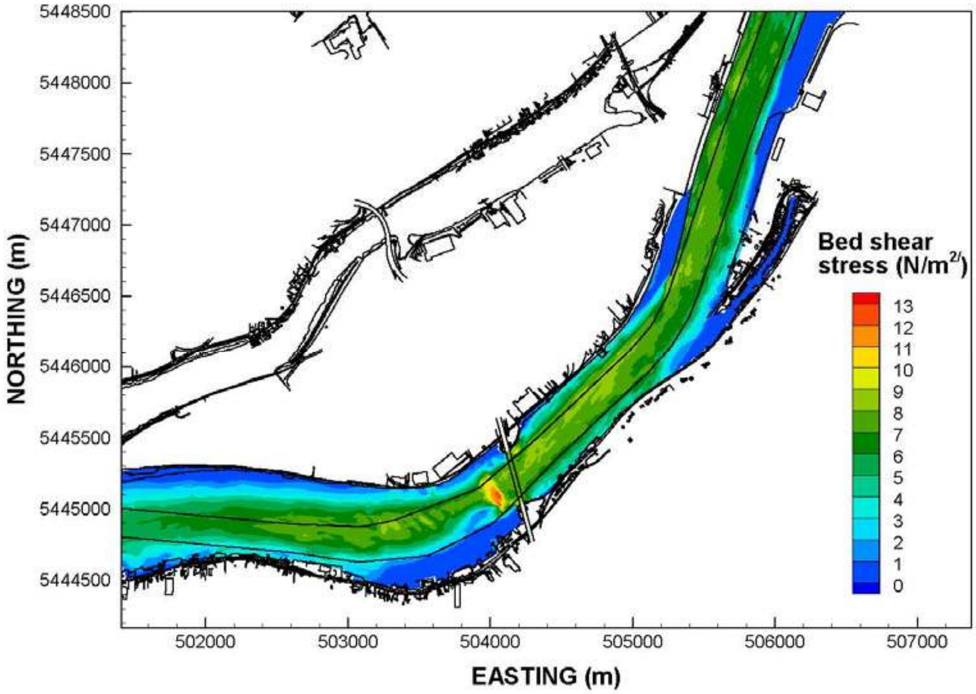


Figure 18: Bed shear stress map – 200yr flood event

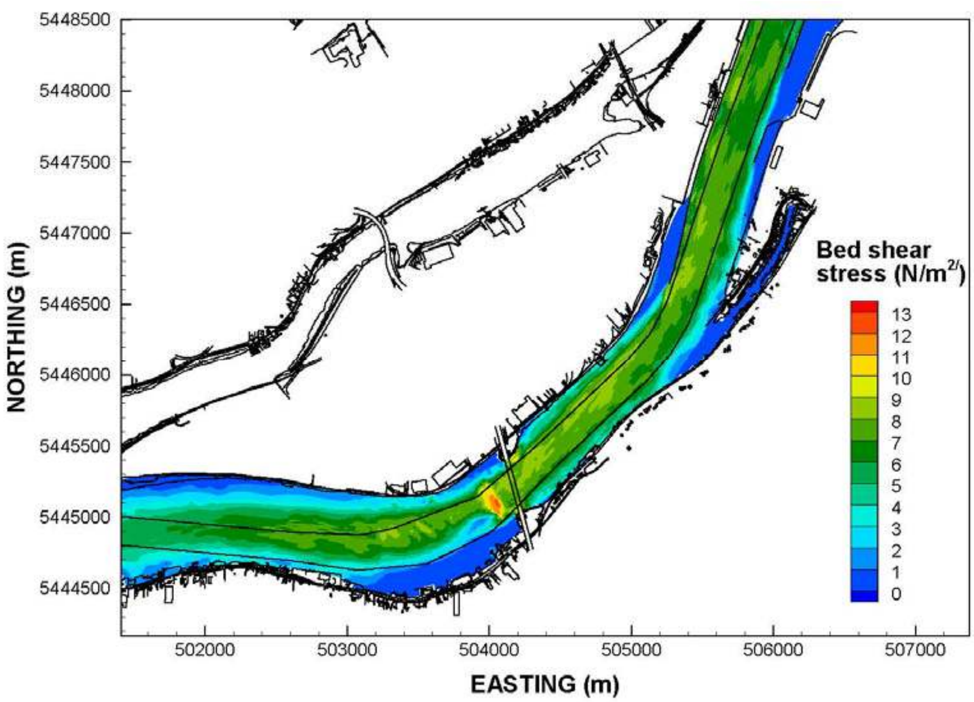


Figure 19: Bed shear stress map – 1894 flood event

The maximum bed shear stresses predicted by the model for these two design events are similar. The bed shear stress within the navigation channel is about 7 to 8 N/m^2. Maximum bed stress is about 13 N/m^2 and occurred over the South Surrey Interceptor. This value is close to the critical bed shear stress for medium gravel (16 mm) of 12.2 N/m^2.

5 HISTORICAL CHANNEL CHANGES

The channel has responded dramatically to the hydraulic changes imposed by the ship collision structures at Alex Fraser Bridge and by the riprap blanket over the South Surrey Interceptor. A scour hole reaching below -32m geodetic has formed where once the bed was at an elevation of -10 m. This section discusses the evolution of this scour hole and accompanying channel bed changes in detail.

5.1 Assessment Approach

Large-scale historical channel changes were evaluated using bathymetric survey data spanning the period 1972 to 2015. Since the early 1970s, these surveys have been conducted on a nearly annual basis during the winter low-flow period and periodically during freshet flood flows. Electronic data for the period from 1998 to the present were obtained from Public Works and Government Services Canada (PWGSC) for annual surveys and selected freshet monitoring surveys. Printed charts for the period from 1972 to 1988 were digitized by NHC. Surveys from 1972 to 1988 typically have points spaced 30-40 m along cross sections that are spaced approximately 150 m apart. Surveys from 1989 to 1994 have points spaced 1-2 m along cross sections spaced approximately 40 m apart. Surveys from 1995 to 2011 utilized a multi-track sounder and resulted in complete grid coverage of the center of the channel at a spacing of approximately 1.5 m with cross sections spaced approximately 50 m apart and extending towards the channel margins. Data for 2013-2015 are from very high-density multibeam bathymetric surveys including one acquired by Fugro Pelagos Inc. (2013).

Bed elevations in these datasets are referenced to a locally stepped low water datum, which varies along the channel and has also varied significantly through time. NHC converted these depth values to Geodetic elevation by applying correction factors recorded in the metadata for the PWGSC dataset. Point data for each survey period were then loaded into an ARCGIS Triangular Irregular Network (TIN) and gridded at a 1m cell size.

Several derivative products were then created to visualize this dataset. These include:

- An animation showing bed elevation changes through time and key infrastructure changes that influenced reach hydraulics.
- Maps showing bed elevations at selected years included in this report.
- Bed elevation profiles extracted along nine cross sections, three longitudinal paths, and three additional longitudinal paths crossing the area of potential locations for new effluent diffusers.

The animation has been archived at the following internet location: http://i.imgur.com/pTawJ4q.gifv. This animation provides one of the most accessible ways to visualize the changes discussed below and it is recommended that readers view it along with figures embedded in this report while reading the following text. Figure 20 through Figure 22 illustrate changes in conditions along long profiles and cross sections throughout the project area.

