Note to the Reader

This report was finalized before the Pattullo Bridge Replacement Project was transferred from TransLink (South Coast British Columbia Transportation Authority) to the BC Ministry of Transportation and Infrastructure (MoTI).

References to TransLink should be read as MoTI unless referring specifically to TransLink policies or other TransLink-related aspects.

RIVER HYDRAULICS AND MORPHOLOGY

TECHNICAL REPORT
REVISION 3

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EXECUTIVE SUMMARY

TransLink (South Coast British Columbia Transportation Authority) is proposing the Pattullo Bridge Replacement Project (PBRep or Project) to replace the existing Pattullo Bridge with a new four-lane bridge, expandable to six lanes, spanning the Fraser River in the same corridor as the existing bridge (Figure 1). The Project will also involve de-commissioning and removal of the existing bridge.

This study assesses potential changes in Fraser River hydraulics and morphology due to the Project. This includes potential changes to water levels, velocities, and flow patterns, and their influence on sedimentation and erosion within the Fraser River. Several tools were employed to yield a robust assessment of potential changes due to the Project. Three types of model studies were used to assess hydraulic and morphologic changes due to the Project. Potential effects of the Project on near-field flow hydraulics were investigated using Flow-3D, a three-dimensional computational fluid dynamics (CFD) model with capabilities for modelling complex geometries and free surface flows. Far-field hydraulics and river morphology (changes to bed elevation) were assessed using the TELEMAC SYSTEM, a 3-dimensional morphodynamic model. A physical model was constructed to assess existing conditions and two earlier iterations of the proposed replacement. Results of the three model studies are synthesized to provide a concise summary of the changes to river hydraulics and morphology expected as a result of the Project. Except where otherwise noted, river hydraulics results are from the CFD model and changes in bed elevation are from the morphodynamic model. Although the Reference Concept was not tested in the physical model, observations from the physical model have been incorporated where relevant. Detailed information on the development, calibration and test results from the numerical and physical models is contained in Appendices A, B and C.

The Fraser River at the Project site is a highly dynamic environment. Flows are tidally influenced, reversing on incoming tides during all times of the year except during the spring/summer freshet. The salt wedge does not extend as far upstream as Pattullo Bridge, even during winter low flows with large tidal swings. Bed levels in the lower Fraser vary on tidal, seasonal, annual and longer timescales by several meters. Large dunes have been observed from Port Mann to the mouth of the Fraser River, typically varying in height from 0.5 to 2.0 m. Riverbed changes due to tidal fluctuations at the Pattullo Bridge can be on the order of several meters, and seasonal changes can be greater than 7 m. Over the longer term, average bed elevations in the lower Fraser River have lowered by approximately 3 m since 1950 as a result of dredging, flood protection dikes, river training, and bank hardening.

Scour conditions at the Project site are potentially the most severe in the lower Fraser River. The Project site is situated in one of the narrowest sections of the river, and just downstream of a long converging left-hand bend. There are three existing bridges within 300 m of the Project, including the New Westminster Rail Bridge (NWRB), the existing Pattullo Bridge, and the Skytrain Bridge. Tidal fluctuations and Fraser River flows combine to yield highly dynamic flow conditions. Flow convergence downstream of Sapperton Bar results in severe scour conditions. General (i.e. contraction) scour adds to the scour potential during extreme floods, since the opening at Pattullo Bridge is relatively narrow (about 500 m net). A weir-like apron of rock is likely present under the NWRB, which results in deep scour when flow plunges over the apron during freshet. Local scour around the Pattullo bridge piers also contributes, and is augmented by the angle of pier skew to the flow alignment. Tide conditions combined with high river flows have been observed to cause local bed levels to fluctuate by up to 7 m over a 24 hour period on both sides of the rail bridge. There is a very large variation in bed levels on the south side of the channel over a year, with long-term variations in the order of 12 m observed. Changes on the north side of the channel are not as pronounced. The hydraulic influence of individual structures, such as piers and scour protection aprons, can extend hundreds of meters upstream and downstream.

The study area includes a number of crossings and other infrastructure with the potential to be affected by the Project. These include eight Metro Vancouver water and sewer crossings, two oil and gas pipelines, seven bridge crossings, and extensive river training works.

Changes in river hydraulics due to the addition of Reference Concept piers were primarily limited to local effects around the new and existing piers, and decreased velocities downstream of the new pylons. The Reference Concept bridge is not expected to result in any significant increase in average velocities. Velocity reductions downstream of the proposed North and South Towers extend well downstream. The Decommissioning scenario produced similar velocities, with minor differences where the riprap cones have been truncated.

No changes to water levels or flow splits are expected to occur as a result of the Project.

Bed level changes are expected to occur as a result of the Reference Concept while the Pattullo Bridge piers remain in place. The most notable is aggradation of 4-5 m downstream of the South Tower (attenuating downstream), and 1-2 m downstream of the North Tower. About 0.5 m of aggradation is expected in the primary navigation channel downstream of the existing Pattullo Pier 4. Based on physical model results, deep local scour is expected at the NWR Bridge piers, and to a lesser degree at the Pattullo Bridge. Both are expected to require scour protection upgrades.

Changes due to the Project after the Pattullo Bridge has been decommissioned (piers removed and riprap mounds partially removed) are expected to be similar, with the some notable differences. Primarily, deposition downstream of the South Tower near the SkyTrain Bridge alignment is expected to increase from 2-3 m to 4-5 m.

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DEFINITIONS

Term	Definition
acoustic Doppler current profiler (ADCP)	Technology that measures water current velocities using the Doppler effect of sound waves scattered back from particles within the water column.
bed load	Sediment particles moving in direct contact with the bed by rolling, sliding and saltating. On the lower Fraser River, bed load consists almost entirely of sand-sized sediments.
bedforms	Feature that develops on a river bed due to the action of fluid flow over a moveable bed.
bed-material load	The transport rate of sediments derived from entrainment and erosion of the bed material deposits in the channel; can be transported both as bed load and as suspended bed material, and has a major influence on the stability of the channel. Also, that part of the total sediment load of a river that is composed of particle sizes present in appreciable quantities in the shifting portions of the bed.
computer aided design (CAD)	Software used to assist in the creation, modification, analysis, or optimization of a design.
draft	Depth of water that is required to safely float a ship.
dunes	A bedform that occurs in sand bed rivers and consists of migrating undulations in the river bed surface.
element	In a finite element model, the unit of subdivision of the model mesh.
flow split	The distribution of flow among individual channels in a multi-channel stream.
mesh	In a finite element model, the model representation of the prototype domain, composed of elements.
morphodynamics	The study of riverbed changes due to erosion and sedimentation.
multibeam surveys	Bathymetric surveys conducted using a transducer that emits an acoustic pulse in a multi-directional cone of energy directed downward towards the bed to measure water depth below the ship. The high density of data collected provides a high resolution of features on the bed.
node	In a finite element model, a point common to two or more elements.
prototype	full-scale or “real-world”
planform	Channel shape as viewed from above

Term	Definition
reach	Any specified length of a stream
river training	River engineering works intended to reduce hydraulic hazards by re-aligning and controlling flow patterns within the channel, (e.g., spurs, groynes, guide banks, etc.).
suspended load	Sediment particles maintained in the water column by the turbulence of the flow, including fine material constantly maintained in suspension and sand temporarily entrained from the river bed (the suspended bed material load).
sill	A non-erodible or erosion resistant horizontal layer or structure protruding above the surrounding riverbed, usually forming a hydraulic control.
velocity	A vector quantity consisting of speed and direction; the speed of something in a given direction
velocity magnitude	The speed component of the velocity vector
washload	Fine sediment load that can be maintained in suspension by the turbulence of the flow and consequently is not found in appreciable quantities in the river channel bed material; in the lower Fraser River, wash load sediments consist of clay, silt and fine sand (less than 0.177 mm).

ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Definition
ADCP	acoustic Doppler current profiler
AEP	annual exceedance probabilities
CAD	Computer aided design
CD	chart datum
CFD	computational fluid dynamics
DEM	digital elevation model
GD	geodetic datum
HWL	High Water Level
LiDAR	light detection and ranging
LSA	local study area
NWR Bridge	New Westminster Rail Bridge
PBRep	Pattullo Bridge Replacement Project
Project	Pattullo Bridge Replacement Project
PWGSC	Public Works and Government Services of Canada
RK	River kilometer
RMS	root mean square
RSA	regional Study Area
TransLink	South Coast British Columbia Transportation Authority

1 INTRODUCTION

1.1 Background

TransLink (South Coast British Columbia Transportation Authority) is proposing the Pattullo Bridge Replacement Project (PBRep or Project) to replace the existing Pattullo Bridge with a new four-lane bridge, expandable to six lanes, spanning the Fraser River in the same corridor as the existing bridge (Figure 1). The Project will also involve de-commissioning and removal of the existing bridge.

This Technical Report presents the River Hydraulics and Morphology study for the Project. Section 1 provides the project background and study objectives. Section 2 summarizes the study methods, including field investigations, background studies, and hydraulic modelling. Section 3 describes the physical setting, including the hydrology, reach morphology and river infrastructure. Section 4 characterizes the hydraulic and scour processes at the project site, under existing (pre-project) conditions. Section 5 summarizes the effects of the Project (with existing Pattullo Bridge in-place) on flow patterns and sedimentation patterns (scour and deposition). Section 6 summarizes the Project effects after the existing Pattullo Bridge has been de-commissioned. Section 7 discusses conclusions regarding the potential effects of the Project on river hydraulics and morphology. Detailed information on the development, calibration and test results from the numerical and physical models is contained in Appendices A, B and C.

1.2 Study Objectives

The purpose of the study is to assess the potential changes in Fraser River hydraulics and morphology due to the Project. River hydraulics is the study of flow in rivers, and is most often related to flow patterns, water levels, and velocities. The study of river morphology focuses on river forms and processes, and is primarily concerned with the interaction between fluid flow and the erodible materials in the channel bed and banks (Knighton, 1998). This study reviews potential Project-related changes to water levels, velocities, and flow patterns, and their influence on sedimentation and erosion within the Fraser River.

1.3 Study Approach

The Project presents a considerable challenge regarding river hydraulics and morphology (refer to Section 3 for further detail). Because of the complexity of hydraulics and sediment transport processes at the crossing, several tools were employed to yield a robust assessment of potential changes due to the Project. We first undertook an overview geomorphic study to further develop our understanding of river processes in the lower Fraser River, and to supplement the modelling studies. Three types of model studies were used to assess hydraulic and morphologic changes due to the Project; two numerical models and a mobile-bed physical model. The models are described in Section 2.3.1 and Appendices A-C.

Project-specific studies completed by Aboriginal Groups and shared through consultation supplemented the project team's understanding of existing conditions described in this report and the assisted with validating the existing conditions model results(Tsleil-Waututh Nation 2016; Cowichan Nation Alliance 2017; Kwantlen First Nation 2017a; Kwantlen First Nation 2017b; Kwikwetlem First Nation 2017a; Kwikwetlem First Nation 2017b; Lake Cowichan First Nation 2017; Lyackson First Nation 2017; Musqueam Indian Band 2017)

1.4 Reference Concept

Figure 2 shows the existing bridges (Sky Train Bridge, Pattullo Bridge and New Westminster Rail Bridge) along with the adopted Reference Concept. The centreline of the Reference Concept alignment is approximately 60 m upstream from the NWR Bridge. The Reference Concept consists of four in-river piers:

- Pier N1: This is a compound pier comprising four 7.5 m wide square piers aligned along the north bank to support the New Westminster off-ramps. Each of the piers is supported by four 1.5 m diameter drilled shafts. All of the shafts are tied together with a 2.5 m thick pile cap. Refer to Figure 3 for Pier N1 details.
- North Tower: The North Tower is located near the north bank, approximately 66 m south of Pier N1. The tower pier is 8 m wide and sits on an 18 m wide x 50 m long pile cap. The pile cap is supported by 19 x 2.5 m diameter piles. Refer to Figure 4 for tower details.
- South Tower: The South Tower is located south of the primary and secondary navigation channels (shown in Figure 2), 333 m south of the North Tower. The South Tower dimensions are identical to the North Tower (Figure 4).
- Pier S0: This pier is located 65 m south of the South Tower. It is a compound pier comprising two 3.5 m wide piers aligned roughly upstream to downstream (across the bridge deck). Each pier sits on four 2.5 m diameter steel piles, tied together by a 10 m wide by 12 m long pile cap. Refer to Figure 5 for Pier S0 details.

The Project will increase the net waterway opening[1] at the crossing. The river is approximately 500 m wide at the Project site. At the existing Pattullo Bridge, the net waterway opening is 397 m. In the post-construction period (new bridge in place, Pattullo Bridge decommissioned) the net waterway opening will be 413 m. The Reference Concept piers are set perpendicular to the crossing alignment, which means that they are not necessarily aligned parallel to the flow.

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[1] Net waterway opening is the width of the river at the New Westminster Rail Bridge alignment minus the cumulative width of flow obstructions projected onto the alignment.

2 METHODS

2.1 Study Area

The Local Study Area (LSA) boundary extends from the existing Pattullo Bridge 1 km upstream and 1 km downstream, incorporating the downstream end of Sapperton Bar to downstream of the Skytrain Bridge Figure 1. The New Westminster Rail (NWR) bridge, existing Pattullo bridge, existing Skytrain bridge, and proposed Pattullo Replacement bridge are incorporated in the LSA. The limits of the LSA correspond to the limits of the physical model.

The Regional Study Area (RSA) boundary extends from the existing Pattullo Bridge 6 km upstream and 5.5 km downstream in the Fraser River Annieville Channel and the North Arm, and 8 km downstream in the South Arm (Figure 1). This includes an area extending from downstream of the Port Mann Bridge to downstream of Alex Fraser Bridge in Annieville Channel. In Annacis Channel the model extends to upstream of the Annacis Channel Bridge. In the North Arm it extends to downstream of the Queensborough Bridge. The RSA corresponds to the limits of the morphodynamic model.

2.2 Temporal Scope

The temporal scope of the study includes three time periods:

1. Existing conditions
2. Construction period
3. Post-construction

The characterisation of existing conditions was based on data from recent years and on the interpretive geomorphology study. Multibeam bathymetric surveys from 2014 were used to represent existing riverbed conditions, and acoustic doppler current profiler (ADCP) transects measured in 2014 and 2016 were used to assess existing flow splits and velocity distributions. Both numerical models and the physical model assessed existing conditions as a baseline for comparison with future conditions.

The construction period comprises the approximately 5-years when the new bridge is under construction and the existing Pattullo Bridge remains in place. While relatively short-lived, this scenario is important as it represents the time when the largest footprint of instream infrastructure will be in place. Both numerical models and the physical model assessed potential changes to river hydraulics and morphology during the construction phase.

The post-construction period begins when the existing Pattullo Bridge is decommissioned, and extends to the end of the new bridge's design life of 100 years. For the purposes of the river hydraulics and morphology study, decommissioning of the Pattullo Bridge included removal of in-river piers and partial removal of the riprap scour protection cones in the navigation channels.

2.3 Tools For Assessing Project Effects

2.3.1 Computational Fluid Dynamics (CFD) Model

The potential effects of the Project on near-field flow hydraulics were investigated using Flow-3D (www.Flow3D.com), a three-dimensional computational fluid dynamics (CFD) model with special capabilities for modelling complex geometries and free surface flows. CFD models are well suited to complex local-scale hydraulic modelling, but are limited in scope due to extensive computational requirements, and are not a preferred tool for sediment transport modelling (this capability has only been added to some CFD models in recent months). In order to reduce computational time, all simulations were performed assuming steady flow with constant discharge and water level. This steady-state assumption is acceptable when comparing the hydraulic effects of the Project.

The CFD model assessed five scenarios: existing conditions, the Reference Concept with and without NWRB Bridge upgrades, and the Pattullo Bridge Decommissioning scenario with and without NWRB upgrades[2]. All scenarios were modelled at three flows: the 1894 flood of record, a typical freshet condition, and an incoming winter flood tide. Details of the CFD model study are provided in Appendix A.

2.3.2 Morphodynamic Model

Far-field hydraulics and river morphology (changes to bed elevation) were assessed using the TELEMAC SYSTEM, a 3-dimensional morphodynamic model. Three-dimensional morphodynamic models can cover larger spatial areas than CFD models, and are capable of modelling sediment transport and changes in riverbed levels. However, the larger spatial scope of the Pattullo morphodynamic model limits its ability to assess small-scale hydraulics and local scour around the bridge piers.

The morphodynamic model assessed existing conditions, the Reference Concept, and the Decommissioning scenario. The 2012 freshet flows were selected to assess potential changes in bed elevations under a typical (but larger than average) freshet. The model was run for the period between May 26th and July 27th when flows at Hope were greater than 6,000 m^3/s (the approximate threshold for significant bed material motion in the Fraser River).

Morphodynamic model results represent the conditions at the end of the modelled freshet period. It is not known if river conditions have reached an equilibrium at this point, or if changes would continue to

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[2] New Westminster Rail Bridge was sourced from Translink 2002-09-18 as-built drawings in TIF files: 49742, 60204, 60704, 49785, 49813, 49913-225, 49803, 49814, 49800, 49785, 49786, 49940, 60187, 60188, 60744, 49921, 49924, and 60418. Also, from McElhanney 2016-0601 Mapping Info – Lidar & Ortho Plan

Pattullo Bridge sourced from Translink 2002-09-18 as-built drawings in DWG files: 09330101A and BC Public Works historical drawings from April 1935 (Drawings 101805 to 101813) and proposed Pier 5 pressure grouting drawing (No. 933-19) from January 1957.

Skytrain Bridge sourced from Translink 2016-07-14 PDF file CN130.

Proposed NWR Bridge upgrades from KCB Drawings P010046A02 *Yale 118.7 Piers 6 to 11 Preliminary Strengthening Design* Fig. 1 Plan and Elevation, and Fig. 2 Plan Elevation and Details.

develop over the longer term. However, general agreement with the physical model bed changes (which are believed to have reached a fully developed bed state) suggests the pattern and spatial distribution of riverbed changes would be likely to remain similar over time. Details of the morphodynamic model are provided in Appendix B.

2.3.3 Mobile-Bed Physical Model

Mobile bed physical models are the most robust tool for assessing local scour and deposition patterns near structures such as bridge piers, abutments and training walls. Physical models are capable of capturing detailed and reach-scale hydraulics, local scour around bridge piers, and larger-scale changes in sediment transport. However they are costly to build and are therefore limited in spatial coverage. Physical models also have a finite lifespan.

The physical model assessed existing conditions and two earlier iterations of the proposed replacement: the Stage 1 Reference Concept (not the same as the Reference Concept) and the Short-Span Option. Details of the physical model study are provided in Appendix C.

2.4 Adopted Boundary Conditions For Project Assessment

Table 1 summarizes the inflow conditions that were simulated in the various model tests. The CFD model and physical model simulated the 1894 freshet flood of record as well as winter tidal flow conditions, including upstream (reversing) flows when the freshwater inflows are low and the tidal range is very large. These tests assessed specific short-duration flood events.

The morphodynamic model simulated the 2012 freshet hydrograph, extending over the entire period from May 26 to July 27, to represent conditions when the flows at Hope exceeded 6,000 m^3/s (the approximate threshold for significant bed material motion in the Fraser River).

Table 1. Inflow boundary conditions in model tests

	Exceedance Probability (%)	Return Period (Years)	CFD Model	Morphodynamic Model	Physical Model
1894 Flood	0.2	500	X		X
2012 Flood	5	20		X	
Mean Annual Flood	43	2.3	X		
Winter Flood, large ebb tide	0.5	200			X
Low Winter Inflow, large Flood Tide	___	___	X		X

3 PHYSICAL SETTING

3.1 Hydrology

The Fraser River drains a 232,000 km^2 area of southern B.C., making it the largest river on the west coast of Canada. The Fraser has a snowmelt-dominated flow regime, with the discharge typically rising in April, peaking between May and July (the freshet period) and then receding during the autumn and winter months. Discharges on the Fraser River have been measured periodically by Water Survey of Canada (WSC) at Hope (180 km upstream from the mouth), Mission (85 km upstream from the mouth) and Port Mann (45 km upstream from the mouth). Flows are often referenced to Hope since the station is not influenced by tides and the continuous gauge record extends back to 1912. The flood of record occurred on June 5, 1894, reaching 17,000 m^3/s at Hope and approximately 19,000 m^3/s at Mission . This event was estimated to have a return period of approximately 500 years (NHC, 2008). Figure 6 shows minimum, mean, maximum annual flow hydrographs for the Fraser River at Hope. The year 2012 is also shown because it was selected to represent freshet conditions in the modelling analyses (Section 2.3.1 and Appendices A-C). Average peak flow of the Fraser River at Hope is about 7,000 m^3/s in June; the average low flow is approximately 850 m^3/s in March.

3.2 Lower Fraser River Hydraulic Characteristics

3.2.1 Reach Characteristics

Near the town of Mission, 85 km from the Strait of Georgia, the river changes abruptly from an anabranching gravel bed to a meandering sand-bed single channel. The reach from New Westminster to the Strait of Georgia represents the modern delta. At this location, 35 km from the river mouth, the main channel splits into the North Arm and South Arm. The North Arm further divides into the Middle Arm, and all three branches discharge into the Strait of Georgia.

During low-flow the tidal influence extends up the Fraser River to the point where the slope steepens at the gravel-sand transition just above Mission. The diurnal tidal range during low flow conditions decreases from about 3 m at Steveston (RK 10) to about 2.4 m at RK 20 and to about 1.8 m at the Project site. Upstream of the project site, the tidal range is reduced to about 1.2 m at Port Mann (RK 40) and to 0.4 by Mission (RK 85) (NHC, 2008). In addition to the water level influence, the downstream tidal control results in the influence of a salt water wedge, which can extend upstream past the Alex Fraser Bridge (about RK 30) (Ward, 1976), strongly influencing near-bed hydraulics and sedimentation patterns (e.g. Kostaschuk et al., 1989a; Kostaschuk, 2002; Dashtgard et al., 2012). The salt wedge does not extend as far upstream as Pattullo Bridge (RK 36), even during winter low flows with large tidal swings. As such, salinity was not incorporated into the model studies.

The channel narrows considerably at the Project site, resulting in strong bi-directional tidal currents (Kwikwetlem 2017). Tidal flows at the project site during low-flow conditions typically reach approximately 8000 m^3/s in both directions, although the duration and magnitude of flood tides is substantially less than that of ebb tides. Average channel flow velocity during flood tides can be 0.5 to 1 m/s (flow moving upstream), while ebb tides range from 1 to 1.5 m/s.

The highest water levels, discharges, and velocities in this reach occur during freshet flows. Although flow never reverses at the Project site during freshet, tides continue to influence hydraulics even during high magnitude freshet floods. The overall effect of the tidally varying base level is a strong pulsed character to the flow over the tidal cycle, decreasing outflow (relative to inflow to the lower river) during the flood tide by 4,000 to 5,000 m^3/s and increasing peak outflow during the ebb tide by 3,000 to 4,000 m^3/s.

As is typical with mixed fluvial-tidal systems, varying inflow has the largest impact on the minimum water level, discharge, and velocity over tidal cycles, while changes in maximum values are much more muted with increasing inflow. Tidal variability in water level decreases from about 2.1 m at ~7000 m^3/s inflow to 1.2 to 1.5 m during 10-20 year recurrence interval flows (11-12,000 m^3/s). Over the same range of inflows, minimum water levels increase from -0.34 m to about 1 m, while maximum water levels only increase from about 1.75 to 2.2 m. Minimum velocities increase from about 0.4 m/s to 1.3 m/s, while maximum velocities increase from about 1.9 to 2.5 m/s.

3.3 Lower Fraser River Morphology

3.3.1 Sediment Loads

Sediment loads on the lower Fraser River were measured by Water Survey of Canada (WSC) at Hope, Agassiz, Mission, and Port Mann during the period 1965 to 1986. Based on that data, the total suspended load averaged 16.5 million tonnes/year, and ranged from 12.3 million to 31.0 million tonnes/year (McLean and Tassone, 1988; NHC, 2002; Tywoniuk, 1972). In the lower Fraser River, fine sediments (also called washload) generally remain in suspension and therefore have little effect on sedimentation patterns. Of primary importance is the bed-material load, which is the bed load and the fraction of sediment load capable of depositing in the river, and therefore exerts an influence on river morphology. The bed-material load averaged 2.9 million tonnes/year, and ranged from 1.2 million to 8.9 million tonnes/year (Northwest Hydraulic Consultants Ltd. (NHC), 2002).

3.3.2 Dunes

Dunes are river bedforms that are characteristic of sand-bed channels. Multibeam surveys conducted at the Pattullo Bridge since 2004 show that dunes occur both upstream and downstream of the crossing. Large dunes have been observed from Port Mann (Northwest Hydraulic Consultants Ltd. (NHC), 2009) to the mouth of the Fraser River. Dune height typically varies from 0.5 to 2.0 m in channels of approximately 12 m in depth, although individual dunes can be considerably larger (Church and McLean 1994).

Near Steveston, dune bedforms of up to four metres in height were measured in the channel. The morphology of dunes in the lower Fraser River varies with discharge (Kostaschuk et al., 1989b); dunes are largest during freshet, then wash out and rebuild over the rest of the year. Results from multibeam surveys (Kostaschuk and MacDonald 1988) show that bedforms in the Sand Heads area have a curved, concave-downstream planform, and crests were continuous for at least 300 m across the river channel. The major bedforms are essentially two-dimensional, transverse dunes migrating directly down-channel. At the river mouth, migration rates were found to be at their maximum during the freshet period with an average migration rate of 14.8 m/day (Kostaschuk et al., 1989b). Field observations by Pretious and Blench (1951) determined that migration occurred at rates of up to 50 to 75 m/day. The dunes produce periodic scour and fill as they migrate along the channel and can considerably increase total scour depths, damaging existing scour protection aprons and rock protection, and potentially exposing existing pipe crossings.

3.3.3 Riverbed Lowering and Dredging

Average bed elevations in the lower Fraser River have lowered by approximately 3 m since 1950 as a result of dredging, flood protection dikes, river training, and bank hardening (McLean et al., 2005; Nelson et al., 2017) (Figure 7). Analysis of the historical bathymetric record dating back to 1898 illustrates the important role that construction of instream infrastructure has played in governing changes in bed elevation, and the long-term and persistent bed degradation that has been occurring due to a sediment budget deficit (Nelson et al., 2017; NHC, 2017).

Sediment removal from dredging, in combination with flood protection dikes, river training, and bank hardening, have significantly altered the channel hydraulics, sediment transport characteristics and morphology of the lower Fraser River. Changes in the river morphology over time are evident in the bathymetric record, historical maps and airphotos, and information provided by Aboriginal Groups through Project-specific studies or through consultation. These effects extend beyond the limits of the localized dredging operations. While dredging has been carried out primarily downstream of New Westminster, bed level lowering (degradation) has extended as far upstream as Mission (NHC, 2008). Furthermore, as the channel has been progressively deepened, the volume of sediment that needs to be dredged to maintain the design grade increases, since the deeper channel is less efficient at transporting the incoming sediment load. This alteration of the river's overall sediment budget is expected to increase the rate of degradation along the river.

Throughout the lower Fraser River, riprap aprons are used to protect bridge and pipeline crossings from scour; these include the existing Pattullo, NWRB and Skytrain bridges (other relevant in-river infrastructure is discussed in Section 3.4). As the channel has deepened over time, these aprons now project above the general river bed level, creating protrusions that induce additional localized scour. The bed lowering has also exposed other non-alluvial sediments along the river that potentially induce similar local scour effects.

Beginning in the early 20th century, the construction of flood control dikes and bank protection have isolated the main channel from its floodplain, while river training structures have narrowed the channel and altered flow patterns. River training at the project site began with construction of a set of three small wing dams (groynes) in the first decade of the 20th century and continued with progressively increased channel confinement and upstream extension of Annacis Island through the early 1970s, culminating in construction of the New Westminster Trifurcation Project, a series of training walls and submerged weirs constructed in an effort to reduce the amount of maintenance dredging required in the navigation channel.

Dredging of the lower Fraser River navigation channels began in 1885 when the main channel was only 2.7 m deep at the river mouth, and the main systematic dredging effort began around 1945 (Dashtgard et al., 2012). Over the years, the depth of the navigation channel has been increased incrementally. In 1973 the permissible vessel draft was 8.8 m; by 2004 it was 11.5 m. Between 1973 and 2016 the design grade of the navigation channel has decreased from El. -9.1 m to El. -12.1 m GD.

In response to river training and dredging, the bed of the lower Fraser River has lowered at an average rate of 8 cm/year between 1965 and 1988 (McLean and Tassone, 1990), but has slowed to an average rate of 2 cm/year since the late 1980s or early 1990s (Nelson et al., 2017) (Figure 7). As average bed levels decrease, existing riprap protection and other non-alluvial materials such as Pleistocene glacial diamicton and Holocene delta foreset beds and peat deposits (Clague et al., 1983, 1991, 1998) begin to project above the riverbed. The increased projection induces turbulence and scour and deepening the lowest parts of the riverbed at a faster rate than the average bed lowering.

Long term degradation of the average riverbed levels and the deepest parts of the channel have implications for the Project and nearby infrastructure. The lowering of bed levels at Pattullo Bridge between construction in 1936 and the present day is probably a result of historical deepening in combination with the protrusion of existing riprap at the Pattullo Bridge and NWRB. Bed levels at the Pattullo crossing alignment have decreased by up to 12 m, with the effect most pronounced on the south side of the channel. Construction of future scour protection should account for project riverbed degradation over the life of the Project.

3.4 River Infrastructure

3.4.1 Pipeline Crossings

The lower Fraser River is crossed by a number of water and sewer mains owned and operated by Metro Vancouver (Figure 9). The following water and sewer crossings are within the RSA:

Sewer Crossings

- New Westminster Interceptor – North Arm Fraser
- New Westminster Interceptor – Annacis Channel
- North Surrey Interceptor – Annieville Channel

Water Crossings

- Annacis Main No. 3 – Fraser River
- Annacis Main No. 2 – Annieville Channel

- Annacis Main No. 2 – Gunderson Slough
- Annacis Main No. 2 – Annacis Channel
- Queensborough Main – North Arm Fraser River

The Port Mann Main, Annacis Main No.2 North Arm, and Annacis Main No.4 Annacis Channel crossings were not included in the list of potentially affected crossings. They are not expected to be susceptible to Project effects.