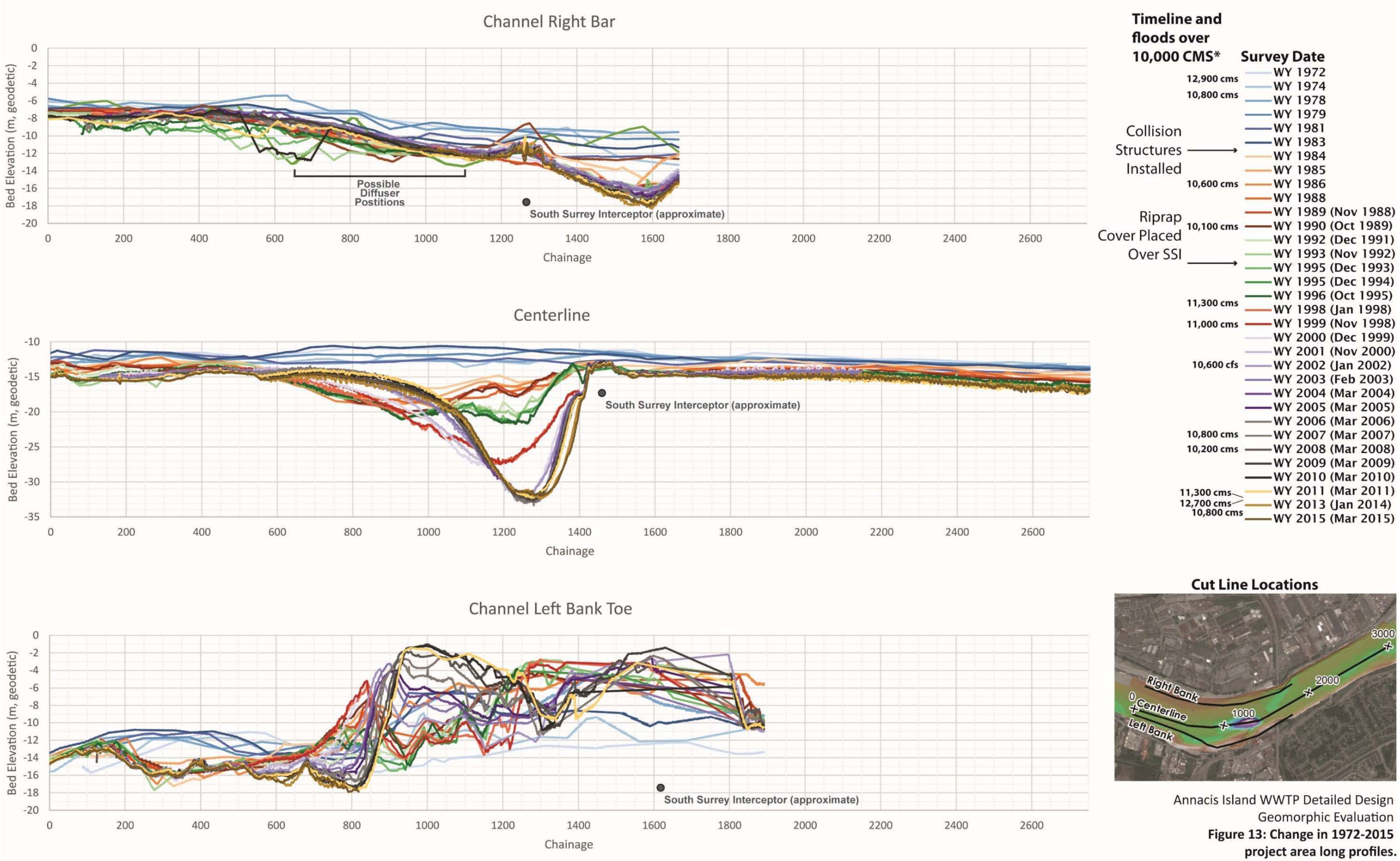


Figure 20: Change in 1972-2013 project area long profiles

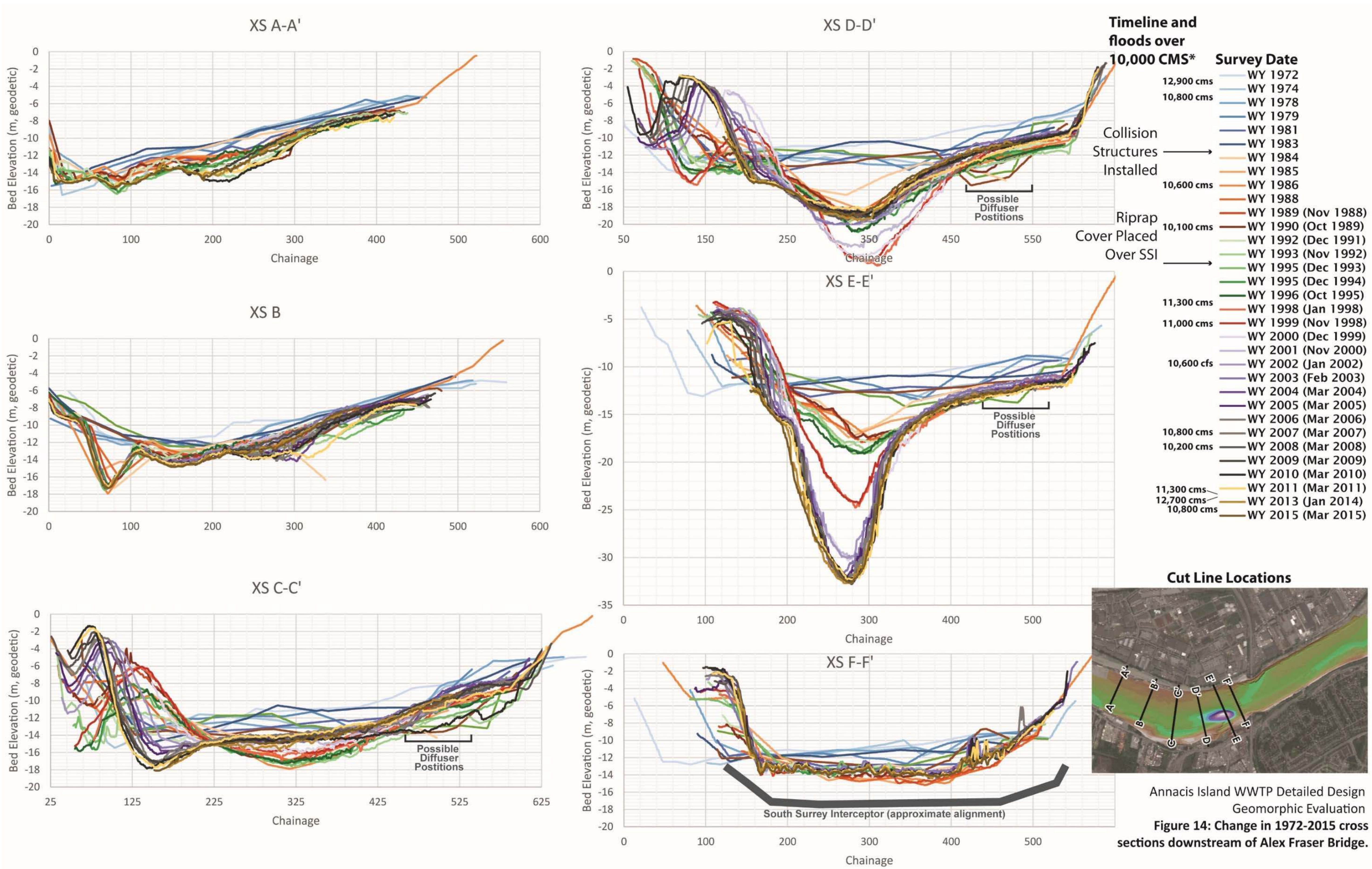


Figure 21: Change in 1972-2013 cross sections downstream of Alex Fraser Bridge

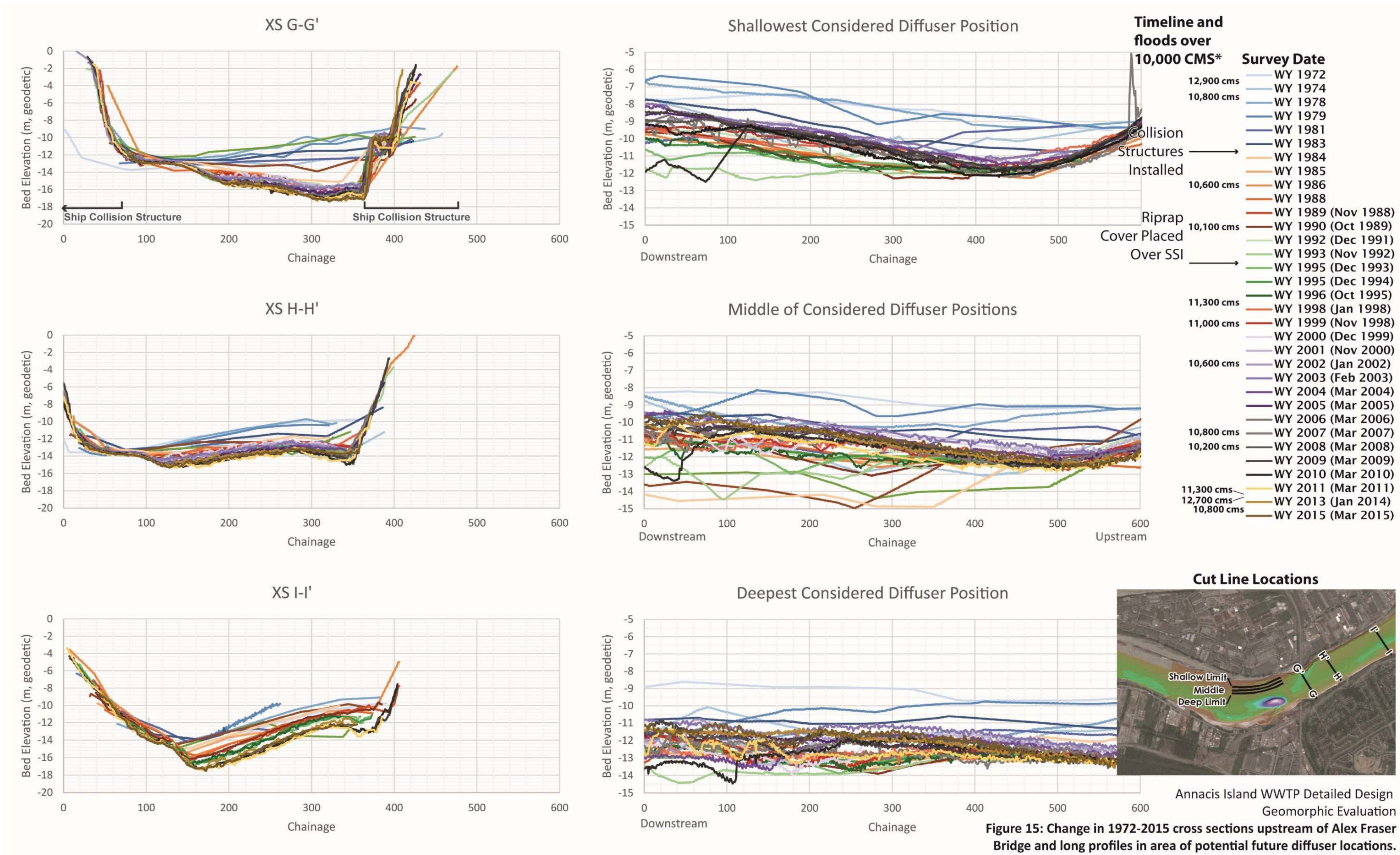


Figure 15: Change in 1972-2015 cross sections upstream of Alex Fraser Bridge and long profiles in area of potential future diffuser locations.

Figure 22: Change in 1972-2013 cross sections upstream of Alex Fraser Bridge and long profiles in area of potential future diffuser locations

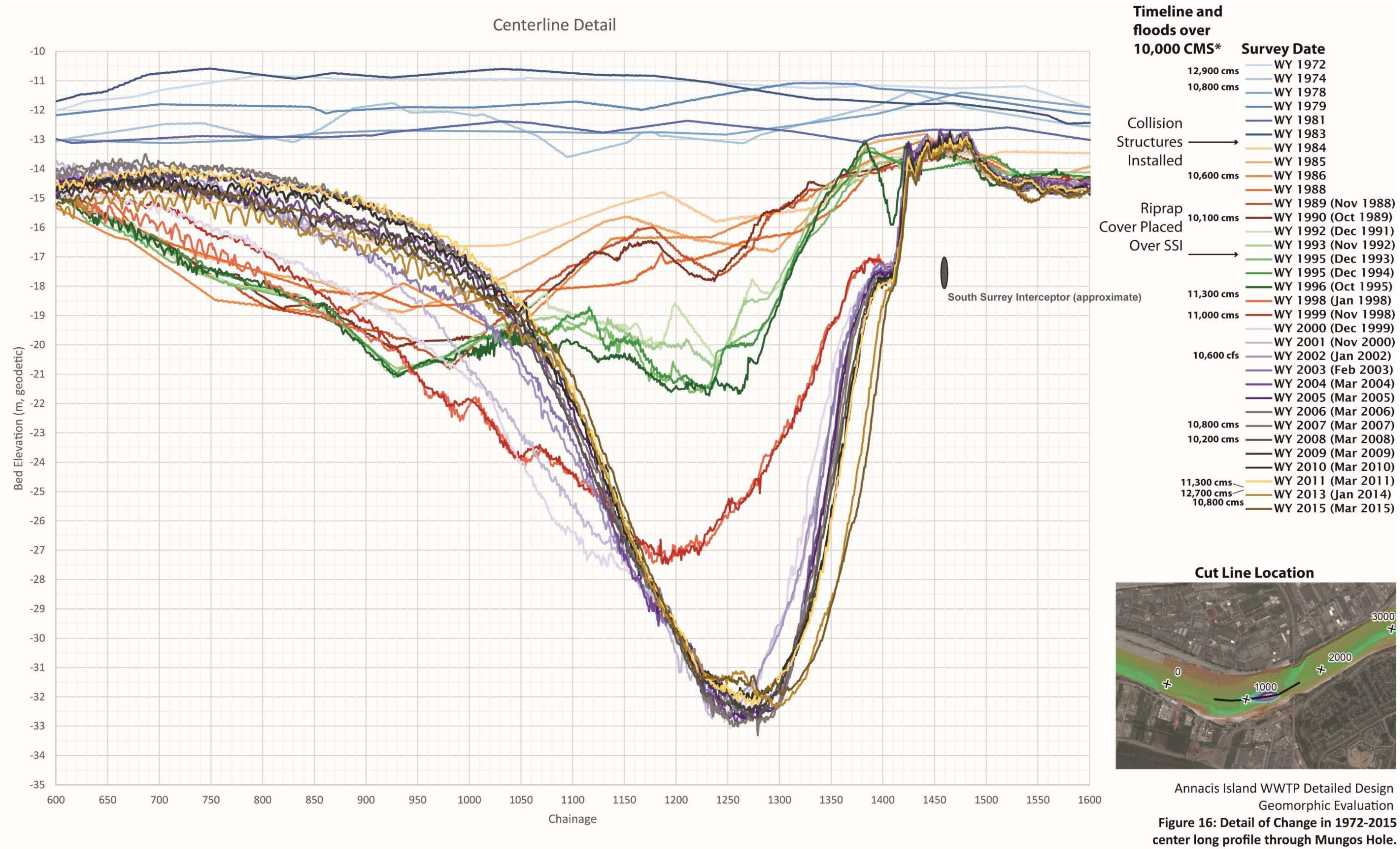


Figure 23: Detail of Change in 1972-2013 center long profile through St. Mungo's Bend Scour Hole

5.2 Observed Channel Changes

5.2.1 1963-1983: Pre-Bridge and Reach-wide Trends

Prior to construction of the Alex Fraser Bridge, the Annieville Channel in the project area had a fairly simple morphology, as illustrated in the 1974 bathymetry (Figure 24). Upstream of the present location of the Alex Fraser Bridge, the straight channel had a simple, approximately trapezoidal cross section (Figure 22 XS G-G' through I-I'), with thalweg elevations of approximately -14m.

Downstream of the bridge location, the channel makes a gentle right bend. Prior to construction of the bridge, hydraulics associated with this bend concentrated flow along the left bank, resulting in scour to an elevation of approximately -15 m at the outside of the bend (Figure 21 XS C-C') and presence of a large bar on the right bank (XS A-A' and B-B').

Through no major local perturbations were present in the reach prior to construction of the Alex Fraser Bridge, the bed elevation in the Annieville Channel has progressively lowered. Between 1963 and 1983, the average bed level at the navigation centerline in the Annieville Channel lowered from -10.3 m to -12.7 m (NHC 2002). At the upstream-most cross section in the project area, the typical bed elevation lowered by 2-3 m between 1972 and 1983 and an additional 2-3 m between 1983 and the present (Figure 22 XS I-I').

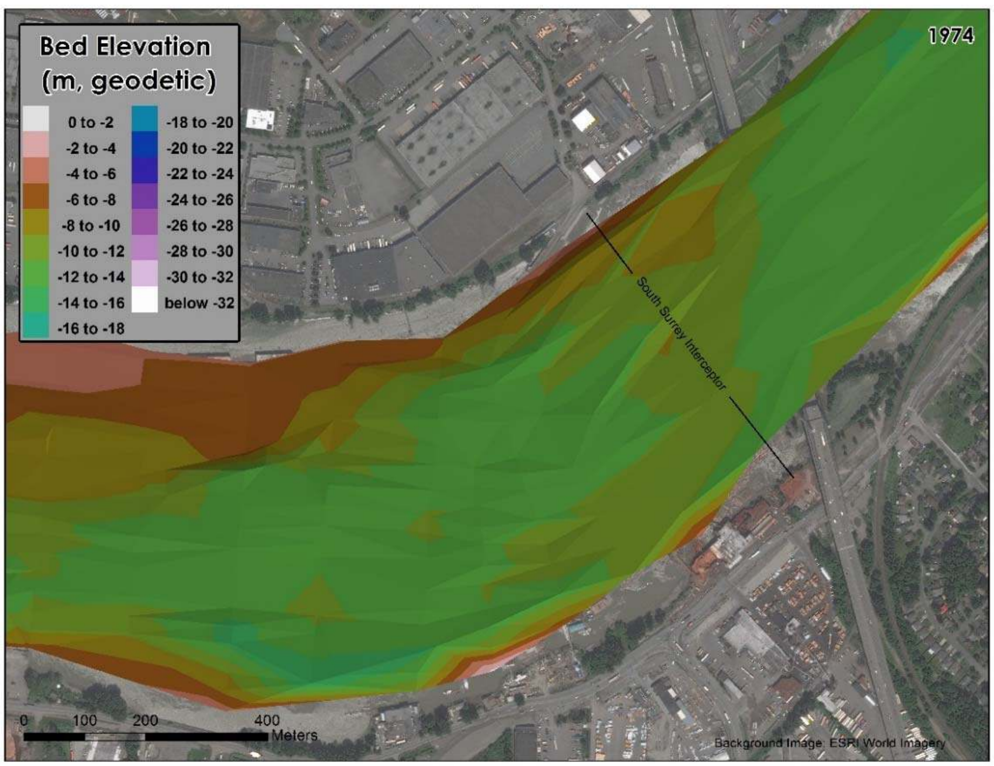


Figure 24: 1974 Bathymetry

5.2.2 1984-1994: Impact of Alex Fraser Bridge

Construction of the ship collision structures protecting the Alex Fraser Bridge created a major hydraulic perturbation, pushing flow away from the banks and toward the center of the channel. The first freshet after the ship collision structures were constructed shifted the deepest point in the channel from the outside of the bend towards the center of the channel, lowering the minimum bed elevation from approximately -15 m to -17 m and lowering the local bed elevation in the center of the channel from approximately -12 m to -17 m (Figure 21 XS C-C', D-D' and Figure 25).

The scour hole downstream of the ship collision structures progressively lowered by several metres over the next decade, reaching a minimum elevation of approximately -22 m by 1994 (Figure 26). During this time, the deepest point of the hole shifted gradually upstream, but it maintained an elongated shape. A large bar grew on the left (north) bank, filling what had been the deepest part of the channel prior to the bridge to an elevation of approximately -7 m (Figure 21 XS C-C').

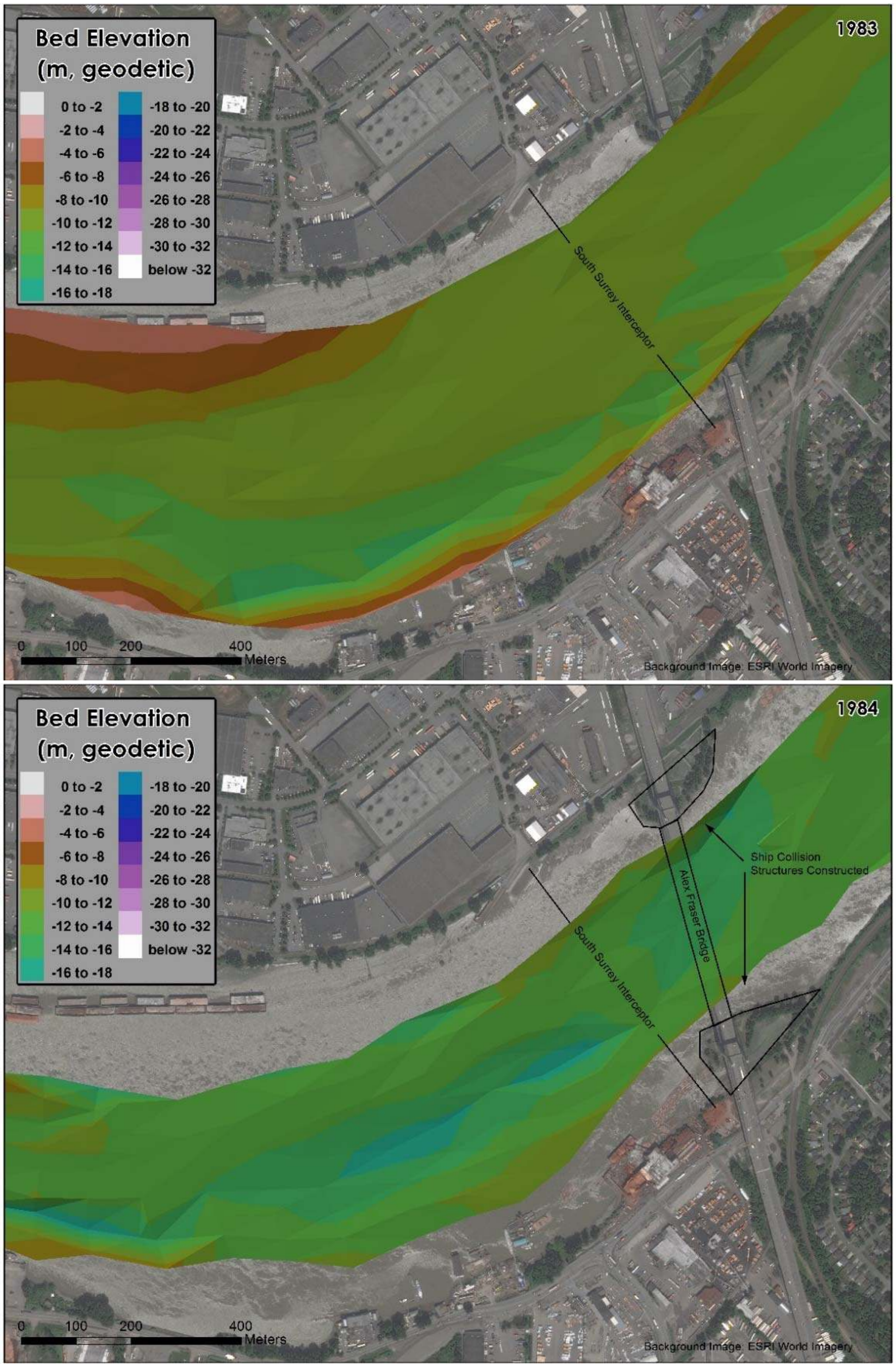
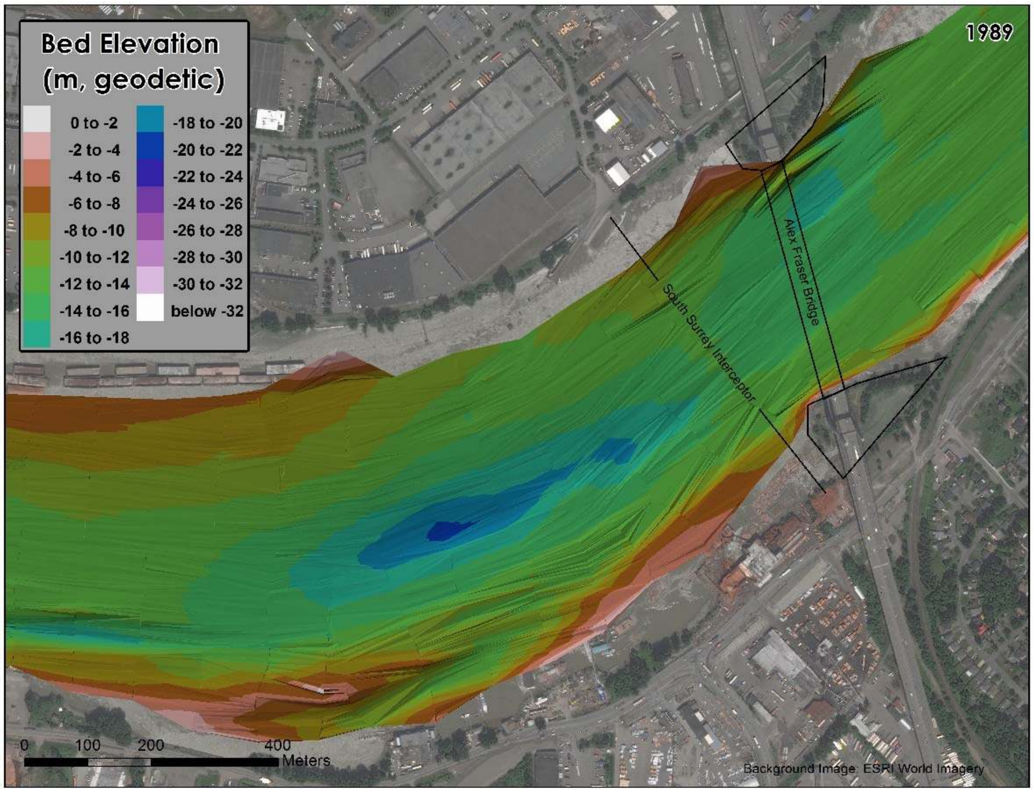


Figure 25: Comparison of channel bathymetry immediately prior to and after construction of the Alex Fraser Bridge ship collision structures. Note abrupt lowering the center channel bed.



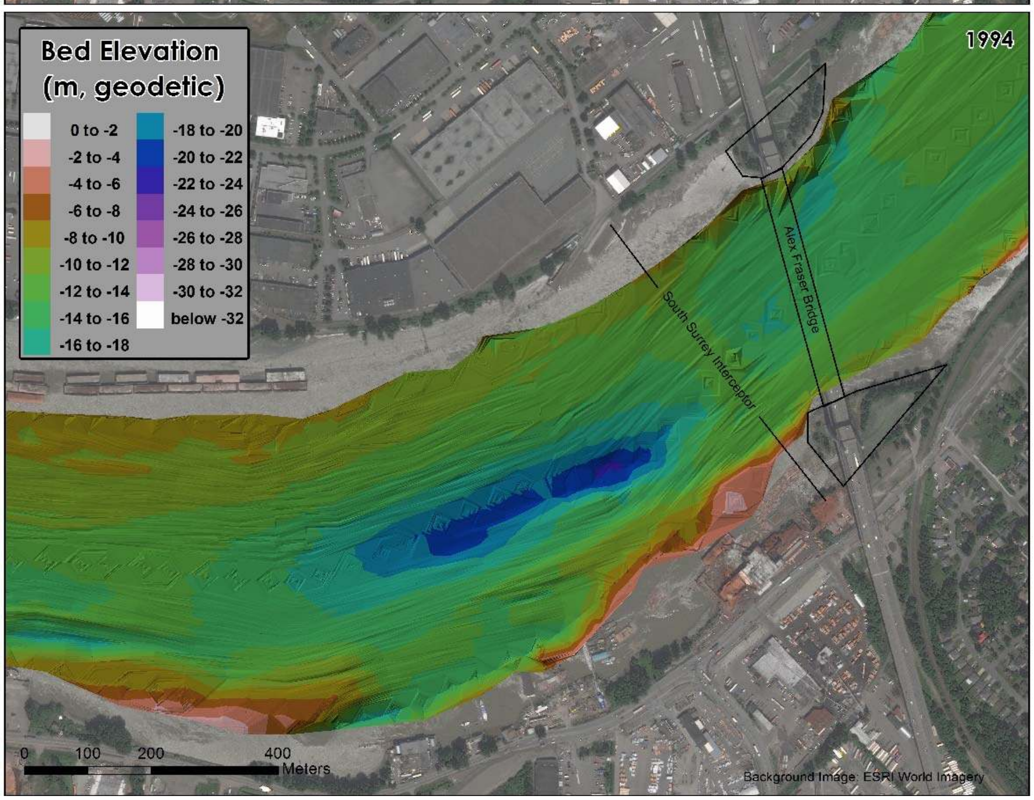


Figure 26: Comparison of reach bathymetry in 1989 and 1994

5.2.3 1995-Present: Impact of Pipeline Scour Protection

Between December 1994 and October 1995, the survey data indicates that additional riprap was placed to an elevation approximately 1m above the typical bed elevation at the South Surrey Interceptor (Figure 27). The bed immediately scoured by approximately 2 m 10 m downstream of the edge of the riprap and by approximately 1.5 m in the area 10-40 m upstream.

These changes were minor, however, compared to those following the first major flood after the new riprap was installed. The elongate scour hole that had formed downstream of the bridge transformed by deepening, widening, and shifting upstream. The largest changes occurred between 1995 and 2000, a period with two floods of 11,000 m^{3}s or greater (compare Figure 26 and Figure 28). Between 1995 and 1998, the minimum bed elevation lowered from -22 to -27 m; and it lowered further to -32 m by December 1999.

The thalweg elevation has remained approximately constant since 2000, but the position of the deepest point in the channel and the upstream slope of the scour hole have shifted progressively upstream over time. Between December 1999 and March 2011, the deepest point shifted approximately 40 m upstream and the upstream slope shifted approximately 30 m upstream. The 2012 flood affected further change, causing the upstream slope to shift another 30 m upstream, nearly eliminating the buffer "shelf" that had persisted between the scour hole and edge of riprap (Figure 29). Little change has occurred in the bed topography between 2013 and 2015.

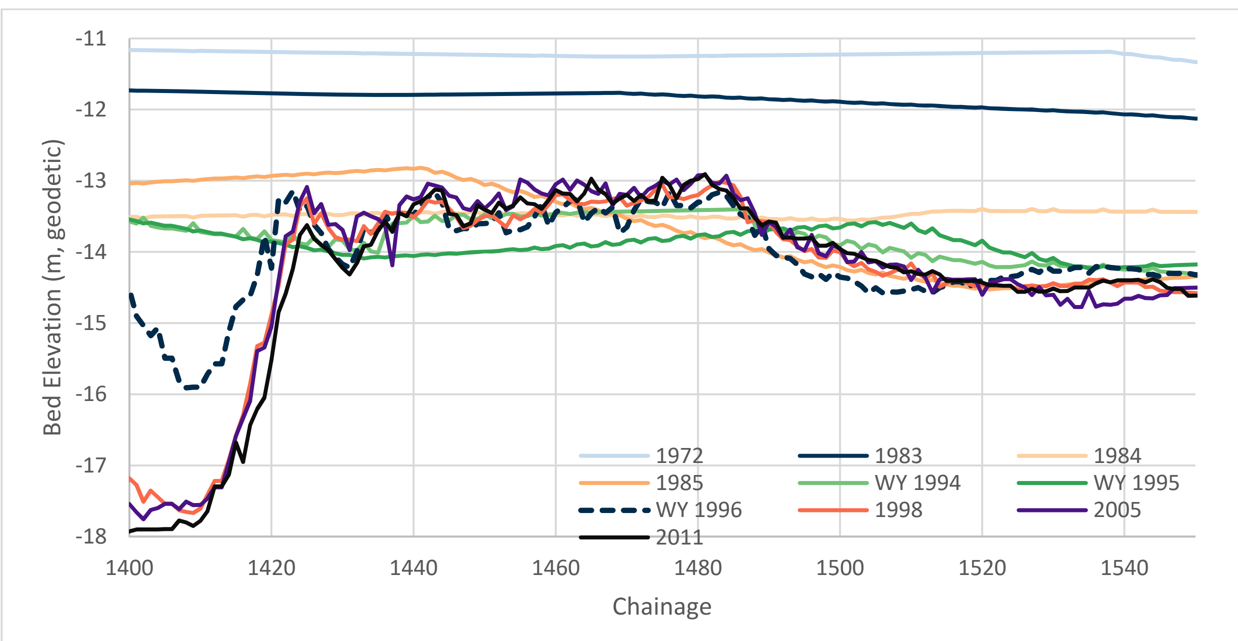


Figure 27: Channel centerline detail over South Surrey Interceptor for select years. Chainage is the same as in Figure 20.