Metro Vancouver will be constructing a new water supply tunnel at the New Westminster Trifurcation. While this crossing will be within the RSA, it is proposed as a deep bored tunnel. As such, it is not expected to be susceptible to potential changes due to the Project.

Oil and Gas Crossings

Several oil and gas pipelines also cross the lower Fraser River within the RSA. These include:

- Fortis BC's PMA-CPH Lateral 914 mm pipeline (Port Mann Crossing)
- Kinder Morgan's pipeline crossing

3.4.2 Bridge Crossings

There are three bridges within the LSA, including the existing Pattullo Bridge, the NWRB, and the Skytrain Bridge. The Queensborough Bridge, Queensborough Rail Bridge, Annacis Island Rail Bridge, and Alex Fraser Bridge are within the RSA (Figure 1).

3.4.3 River Training

The hydraulics and morphology of the Fraser River within the RSA have been extensively modified by river training works including: the Annieville and Phase 3 trifurcation dikes; expansion of Annacis Island; two rock sills extending from the north bank; a rock sill across Annacis channel and the North Arm; two wing dams (pile groins) extending from the south bank of Sapperton Bar; and the Sapperton V-dike.

4 EXISTING CONDITIONS NEAR PATTULLO BRIDGE

4.1 Flow Patterns

Figure 10 shows the general bed topography and the configuration of the existing bridge crossings (Sky Train Bridge, Pattullo Bridge and NWRB near the project. Figure 19 shows the flow pattern and current speed in the reach, as estimated from the Telemac 3D model at the peak of the 2012 flood event (reproduced from Appendix B, Figure 14).

About 2.4 km upstream of the crossing, flow diverges around Sapperton Bar; Queens Reach (the main channel) runs along the south side of the bar, and Sapperton Channel conveys flow to the north of the bar (Figure 1 and Figure 10). Flow then converges downstream of Sapperton Bar before passing through the NWRB, Pattullo and Skytrain Bridges. A training wall (the Phase 3 Trifurcation wall) protrudes into the channel and constricts flow about 740 m downstream of the Skytrain bridge (about 1 km downstream of the existing Pattullo bridge), at Fraser Surrey Docks. Roughly another 1 km downstream the Fraser River splits into the North Arm, Annacis Channel, and Annieville Channel; this area is referred to as the New Westminster Trifurcation.

Flow distribution around Sapperton Bar, through the bridge crossings and at the trifurcation was measured using ADCP on 15 June, 2016 between 10:30 and 12:30 PST. Paired transect locations at shown in Figure 11. River discharge varied over the course of the measurements due to the tidal influence. Total flow at Sapperton Bar was 8276 m^3/s, with 30% of the flow going through Sapperton Channel and 70% through Queens Reach. At the bridge crossings, total flow averaged 7852 m^3/s, with about 60% of the flow passing to the north of NWRB Pier 5 and 40% to the south. Total flow at the New Westminster Trifurcation was 7129 m^3/s, and was split 78% in Annieville Channel, 10% in Annacis Channel, and 12% in the North Arm.

As flow passes under the NWRB it plunges over a submerged weir, or sill, formed by the riprap scour protection around the NWRB piers. Figure 12 shows an idealized case of local scour due to flow over a submerged weir. The riprap protrusion is most pronounced on the south side of the channel, where riverbed elevations go from approximate El. -12 m upstream of the NWRB to El. -20 m beneath the Pattullo bridge. The abrupt drop in riverbed elevations results in turbulent flow and enhanced scour at the Pattullo bridge.

4.2 Scour

Scour conditions at the Project site are potentially the most severe in the lower Fraser River. The Project is situated in one of the narrowest sections of the river, approximately 50 m upstream of the NWRB and just downstream of a long converging left-hand bend. Tidal fluctuations and Fraser River flows combine to yield highly dynamic flow conditions. During winter, flows are fully reversing due to larger tidal influence and smaller Fraser River flows. During construction in 1936, a very large freshet resulted in deep scour, nearly overturning the Pier 4 caisson during construction. The Pier 5 caisson was punctured by a loose shearwater and flooded, but did not settle (Swan, 1937).

Flow convergence downstream of Sapperton Bar results in severe scour conditions. Flow converges downstream of Sapperton Bar between Pattullo Piers 2 and 3 . The combination of channel contraction, convergence, and a slight bend in the river causes deep scour here, making this area the deepest part of the channel at the Pattullo Bridge crossing (NHC, 2007). Riverbed elevations here are normally on the order of El. -23 m.

General (i.e. contraction) scour adds to the scour potential during extreme floods, since the opening at Pattullo Bridge is relatively narrow (about 500 m net). A weir-like apron of rock is likely present under the CN Rail Bridge, which results in deep scour around Pattullo Piers 4 and 5 when flow plunges over the apron during freshet. Local scour around the bridge piers also contributes, and is augmented by the angle of pier skew to the flow alignment of about 16 degrees (NHC, 2007). Scour protection is present around all of the Pattullo Bridge piers. The extents of existing riprap around Piers 4 and 5 are reasonably known following upgrades in 2008.

Since construction of the rail bridge early this century, the bed downstream of the rail bridge has permanently lowered 10 to 15 m. This has caused large “cones” to form around the Pattullo piers. Tide conditions combined with high river flows have been observed to cause local bed levels to fluctuate by up to 7 m over a 24 hour period on both sides of the rail bridge. The hydraulic influence of individual structures, such as piers and scour protection aprons, can extend hundreds of meters upstream and downstream (NHC, 2009).

NHC has been monitoring scour at the Pattullo Bridge on behalf of TransLink since 2004; a regular bi-annual monitoring program has been in place since 2011. Riverbed elevations are surveyed during freshet and during the large winter tidal cycles. Flow conditions at the bridge, particularly at Piers 4 and 5 and the upstream railway bridge vary significantly throughout the year. Severe conditions can occur during freshet or during the winter low discharges as a result of the large tidal cycles. There is a very large variation in bed levels on the south side of the channel over a year, with long-term variations in the order of 12 m observed. Changes on the north side of the channel are not as pronounced. Between the freshet and the winter surveys, sediment deposits in the region between and downstream of Piers 4 and 5; it is suspected that some of the deposition is due to material being transported from downstream. In addition, relatively large and deep scour holes develop upstream of the gaps between the railway bridge piers. During the freshet, material between the bridge piers is generally scoured away, the mounds around these piers become more pronounced due to the development of “horseshoe” scour on the upstream side, and the scour holes upstream of the railway bridge refill. Early monitoring identified scour hazards at Piers 4 and 5 which were addressed by protection upgrades in 2008. NHC and TransLink continue to re-assess scour conditions at the bridge twice per year: once during the large winter tidal cycles and again during spring freshet. No further upgrades have been required since 2008, but launching of riprap at Pier 4 has been occurring since at least 2013 (NHC, 2013).

5 PROJECT EFFECTS – REFERENCE CONCEPT WITH EXISTING PATTULLO BRIDGE

Results of the three model studies are synthesized to provide a concise summary of the changes to river hydraulics and morphology expected as a result of the Project. Except where otherwise noted, river hydraulics results are from the CFD model and changes in bed elevation are from the morphodynamic model. Although the Reference Concept was not tested in the physical model, observations from the physical model have been incorporated where applicable.

Detailed model results from the CFD, morphodynamic, and physical models are provided in Appendices A, B, and C, respectively. The accuracy and precision of the model results are limited by available data for calibration and validation, natural variability and inherent randomness in river systems, and the representation of complex natural systems in simplified models. The three models in combination provide a robust basis for assessing potential Project effects, but do not deterministically predict future conditions.

5.1 River Hydraulics

Changes in river hydraulics due to the addition of Reference Concept piers were primarily limited to local effects around the new and existing piers, and decreased velocities downstream of the new pylons. Velocities in the physical model existing conditions tests were generally similar to the CFD results, with the exception that surface velocities in the physical model are not always directly comparable to depth-averaged velocities in the CFD model. Mid-depth point velocity measurements in the physical model are generally a more appropriate comparison.

5.1.1 Effect on Local Current Velocities

The Reference Concept bridge is not expected to result in any significant increase in average velocities. Inclusion of the Reference Concept piers in the CFD model increased velocities in the primary navigation channels by 0.1 m/s for the 1894 flood of record (Figure 13) and the typical freshet flows (Figures A6-A7). These differences are within the numerical accuracy of the model and are not considered significant. There was no change in velocities in the secondary navigation channel.

A low-velocity shadow occurred downstream of the South Tower. At this location, flow velocity reduces from 2.7 m/s to 0.4 m/s under flood of record conditions (Figure 13), and from 1.6 m/s to 0.3 m/s under Typical Freshet flow (Figure 14). The decrease in depth-averaged velocities is attenuated downstream of the south pylon, but persists as far downstream as the Skytrain Bridge (Figure 21). Near-bed velocities closer to the Tower are also reduced, as shown in Figure 15. Similar but more moderate effects occurred at the North Tower.

Velocities between the South Tower and Pier S0 increased by 0.3 m/s and 0.4 m/s for the typical freshet and flood of record flows, respectively. A localized region of high velocity developed on the upstream-north side of the South Tower. Downstream of the South Tower, a strong shear plane was noted where faster flow meets the slower flow in the eddy downstream of the Tower (Figure 15 and Figure 16).

Velocity changes for the winter flood (incoming) tide condition were less pronounced (Figure 17 and Figure 18). Velocities at the South Tower increased from 1.3 m/s under existing conditions to 1.5 m/s. In the lee of South Tower velocities reduced to 0.4 m/s, compared with 1.4 m/s for existing conditions. Similar but weaker low-velocity areas were observed behind the remaining Reference Concept piers.

5.1.2 Effect on Current Velocities Downstream of Crossing

Figure 21 show the predicted changes in velocity downstream of the crossing using the results from the Telemac 3D simulation at the peak of the 2012 freshet. The Reference Concept will result in formation of low velocity regions behind the Reference Concept piers due to flow obstruction and flow separation. The zone of reduced velocity (> 0.1 m/s) extends approximately 1 km downstream of the bridge along the south edge of the navigation channel. The zone of reduced velocity along the north side extends approximately 0.7 km downstream of the bridge.

5.1.3 Effect on Water Levels

No significant effects to water levels are expected to result from the Reference Concept or the decommissioning of Pattullo Bridge.

Table 2. Modelled water levels for existing conditions, Reference Concept, and Decommissioning scenarios.

Location	Existing Conditions	Reference Concept	Decommissioning
Primary navigation channel at Pattullo	0.68	0.66	0.68
Secondary navigation channel at Pattullo	0.68	0.69	0.68
Navigation channel at Skytrain	0.65	0.64	0.64
Navigation channel at Sapperton Channel	0.87	0.83	0.85
Navigation channel at Queens Reach	0.88	0.87	0.87
South of NWRB Pier 5	0.64	0.62	0.64

5.1.4 Effect on Flow Split

Flow splits are not expected to change measurably as a result of the Project. Table 3 shows modelled flow splits for the existing, Reference Concept, and Decommissioning scenarios. Measured flow splits are discussed in Appendix B.

Table 3. Modelled flow splits for existing conditions, Reference Concept and Decommissioning scenarios.

Location	Existing Conditions	Reference Concept	Decommissioning
Sapperton V-Dike			
Sapperton Channel	30%	30%	30%
Queens Reach	70%	70%	70%
Pattullo Bridge			
North of NWRB Pier 5	65%	66%	66%
South of NWRB Pier 5	35%	34%	34%
Trifurcation			
North Arm	12%	12%	12%
Annacis Channel	9%	9%	9%
Annieville Channel	79%	79%	79%

Notes:

1. Modelled flow splits from typical freshet flow (2012).
2. Flow splits at Sapperton V-Dyke and Pattullo Bridge from CFD model.
3. Flow split at New Westminster Trifurcation from morphodynamic model.

5.2 Effect on River Morphology

The effects of the Reference Concept on riverbed elevations were assessed by comparing morphodynamic model results for proposed conditions versus morphodynamic model results for existing conditions. The model was run using freshet flows from 2012, approximately a 20-year discharge. The physical and CFD model results were consulted for additional insight and validation.

Changes to bed elevations due to the Reference Concept piers are expected in the area near the Pattullo Bridge, with minor changes as far downstream as the New Westminster Trifurcation. Various “points of interest” were identified by POV, Metro Vancouver and the PBRep Archaeology team. These are identified in Figure 8, Table 4, and Table 5. Bed level changes for existing versus Reference Concept conditions are illustrated in Figure 22, and changes in velocity are shown in Figure 21. The Project is not expected to result in any significant changes in river velocity or bed elevations at the archaeological sites of interest.

A number of constructed tidal marshes have been identified as areas which would be sensitive to any bed level changes. Constructed tidal marshes reviewed for potential Project effects are shown in Section 4.2 Figure 4.1-A-15. These were compared with modelled velocity (Figure 21) and bed level changes (Figure 22) from the morphodynamic model. No Project-induced changes in velocity or bed levels are expected at any of these sites.

5.2.1 Bed Level Changes in the Navigation Channels

Comparison of riverbed elevations for the existing conditions and Reference Concept simulations indicated there is potential for changes in the navigation channels. Results represent conditions at the end of the approximately nine week freshet simulation. Upstream of the Reference Concept bridge, the model showed 0.5 – 1.0 m of bed lowering in the main navigation channel, probably due to moderate flow acceleration in between the new towers.

About 0.5 m of aggradation occurred downstream of the existing Pattullo Pier 4 along the margin of, and encroaching slightly into, the primary navigation channel. The aggradation appears to be due to a reduction in velocities in the wake of the South Tower on the new bridge. Similar deposition patterns were observed downstream of the south pylon in the physical model tests.

Downstream of the Skytrain Bridge about 0.5 m of bed lowering occurred in the primary navigation channel. There is no notable difference in flow velocities here, so the bed lowering is believed to be a result of less available sediment due to the deposition along the margin of the navigation channel.

5.2.2 Bed Level Changes at the Bridge Crossings

Flow deceleration downstream of the new towers is expected to result in local deposition. At the Reference Concept bridge, 3-4 m of bed level increase occurred downstream of the South Tower between NWRB piers 7 and 8. Approximately 1 - 2 m of aggradation is expected downstream of Pier S0 between Pier S0 and existing bridge.

Flow accelerates between the South Tower and Pier S0 resulting in bed lowering of about 1.5 m upstream of NWRB Pier 8.

At Pattullo Bridge, about 1 m of bed lowering occurred between Piers 5 and 6, extending upstream to between NWRB Piers 9 and 10, and downstream for about 100 m. This lowering occurs because of increased velocities in the area.

Results of the physical model tests suggested that addition of new piers at the Reference Concept alignment has the potential to cause deep local scour at the NWRB piers, and to a lesser degree at the Pattullo Bridge (Appendix C). The physical model tested two replacement concepts that were precursors to the Reference Concept. These concepts both incorporated two large pylons and several other piers upstream of the NWRB. Test results indicated that scour protection upgrades would be required at the NWRB piers and most probably at the Pattullo Bridge piers. It is expected that the Reference Concept would result in similar local scour effects.

5.2.3 Bed Level Changes Downstream of Crossing

The bed level increased by 2-3 m in the area downstream of Pattullo Pier 4 between km 35 and 36. This depositional area borders on the navigation channel, but as mentioned above only about 0.5 m of increase extends into the navigation channel and covers a limited area. The deposition in this area is a result of lower velocities downstream of the South Tower.

Up to 2 m of infilling was noted downstream of the Pattullo Bridge between Piers 1 and 2, where velocities decrease in the wake of the North Tower.

Bed lowering of 0.5 – 1.0 m near the upstream end of the Phase III Trifurcation Training Wall is expected to occur. This is a result of a sediment deficit caused by upstream deposition in the wake of the South Tower between km 35 and km 36. There are no notable changes in velocity in this area, so the bed lowering is believed to be a result of a localized sediment deficit adjacent to the area of deposition which borders the navigation channel.

At the New Westminster Trifurcation, the model showed about 0.5 m of bed lowering in Annieville Channel along the Annieville Dyke, and 0.5 - 1.0 m of lowering downstream of the sheet pile wall at the tip of Annacis Island (there is a deep scour hole in this area). Lowering in these areas is believed to be a result of a sediment deficit due to the upstream deposition.

6 PROJECT EFFECTS AFTER DECOMMISSIONING OF PATTULLO BRIDGE

6.1 Assumed Test Conditions

The Pattullo Bridge Decommissioning scenario represents a long-term condition, after the new bridge has been constructed and the existing Pattullo Bridge has been decommissioned. The existing Pattullo piers were removed, and the riprap scour protection cones were truncated at El. -10.0 m GD in the secondary navigation channel and at El. -14.35 m GD in the primary navigation channel.

6.2 River Hydraulics

6.2.1 Effect on Local Current Velocities

Local regions of high velocities caused by flow interaction with existing Pattullo piers 3 and 4 (Figure 23 and Figure 24), are no longer present after decommissioning, resulting in a velocity reduction in these regions of approximately 0.5 m/s after decommissioning during flood of record flows, and of 0.3 m/s under typical freshet conditions.

For the winter flood tide scenario (Figure 25), the absence of low-velocity shadow from the existing piers results in slightly higher velocities west of the NWRB pier after decommissioning. The highest increases in velocity are about 0.2 m/s directly west of NWRB piers 3 and 4.

Decommissioning of the existing bridge will increase the cross-sectional flow area at the crossing. This results in an overall reduction in velocity and increase in bed elevation. However, the low velocity regions behind where existing bridge piers are located will experience faster velocity with the bridge decommissioned.

6.2.2 Effect on Downstream Current Velocities

Figure 26 shows the predicted change in velocity after de-commissioning downstream of the crossing. These results represent conditions during the peak of the 2012 freshet as determined from the Telemac 3D model. The predicted changes are very similar to the Reference Concept case with existing Pattullo Bridge in-place. Low velocity areas exist downstream of the new piers, with the greatest effect occurring downstream of the South Tower. Also similar to the Reference Concept scenario, velocities increase between south of the new pier S0 and downstream beyond the rail bridge.

Velocities in the decommissioning scenario differ from the Reference Concept scenario differ most markedly in the areas where Pattullo Piers have been decommissioned. Velocities are higher downstream of where the Piers have been removed, and are slower to the south of Piers 4 and 5 where riprap mounds have been partially removed. The latter effect is due to a reduction in flow acceleration around the riprap mounds.

6.2.3 Effect on Water Levels

No significant effects to water levels are expected to result from decommissioning of the Pattullo Bridge (Table 2).

6.2.4 Effect on Flow Split

Flow splits are not expected to change significantly as a result of the decommissioning (Table 3).

6.3 River Morphology

Changes in river bed levels in the Decommissioning scenario were similar to the Reference Concept scenario, with a few notable differences. Removal of the Pattullo piers and truncation of the riprap cone at Pier 4 eliminated the bed lowering that occurred between Piers 5 and 6 in the Reference Concept Scenario. Deposition south of the navigation channel near the Skytrain alignment increased from 2-3 m in the Reference Concept scenario to 4-5 m for Decommissioning, and deposition on the order of 1 m may extend a few meters in to the navigation channel further downstream. These changes are believed to be a result of the reduced velocities around the decommissioned Pattullo Pier 4 (Figure 26), allowing sediment to deposit sooner than it did before partial removal of the riprap around Pier 4. Bed lowering around the flow splitter at the upstream end of Annacis Island was reduced under the Decommissioning scenario. Also, with the Pattullo Bridge decommissioned, about 0.5 m of aggradation is expected in the navigation channel in Annieville Channel around km 34. A summary of modelled bed level changes resulting from the Decommissioning scenario is provided in Table 5.

6.4 New Westminster Rail Bridge (NWRB) Upgrades

CN Rail has proposed structural upgrades to the NWRB piers. The proposed upgrades consist of two new 2.5 m diameter piles at the upstream and downstream ends of NWRB Piers 6-10, and the addition of a pile cap tying the new piles to the existing piers, removal of the Pier 6 protection, and addition of two more 2.5 m diameter piles in its place. Potential changes to river hydraulics resulting from the proposed NWRB upgrades were assessed using the CFD model. Effects were limited to local increases in the size of back eddies forming downstream of the NWRB piers (Figure 13, Figure 14, and Figure 17). However, further assessment of the proposed upgrades is recommended. The CFD model was developed for the purpose of assessing changes due to the addition of new piers; a finer local mesh may be required to fully examine the local near-field effects of the NWRB upgrades.

7 CONCLUSIONS

The study used three models to assess potential changes to river hydraulics and morphology as a result of the Project. A CFD model was used to provide detailed hydraulics, a 3-dimensional morphodynamic model was used to assess changes to the river bed level, and a mobile-bed physical model was used to assess detailed local-scale hydraulics and sedimentation. The CFD model and morphodynamic models compared the Reference Concept and Pattullo Decommissioning scenarios with existing conditions. The physical model tests were undertaken for two earlier iterations of the Reference Concept.

Limited changes to river velocities are expected to occur as a result of the Reference Concept. No significant change in average velocities is expected. Model results suggest local areas of increased velocity may occur between the South Tower and Piers S0, and on the upstream side of the South Tower. A low-velocity area occurred downstream of the South Tower, and persists as far downstream as the Skytrain Bridge. The Decommissioning scenario produced similar velocities, with minor differences where the riprap cones have been truncated.

No changes to water levels or flow splits are expected to occur as a result of the Project.

The following bed level changes are expected to occur as a result of the Reference Concept while the Pattullo Bridge piers remain in place:

- 0.5 – 1.0 m of bed lowering in the primary navigation channel upstream of the Reference Concept
- About 0.5 m of aggradation downstream of the existing Pattullo Pier 4 in the primary navigation channel
- About 0.5 m of bed lowering in the primary navigation channel downstream of the Skytrain Bridge
- 4-5 m of bed level increase downstream of the South Tower between NWRB piers 7 and 8
- 2-3 m bed level increase downstream of the South Tower between km 35 and 46
- Bed lowering of about 1.5 m between the South Tower and Pier S0, upstream of NWRB Pier 8.
- About 1 m of bed lowering between Pattullo Piers 5 and 6, extending upstream to between NWRB Piers 9 and 10, and downstream for about 100 m
- 1-2 m of bed level increase downstream of the Pattullo Bridge, between Piers 1 and 2 in the wake of the North Tower.
- Based on physical model results, deep local scour is expected at the NWRB piers, and to a lesser degree at the Pattullo Bridge. Both are expected to require scour protection upgrades.

Changes due to the Project after the Pattullo Bridge has been decommissioned (piers removed and riprap mounds partially removed) are expected to be similar, with the following differences:

- No bed lowering between Piers 5 and 6

- 4-5 m of deposition downstream of the South Tower, south of the navigation channel near the Skytrain alignment (compared with 2-3 m in the Reference Concept scenario)
- Less bed lowering at the Annacis Island flow splitter compared with the Reference Concept
- About 0.5 m of aggradation in the navigation channel in Annieville Channel around km 34.

Expected changes to the riverbed under the Reference Concept and Decommissioned scenarios represent conditions after the modelled freshet period. While the spatial distribution of bed elevation changes is expected to remain similar over time, the magnitude of these changes may continue to evolve over time.

Modelled effects of the NWRB upgrades were limited to local increases in the size of back eddies downstream of the NWRB piers. However, further assessment of the proposed upgrades is recommended. Refinement of the CFD model may be required to fully examine the local near-field effects of the NWRB upgrades.

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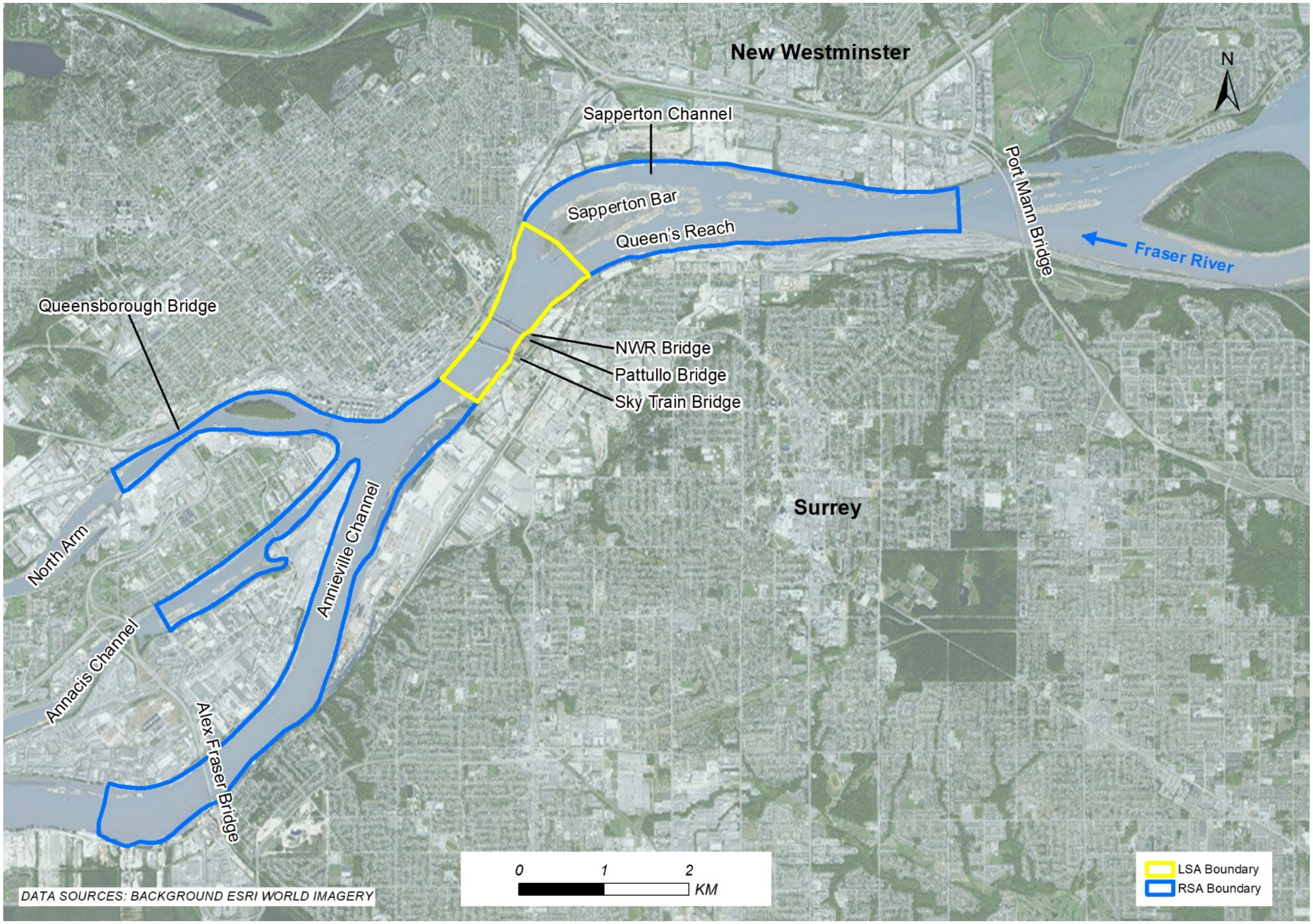
FIGURES