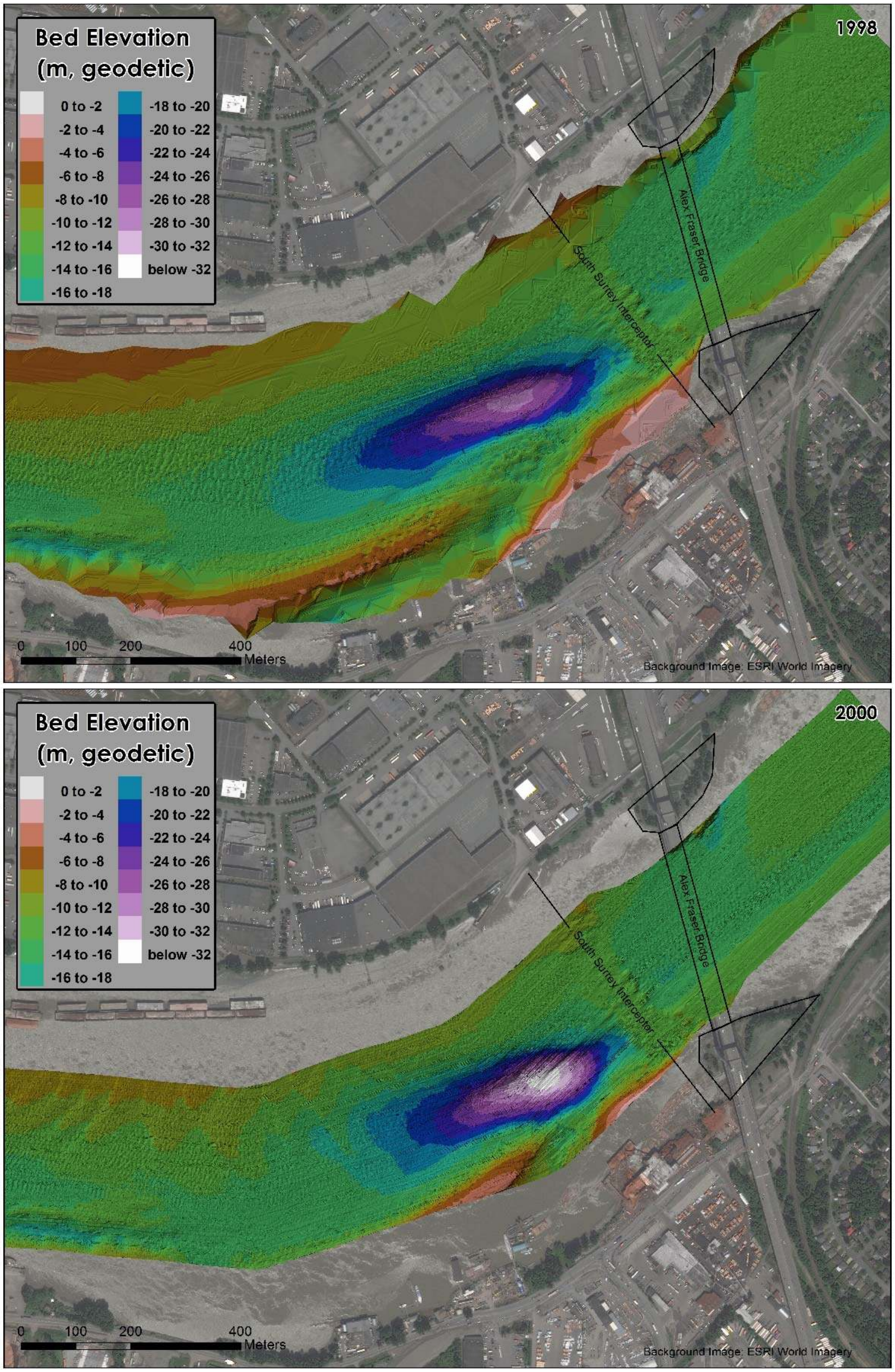


Figure 28: Comparison of 1998 and 2000 bathymetry in the project area

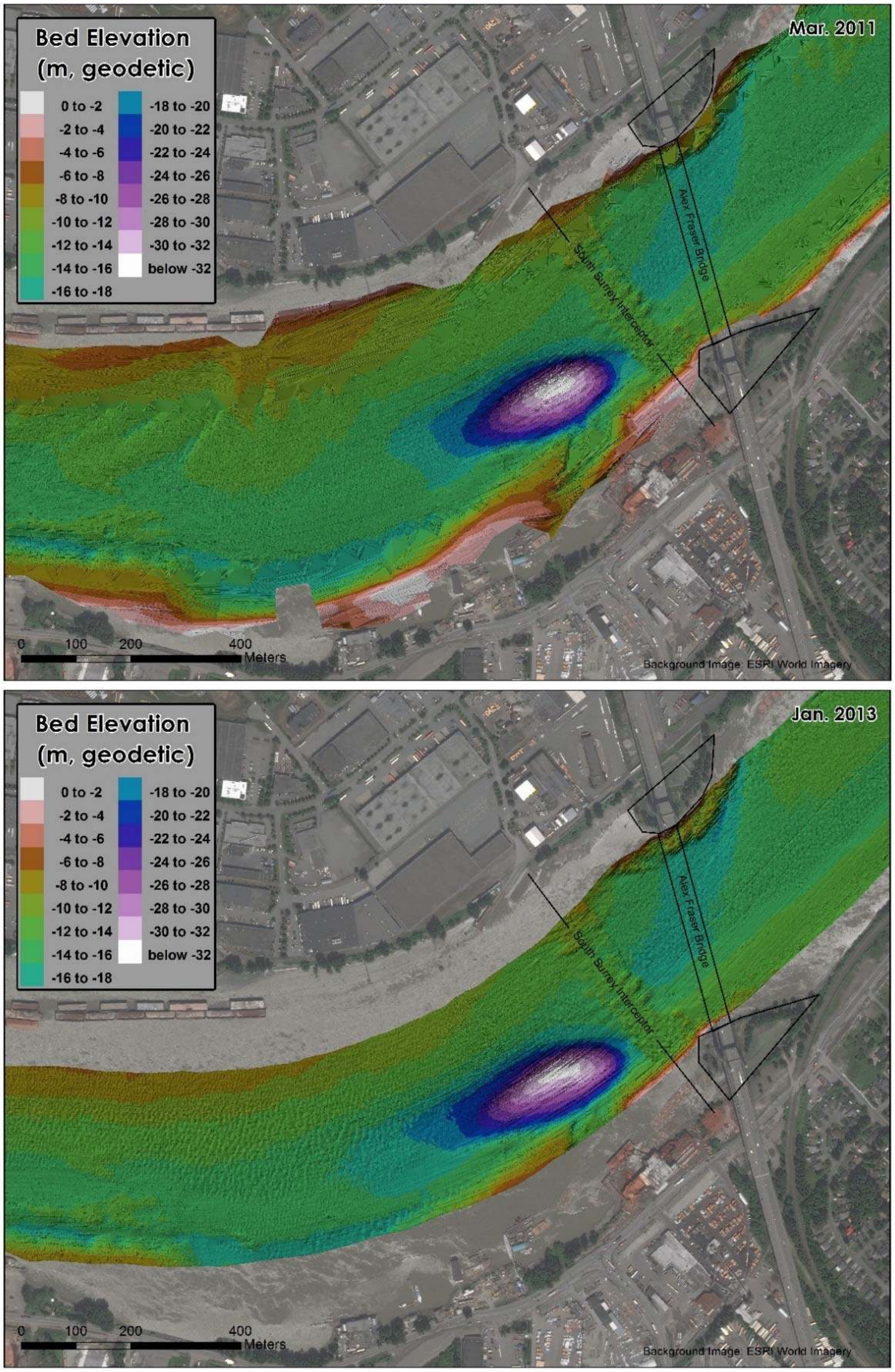


Figure 29: Comparison of 2011 and 2013 bed topography showing continued headward erosion of scour hole

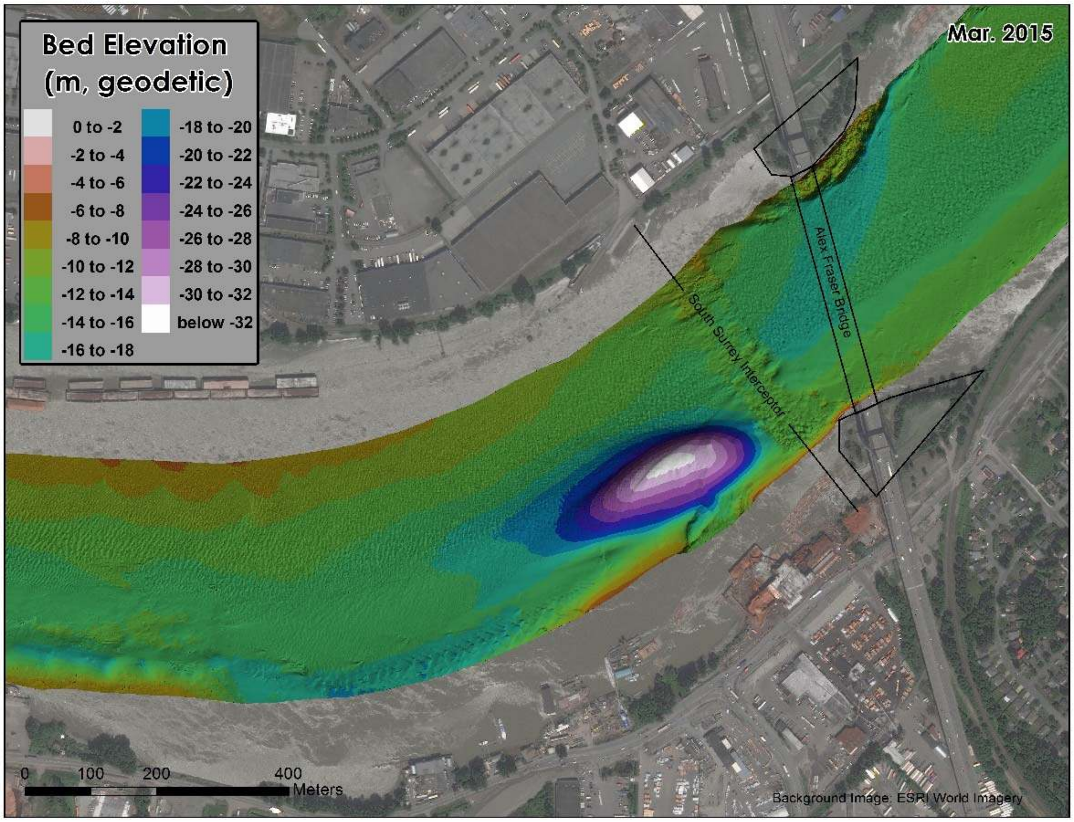


Figure 30: March 2015 bed topography

5.3 Interpretation of Results

5.3.1 Annieville Channel Upstream of Alex Fraser Bridge

The Annieville Channel upstream of the hydraulic influence of Alex Fraser Bridge has been persistently degrading over (at least) the past half century. From the 1972 survey to the present, the channel has degraded by approximately 5m, with fairly consistent changes occurring both along the channel centerline (Figure 20) and cross sections (sections H and I in Figure 22).

Because this area is upstream of the hydraulic impact of the Alex Fraser Bridge (and the lowering trend has been the opposite of what would be predicted in the area upstream of the bridge constriction) another factor must be causing the degradation. Over the period of record, the channel has been persistently below the design dredging grade (locally -11.68 m geodetic) suggesting that this degradation has not been directly due to local dredging operations. Rather, it is interpreted to be a consequence of a sediment budget imbalance, which is an indirect consequence of river-wide dredging and river training activity. Past borrow dredging and navigation dredging removed a volume approaching 100% of the bed material load inflow at Mission upstream of the project reach (NHC 2002). This interpretation is supported by the relative timing of bed lowering and historic dredge removals from the reach upstream, with the most rapid degradation occurring between approximately 1983 and 1995 (Figure 31), which corresponds to the period of major borrow dredging. Additionally, the pattern of bed lowering is consistent with the pattern of changes in the minimum water level at New Westminster (which is believed to be mostly controlled by the bed elevation). The pattern is also consistent with the changes at the furthest downstream cross section considered in detail in this study, which is probably downstream of the local hydraulic influence of Alex Fraser Bridge and the riprap blanket over the South Surrey Interceptor.

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[1] along the left bank toe area. Exposure of this material has likely increased the hydraulic complexity of the channel through this reach.

[1] At- and upstream of the South Surrey Interceptor, this is clearly the Pleistocene gravel on which the left bank pier of the Alex Fraser bridge is footed. Downstream, it is probably also that same material, although the feature is not topographically continuous raising the possibility that it is some other non-alluvial material.

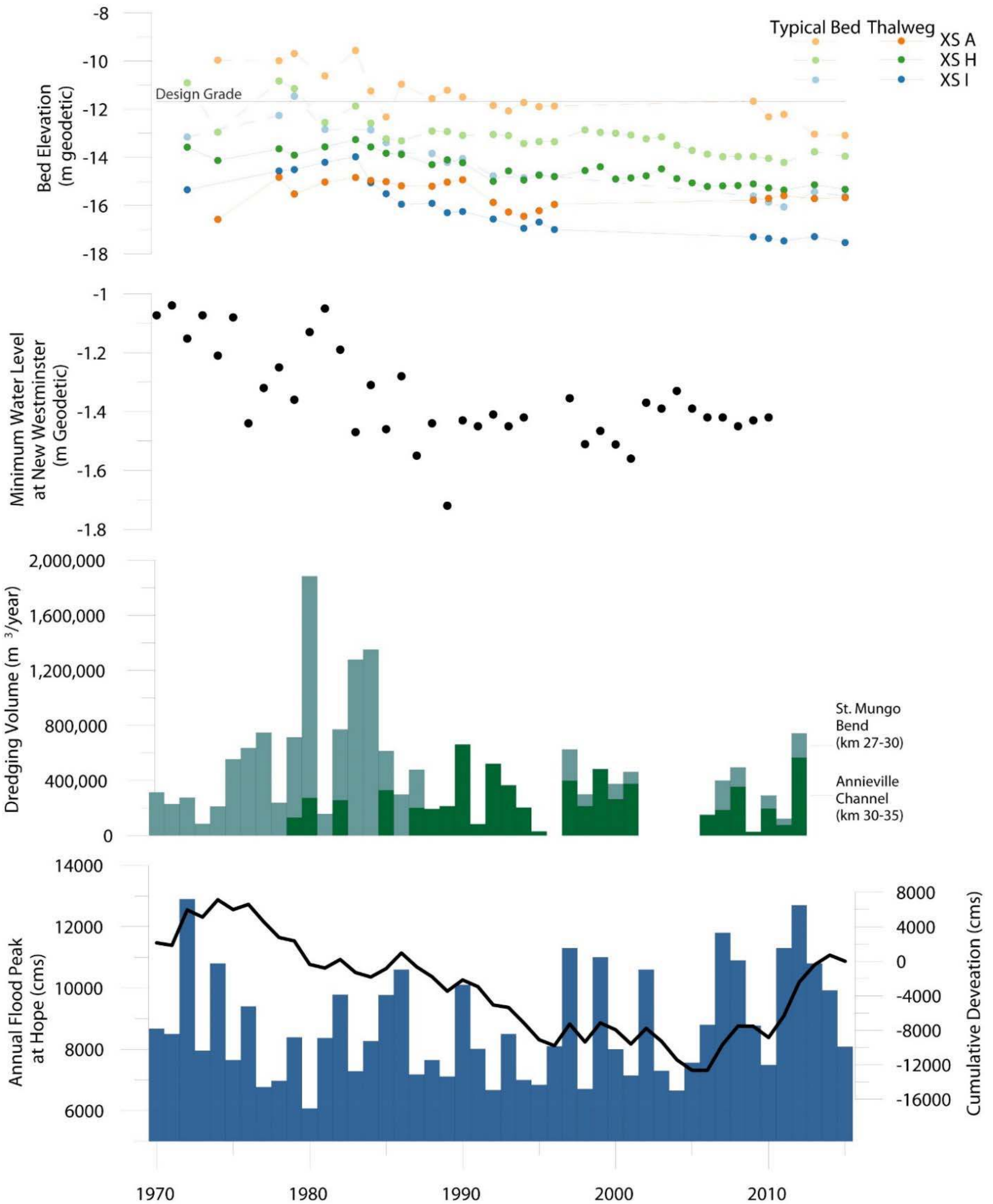


Figure 31: Timing of bed lowering at cross sections away from the local hydraulic influence of Alex Fraser Bridge compared with historic dredging activity and flood flows. See Figure 20 for cross section locations.

5.3.2 Main Channel Downstream of Alex Fraser Bridge

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 protruding left abutment of Alex Fraser Bridge, located on the outside of a bend in the Fraser River created a protected "shadow" area behind it where flow velocity would be much slower that in the main flow current. If so, a shear layer of strong convective acceleration would develop between the fast main current and the slow moving water behind the abutment. The aerial image in Figure 32 indicates that a large recirculation zone (eddy) is present downstream of Alex Fraser Bridge's left abutment with the sketched flow lines illustrating the possible two-dimensional (2D) flow patterns in the horizontal plane.

Based on the flow conditions sketched in Figure 32 and the time sequence of scour hole development (Figure 34) it is interpreted that a long scour hole developed downstream of the left ship collision structure following a shear layer between the main flow and eddy, and possibly between convergence of flows deflected by the two ship collision structures. The abutments of the Alex Fraser Bridge were built around 1984. Bathymetric surveys show that a long and relatively shallow scour hole had developed over the subsequent decade downstream of the left abutment in the area where the shear layer would be expected to develop (Figure 26). Therefore, the scour hole observed up to 1994 can be explained mainly by the 2D flow patterns in the horizontal plane generated by the protruding left abutment.

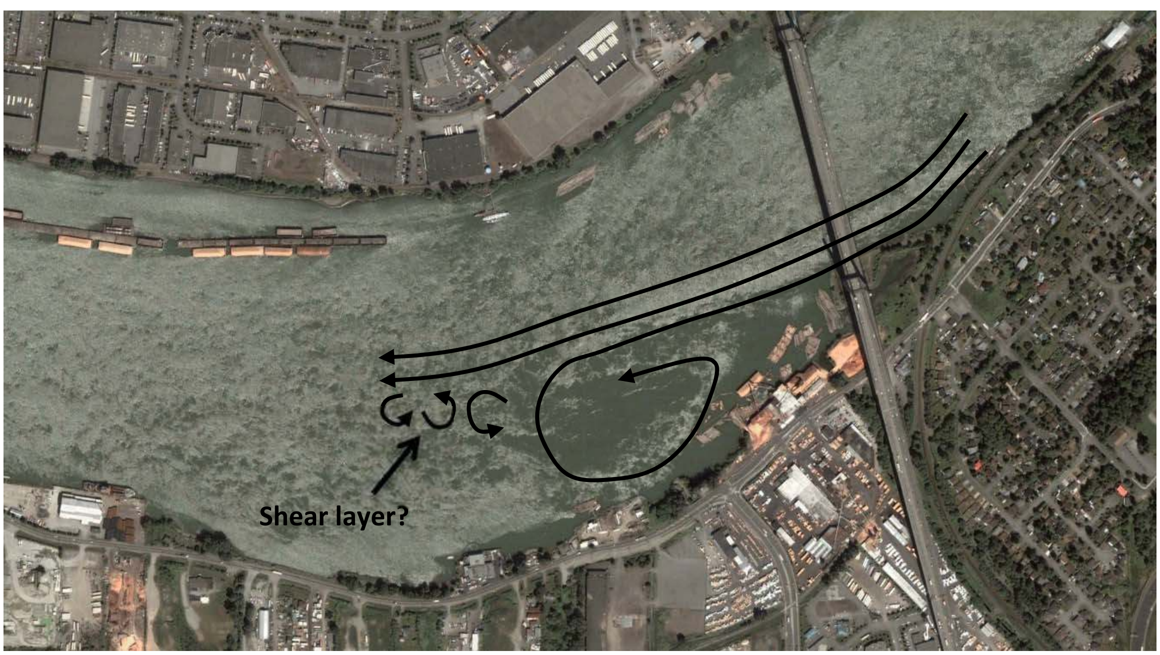


Figure 32: Google Earth image of Alex Fraser Bridge (2004) and possible flow patterns

After 1994, when additional riprap protection was placed on top of South Surrey Interceptor, the scour hole became smaller in extent and deeper (Figure 28 through Figure 30) despite the absence of major changes in the 2D approach flow conditions upstream. The historic centerline longitudinal bed profiles (Figure 20 and Figure 27) show the riprap apron elevated above the upstream bed level, followed immediately by development of a deep scour hole. Subsequent lowering of the navigation channel upstream in response to dredging and navigation channel deepening raised the effective height of the sill. The riprap apron at the crossing elevated above the bed level behaved as a submerged weir or sill, causing in the vertical plane a plunging or diving flow that generates deep local scour downstream, as illustrated in Figure 33. Depending on the flow intensity and relative height of the submerged weir, the scour hole depth can be as large as 1.5 times the water depth in the approach channel (Melville 2014).

The steep upstream slope of the scour hole is typical of scouring processes involving diving flows directed towards the bed. This hole however, is substantially deeper than would be predicted from the geometry of the bed and weir upstream: scour to an elevation of -24 m would be expected for the 2012 freshet flood condition.

Recent erosion of the upstream wall of the scour hole into material believed to be the “essentially inerodable” Pleistocene gravel deposit has occurred (Figure 5). The detailed view of the channel centreline through the scour hole shown in Figure 23 shows the timing of this erosion. The channel boundary was fairly stable between 2001 and 2003, a period with floods up to 10,800 m^3/s at Hope, but retreated dramatically during the 12,700 m^3/s and 11,300 m^3/s floods of 2012 and 2011 respectively.

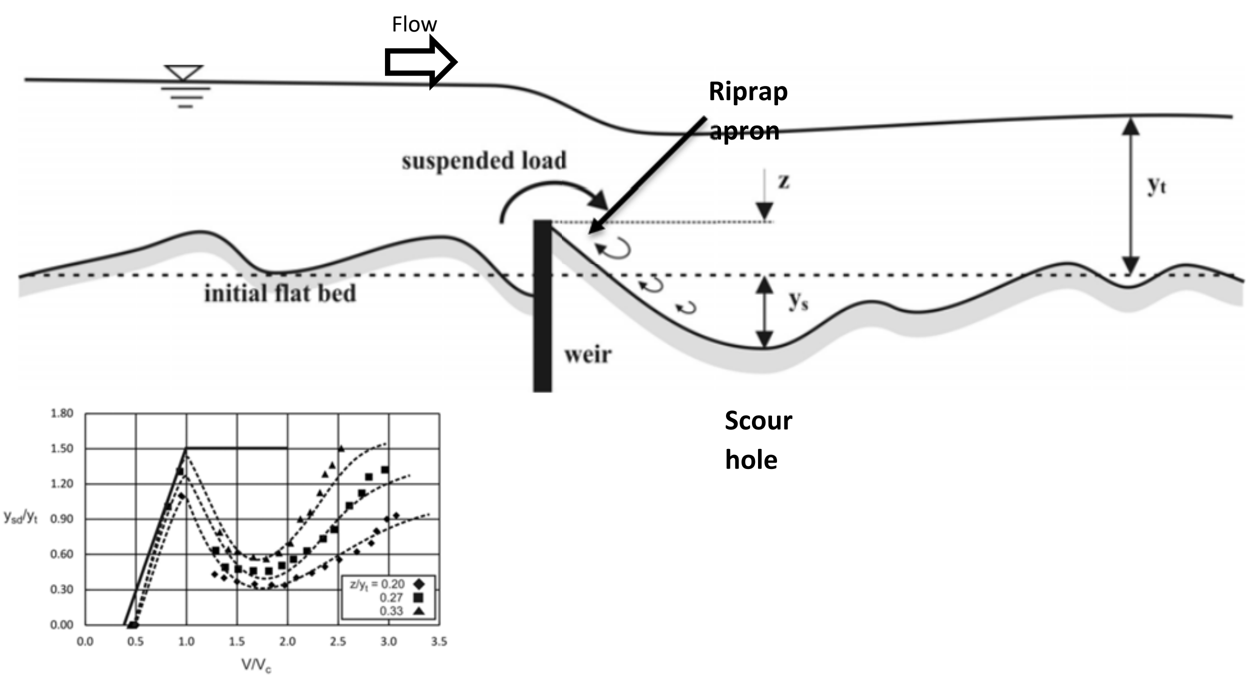


Figure 33: Definition sketch of scour downstream of submerged weir (Melville 2014)