DATA SOURCES: BACKGROUND ESRI WORLD IMAGERY

Figure 1. Lower Fraser River between Port Mann Bridge and Alex Fraser Bridge

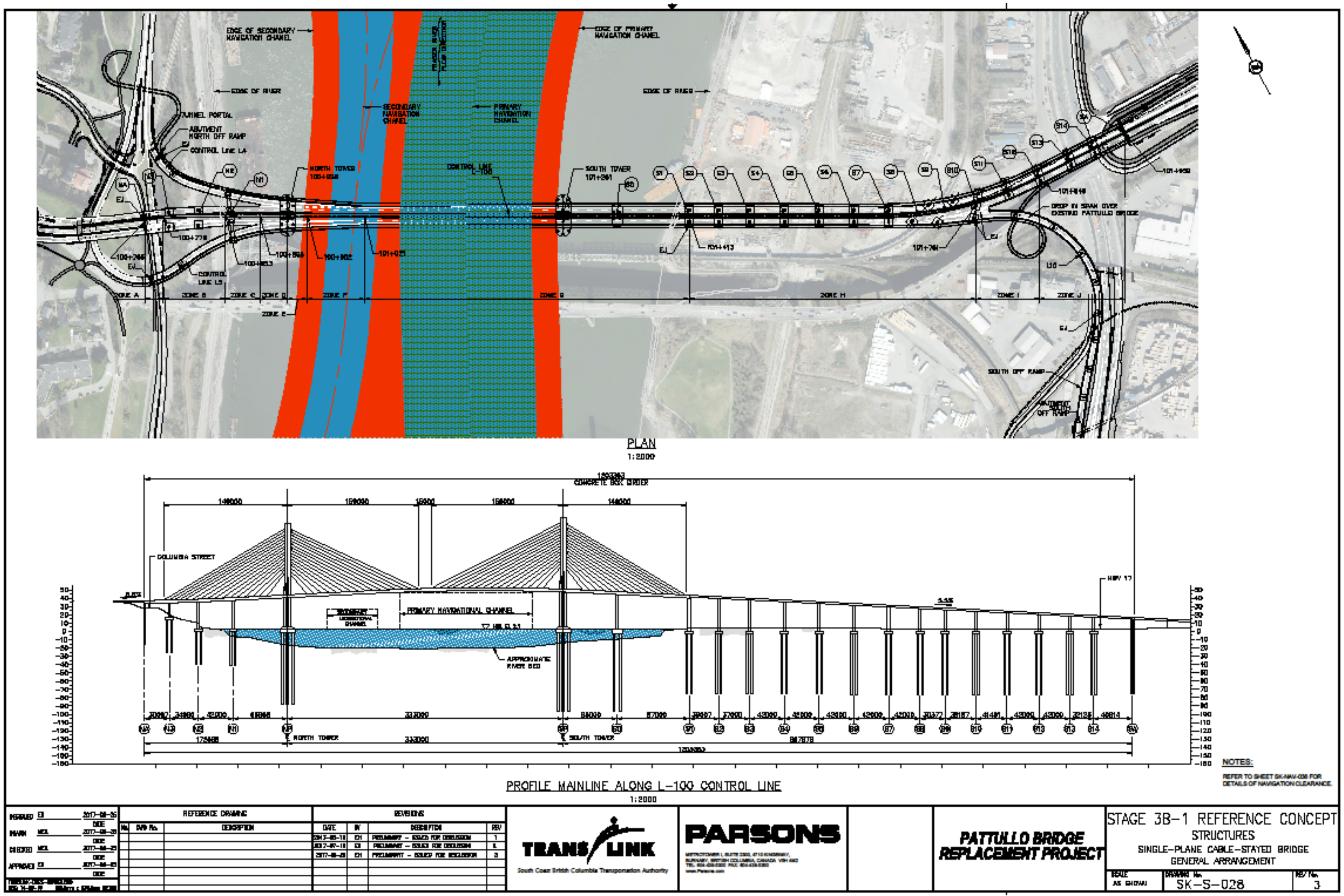


Figure 2. Reference Concept piers plan and elevation

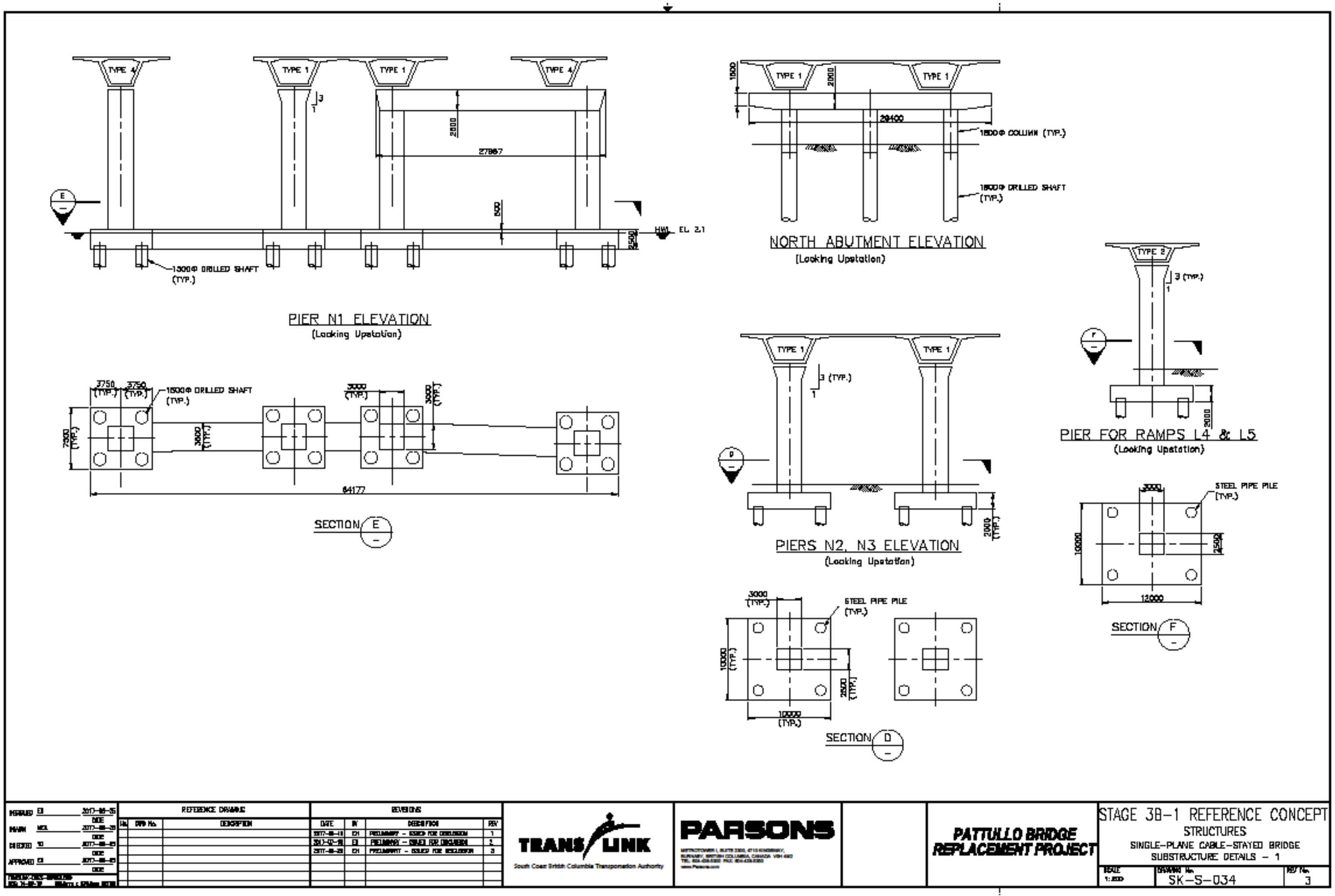


Figure 3. Reference concept north piers details

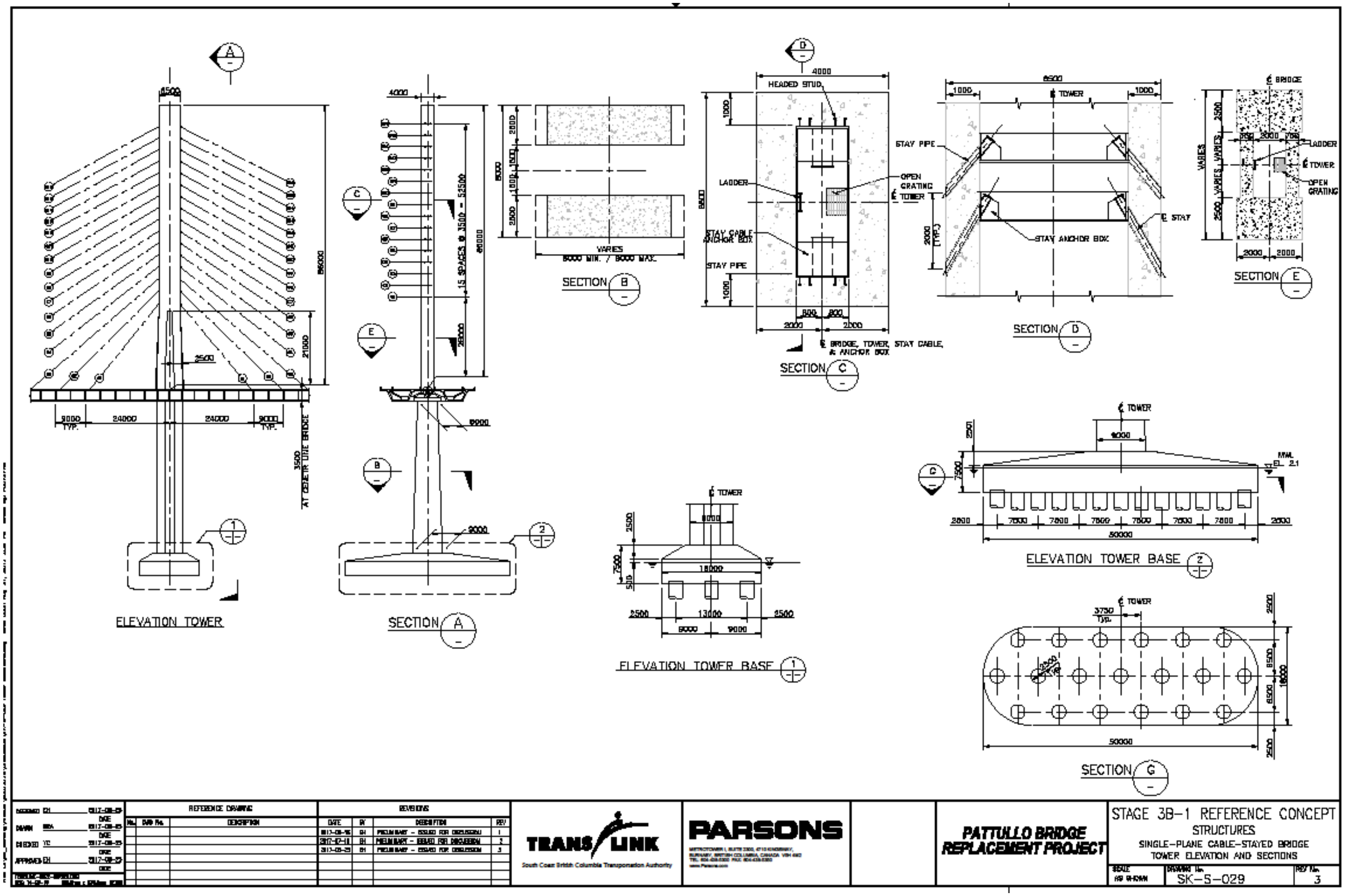


Figure 4. Reference concept tower elevation and sections

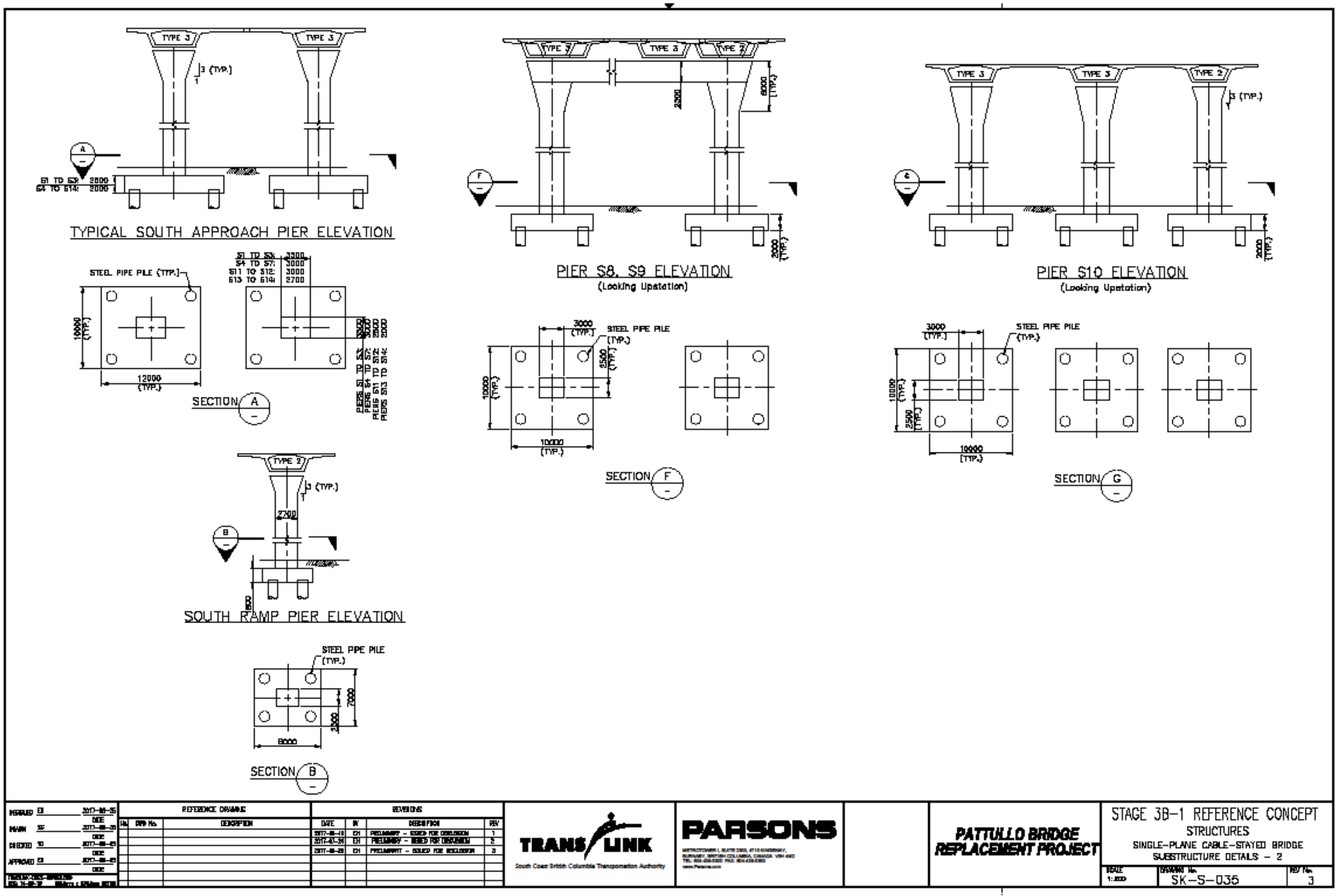
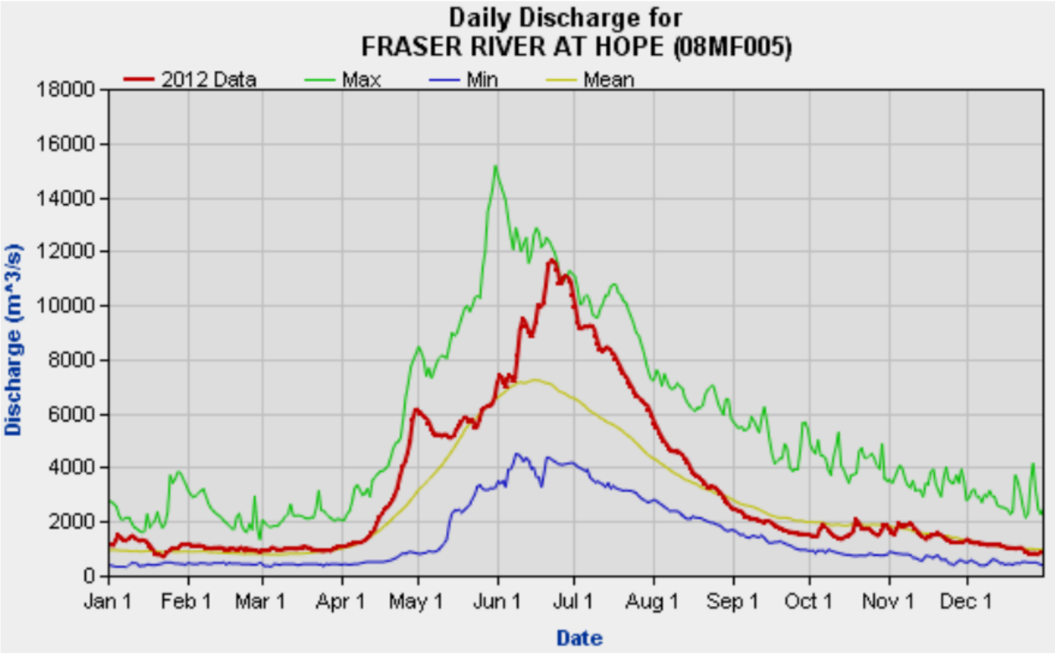


Figure 5. Reference concept south piers details



Statistics corresponding to 101 years of data recorded from 1912 to 2012.*

Figure 6. **Annual hydrograph for the Fraser River at Hope (from Water Survey of Canada).**

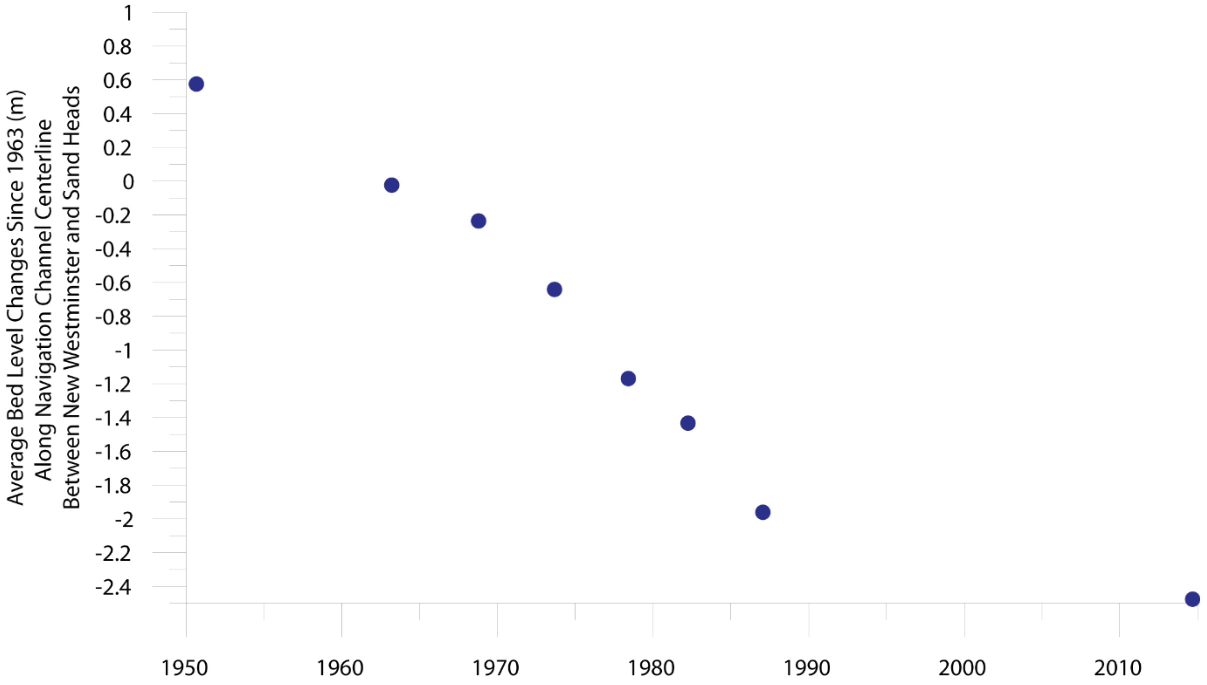
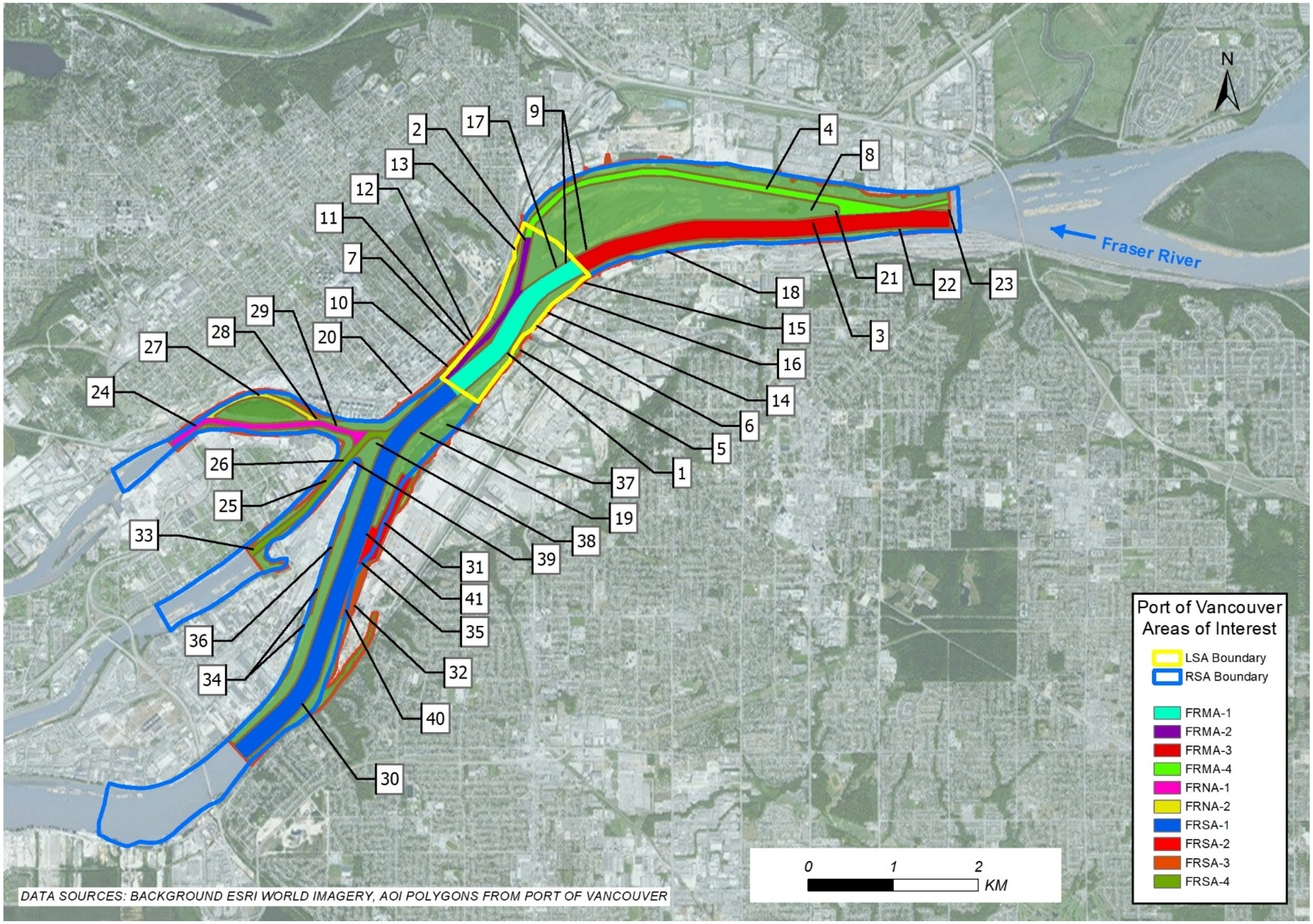


Figure 7. **Average Channel Changes Along Fraser River Below New Westminster. 1950-1988 data from Mclean and Tassone (1990), 1988-2014 comparison completed as a part of the present study.**



DATA SOURCES: BACKGROUND ESRI WORLD IMAGERY, AOI POLYGONS FROM PORT OF VANCOUVER

Figure 8. **Areas of interest identified by POV. Site names and model results are summarized in Table 4 and Table 5.**

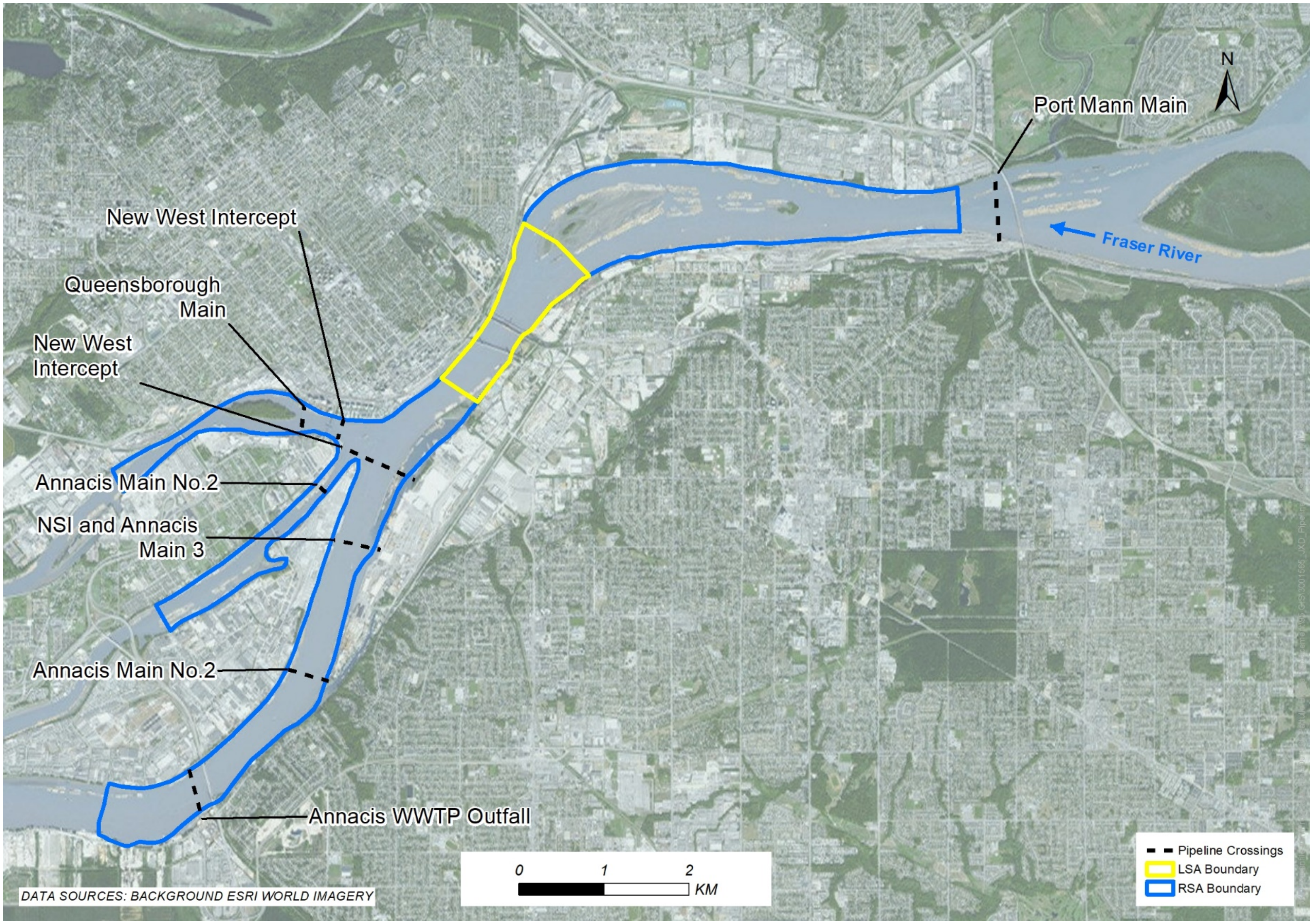


Figure 9. Pipeline crossings in the lower Fraser River near the Project.

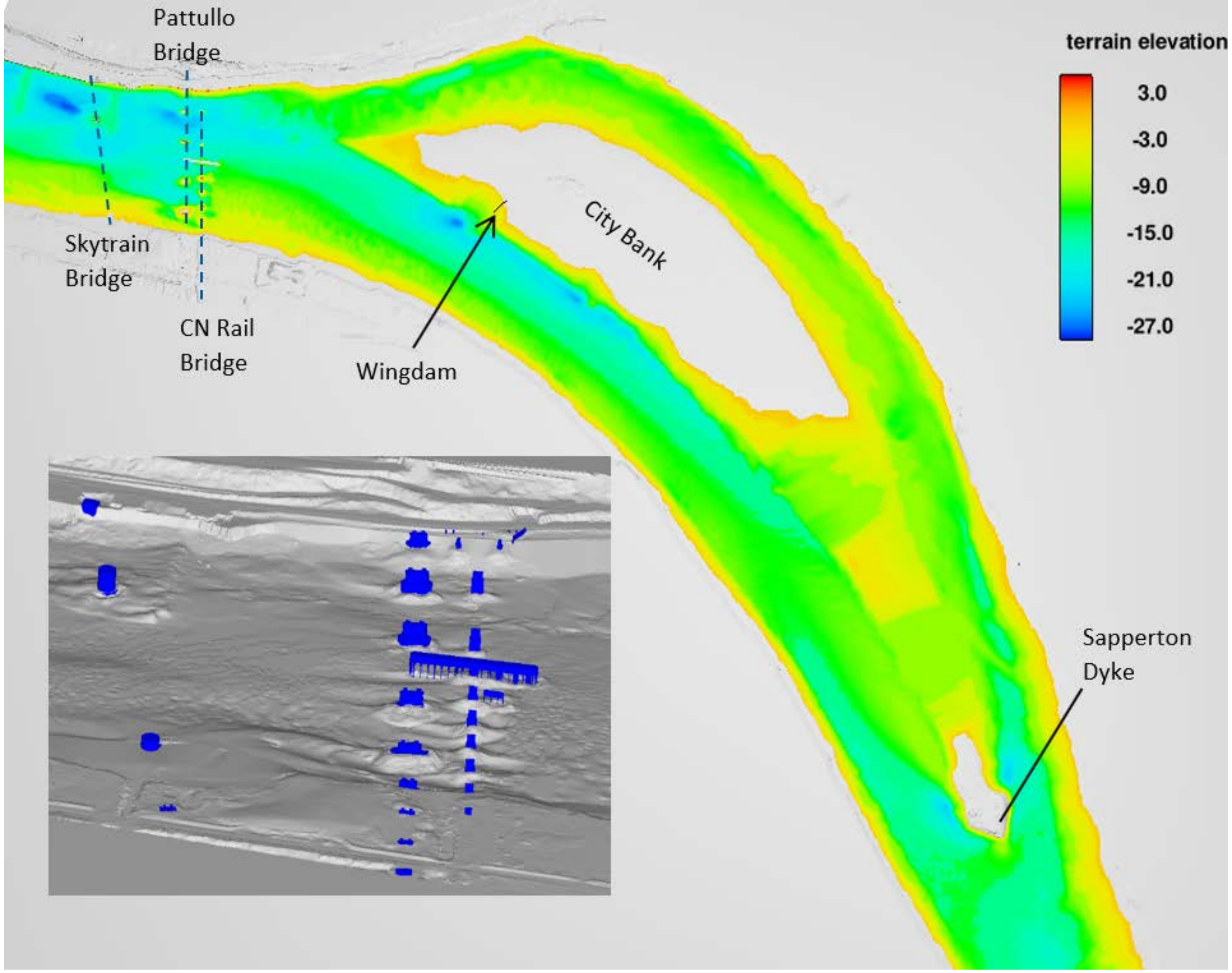


Figure 10. CFD model domain and sample of the digital elevation model (DEM).

Figure 11. ADCP transect locations showing paired transects by colour.

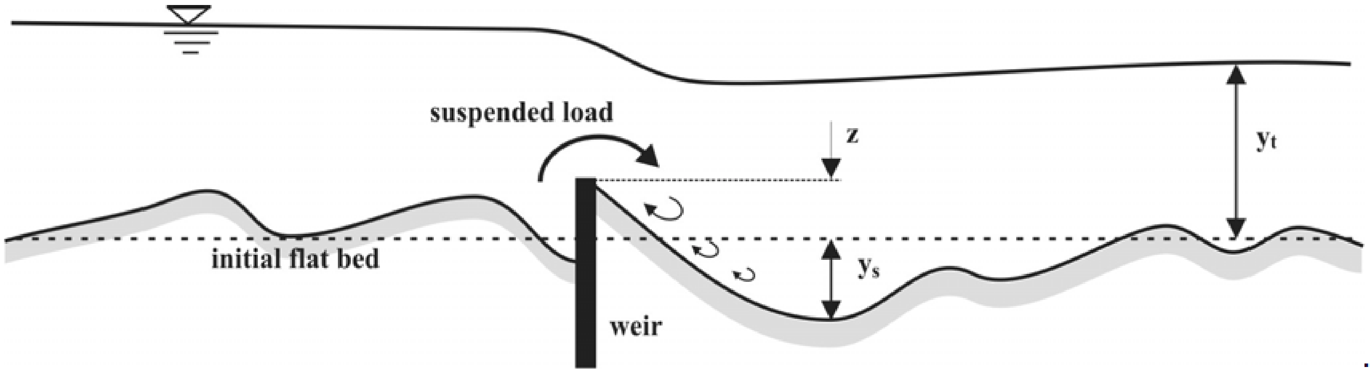
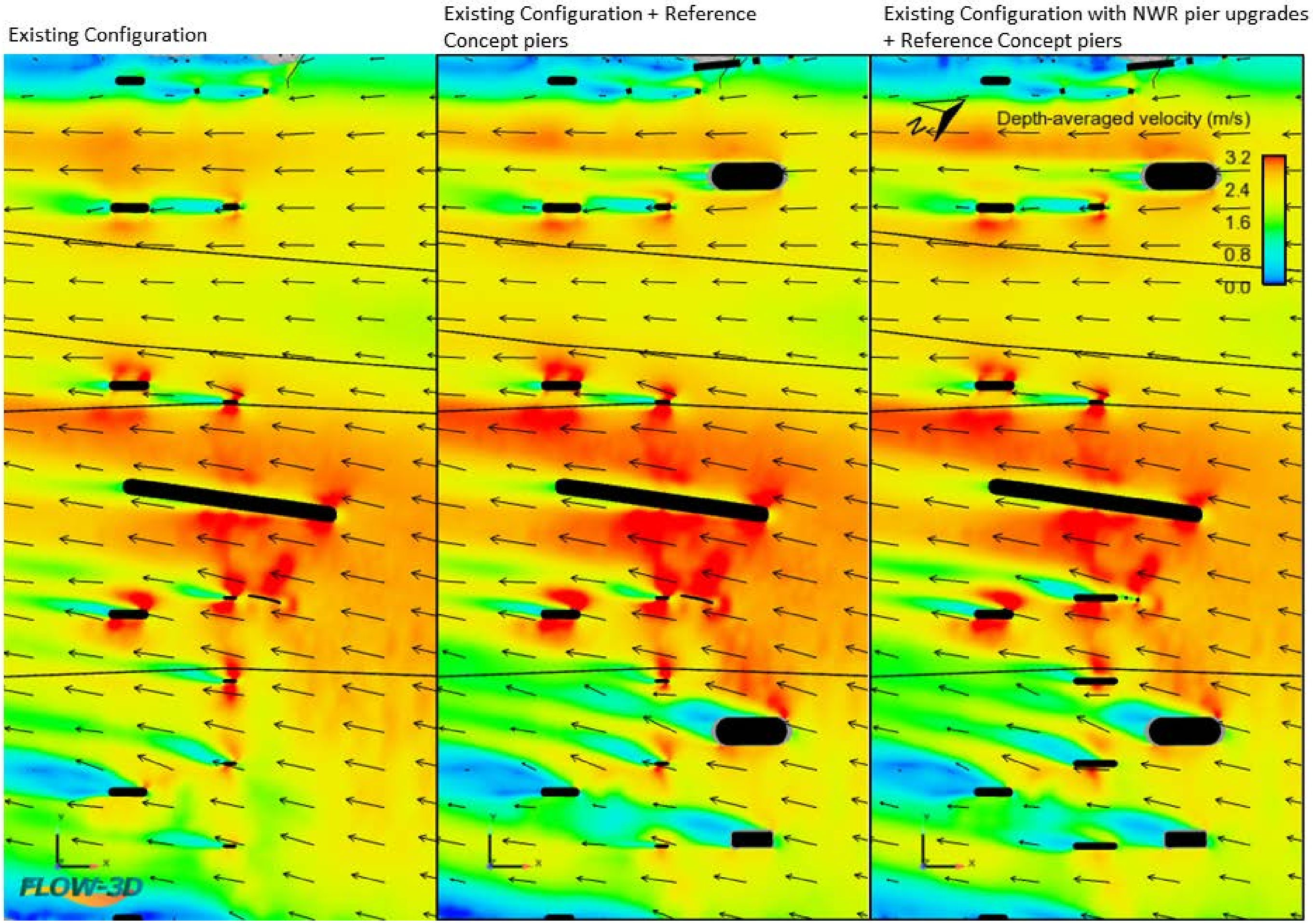


Figure 12. Idealized sketch of scour at a submerged weir from Melville (2014)


Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

Figure 13. **CFD model depth-averaged velocities, 1894 flood of record**

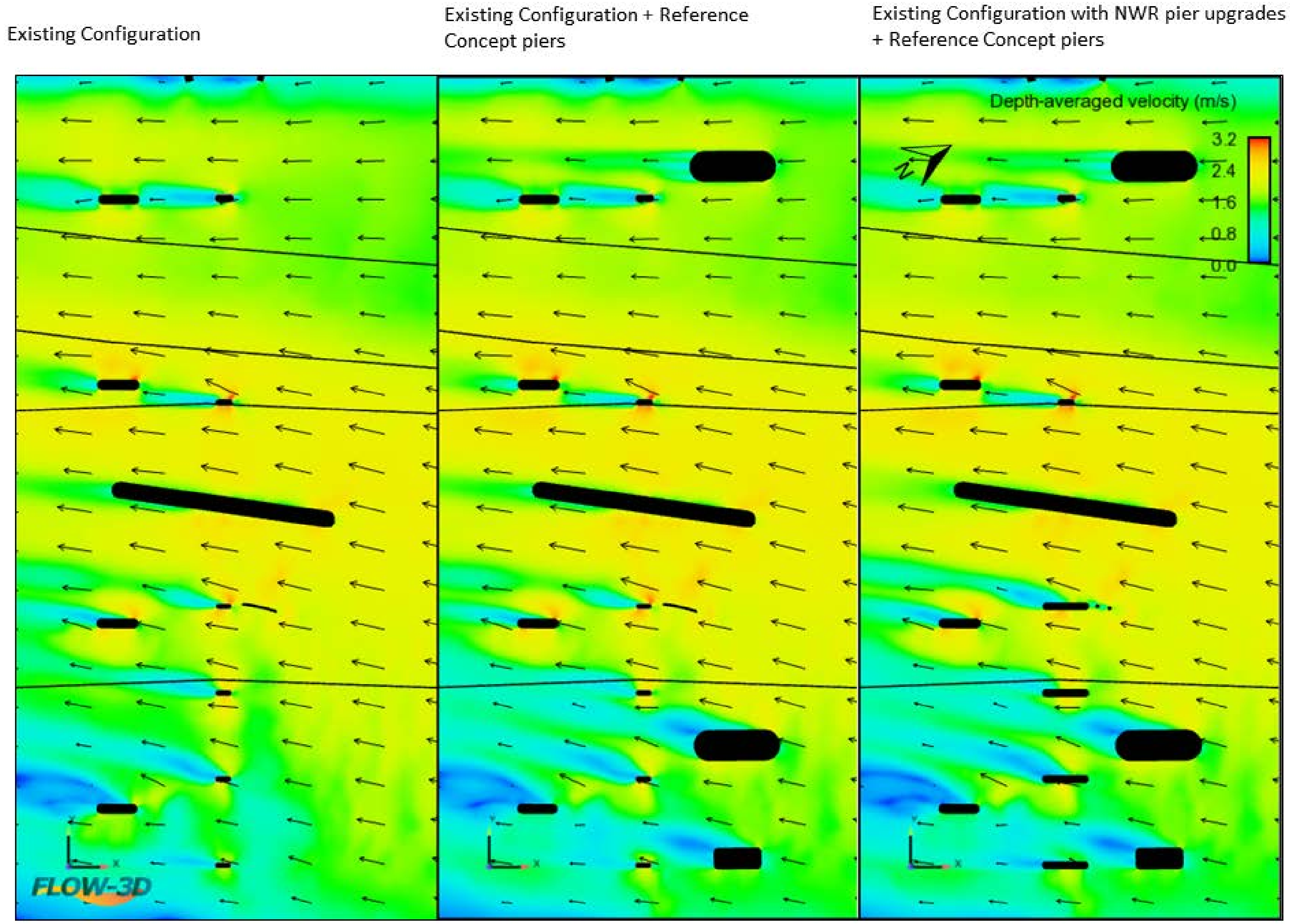


Figure 14. CFD model depth-averaged velocities, typical freshet condition

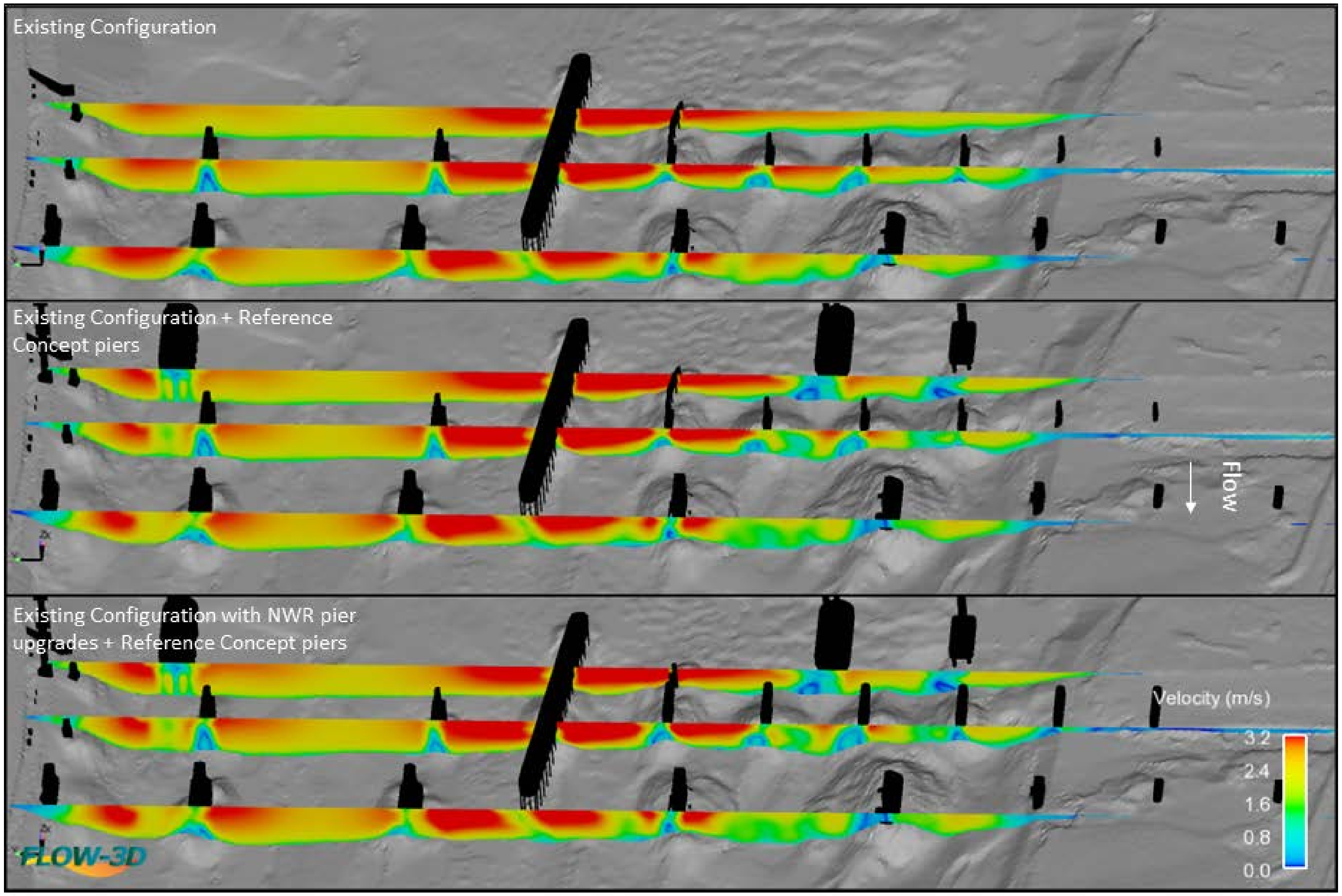


Figure 15. CFD model velocity transect looking east, flood of record

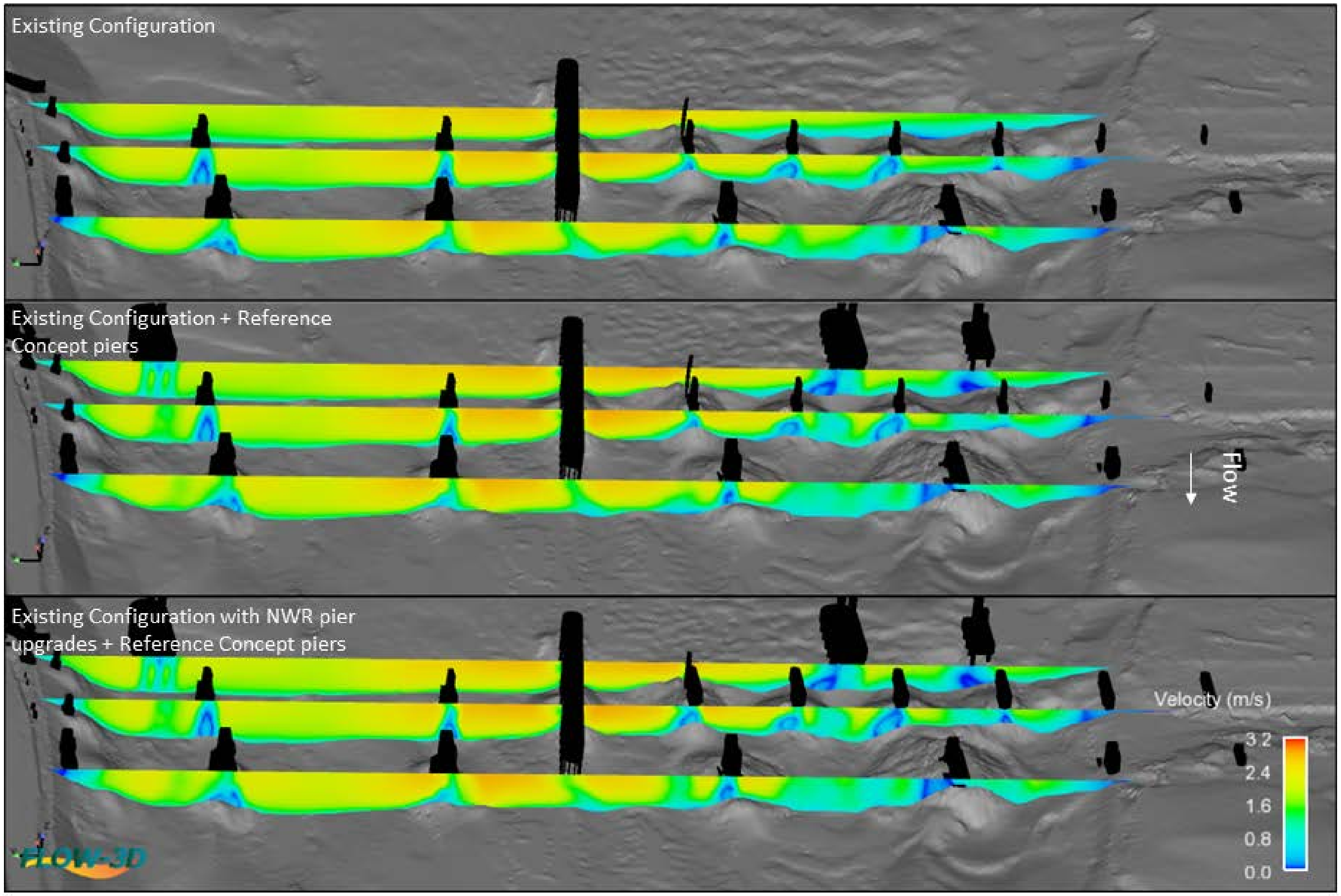


Figure 16. CFD model velocity transect looking east, typical freshet condition

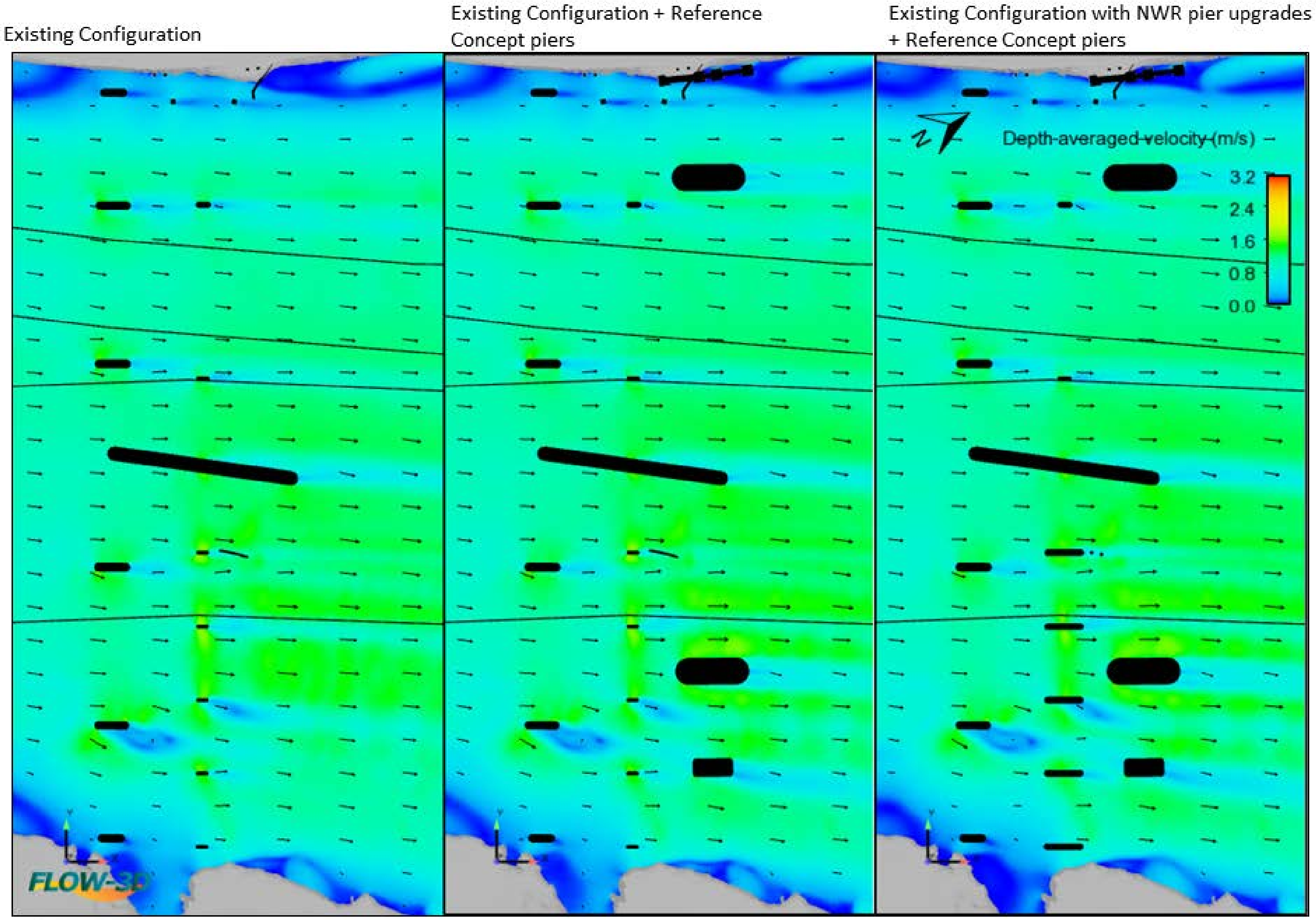


Figure 17. CFD model depth-averaged velocities, winter flood tide condition

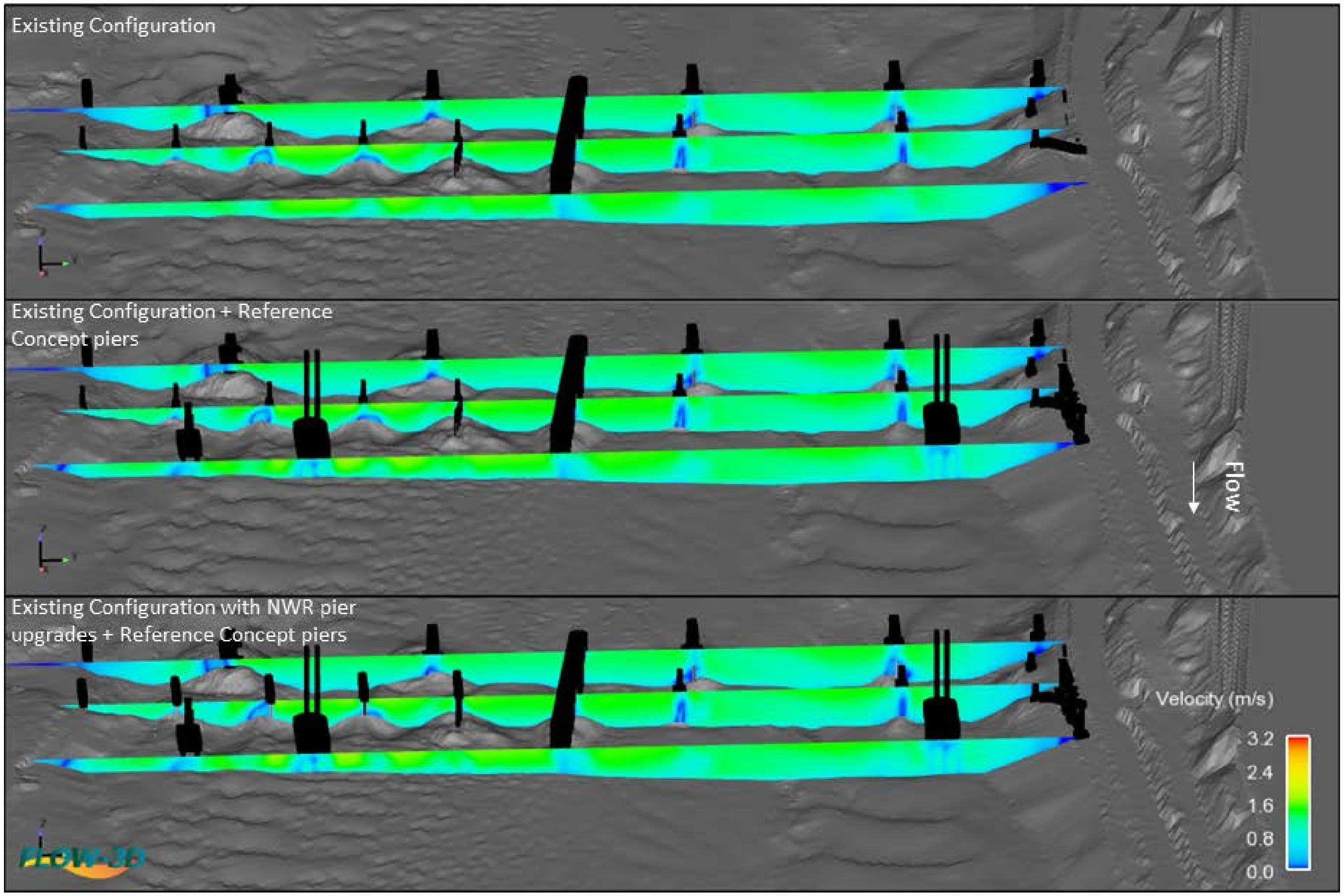


Figure 18. CFD model velocity transects looking east, winter flood tide condition

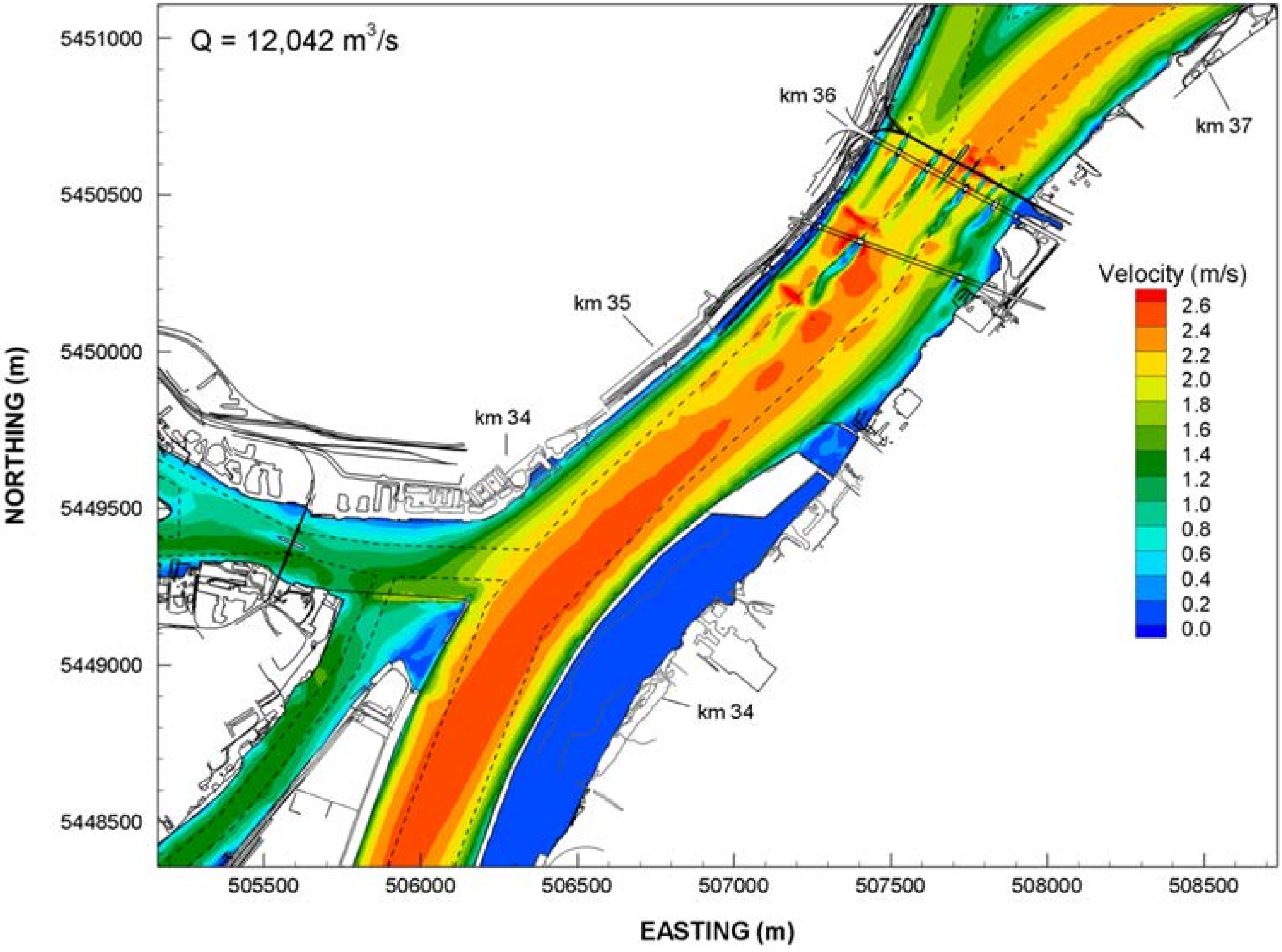


Figure 19. **Depth-averaged velocity during 2012 flood peak for existing conditions, Telemac model output**

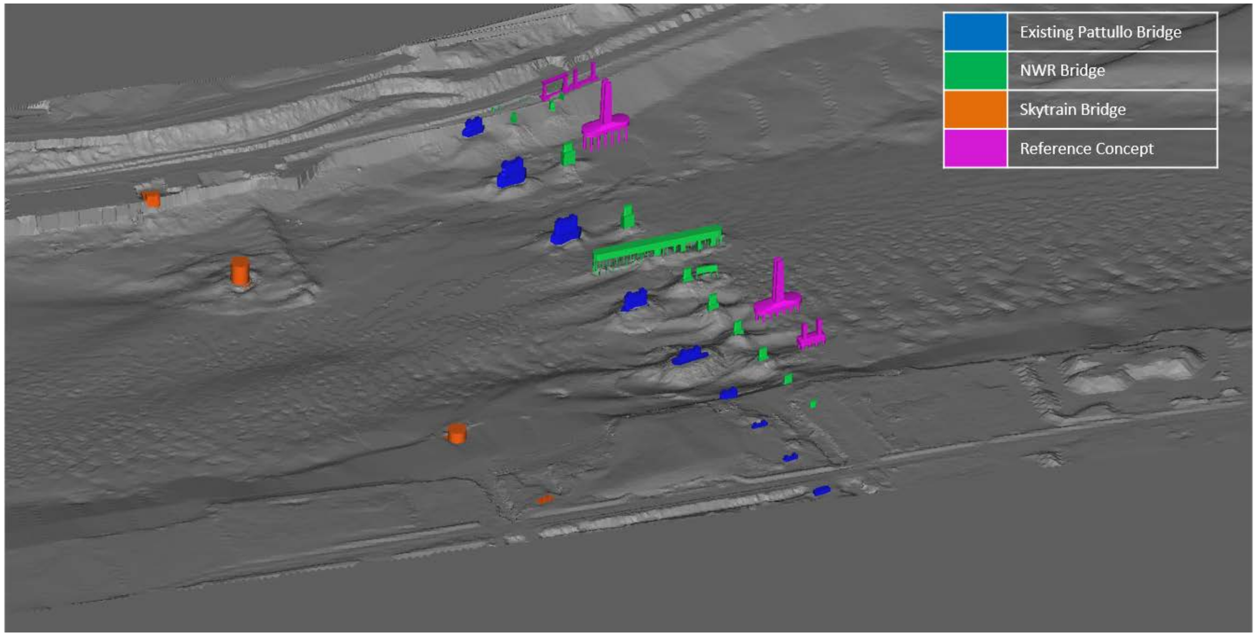


Figure 20. **Existing bridges near New Westminster with Reference Concept added**