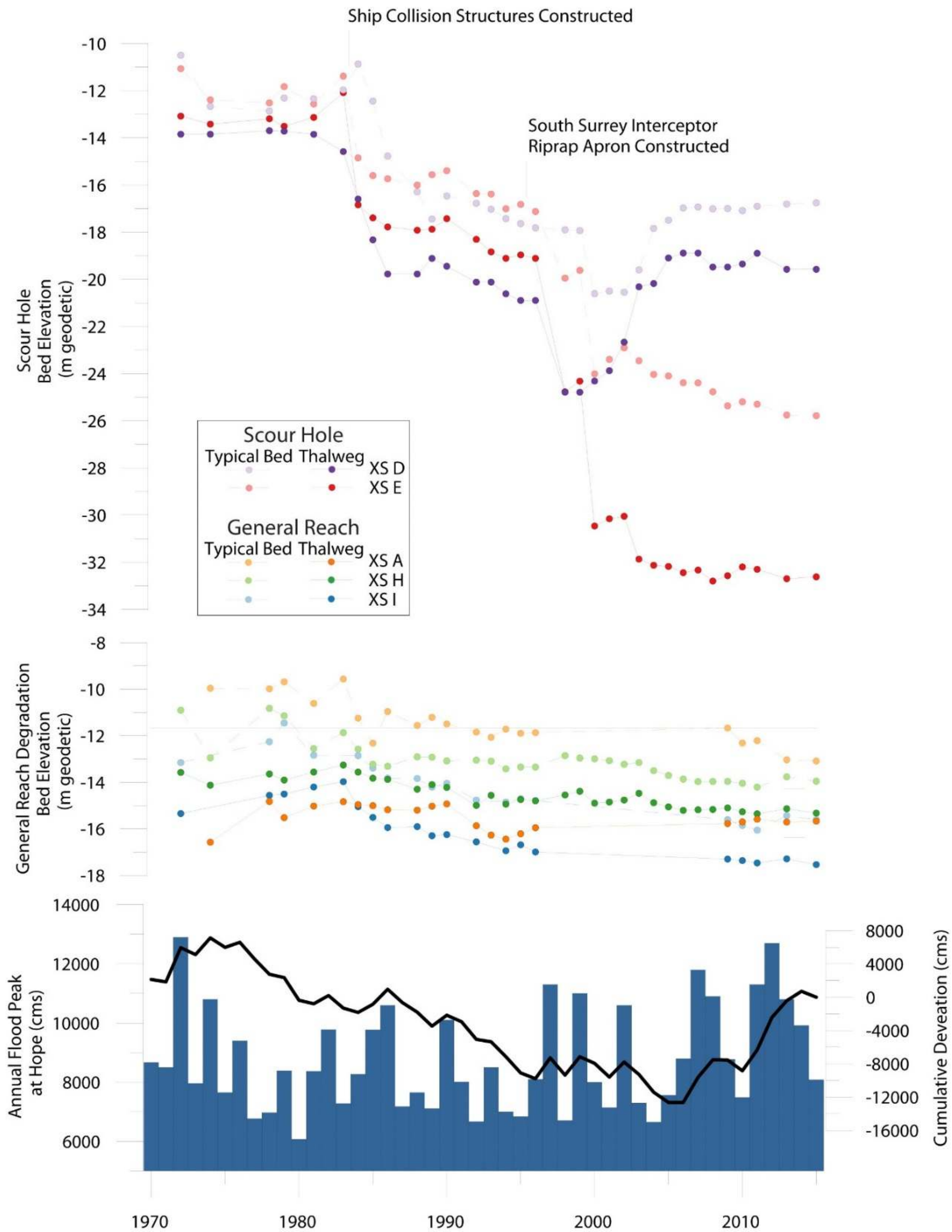


Figure 34: Scour hole development compared with reach-wide degradation, historic changes to controlling infrastructure, and flow history

Based on the discussion above, it is believed that the scour hole currently observed downstream of Alex Fraser Bridge and South Surrey Interceptor is the result of the interaction of scouring processes: shear layer flow shedding from the Alex Fraser Bridge's left abutment (horizontal plane) enhanced by diving flows coming from the submerged apron protection of South Surrey Interceptor (vertical plane). Neither process alone is sufficient to explain the observed geometry. The combination of these two scouring mechanisms acting mainly on two different planes should lead to very complex three-dimensional flow patterns and eddies, which in turn should increase turbulence intensity and hence the capacity of the flow to entrain sediment from the bed.

5.3.3 North Side of Channel Downstream of South Surrey Interceptor

Historic changes in the bed elevation on the north side of the channel downstream of the South Surrey Interceptor are of particular interest because this is the area under consideration for location of future outflow diffusers. Figure 35 shows the magnitude of long-term historic changes in the bed level in this area has been approximately 3 m, with typical inter-annual fluctuations of 0.25 to 1 m. The trend of bed lowering in the 1970s and early 1980s roughly paralleled reach-wide patterns, except for the occurrence of abrupt lowering immediately after construction of the Alex Fraser Bridge ship collision structures. Since then, the bed elevation has varied by up to 2 m, with no clear association with reach-wide patterns, local infrastructure change, or flood flows. Presently, the bed in this area is near a historical low suggesting that up to 2 m of aggradation should be expected in the absence of continued reach-wide degradation (which is possible).

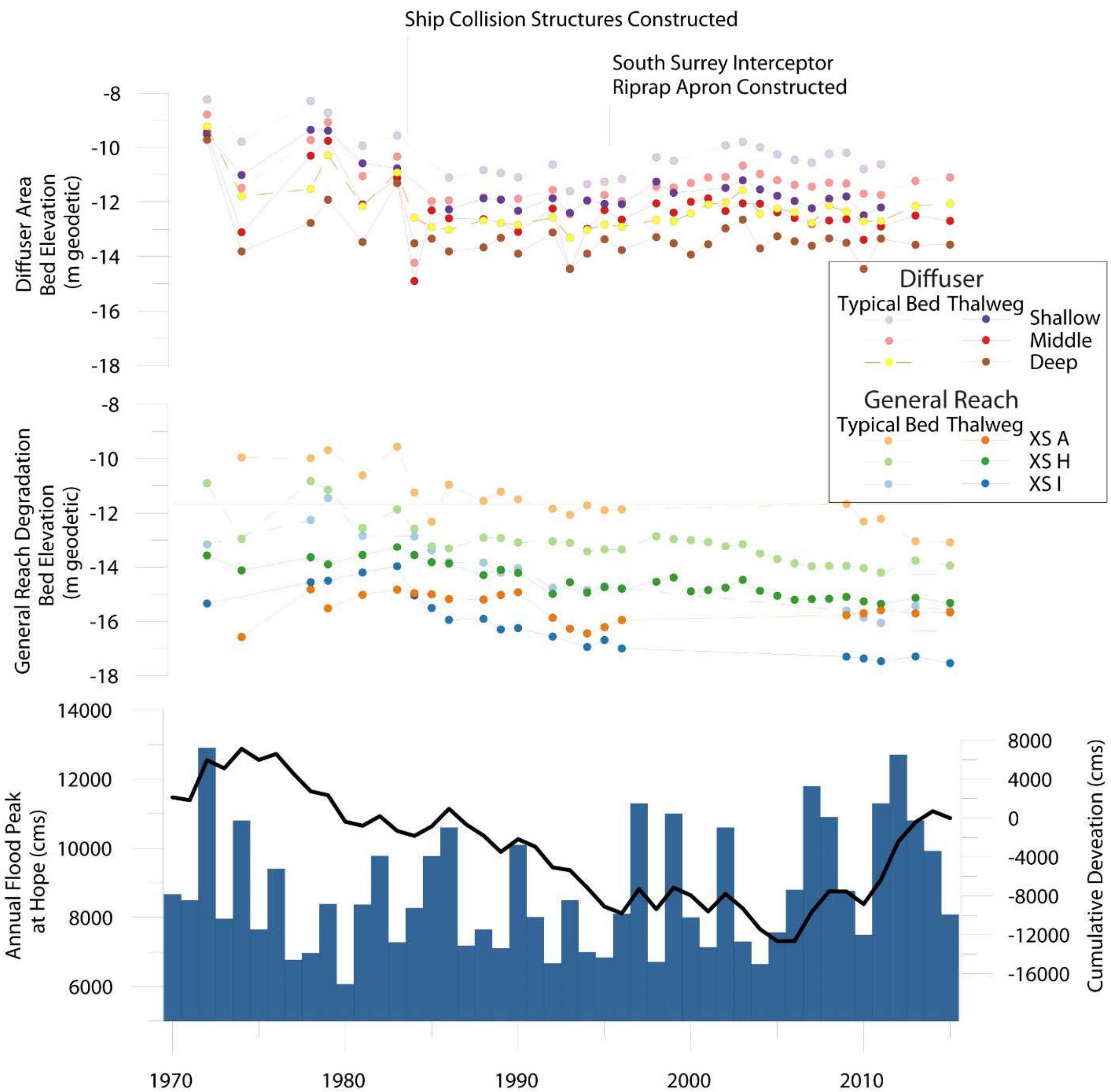


Figure 35: Bed elevation variability in the vicinity of potential diffuser locations compared with reach-wide degradation, historic changes to controlling infrastructure, and flow history.

6 SHORT TERM CHANNEL CHANGES

6.1 Method of Approach

In addition to the historical channel changes described above that occurred over a timescale of years to decades the position of the channel boundary may fluctuate on a much shorter timescale. Two principle processes may drive this variability:

- It is possible that flow variability on an annual timescale can cause scour depths to vary and positions of bars to shift, causing the bed elevation to change on an annual cycle.
- Substantial dune bed forms have been observed at other locations on the lower Fraser River (e.g. Kostaschuk and Church 1993, Villard and Church 2003, 2005, Bradley et al. 2013) and are commonly visible in high-resolution bathymetric surveys of the reach. Formation and migration of these features can cause the river bed elevation to vary by a few metres at a timescale of hours to days.

The nature of alluvial bed forms depends on the size of the bed material, flow depth, and flow velocity as illustrated in Figure 36. An understanding of the dynamics of short-term channel changes at the project site, then, requires observations over a variety of flow conditions. Monitoring surveys of the project reach have periodically collected bathymetric data during and after springtime freshet floods, and so NHC gathered a set of these surveys (conducted at flows up to 9,700 m^3/s at Hope) to evaluate short-term channel changes.

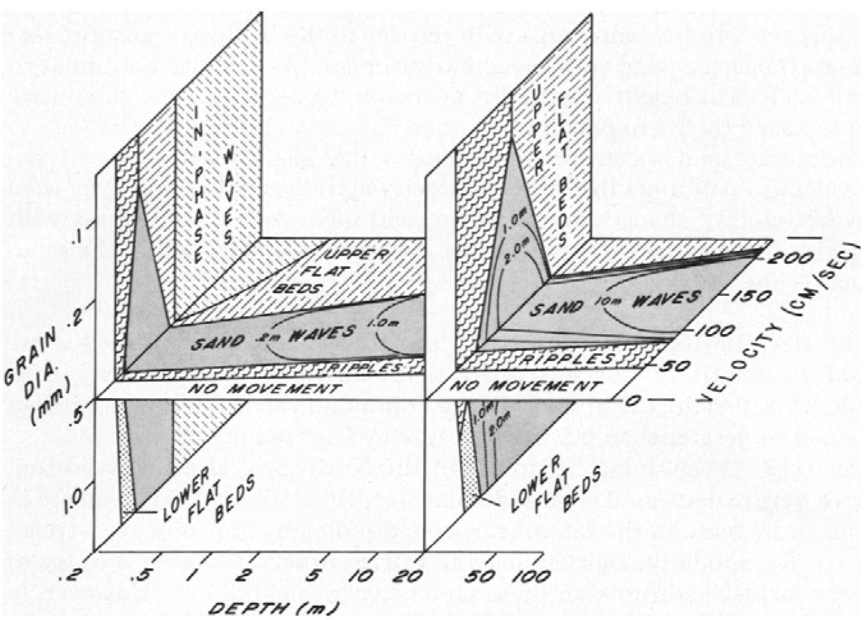
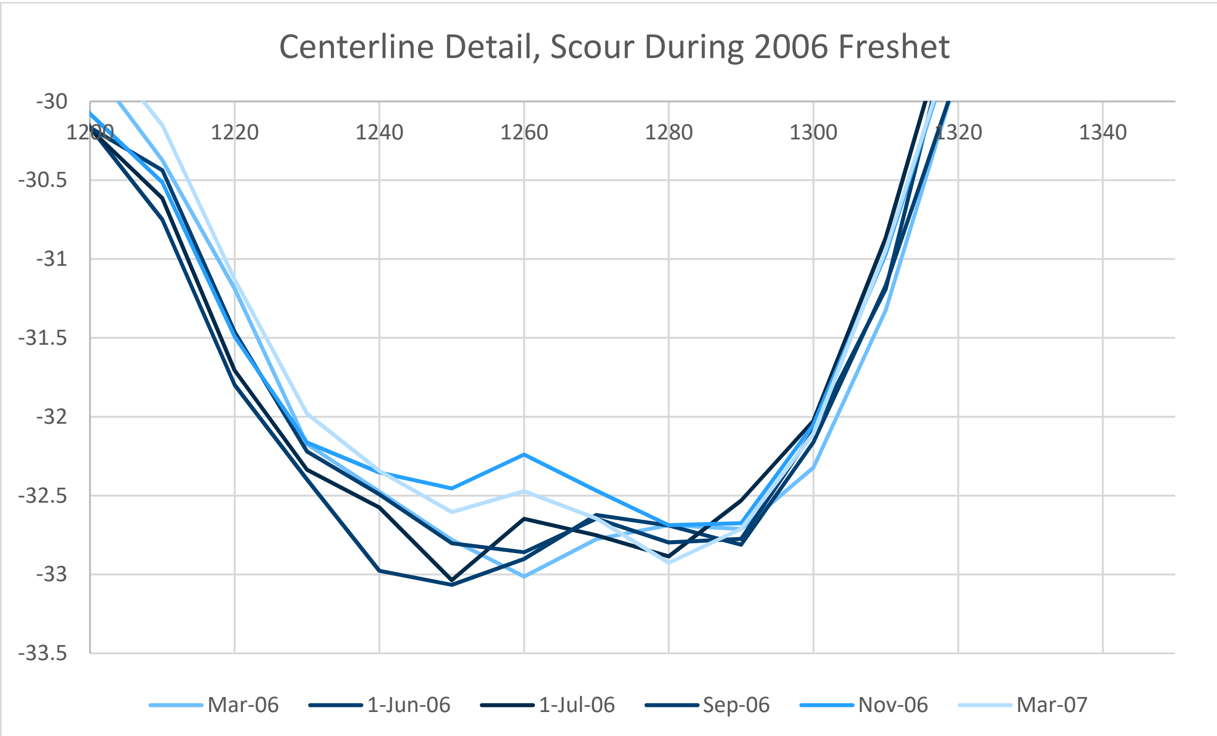


Figure 36: Generalized diagram showing the relationship between grainsize, flow depth, and flow velocity and resulting bed forms. Reproduced from Rubin and McCulloch (1980), who used the term "Sand Waves" instead of dune.