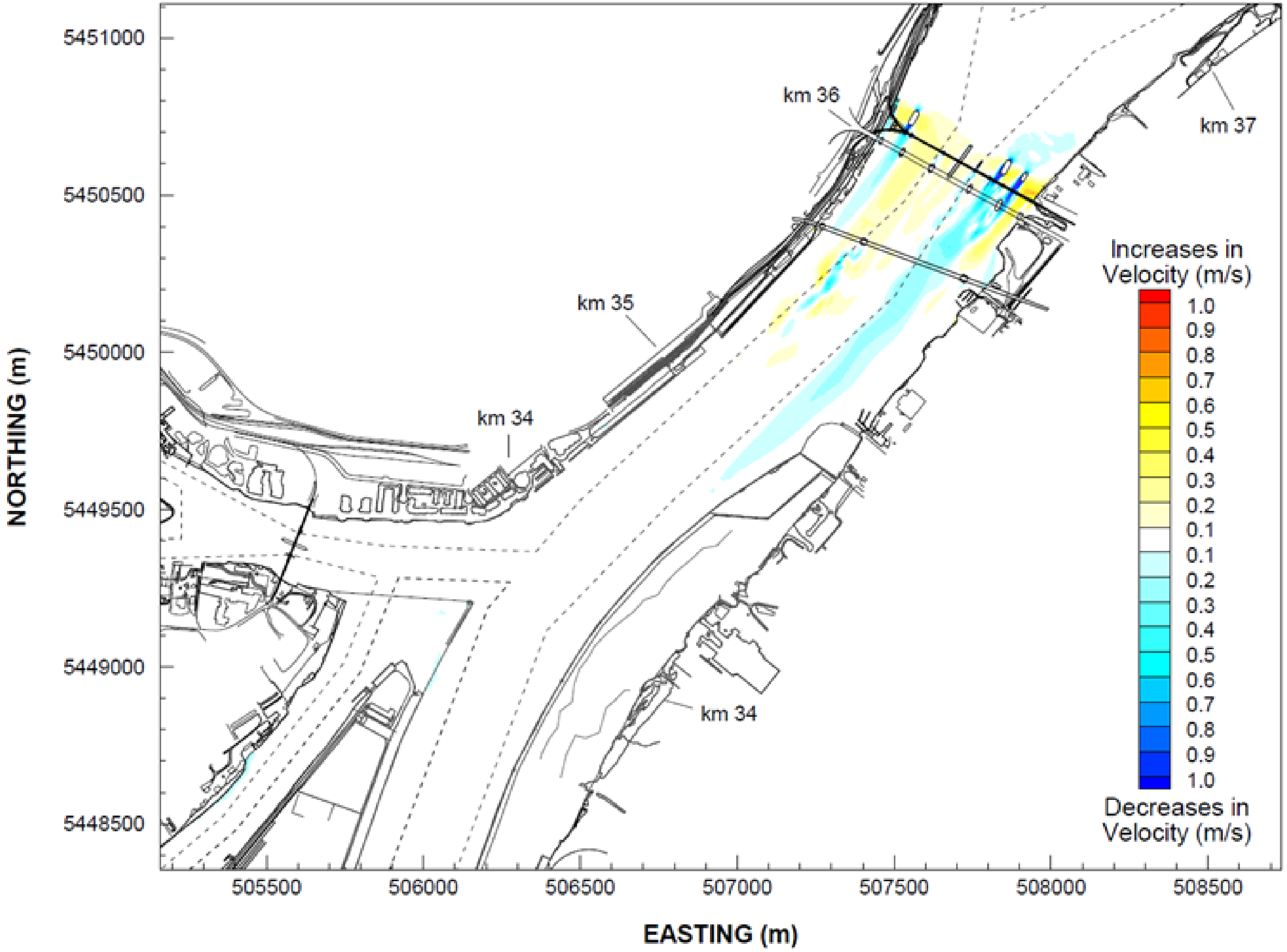


Figure 21. **Difference in depth-averaged current speed (Reference Concept minus existing condition) after 2012 freshet, from morphodynamic model.**

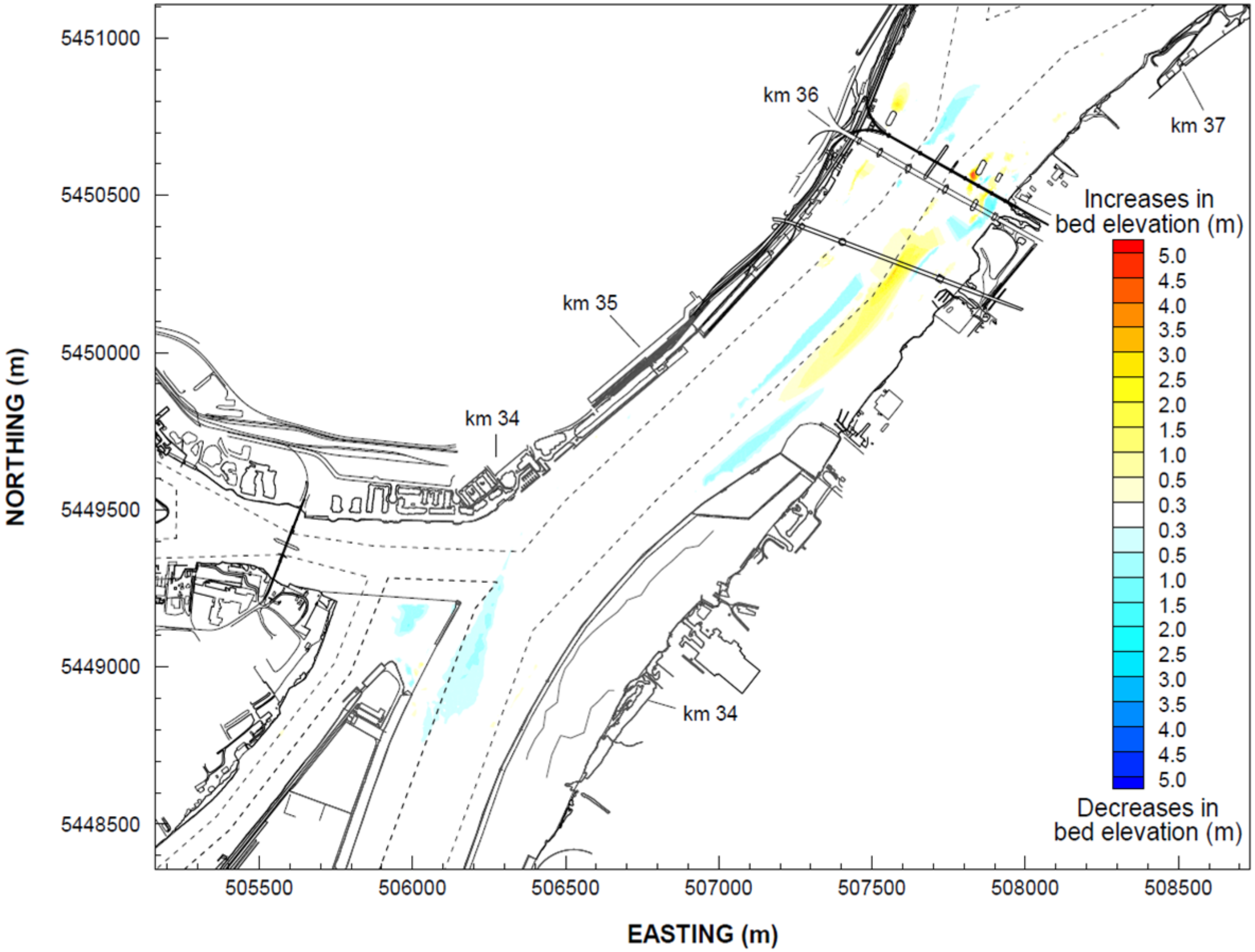
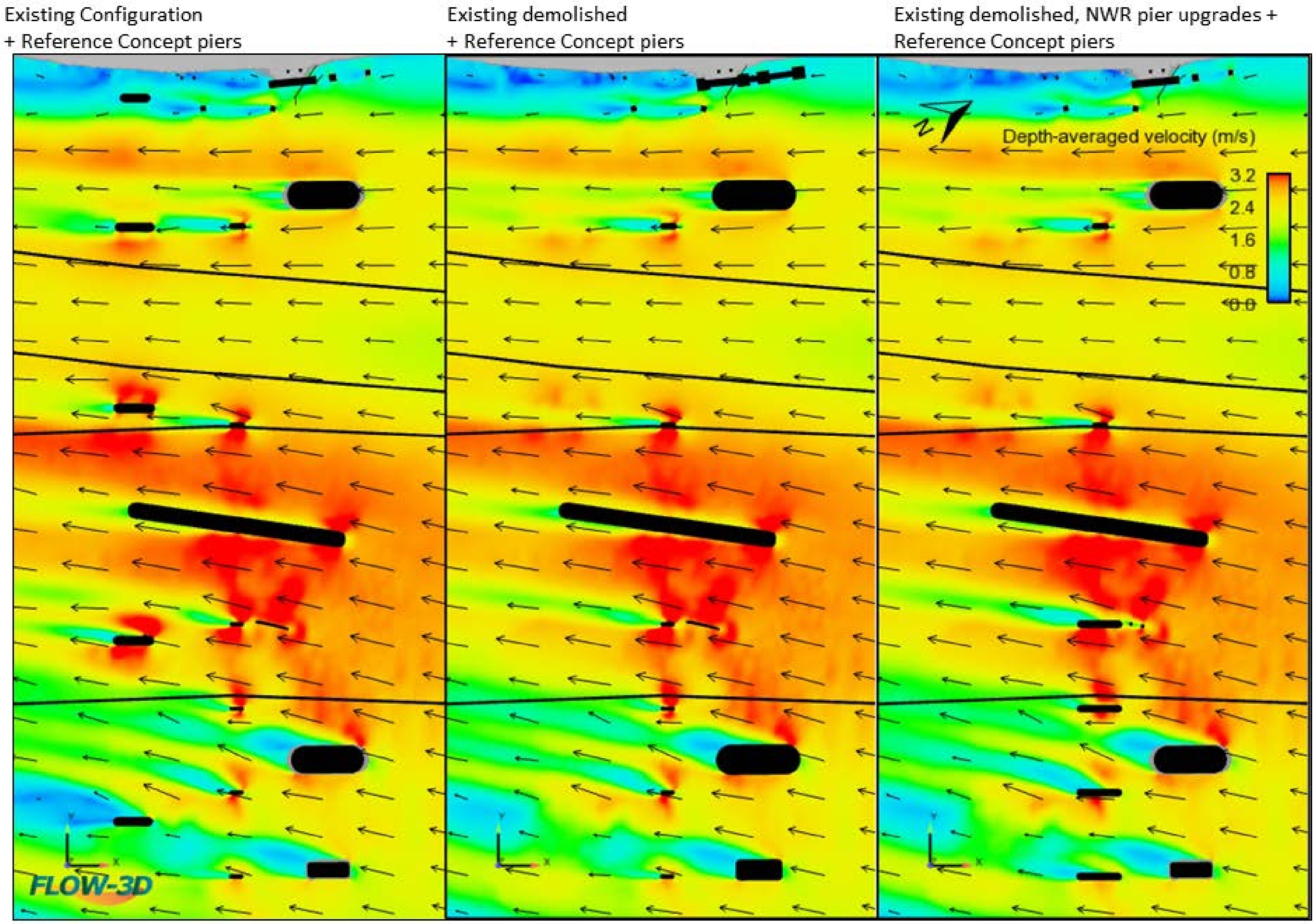


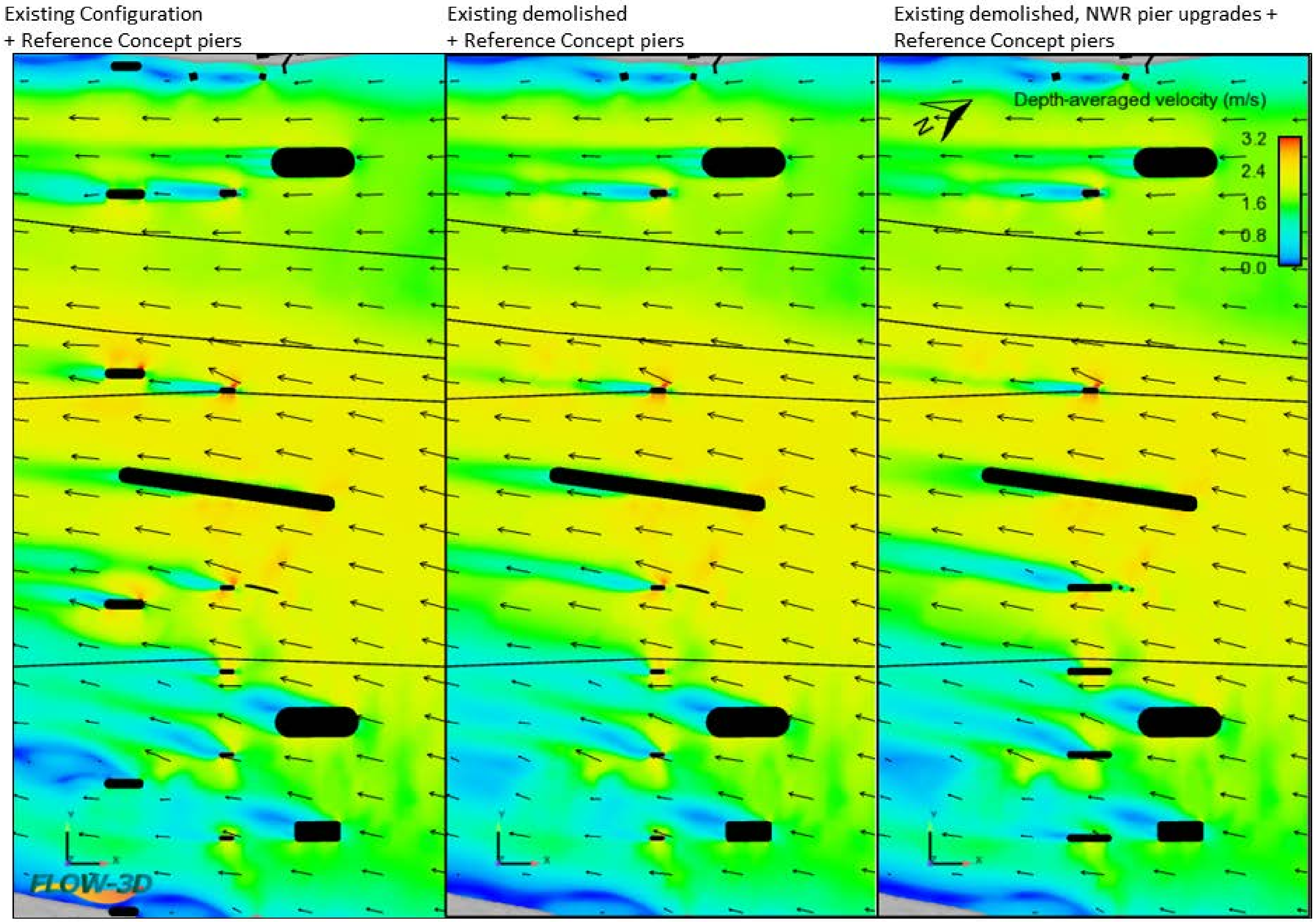
Figure 22. **Difference in bed levels (Reference Concept minus existing condition) after 2012 freshet, from morphodynamic model.**


Existing Configuration
+ Reference Concept piers

Existing demolished
+ Reference Concept piers

Existing demolished, NWR pier upgrades +
Reference Concept piers

Figure 23. CFD model depth-averaged velocities with Pattullo Bridge decommissioned, flood of record

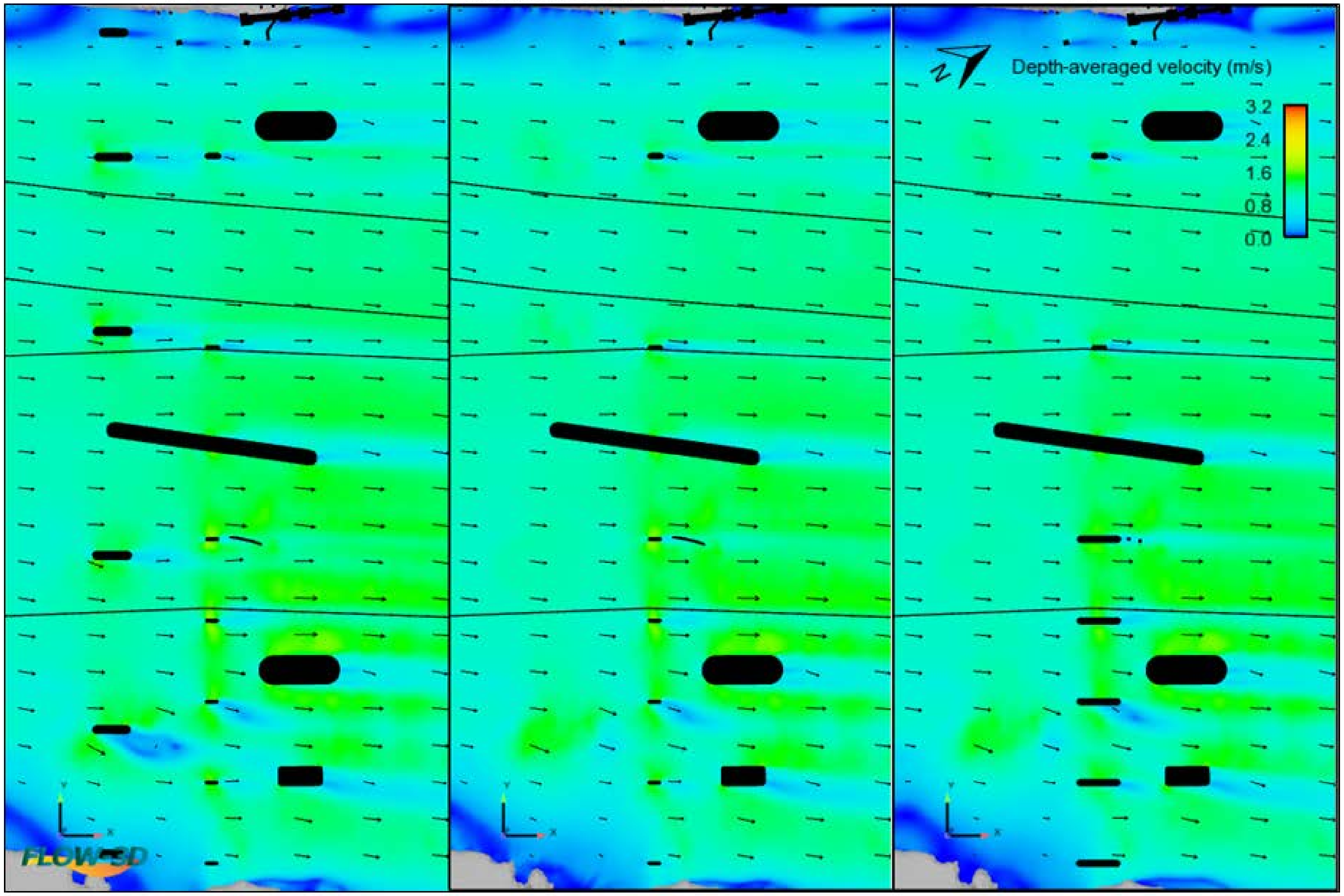


Existing Configuration
+ Reference Concept piers

Existing demolished
+ Reference Concept piers

Existing demolished, NWR pier upgrades +
Reference Concept piers

Figure 24. CFD model depth-averaged velocities with Pattullo Bridge decommissioned, typical freshet scenario



Existing Configuration
+ Reference Concept piers

Existing demolished
+ Reference Concept piers

Existing demolished, NWR pier upgrades +
Reference Concept piers

Figure 25. CFD model depth-averaged velocities with Pattullo Bridge decommissioned, winter flood tide condition.

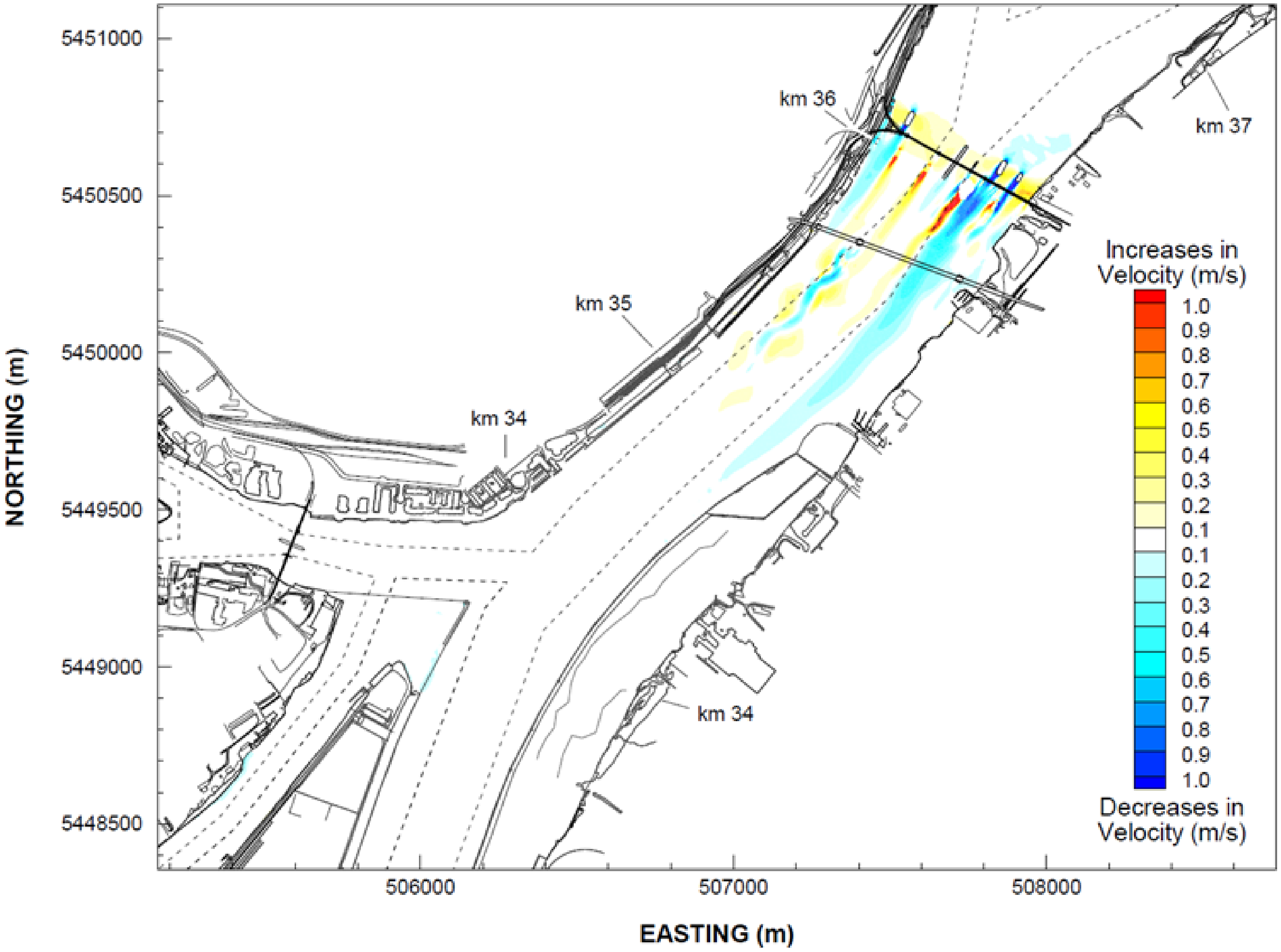


Figure 26. **Difference in depth-averaged current speed after Pattullo Bridge de-commissioning (decommissioning scenario minus existing conditions) during 2012 flood peak, from Telemac 3D model.**

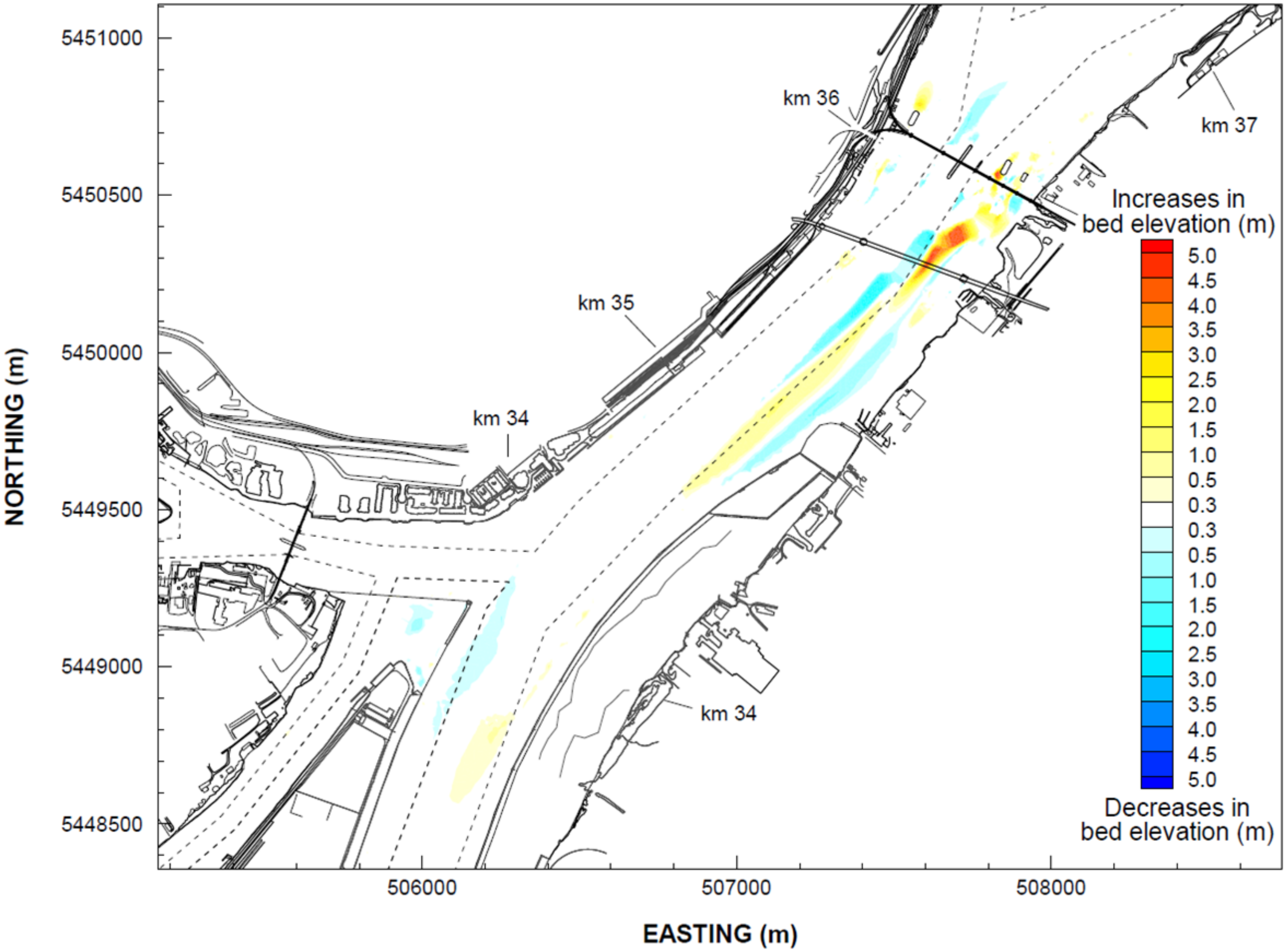


Figure 27. **Difference in bed levels after de-commissioning (decommissioning scenario minus existing condition) after 2012 freshet, from Telemac morphodynamic model.**

TABLES

Table 4. Modelled morphological changes at sites of interest for Reference Concept scenario.

No.	ID	Type	Site/Area	Expected Bed Level Changes
1	FRMA-1	Navigation Channel - Main	Main Navigation Channel - Near Bridge	▪ 0.5 – 1 m lowering upstream of the Reference Concept alignment ▪ about 0.5 m lowering downstream of Skytrain Bridge
2	FRMA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Near Bridge	none
3	FRMA-3	Navigation Channel - Main	Main Navigation Channel - Queens Reach	none
4	FRMA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Sapperton Channel	none
5	FRMA-11	Infrastructure	Existing Pattullo Bridge Piers (during construction phase)	▪ about 1 m lowering between Pattullo Piers 5 and 6 ▪ about 2 m aggradation downstream between Piers 1 and 2 ▪ 2-3 m aggradation downstream of Pier 4 between Skytrain piers
6	FRMA-12	Infrastructure	NWRB Piers	▪ about 1.5 m lowering upstream of NWRB Pier 8 ▪ 0.5 – 1 m lowering between NWRB Piers 9-10 ▪ 2-3 m aggradation between NWRB Piers 7-9 and downstream of Ref Concept South Tower
7	FRMA-13	Infrastructure	Skybridge Piers	2-3 m aggradation between Skytrain piers downstream of Pattullo Pier 4
8	FRMA-14	Infrastructure	Sapperton V-Dyke	none
9	FRMA-15	Infrastructure	Sapperton Wing Walls	none

10	FRMA-16	Infrastructure	New West Board Walk	none
11	FRMA-17	Infrastructure	New West Submerged Weir 1	none
12	FRMA-18	Infrastructure	New West Submerged Weir 2	none
13	FRMA-19	Tenant	Valley Towing Site	none
14	FRMA-20	Tenant	Amix Sites (Upriver and Downriver of Bridge)	none
15	FRMA-21	Tenant	Schnitzer	none
16	FRMA-22	Tenant	Lehigh Hanson	none
17	FRMA-23	Tenant	Seaspan Barge Tie-Up	none
18	FRMA-24	Tenant	Mill & Timber Site	none
19	FRMA-25	Tenant	Harken Log Storage Areas	none
20	FRMA-26	Tenant	Cathedral Ventures Basin	none
21	FRMA-27	Infrastructure	Transmountain Pipeline	none
22	FRMA-28	Infrastructure	Gas Pipeline	none
23	FRMA-30	Infrastructure	Metro Vancouver Utilities - Port Mann	none
24	FRNA-1	Navigation Channel - Secondary	Secondary Navigation Channel - North Arm	none
25	FRNA-11	Infrastructure	MV Utilities - Annacis Main # 3	none
26	FRNA-12	Infrastructure	MV Utilities - Annacis Main # 3	none
27	FRNA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Poplar Channel	none
28	FRNA-29	Infrastructure	Metro Vancouver Utilities - Downriver of Queensborough Rail Bridge	none
29	FRNA-30	Infrastructure	Metro Vancouver Utilities - Upriver of Queensborough Rail Bridge	none
30	FRSA-1	Navigation Channel - Main	Main Navigation Channel - Annieville Channel	none
31	FRSA-2	Deep-Sea Berth & Approach	Fraser Surrey Docks - Upriver Berths	none
32	FRSA-3	Deep-Sea Berth & Approach	Fraser Surrey Docks - Downriver Berths	none

33	FRSA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Annacis Channel	none
34	FRSA-4	Deep-Sea Berth & Approach	WWL - Berths	none
35	FRSA-11	Infrastructure	Trifurcation Phase 1 Wall	none
36	FRSA-12	Infrastructure	Trifurcation Phase 2 Wall	none
37	FRSA-13	Infrastructure	Trifurcation Phase 3 Wall	about 0.5 m lowering near Trifurcation Phase 3 wall, between Harken log storage areas and Skybridge Piers
38	FRSA-14	Infrastructure	Flow Splitter	▪ about 0.5 m lowering upstream of flow splitter ▪ 0.5 – 1 m lowering downstream of flow splitter
39	FRSA-15	Tenant	Annacis Marine Base	none
40	FRSA-16	Infrastructure	MV Utilities - Annacis Main # 2	none
41	FRSA-17	Infrastructure	MV Utilities - Annacis Main # 3	none
42	ZCCG-1	Infrastructure	CCG Nav Aids (Upriver and Downriver of Bridge)	none

Table 5. Modelled morphological changes at sites of interest for Decommissioning scenario.