6.2 Scour and Fill

There is no indication of significant scour and fill occurring as a consequence of seasonal flow variability. Figure 37 shows bathymetry in the bottom of St. Mungo's hole from several surveys collected during the 2006 and 2007 freshets compared with surveys from bracketing low-flow periods. Maximum depths of local scour appear to be approximately 0.5 m, which is much less than potential bed elevation variability caused by the passage of bed forms. The insensitivity of the maximum depth of St. Mungo's hole to seasonal flow variability is consistent with the interpretation that the bottom of the scour hole lies within the over consolidated Pleistocene material in this area.



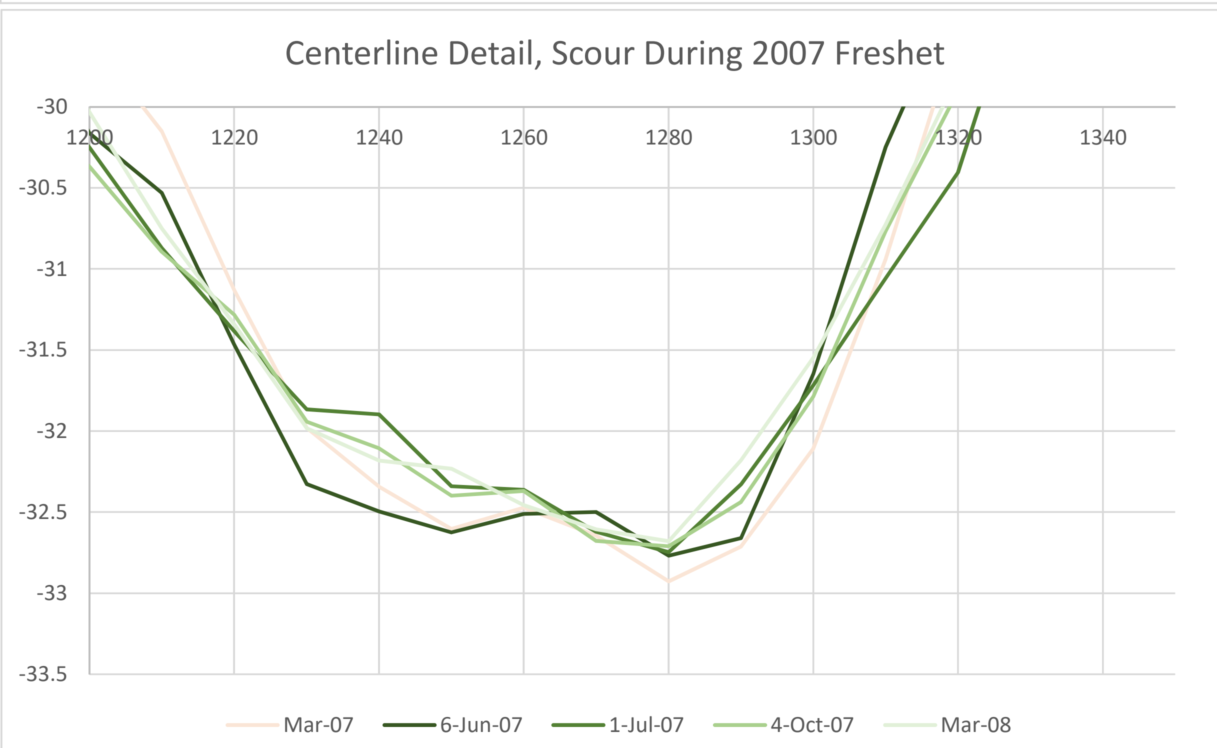


Figure 37: Scour during 2006 and 2007 freshets. Maximum scour depths along channel centerline reach -32 m, approximately 0.5 m deeper than observed during winter surveys.

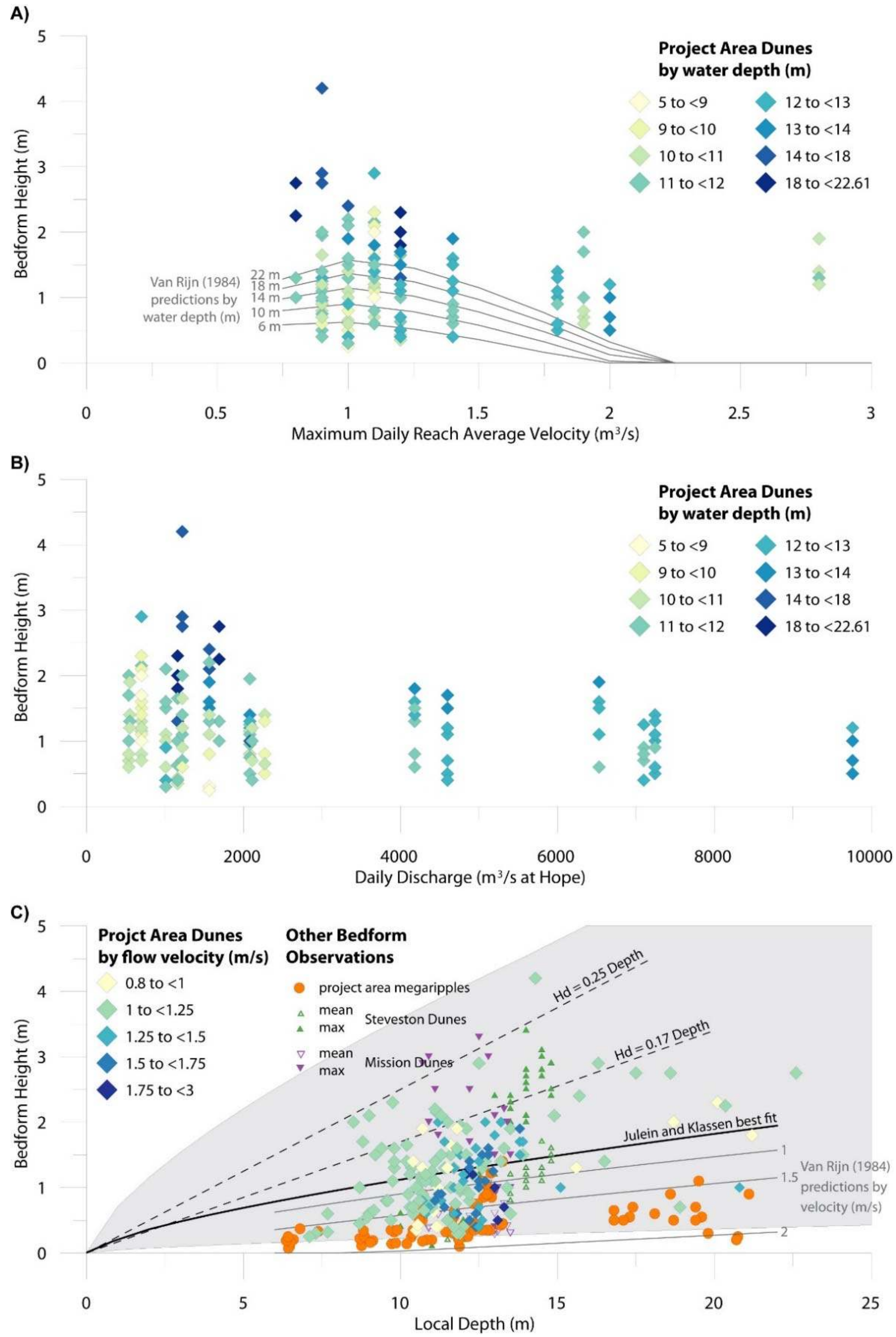


Figure 38: Comparison of dunes observed in the project area and various empirical predictors of dune geometry

6.3 Bedforms

Formation of dunes in the region of the diffusers will cause periodic infilling and scour as the features migrate through the reach. Megaripples (small dunes with wavelength of approximately 10 m or less) were ubiquitous through the project area across the range of observed hydraulic conditions. The observed height of these features typically ranged from 0.25 to 1 m.

Dunes are observed in the project area across the range of observed flows. Most dunes ranged in height from 0.5 to 2.5 m, but the largest observed dune was over 4m in height. Counterintuitively, the size of dunes appears to decrease with increasing discharge (Figure 38 A); the largest dunes observed occurred at moderate depths (10-20 m) during the winter months at fairly low river discharge <2000 m^3/s), while the largest dunes observed during freshet floods were approximately 2m high. Figure 39 shows the sequence of bed forms observed along a single profile line through three winter seasons and two freshet floods. Large dunes form during the recession of the freshet flood and persist through the winter low-flow season.

Dunes were rarely observed toward the center of the channel at depths below approximately 15 m, and were most common on the right bank bar, downstream of the potential area where the new diffusers may be sited (as is visible in Figure 28 through Figure 30).

The pattern of initially increasing, and then decreasing dune height with increasing velocity is consistent with van Rijn's (1984) theoretical prediction of dune behavior, except that dunes observed in the project area are much higher than would be predicted by van Rijn's method (Figure 38 A).

An alternate approach is to evaluate dune height as a function of water depth, as proposed by Julien and Klassen (1995) and plotted in Figure 38 C. Observations from the project site and two other locations on the lower Fraser River all lie within the 95% confidence bounds for Julien and Klassen's empirical prediction, but bedform height increases more rapidly with depth than their best fit prediction. The maximum observed dune heights follow closely with the theoretical maximum depth based on the size of the dune wake within the water column. No dunes were higher than either the Julien and Klassen upper bound or the third of the total water depth. Few were larger than one quarter of the water depth, which is the threshold where dune flattening has been observed in flume experiments (Allen 1980).

It appears as through local hydraulics influence the likelihood of dune formation across the area under consideration for potential outfall diffuser locations. Figure 40 and Figure 41 show profiles cut from available survey data through the deepest portion and middle of this area, respectively. On the basis of the profiles plotted in these figures, it appears as though dunes are most likely to develop in the area downstream of chainage 200 at the deep diffuser and chainage 300 at the middle diffuser. The area upstream where dunes are less common is in the lee of the riprap over the South Surrey Interceptor, which likely interrupts the near-bed hydraulic and sediment transport conditions necessary to produce dune bedforms.

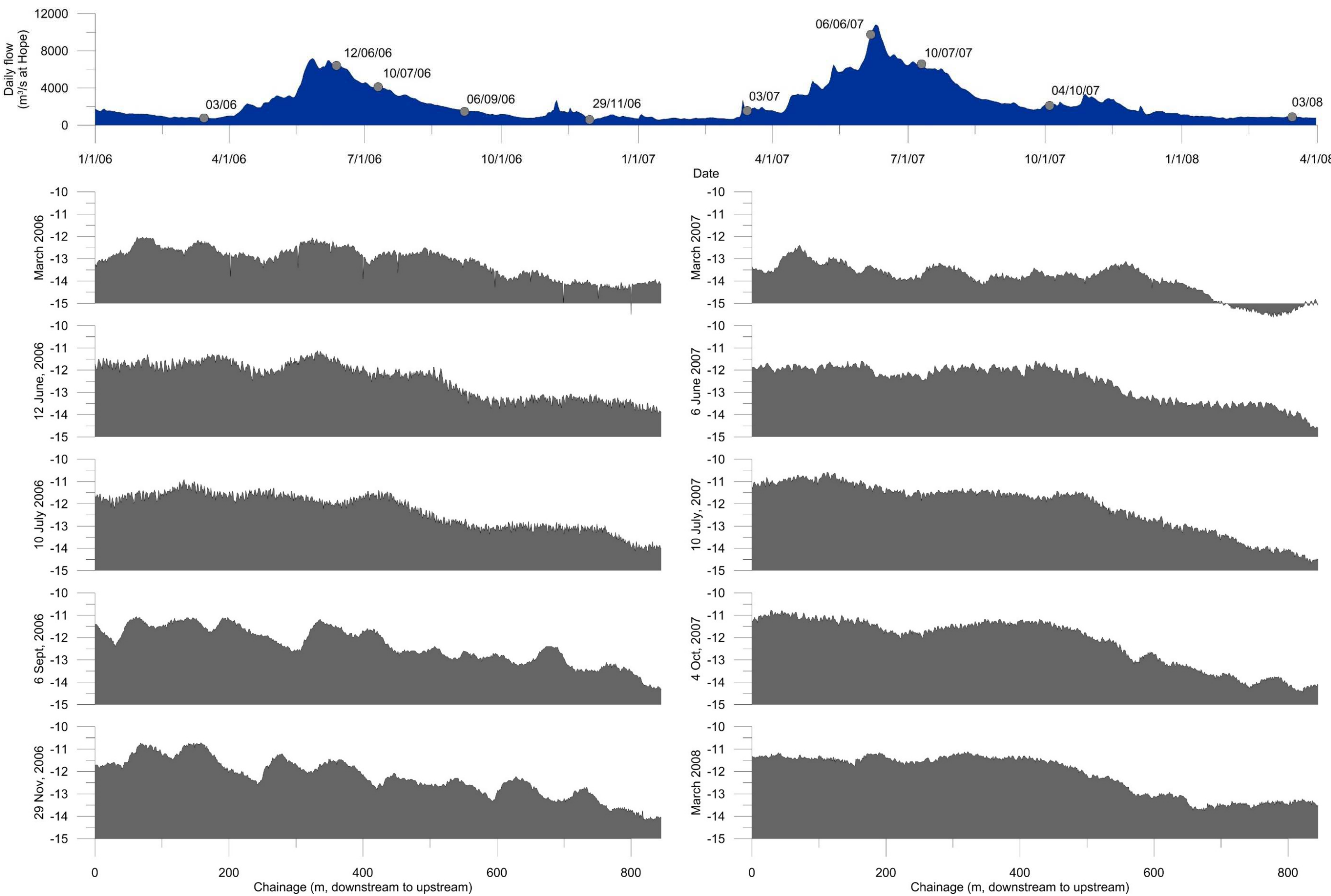


Figure 39: Sequence of bed forms observed along right bank over two years, showing dominance of dune bed forms during relatively low river discharge conditions