No.	ID	Type	Site/Area	Expected Bed Level Changes
1	FRMA-1	Navigation Channel - Main	Main Navigation Channel - Near Bridge	▪ 0.5 – 1 m lowering upstream of the Reference Concept alignment ▪ 1.5 - 2 m lowering downstream of Skytrain Bridge ▪ about 1 m aggradation along margin of navigation channel between Harken log storage and Skytrain Bridge ▪ about 0.3 m aggradation along Trifurcation Phase 3 wall at km 34.
2	FRMA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Near Bridge	none
3	FRMA-3	Navigation Channel - Main	Main Navigation Channel - Queens Reach	none
4	FRMA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Sapperton Channel	none
5	FRMA-11	Infrastructure	Existing Pattullo Bridge Piers (during construction phase)	▪ about 2 m aggradation downstream between Piers 1 and 2 ▪ 4-5 m aggradation downstream of Pier 4 between Skytrain piers
6	FRMA-12	Infrastructure	NWRB Piers	▪ about 1.5 m lowering upstream and downstream of NWRB Pier 8 ▪ 0.5 – 1 m lowering between NWRB Piers 9-10 ▪ 2-3 m aggradation between NWRB

				Piers 7-9 and downstream of Ref Concept South Tower
7	FRMA-13	Infrastructure	Skybridge Piers	4-5 m aggradation between Skytrain piers downstream of Pattullo Pier 4
8	FRMA-14	Infrastructure	Sapperton V-Dyke	none
9	FRMA-15	Infrastructure	Sapperton Wing Walls	none
10	FRMA-16	Infrastructure	New West Board Walk	none
11	FRMA-17	Infrastructure	New West Submerged Weir 1	none
12	FRMA-18	Infrastructure	New West Submerged Weir 2	none
13	FRMA-19	Tenant	Valley Towing Site	none
14	FRMA-20	Tenant	Amix Sites (Upriver and Downriver of Bridge)	none
15	FRMA-21	Tenant	Schnitzer	none
16	FRMA-22	Tenant	Lehigh Hanson	none
17	FRMA-23	Tenant	Seaspan Barge Tie-Up	none
18	FRMA-24	Tenant	Mill & Timber Site	none
19	FRMA-25	Tenant	Harken Log Storage Areas	none
20	FRMA-26	Tenant	Cathedral Ventures Basin	none
21	FRMA-27	Infrastructure	Transmountain Pipeline	none
22	FRMA-28	Infrastructure	Gas Pipeline	none
23	FRMA-30	Infrastructure	Metro Vancouver Utilities - Port Mann	none
24	FRNA-1	Navigation Channel - Secondary	Secondary Navigation Channel - North Arm	none
25	FRNA-11	Infrastructure	MV Utilities - Annacis Main # 3	none
26	FRNA-12	Infrastructure	MV Utilities - Annacis Main # 3	none
27	FRNA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Poplar Channel	none
28	FRNA-29	Infrastructure	Metro Vancouver Utilities - Downriver of Queensborough Rail Bridge	none
29	FRNA-30	Infrastructure	Metro Vancouver Utilities - Upriver of	none

			Queensborough Rail Bridge	
30	FRSA-1	Navigation Channel - Main	Main Navigation Channel - Annieville Channel	none
31	FRSA-2	Deep-Sea Berth & Approach	Fraser Surrey Docks - Upriver Berths	none
32	FRSA-3	Deep-Sea Berth & Approach	Fraser Surrey Docks - Downriver Berths	none
33	FRSA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Annacis Channel	none
34	FRSA-4	Deep-Sea Berth & Approach	WWL - Berths	none
35	FRSA-11	Infrastructure	Trifurcation Phase 1 Wall	none
36	FRSA-12	Infrastructure	Trifurcation Phase 2 Wall	none
37	FRSA-13	Infrastructure	Trifurcation Phase 3 Wall	▪ 1.5 - 2 m lowering near Trifurcation Phase 3 wall, between Harken log storage areas and Skytrain Bridge
38	FRSA-14	Infrastructure	Flow Splitter	▪ about 0.3 m lowering upstream of flow splitter ▪ about 0.5 m lowering downstream of flow splitter
39	FRSA-15	Tenant	Annacis Marine Base	none
40	FRSA-16	Infrastructure	MV Utilities - Annacis Main # 2	none
41	FRSA-17	Infrastructure	MV Utilities - Annacis Main # 3	none
42	ZCCG-1	Infrastructure	CCG Nav Aids (Upriver and Downriver of Bridge)	none

APPENDIX A: COMPUTATIONAL FLUID DYNAMICS MODEL

1 INTRODUCTION

Preliminary computational fluid dynamics (CFD) modelling was conducted by NHC to evaluate long-span and short-span conceptual options for the replacement Pattullo Bridge to aid in developing the Reference Concept. The CFD modelling results presented in this Appendix focus on evaluating the selected Reference Concept, and addresses proposed structural upgrades to the New Westminster Rail (NWR) bridge (also known as Canadian National Rail – CN Rail bridge) that will alter the NWR bridge pier geometry.

2 METHODOLOGY

2.1 Approach

The potential effects of the bridge replacement on flow hydraulics due to the project were investigated using Flow-3D (www.Flow3D.com), a three-dimensional CFD model with special capabilities for modelling complex geometries and free surface flows. Flow-3D can simulate highly unsteady flows and hence can simulate tidal flows (Vasquez and Walsh 2009). However in order to minimize runtime, all simulations were performed assuming steady flow with constant discharge and water level. This steady-state assumption is acceptable when comparing the hydraulic effects of the replacement options and NWR structural upgrades.

Under identical inflow and outflow conditions, the CFD model was applied to compute the hydraulic flow field (velocity and water depths) produced by alternative bridge structure geometries (e.g. replacement options, NWR pier upgrades) such that their hydraulic effects could be compared and assessed.

2.2 Model Development

The Pattullo Bridge CFD model mesh extends for more than 6 km along the main channel of the Fraser River (Figure 1), starting upstream near the Port Mann Bridge and ending downstream at a section 650 m from the Pattullo Bridge centerline. Within this reach, local features, such as islands and bridge piers have been included to get a more realistic representation of existing hydraulic conditions. Three existing bridges include: NWR Bridge (13 piers), Pattullo Bridge (9 piers) and Skytrain Bridge (4 piers). A detail of the piers is also shown in Figure 1. Sapperton Dyke was also included upstream to provide a better representation of flow split around City Bank (also called Sapperton Bar). Approximate geometry of one of the Wingdam No. 1 on the south border of City Bank was adapted from Canadian Coast Guard (1997) and included in the model.

The Flow-3D rectangular computational mesh is made of cubic cells 5 m in length far upstream of the bridges, 2.5 m cells for a 1.68 km reach extending upstream and downstream of the bridges, and smaller

1.25 m cells in a 500 m long reach directly covering the Pattullo and NWR Bridges. The total number of cells exceeds 11 million.

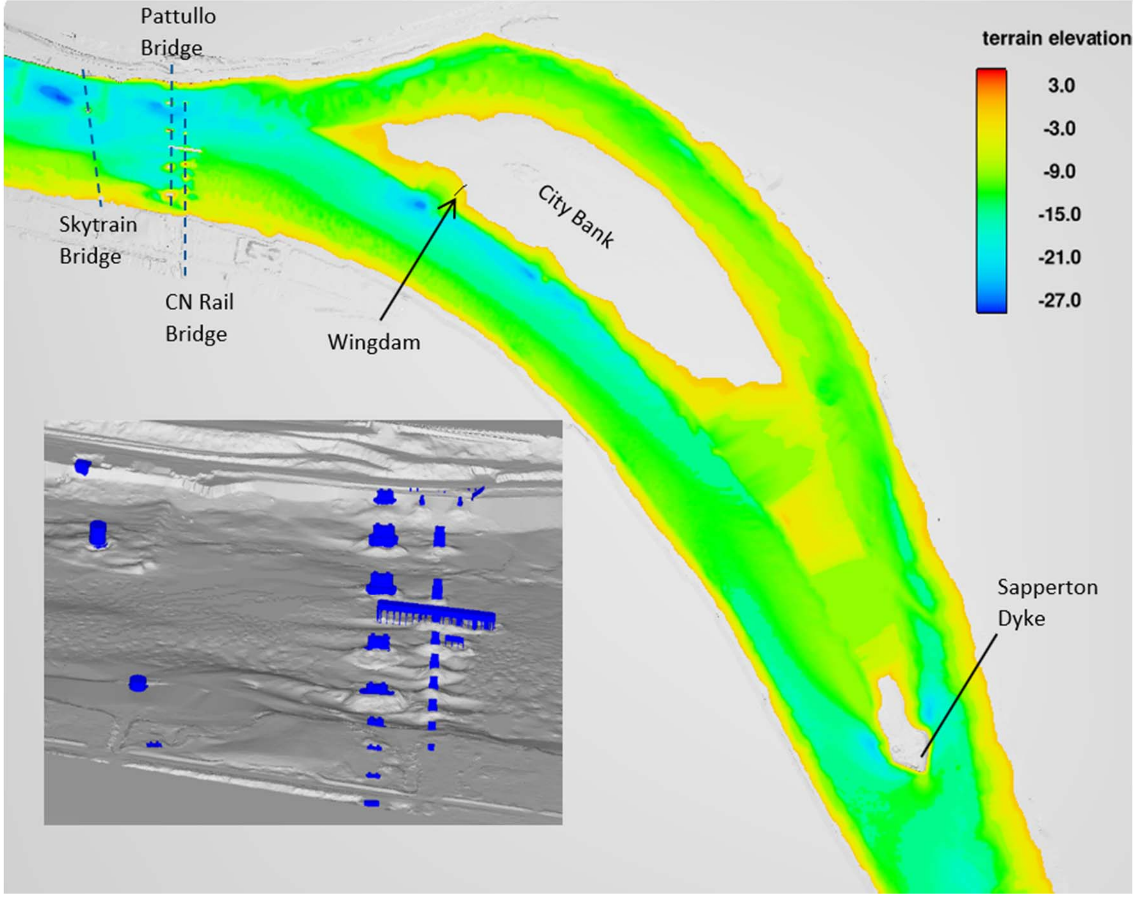


Figure 1. **Pattullo CFD Model extent. Insert shows detail of existing bridge piers**

2.3 Model Discharge and Boundary Conditions

Water levels and discharges for the CFD model were extracted from NHC's MIKE 11 one-dimensional tidal flow model of the Lower Fraser River. In the MIKE 11 Fraser River model, inflow discharges are defined upstream at Mission; while tidal water levels downstream are defined at the outflow of the model in the Strait of Georgia. With this information, MIKE 11 can compute tidally-varying water levels and discharges at any intermediate section of the Fraser River between Mission and the Pacific Ocean. For the purposes of the CFD steady-state flow analysis and in order to be conservative, flow conditions selected correspond to tide levels when flow discharges and average velocities are highest.

The following flow discharges computed by MIKE 11 at the boundaries of the Pattullo CFD model were used to assess each of the geometries included in the study:

1. 1894 flood of record (Q = 21,155 m^3/s)
2. Typical freshet (Q = 13,215 m^3/s)
3. Winter flood tide (Q = -8,311 m^3/s)

The 1894 flood of record condition had an upstream model inflow boundary condition of 21,155 m^3/s. The downstream model water level boundary condition was set at El. 3.4 m.

The Typical Freshet condition had a flow of 13,215 m^3/s and water level at El. 0.6 m. This flow was obtained by taking the average of peak annual daily discharge records for Fraser River at Mission (Water Survey of Canada gauge 08MH024), and using NHC's MIKE 11 model to determine the corresponding discharge at Pattullo.

The winter flood tide scenario represents a tidal flow reversal condition; flow is from west to east. Discharge was set at the eastern model boundary at 8,311 m^3/s flowing east (out of the model); this represents a large winter flow reversal, based on stage-discharge records from a December 2012 King Tide event. The western model boundary water level was set at El. 1.45 m.

2.4 Model Geometry

The following geometries were assessed:

1. Existing Pattullo Bridge configuration
2. Existing Pattullo Bridge configuration with addition of Reference Concept piers
3. Existing Pattullo Bridge configuration with addition of Reference Concept piers, and with structural upgrades to NWR piers included
4. Reference Concept piers in place with existing Pattullo Bridge decommissioned
5. Reference Concept piers in place with existing Pattullo Bridge decommissioned and NWR pier upgrades included

Bathymetric data of the Fraser River used to establish CFD model geometry comes from the following datasets:

- Bathymetric survey data collected by NHC on May 14, 2014 (survey extending approximately 50 m upstream and 500 m downstream of the Pattullo Bridge)
- 2014 PWGSC bathymetric surveys and 2005 Fraser Basin Council LiDAR

Riverbed roughness height was assumed as 0.4 m based on previous calibration using the depth-averaged model River2D (NHC 2007).

Pier configurations tested are illustrated and described below.

2.4.1 Existing Conditions

The model was evaluated with the existing pier configurations, as shown in Figure 2.

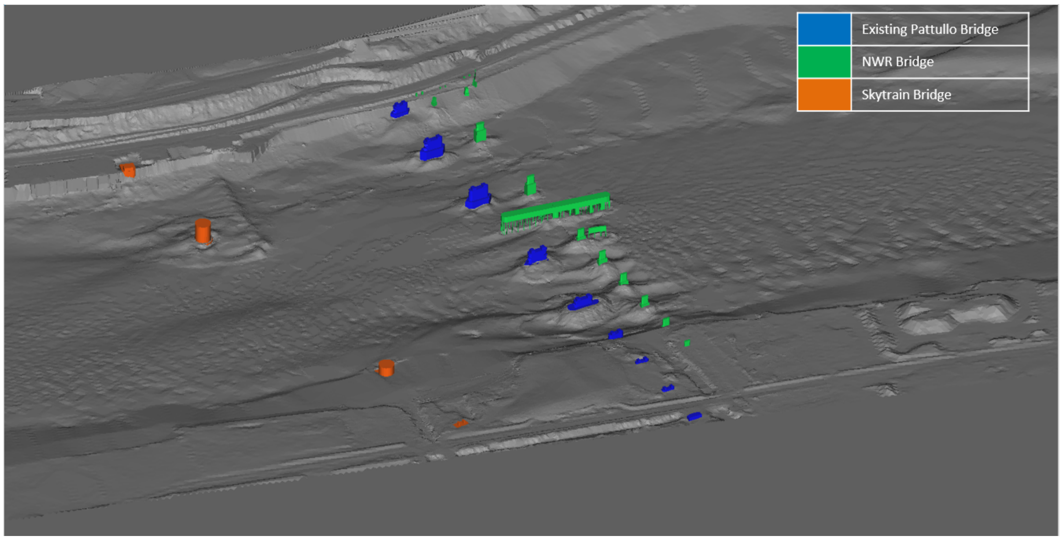


Figure 2. Existing bridge configuration

2.4.2 Reference Concept

The hydraulic effects of adding reference concept piers were evaluated both with (Figure 3) and without (Figure 4) proposed upgrades to NWR piers. These model geometries include the existing Pattullo piers, prior to decommissioning. NWR pier upgrades consist two 2.5 m diameter piles added to NWR piers 6 to 11, braced to existing piers by concrete pile caps.

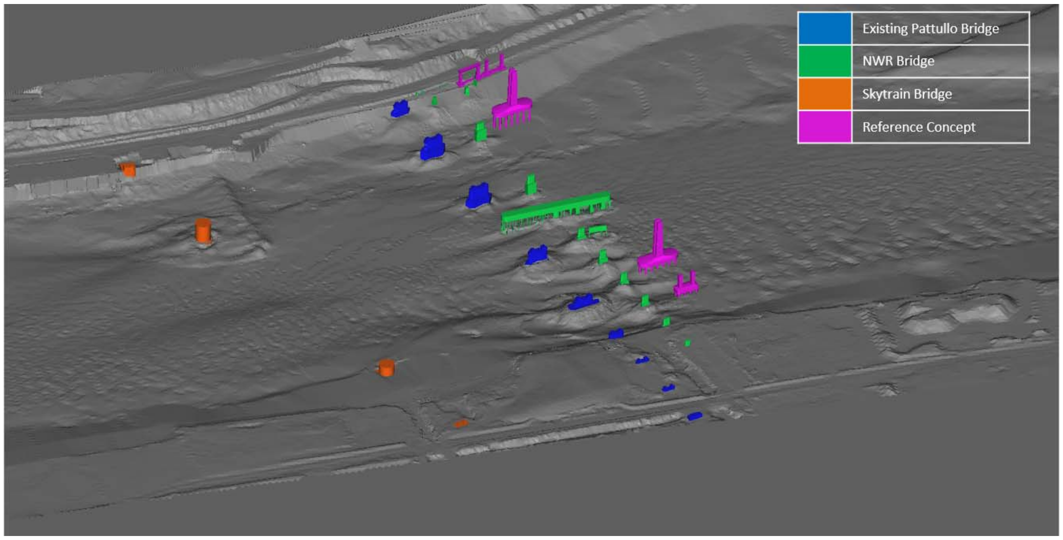


Figure 3. Existing bridge with Reference Concept

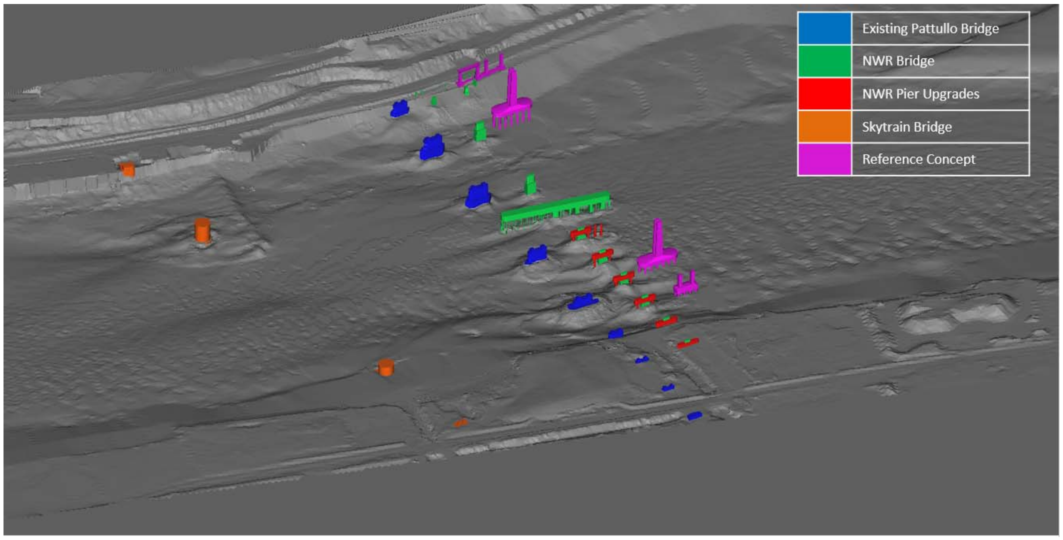


Figure 4. **Existing bridge with Reference Concept and NWR pier upgrades**

2.4.3 Pattullo Bridge Decommissioning

Two scenarios with the reference concept piers in place and existing Pattullo Bridge decommissioned were tested, one without NWR pier upgrades (Figure 5) and one with (Figure 6). Decommissioning scenarios (4) and (5) have the existing Pattullo Bridge piers removed, and the riprap cones truncated at El. -14.35 m within the Main Navigation Channel and at El. -10.00 m within the Secondary Navigation Channel.

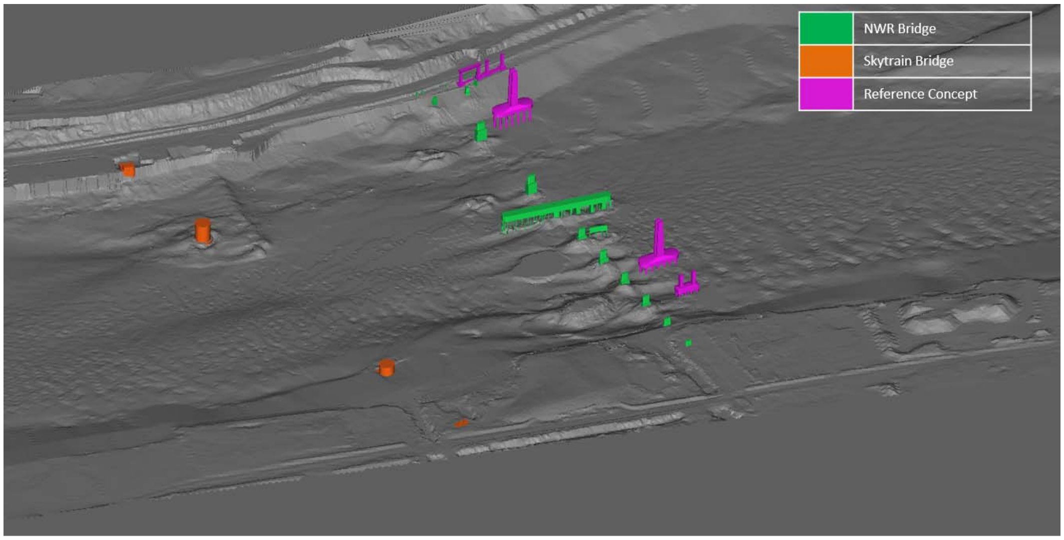


Figure 5. **Existing bridge decommissioned with Reference Concept**

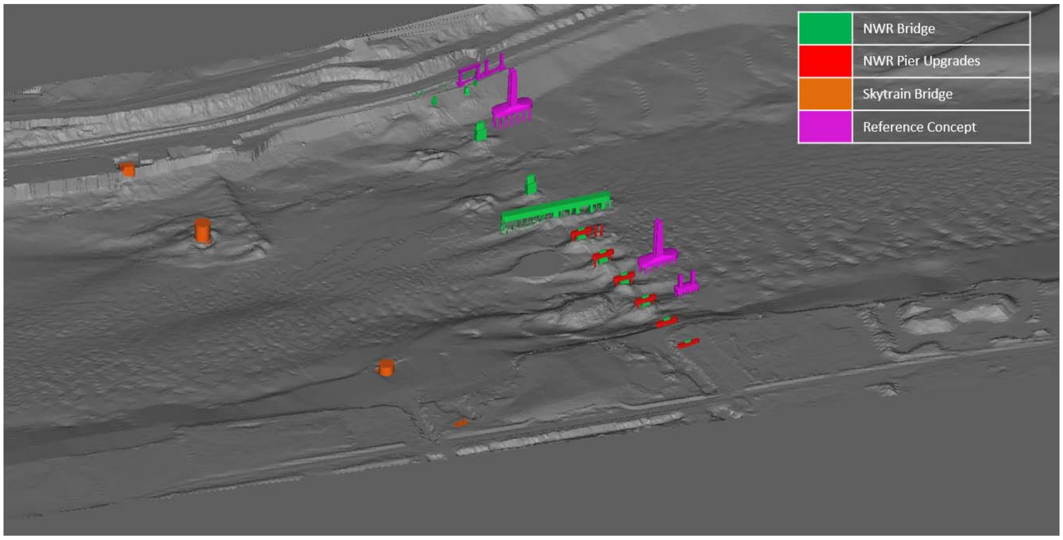


Figure 6. **Existing bridge decommissioned with Reference Concept and NWR pier upgrades**

2.5 Calibration and Validation Tests

Before starting the CFD analysis of the Reference Concept and NWR upgrades, validation tests were conducted by comparing the velocity profiles computed by the CFD model with velocity data measured in the field in both 2006 and 2016.

2.5.1 2006 ADCP data

On May 10, 2006, several transects were surveyed around Pattullo Bridge using an ADCP (acoustic Doppler current profiler) in order to measure flow velocity and discharge. The flow discharge measured varied between 7,950 and 8,450 m^3/s during a receding tide when water levels upstream at Port Mann varied between 0.16 and 0.38 m. In the CFD model calibration test, the inflow discharge was assumed constant at 8,400 m^3/s, while the downstream water level was set constant at 0.0 m. Figure A1 shows a comparison of ADCP profiles with Flow-3D results. In general, the CFD model captures well the transverse shape of the velocity profiles, although it overestimates velocity in the two most upstream ADCP transects 1 and 3, because flow discharge in those transects measured during the ADCP surveys was smaller than assumed in the CFD model. The agreement in transects 5, 6 and 7 - which are affected by the bridge piers - appears to be good.

The overall results of the model are good considering that the model bathymetry is based on 2014 data, 8 years after the ADCP data was collected; the geometry of wingdams is only approximate and the CFD model neglects unsteady tidal effects.

2.5.2 2016 ADCP data

A more recent ADCP survey was conducted on June 15, 2016 around Pattullo Bridge along several transects. The Fraser river flow discharge varied between 7,680 and 8,070 m^3/s and the water level at New Westminster varied between 0.11 m and 0.57 m. A representative inflow discharge of 7,868 m^3/s and a constant downstream flow depth of 0.2 m were used for the CFD simulation.

Figure A2 shows a comparison of ADCP profiles with Flow-3D results. In general, the CFD model reproduced the transverse shape of the velocity profiles reasonably well. Velocities were underestimated at the two most upstream ADCP transects 1 and 2, which can be attributed to higher river discharges at these two transects than the one assumed in the CFD model. In the vicinity of the bridge; i.e. transects 3, 4, 5 and 6, the agreement between the ADCP data and the CFD model is good, as the model is able to capture the sharp changes in velocity caused by the presence of bridge piers.

3 RESULTS

This section provides description and discussion of the CFD model results. Figures are included in **Section** Error! Reference source not found., at the end of this memo.

3.1 Reference Concept

To evaluate the effects of the Reference Concept piers, we compared model results for the existing configuration with and the Reference Concept. The comparison was done both with and without NWR pier upgrades installed. Figures A3-A5 show results for the flood of record. Figures A3 and A4 compare depth-averaged velocities for the flood of record. Figure A5 shows velocity transects downstream of the each of the existing bridges and the proposed bridge. Figures A5-A8 show similar results for the typical freshet flow. The reference concept configuration is shown in Figure 3.

Flood of record and typical freshet flow conditions show similar results. The model indicates that inclusion of the Reference Concept piers slightly increased velocities in the primary navigation channel by approximately 0.1 m/s for both the Flood of Record and Typical Freshet flows. Note that differences of 0.1 m/s or less are within the numerical accuracy of the model and are not considered significant. There was no recorded significant change in velocities for the secondary navigation channel.

Downstream of bridge piers, addition of the Reference Concept piers results in a larger low-velocity shadow, which is expected to cause deposition downstream of the Reference Concept South Pylon. At this location, flow velocity reduces from 2.7 m/s to 0.4 m/s under Flood of Record conditions, and from 1.6 m/s to 0.3 m/s under Typical Freshet flow. Near-bed velocities in these low-velocity shadows are also reduced, as shown in Figure A5.

Slightly higher velocities between Reference Concept South Pylon and Pier S0 were observed compared to existing, with highest velocities in the direct vicinity of piers. When sampling velocity at the approximate midpoint between these two piers, velocity increased by 0.4 m/s and 0.3 m/s under flood of record and typical freshet conditions, respectively. There was also a localized region of high velocity on the upstream-north side of the South Pylon, reaching 3.2 m/s during flood of record and 2.3 m/s during typical freshet.

Results from the winter flood (incoming) tide condition are shown in Figures A9-A11; these tests showed similar changes compared with the other two flows. Effects are strongest around the South Pylon. The strongest effects are observed near the Reference Concept South Pylon and Pier S0. Under existing conditions, this region was subject velocities of 1.3 m/s, resulting from the contraction between NWR piers. With the addition of the Reference Concept piers, velocities local to the South Pylon increase slightly to 1.5 m/s, a minor change not anticipated to greatly impact the navigation channel nor bed elevations. A low-velocity shadow behind the South Pylon has velocities reduced to 0.4 m/s. Weaker low-velocity shadows were observed behind all Reference Concept piers.

Model results showed no significant macroscopic effects of implementing the NWR pier upgrades. Flow patterns were modelled to be similar with and without the upgrades. While the CFD results presented give a reasonable representation of the effect of the Reference Concept piers, a finer local mesh may be required to fully examine the local near-field effects of the NWR upgrades.

3.2 Pattullo Bridge Decommissioning

CFD results with the Reference Concept in place, before and after decommissioning of the existing bridge, are compared (Figures A12-A20). For flows from the east (Flood of Record, Figures A12-A14; and Typical Freshet conditions, Figures A15-A17), there was little reduction in navigation channel velocities after removing the existing piers. Velocities appear largely controlled by the contraction between the Reference Concept South Pylon and NWR piers. The riprap cones of the existing bridge continue to impede flows even after the piers are removed, though velocities near the riprap cones are slightly higher after decommissioning, increasing by 0.2 to 0.3 m/s under flood of record and typical freshet flows.

Local regions of high velocities caused by flow interaction with existing Pattullo piers 3 and 4, shown in Figures A13 and A16, are no longer present after decommissioning, resulting in a velocity reduction in these regions of approximately 0.5 m/s after decommissioning during Flood of Record flows, and of 0.3 m/s under Typical Freshet conditions.

For flows from the west (winter flood tide scenario, shown in Figures A18-A20), the absence of low-velocity shadow from the existing piers results in slightly higher velocities near the NWR pier after decommissioning. The highest increases in velocity are directly west of NWR piers 3 and 4, a 0.2 m/s increase.