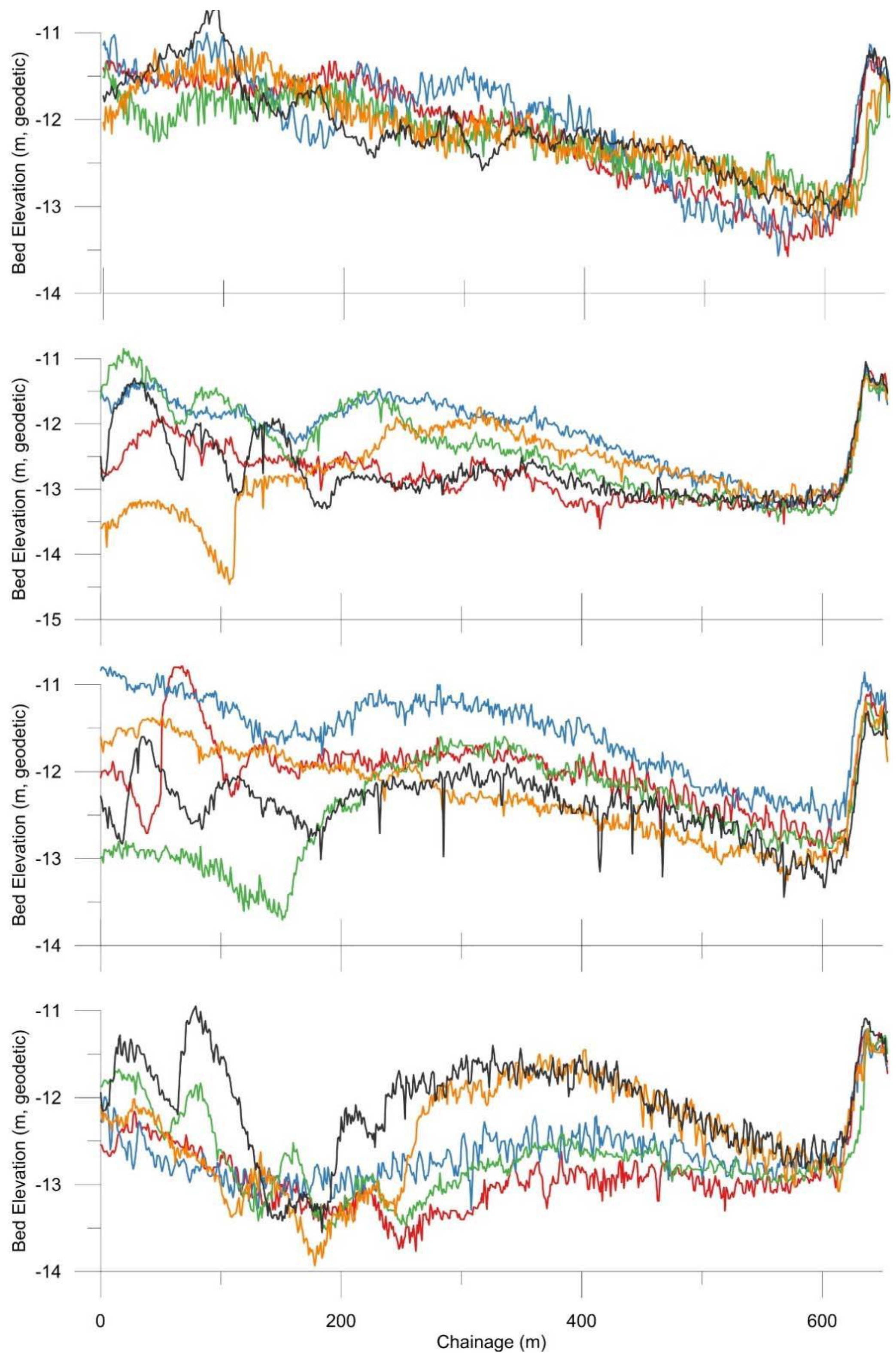


Figure 40: Profiles cut along deepest potential position for outfall diffusers. Flow is from right to left.

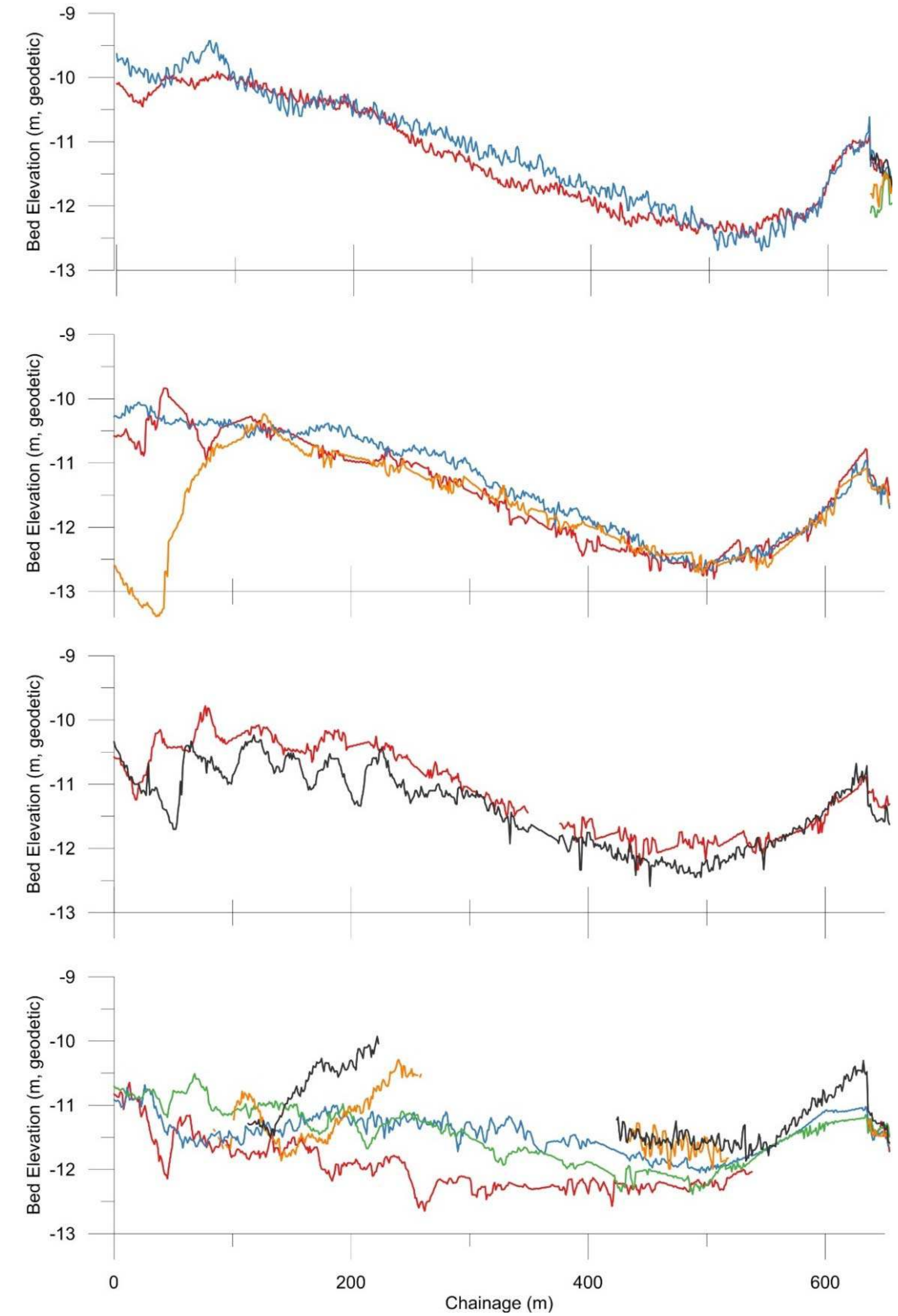


Figure 41: Profiles cut along the mid-depth position for potential outfall diffusers. Flow is from right to left.

7 SUMMARY AND CONCLUSIONS

7.1 Long-term Trends in Bed Levels

The river bed lowered at least 20 m near the project site over the last 40 years in response to three main factors:

- Construction of the ship collision structures at the Alex Fraser Bridge in 1984, which created a notable constriction and zone of flow separation along the south bank.
- Construction of a raised riprap apron over the South Surrey Interceptor around 1995 which has acted as a sill.
- Ongoing dredging and navigation channel improvements which have lowered the riverbed by 2 to 3 metres upstream of the site.

The initial scour hole developed in response to the constriction created by the bridge. The scour hole deepened an additional 10 m and migrated upstream towards the South Surrey Interceptor after additional riprap was placed over the South Surrey Interceptor in the mid-1990s. The change in the scour hole is the result of the interaction of scouring processes: shear layer flow shedding from the Alex Fraser Bridge's left abutment (horizontal plane) enhanced by diving flows coming from the submerged apron protection of South Surrey Interceptor (vertical plane).

After a relatively large freshet in 2012 the edge of the scour hole migrated upstream towards the South Surrey Interceptor through Pleistocene gravel sediments that underlie the south side of the river. There is a significant risk that future high flood events will erode through this material and undermine the existing riprap apron that protects the crossing.

Bed level changes on the north side of the river in the area of the outfalls have been less severe than on the south side. The trend of bed lowering in the 1970s and early 1980s roughly paralleled reach-wide patterns, except for the occurrence of abrupt lowering immediately after construction of the Alex Fraser Bridge ship collision structures. Since then, the bed elevation has varied by up to 2 m, with no clear association with reach-wide patterns, local infrastructure change, or flood flows.

7.2 Factors Affecting Future Bed Levels Near the Site

The depth and geometry of the existing deep scour hole is quite sensitive to the height of the sill that has been formed over the South Surrey Interceptor. Adding more riprap to the existing scour protection apron would raise the height of the sill and would lead to further local scour both upstream and downstream of the crossing. Lowering the sill by removing or reconfiguring some of the riprap over the South Surrey Interceptor could lead to the scour hole partially filling in.

Future deepening of the navigation channel could also affect bed levels at the site, particularly if the amount of dredging increased substantially to maintain the deepened channel. Further lowering of the navigation channel upstream of the South Surrey Interceptor could effectively increase its tendency to act as a sill, increasing the local scour downstream of the crossing. Further deepening the navigation channel could also affect bed levels outside of the navigation channel; for example on the north side of the channel.

7.3 Implications for South Surrey Interceptor

The existing South Surrey Interceptor is susceptible to undermining due to progressive upstream migration of the deep scour hole that has formed. The existing scour protection apron will need to be modified and re-configured if the crossing is to be maintained in the long-term. This will require extending the apron further downstream as well as possibly lowering its crest height.

Previous practice on the Fraser River has required maintaining at least 1 m of cover over the crown of the pipes during any scour protection maintenance work. Using this criteria, the bottom of the new riprap apron would need to vary across the channel as follows:

- Not lower than elevation -15.0 m on the north side of the existing navigation channel.
- Not lower than elevation -15.5 m near the centre of the navigation channel
- Not lower than elevation -15.8 m near the south side of the navigation channel.

The thickness of the scour protection apron at the recently completed Port Mann crossing project was1.2 m, which corresponded to four times the D_{50} rock size. With a 1.2 m thick riprap layer, the top of the apron across the channel would vary as follows:

- -13.8 m on the north side of the navigation channel.
- -14.3 m near the centre of the channel.
- -14.6 m near the south side of the channel.

It should be noted that detailed design of scour protection modifications may yield different stable rock sizes, which would affect the required apron thickness over the crossing.

7.4 Implications for Outfalls

The new outfalls on the north side of the navigation channel are located in a relatively stable section of the river compared to the south side. Since the mid-1980s, the bed elevation has varied by up to 2 m, with no clear association with reach-wide patterns, local infrastructure change, or flood flows. Presently, the bed in this area is near a historical low suggesting that up to 2 m of aggradation could occur in the absence of continued reach-wide degradation (which is also possible if future navigation channel deepening is carried out).

Additional short-term periodic scour and fill caused by dunes that migrate through the reach. The development and migration of bedforms (dunes) create periodic scour and fill on the north side of the navigation channel. A provision for bed elevation variability over annual timescales and dune migration should be made when designing the new outfalls to account for periodic scour and fill. This value should be added to estimates of other longer term bed profile adjustments (due to future navigation channel deepening, for example).

Figure 40 and Figure 41 illustrate the typical magnitude of this variability. Dune amplitude (half of the dune height) is commonly used as a parameter to account for scour and fill by dunes that would occur on a daily to weekly timescale. Because dunes are most commonly observed during the winter season, when flow depths are at their shallowest, these values are smaller than the maximum values that would theoretically be possible at this site. Were dunes to form during the freshet flood, they could range in amplitude from 1.8 m for a flood equivalent to the 2012 event to 2 m for the 500-year freshet water level. These values are representative of conditions approximately 200 m downstream from the South Surrey Interceptor at the north side of the navigation channel. The dunes are considerably lower in amplitude immediately downstream of the South Surrey Interceptor, probably due to the effect of the raised riprap apron. We recommend providing a vertical allowance of ± 2 to account for short-term scour and fill.

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