Once again, negligible macroscopic effects are shown by the NWR pier upgrades.

4 CONCLUSIONS

The CFD results have assisted in evaluating the effects of the Reference Concept piers, both before and after decommissioning the existing bridge. Prior to decommissioning, during outgoing flows the Reference Concept piers result in a very small increase in velocity in the navigation channels and in the vicinity of existing spans. The proximity of the South Pylon to the existing NWR pier results in a constriction of the channel that causes the observed increases in velocities and scour potential. After decommissioning, during flows from the east, velocities in the navigation channel are largely unchanged, governed by the location of the South Pylon relative to NWR piers. For flows from the west, velocities at the NWR bridge show minor increase as a result of the loss of low-velocity shadow of the existing Pattullo piers.

5 REFERENCES

NHC (2007). “Pattullo Bridge Modeling – River2D modeling”. Technical memo prepared by Northwest Hydraulic Consultants Ltd. for Translink.

NHC (2016). “Pattullo Bridge Replacement Project - Preliminary Hydraulic Assessment”. Technical memo prepared by Northwest Hydraulic Consultants Ltd. for Parsons Corporation, October 14, 2016.

Vasquez, J.A., and Walsh, B.W. (2009) “CFD simulation of local scour in complex piers under tidal flow”. IAHR Conference, Vancouver, Canada. Aug. 9-14, 2009.

DISCLAIMER

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FIGURES

Figure A1. Transverse depth-averaged velocity profiles computed by Flow-3D compared with ADCP field data measured on May 10, 2006 (river discharge between 7,950 and 8,450 m3/s)

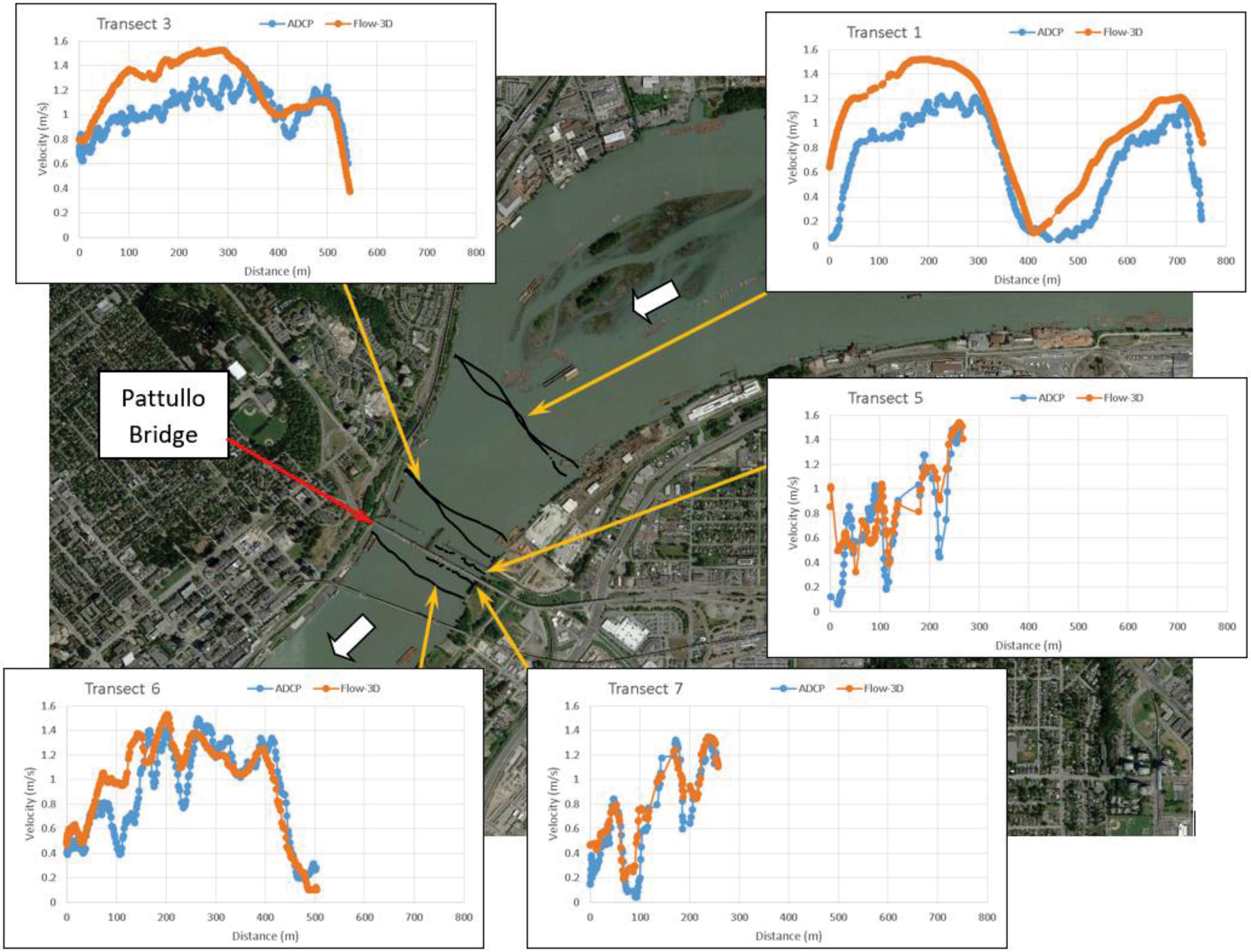


Figure A2. Transverse depth-averaged velocity profiles computed by Flow-3D compared with ADCP field data measured on June 15, 2016 (river discharge around 7,868 m3/s)

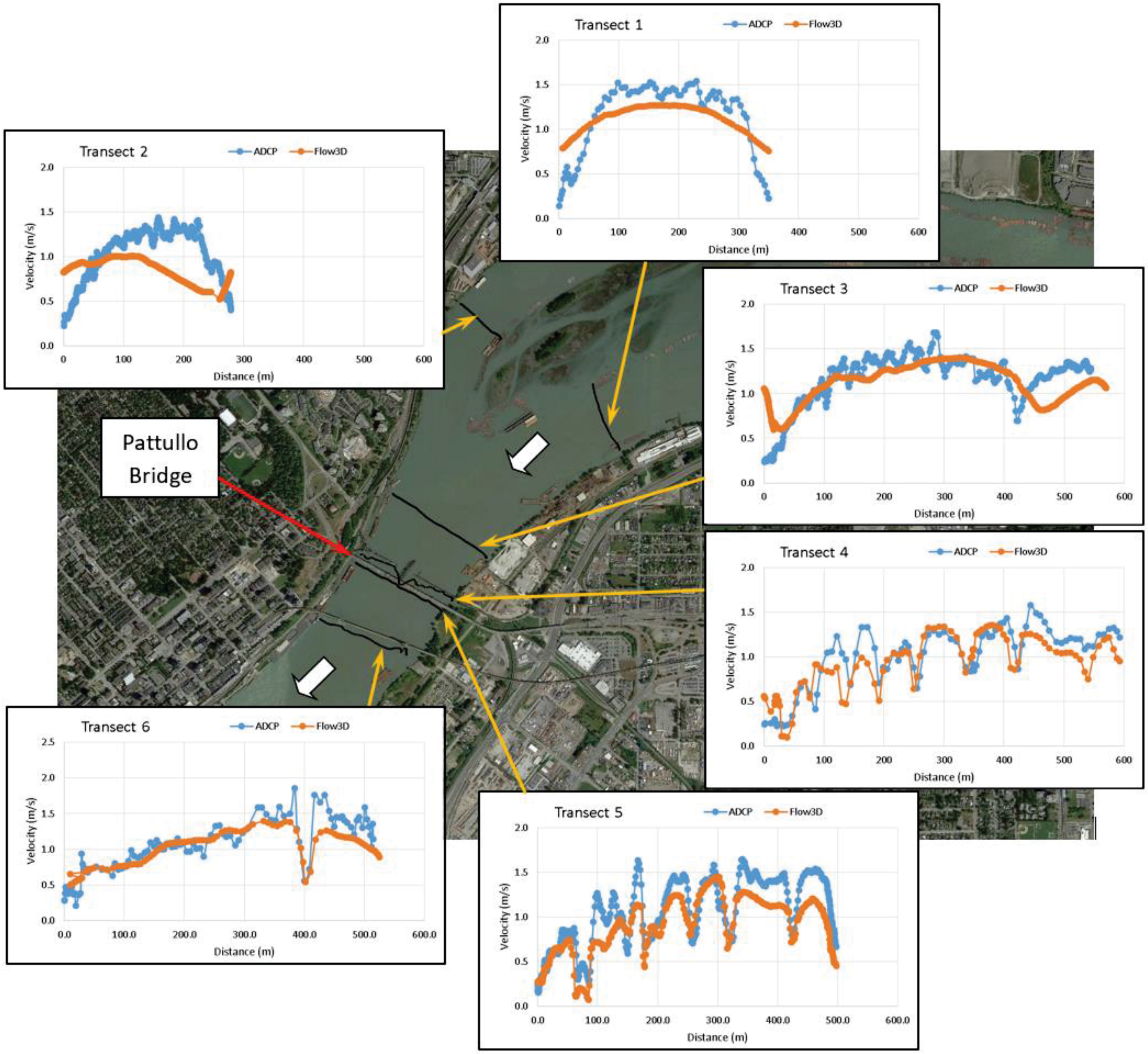


Figure A3. 1894 Flood of Record (Q = 21,155 m^3/s) Depth-Averaged Velocity

Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

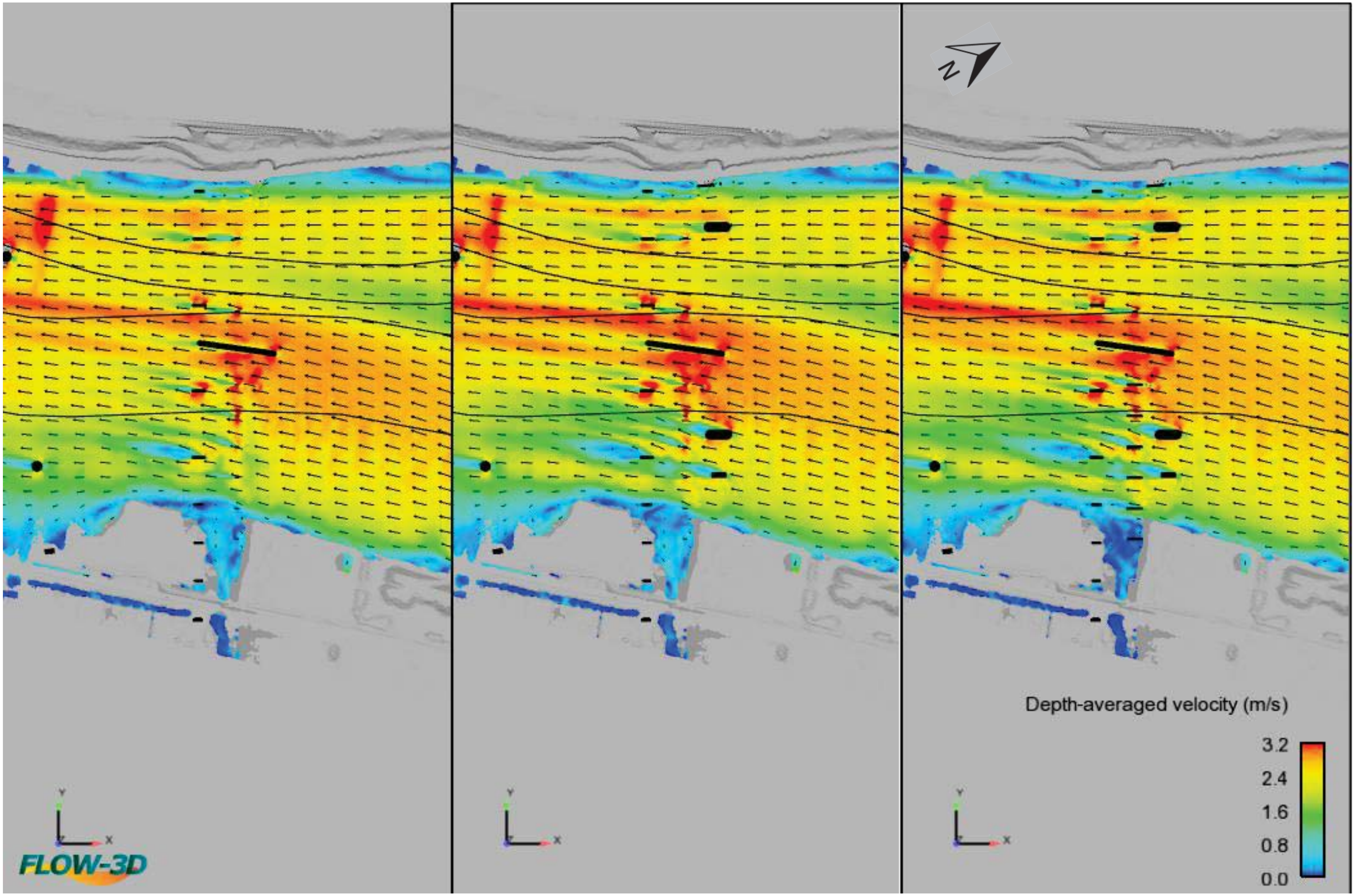


Figure A4. **1894 Flood of Record (Q = 21,155 m^3/s)**
Depth-Averaged Velocity

Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

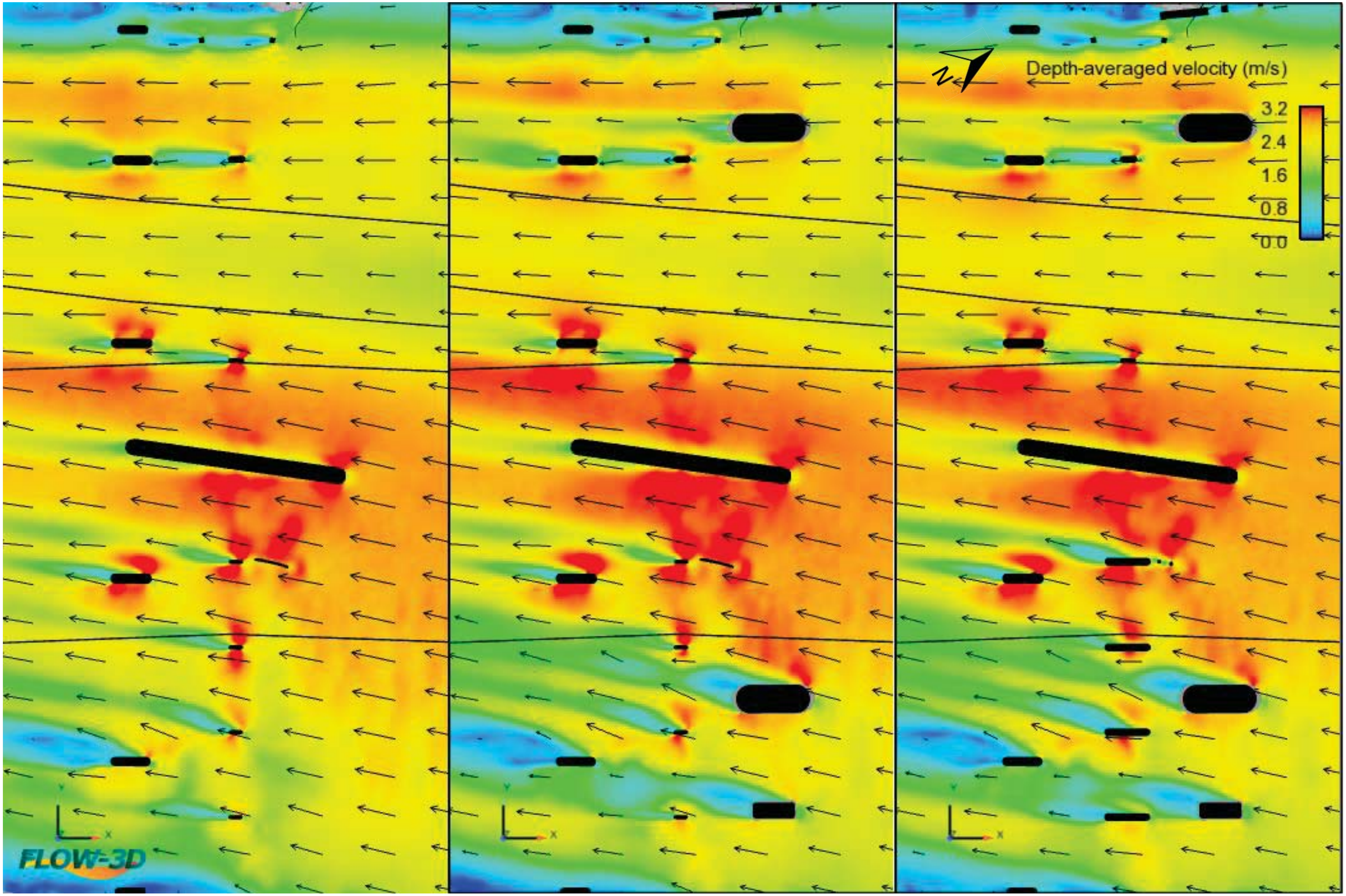


Figure A5. 1894 Flood of Record (Q = 21,155 m^3/s) Velocity Transects (looking east)

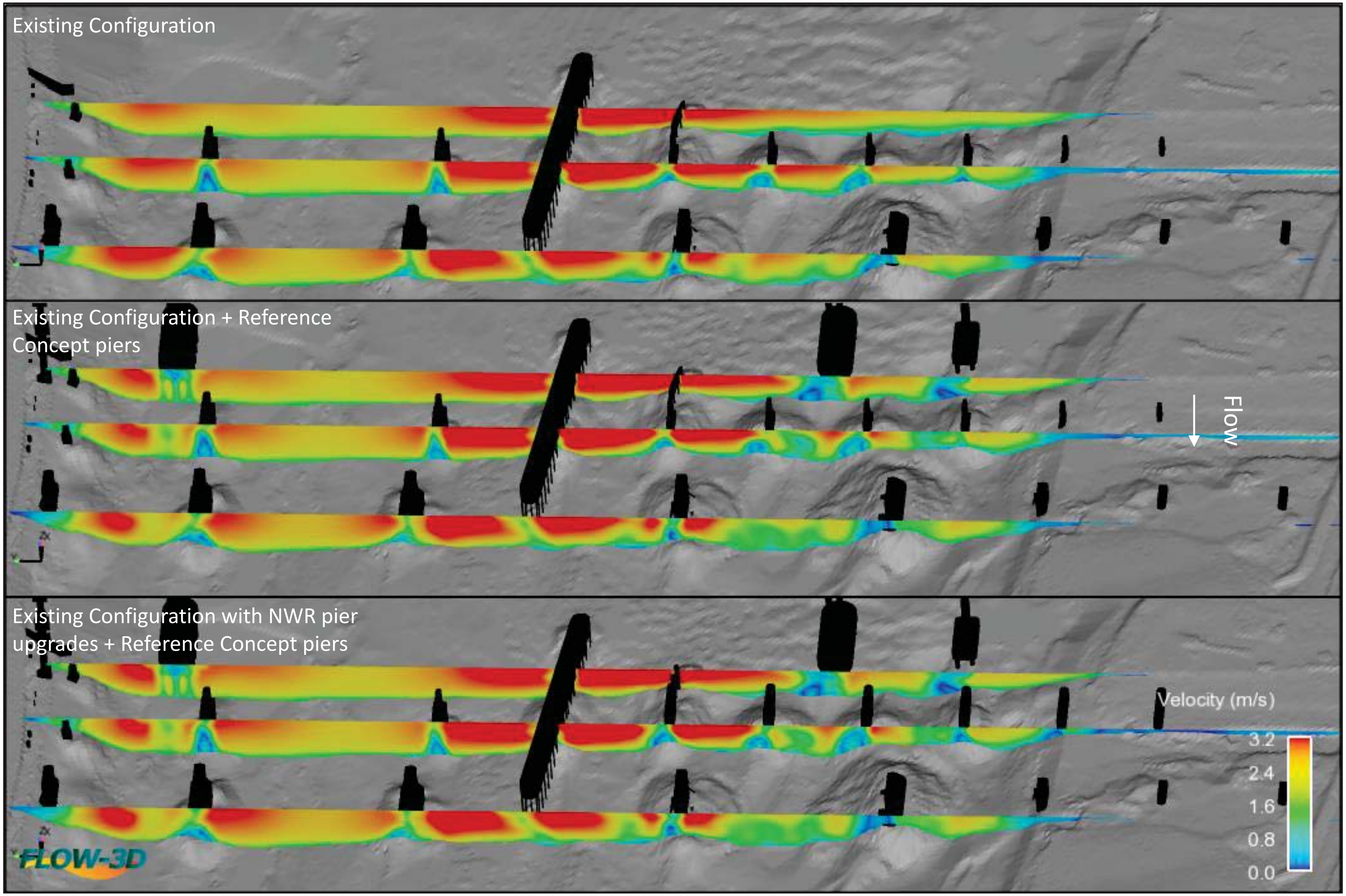
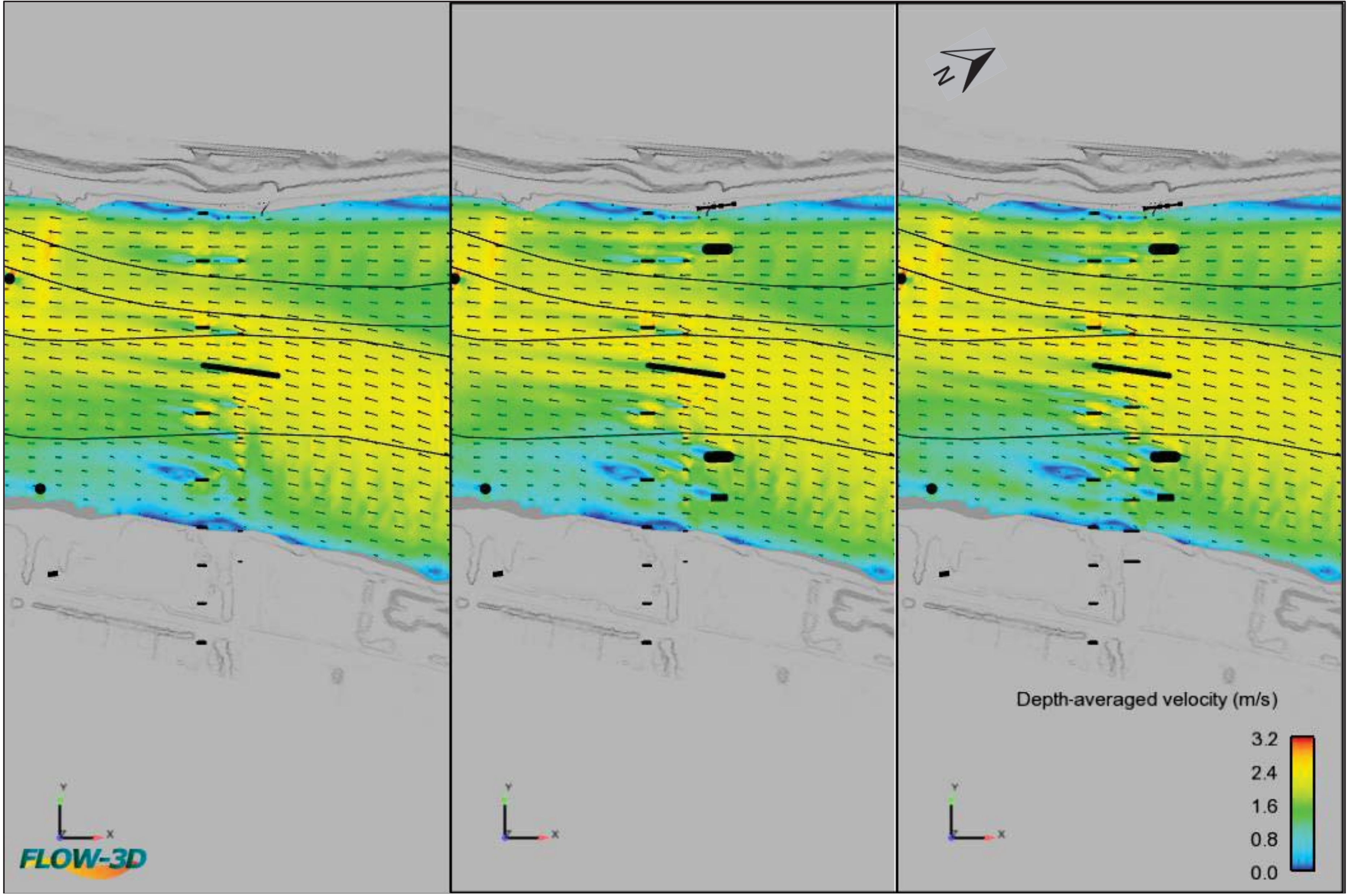


Figure A6. Typical Freshet Flow (Q = 13,215 m^3/s)
Depth-Averaged Velocity

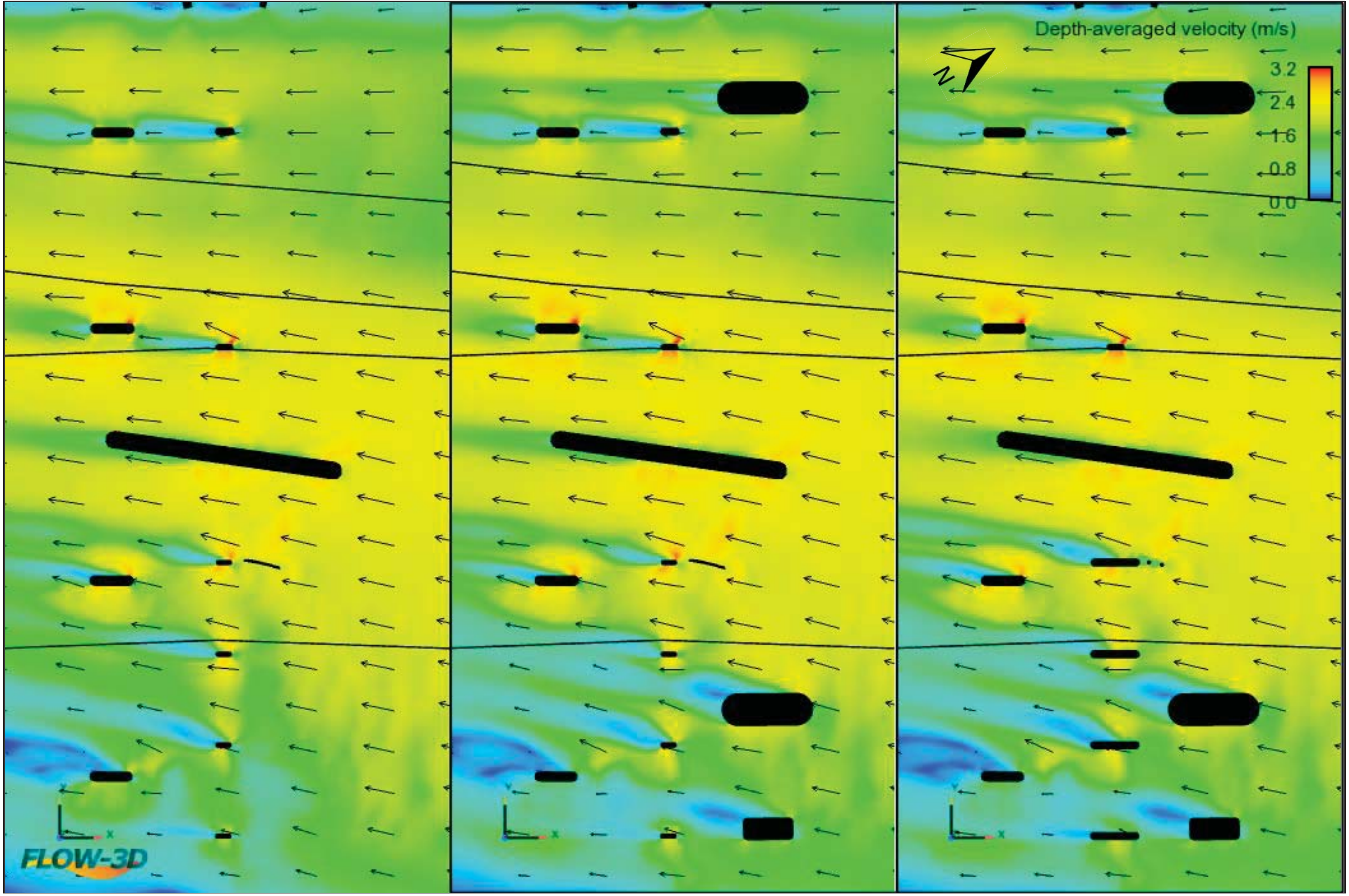


Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

Figure A7. Typical Freshet Flow ($Q = 13{,}215\ m^3/s$)
Depth-Averaged Velocity



Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

Figure A8. Typical Freshet Flow (Q = 13,215 m^3/s) Velocity Transects (looking east)

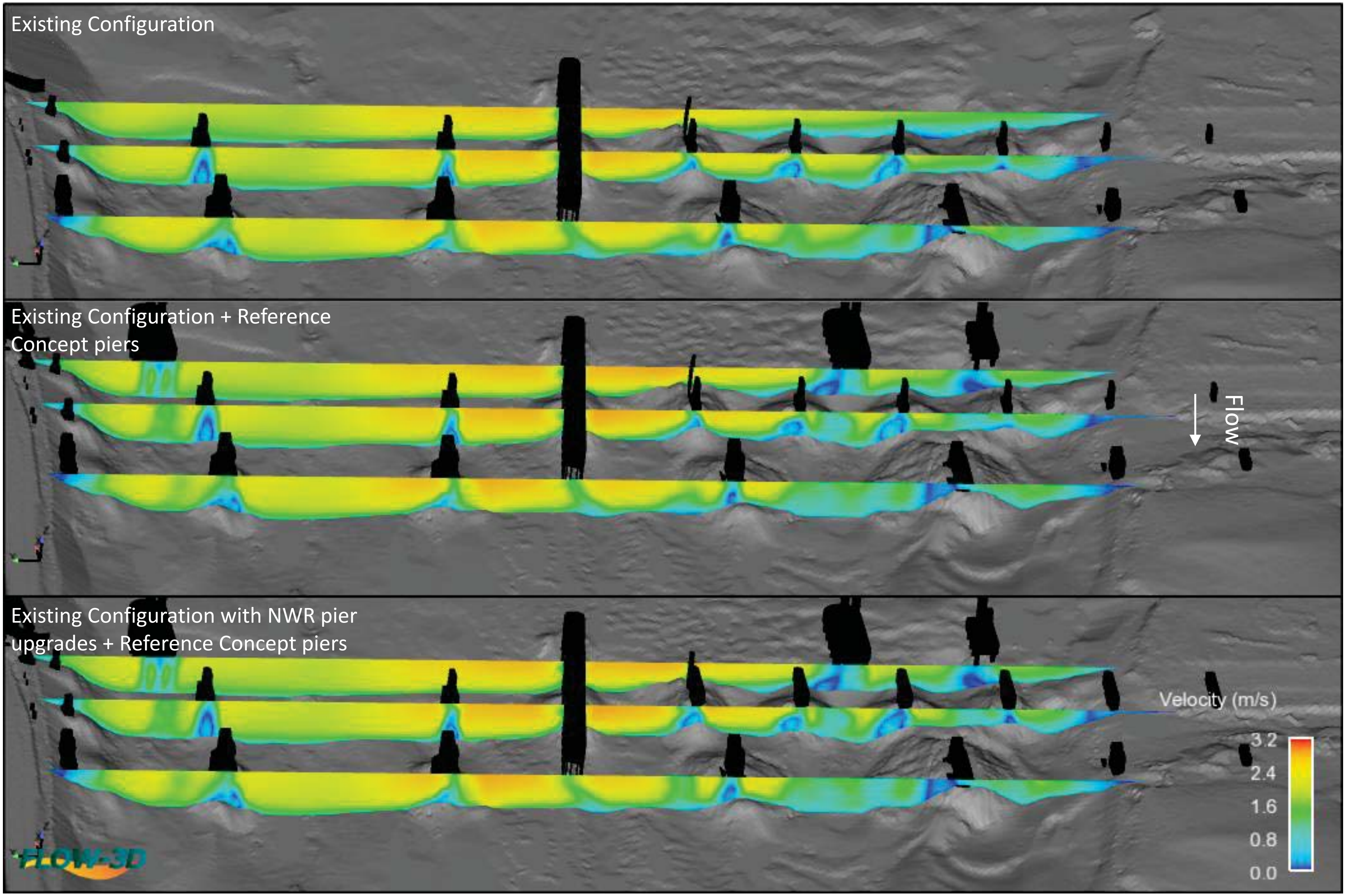
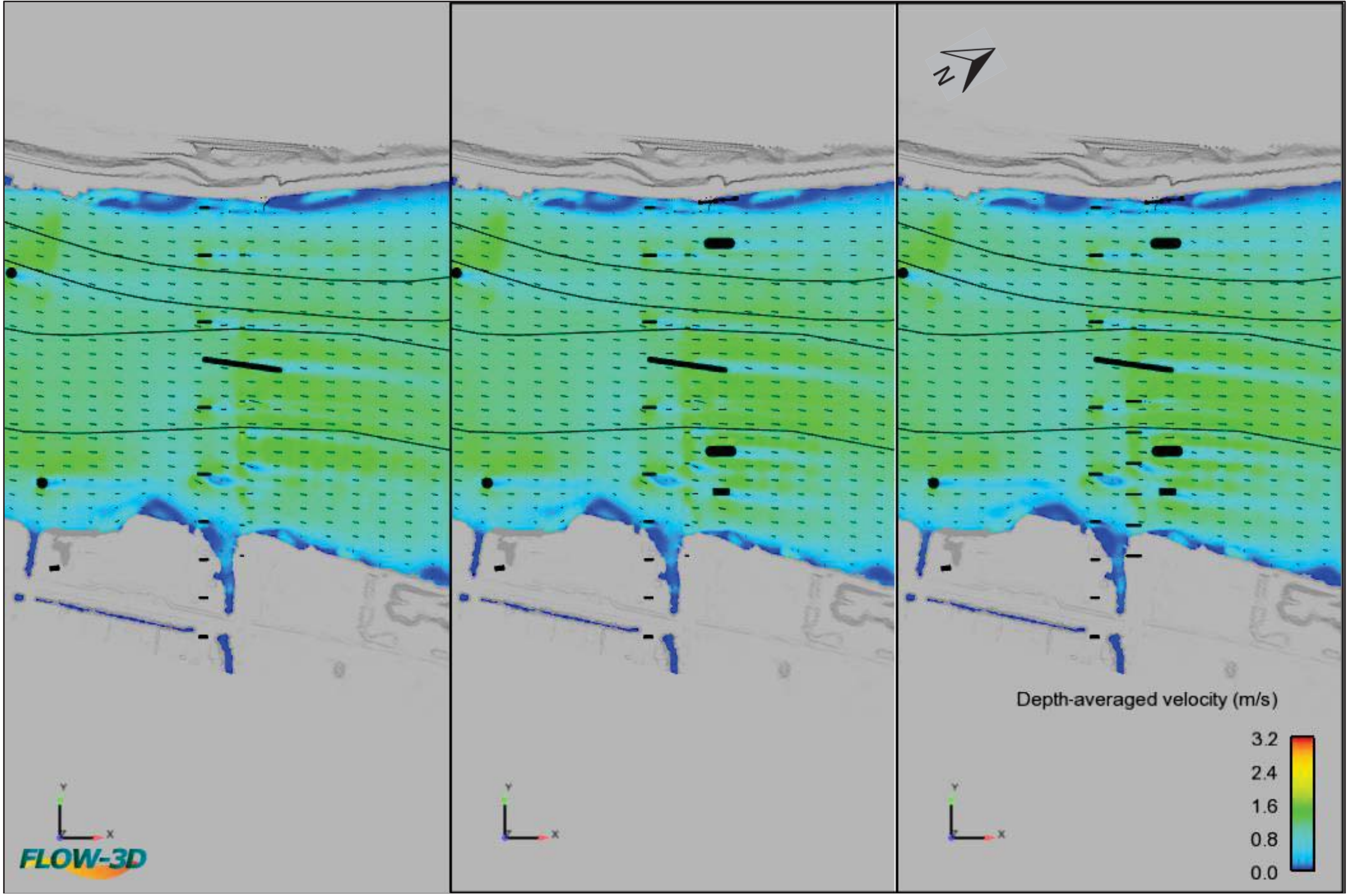


Figure A9. **Winter Flood Tide (Q = -8,311 m^3/s) Depth-Averaged Velocity**

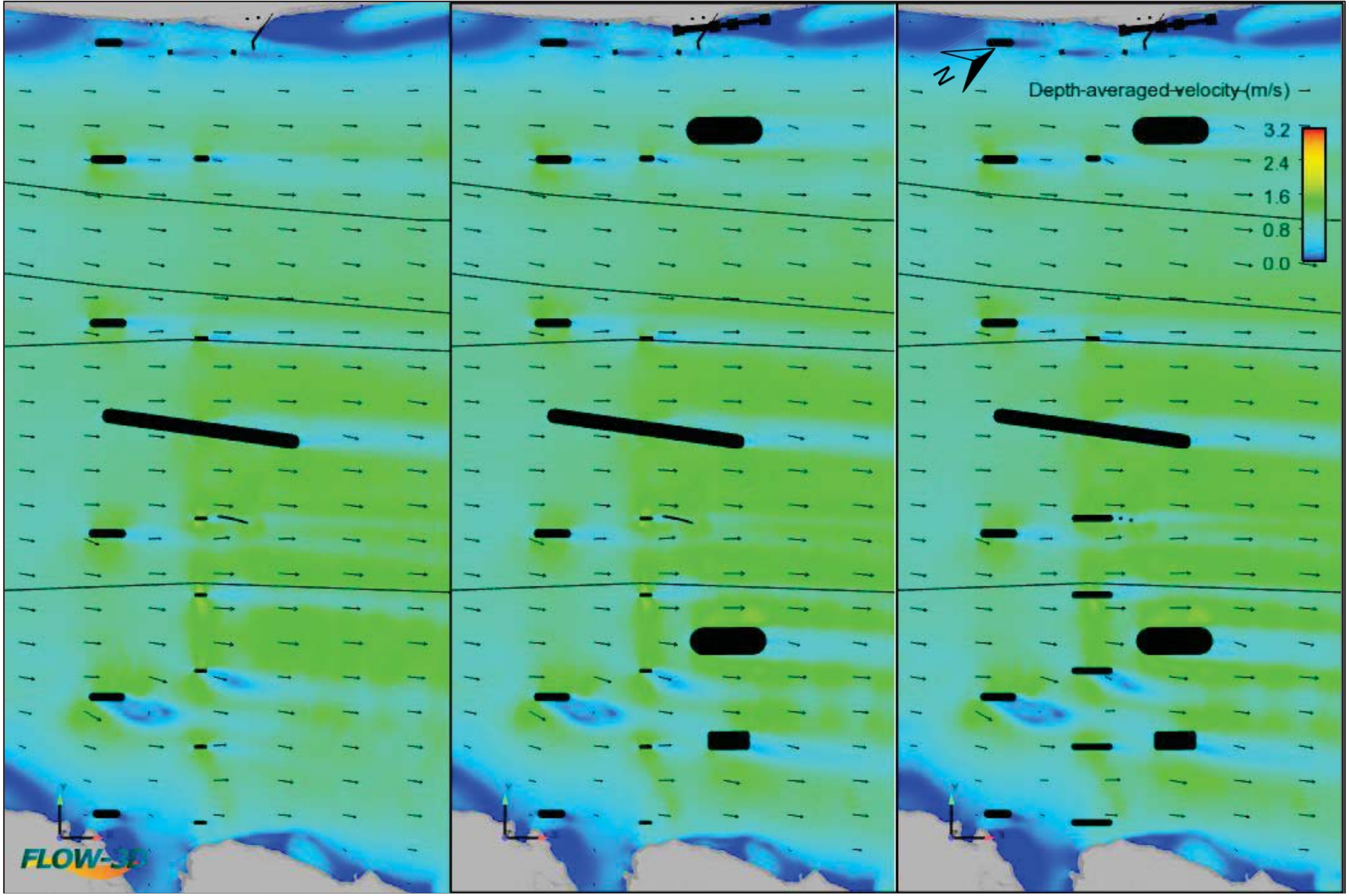


Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

Figure A10. Winter Flood Tide (Q = -8,311 m³/s)
Depth-Averaged Velocity

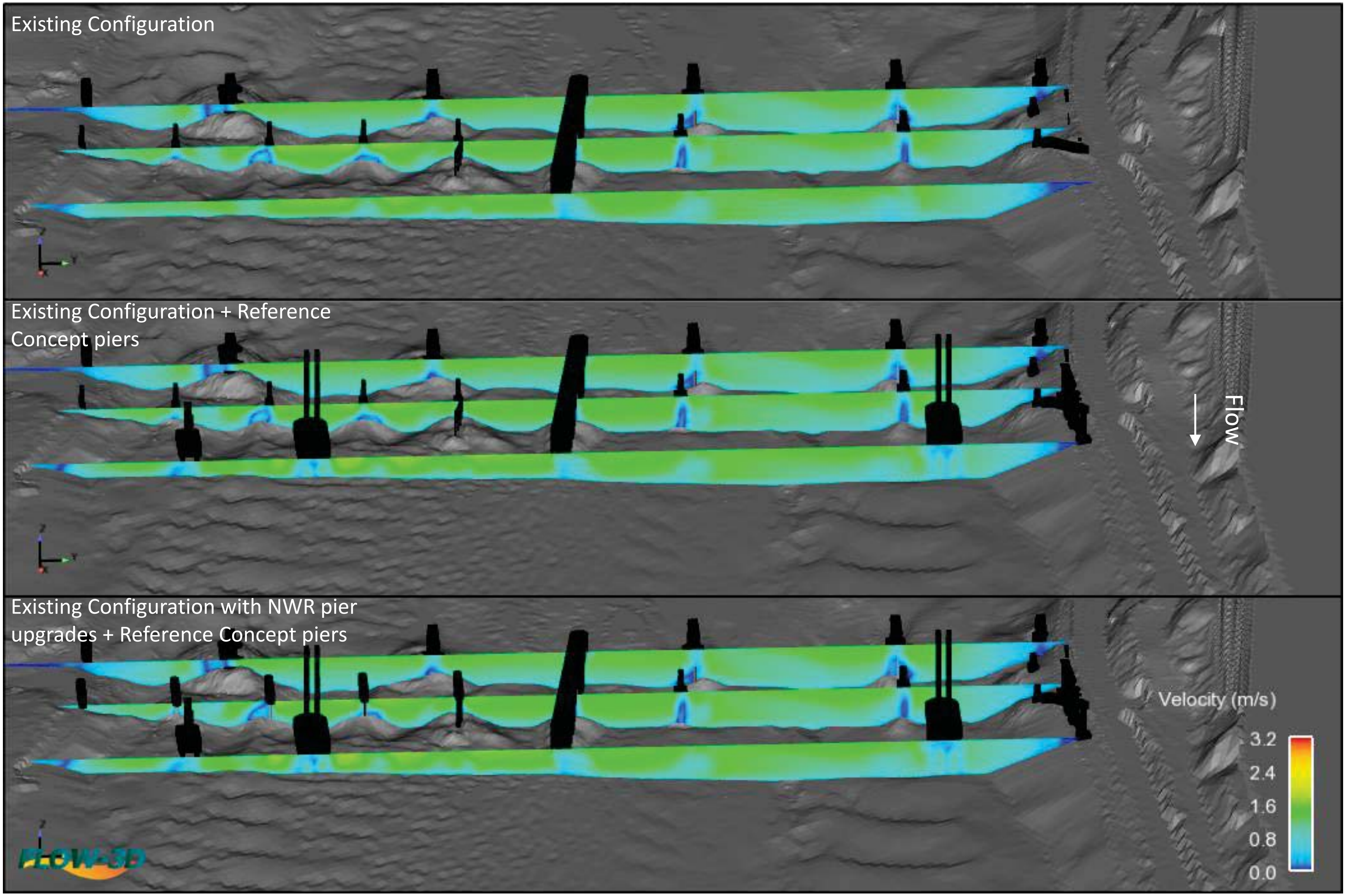


Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

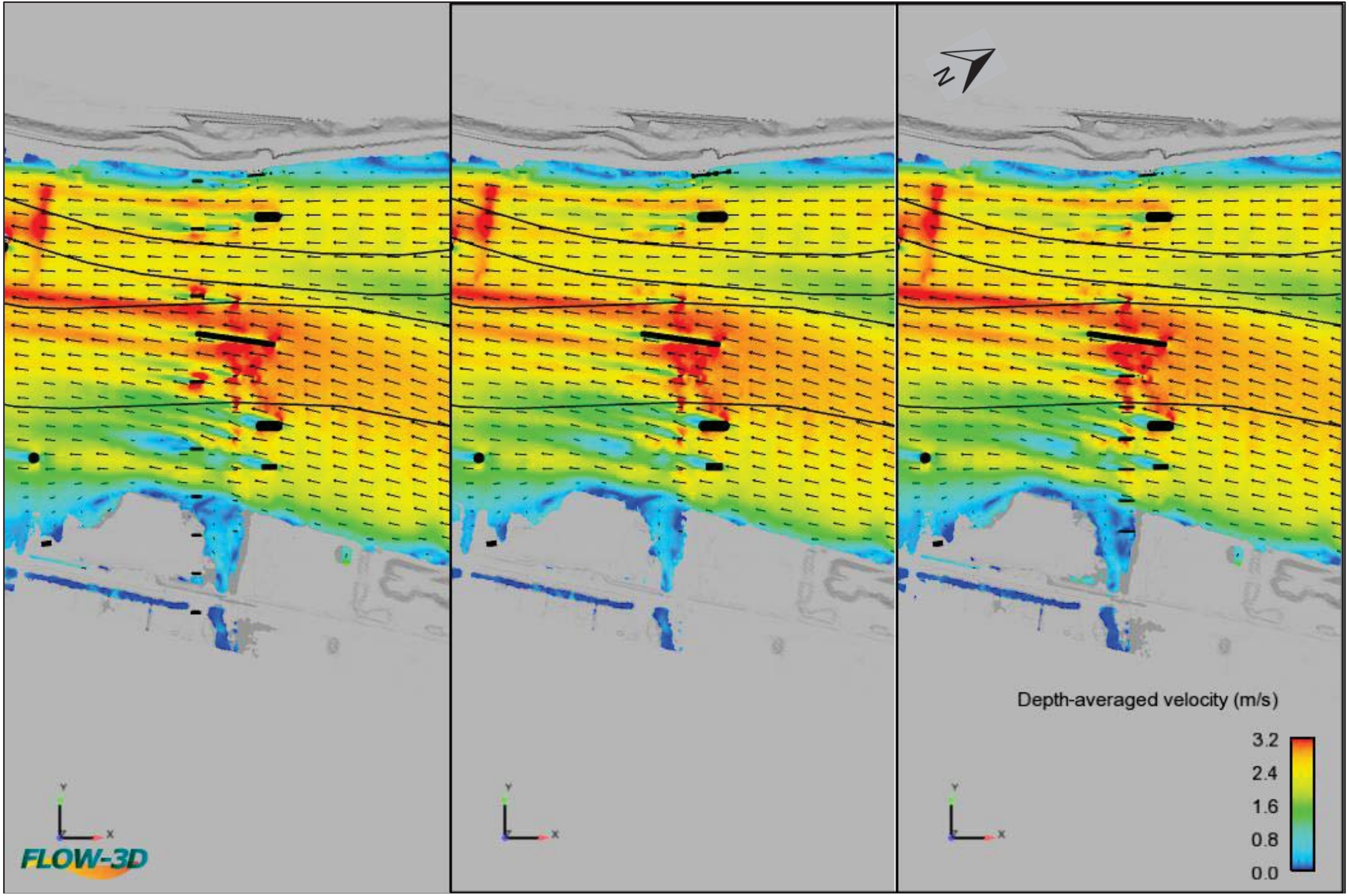
Figure A11. Winter Flood Tide (Q = -8,311 m^3/s)
Velocity Transects (looking west)


Existing Configuration

Existing Configuration + Reference Concept piers

Existing Configuration with NWR pier upgrades + Reference Concept piers

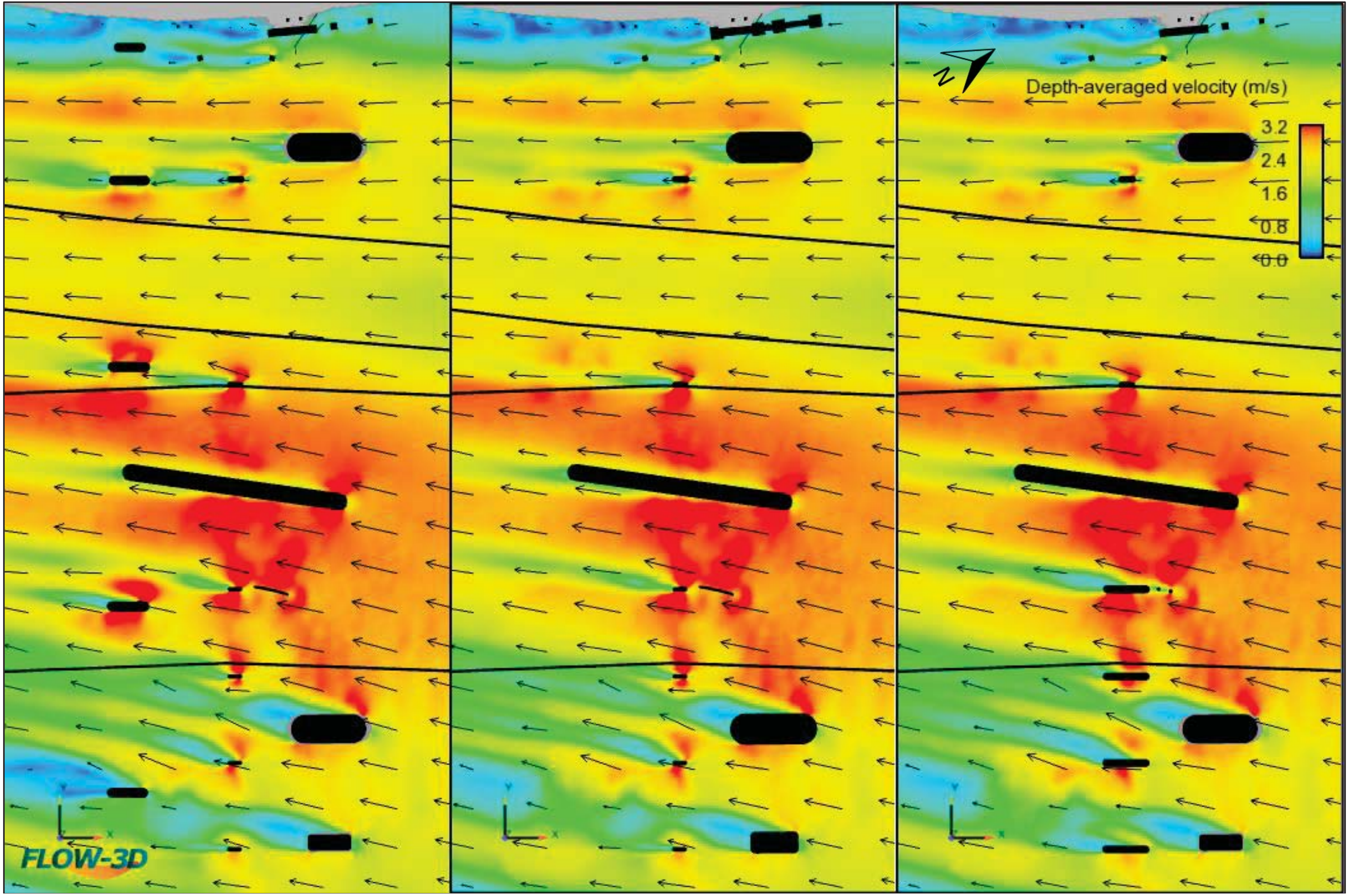
Figure A12. 1894 Flood of Record (Q = 21,155 m^3/s)
Depth-Averaged Velocity


Existing Configuration
+ Reference Concept piers

Existing demolished
+ Reference Concept piers

Existing demolished, NWR pier upgrades +
Reference Concept piers

Figure A13. **1894 Flood of Record (Q = 21,155 m^3/s)**
Depth-Averaged Velocity



Existing Configuration + Reference Concept piers

Existing demolished + Reference Concept piers

Existing demolished, NWR pier upgrades + Reference Concept piers

Figure A14. 1894 Flood of Record (Q = 21,155 m^3/s) Velocity Transects (looking east)

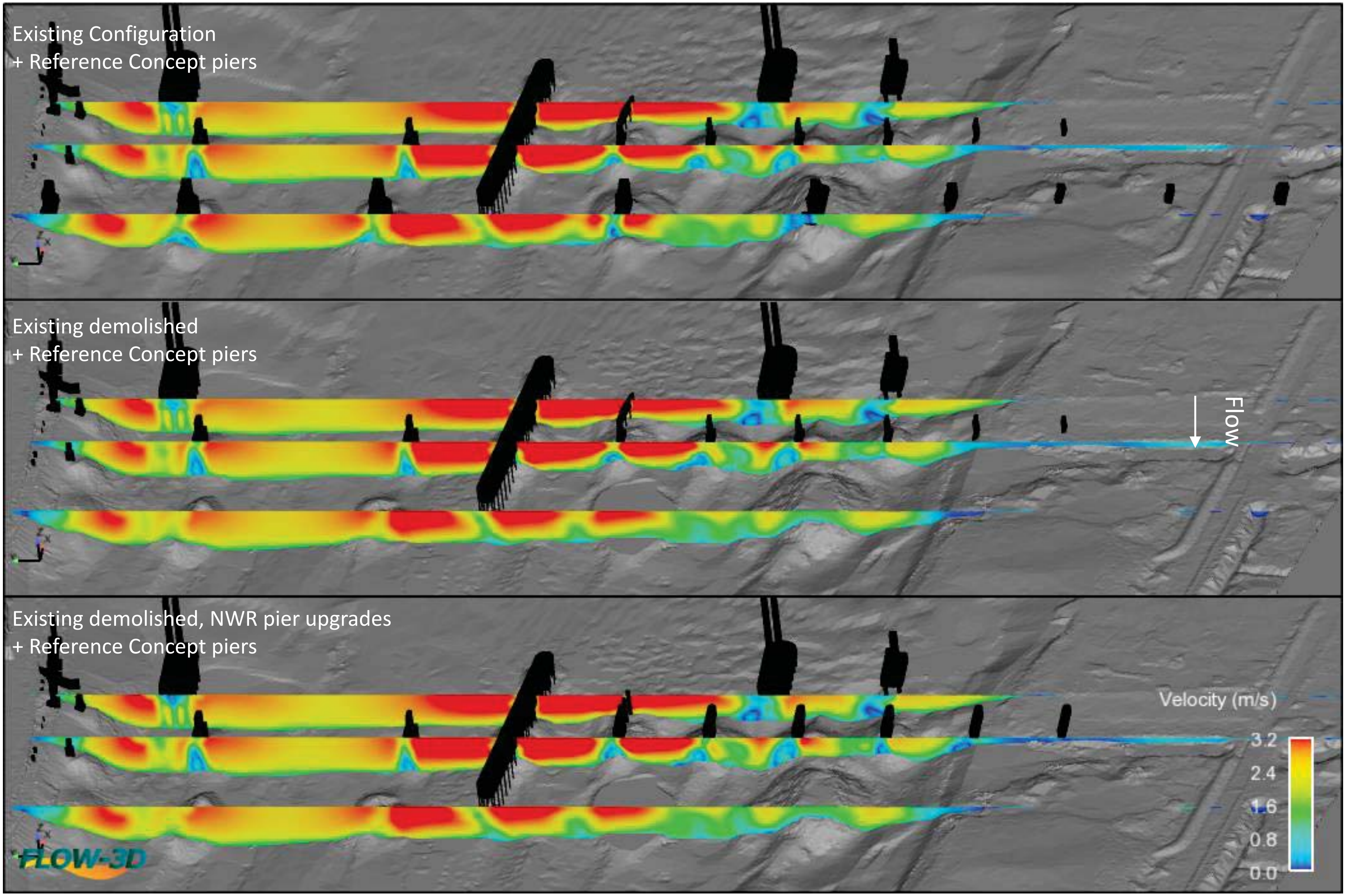


Figure A15. Typical Freshet Flow (Q = 13,215 m^3/s) Depth-Averaged Velocity

Existing Configuration
+ Reference Concept piers

Existing demolished
+ Reference Concept piers

Existing demolished, NWR pier upgrades +
Reference Concept piers

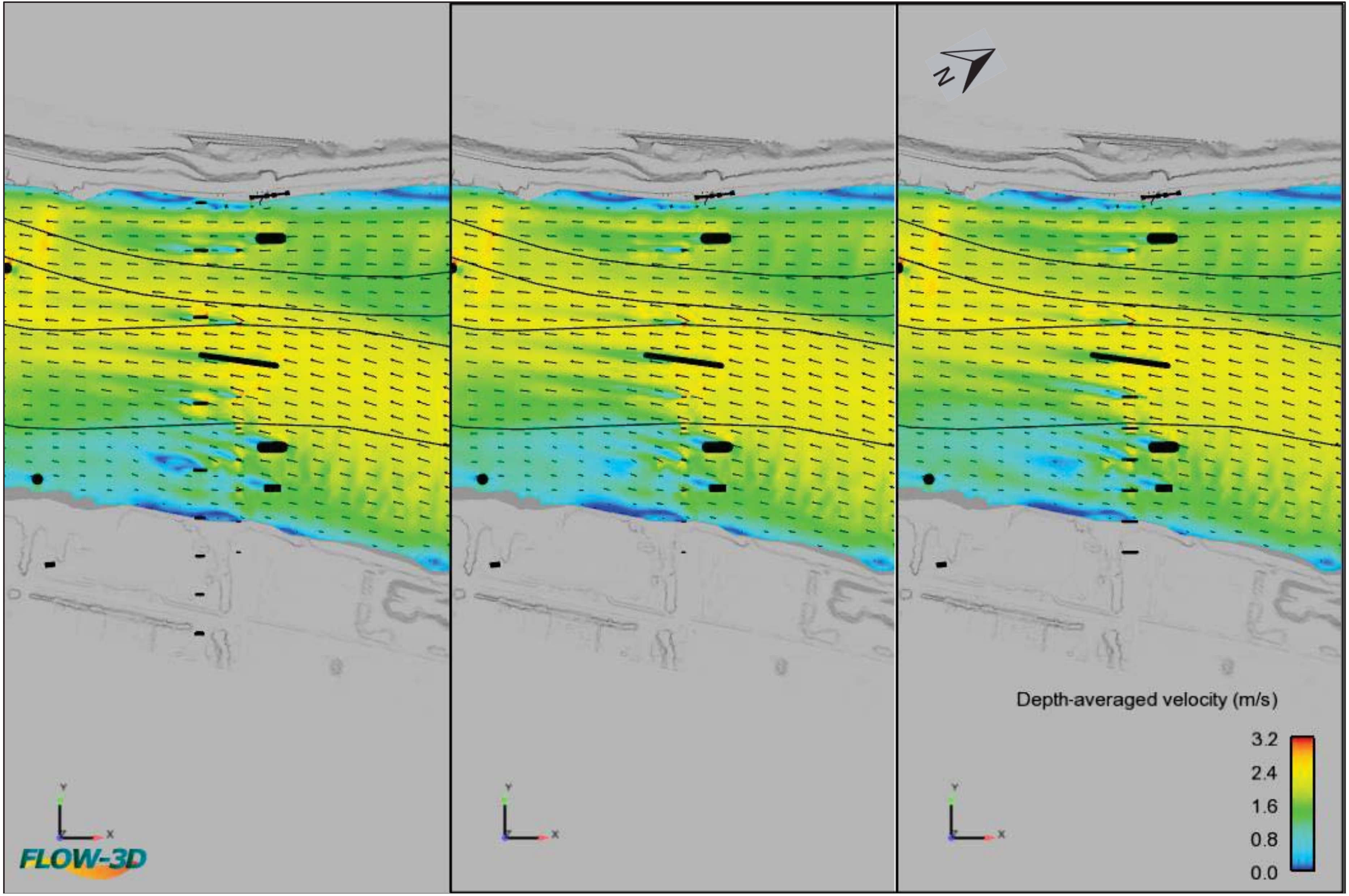
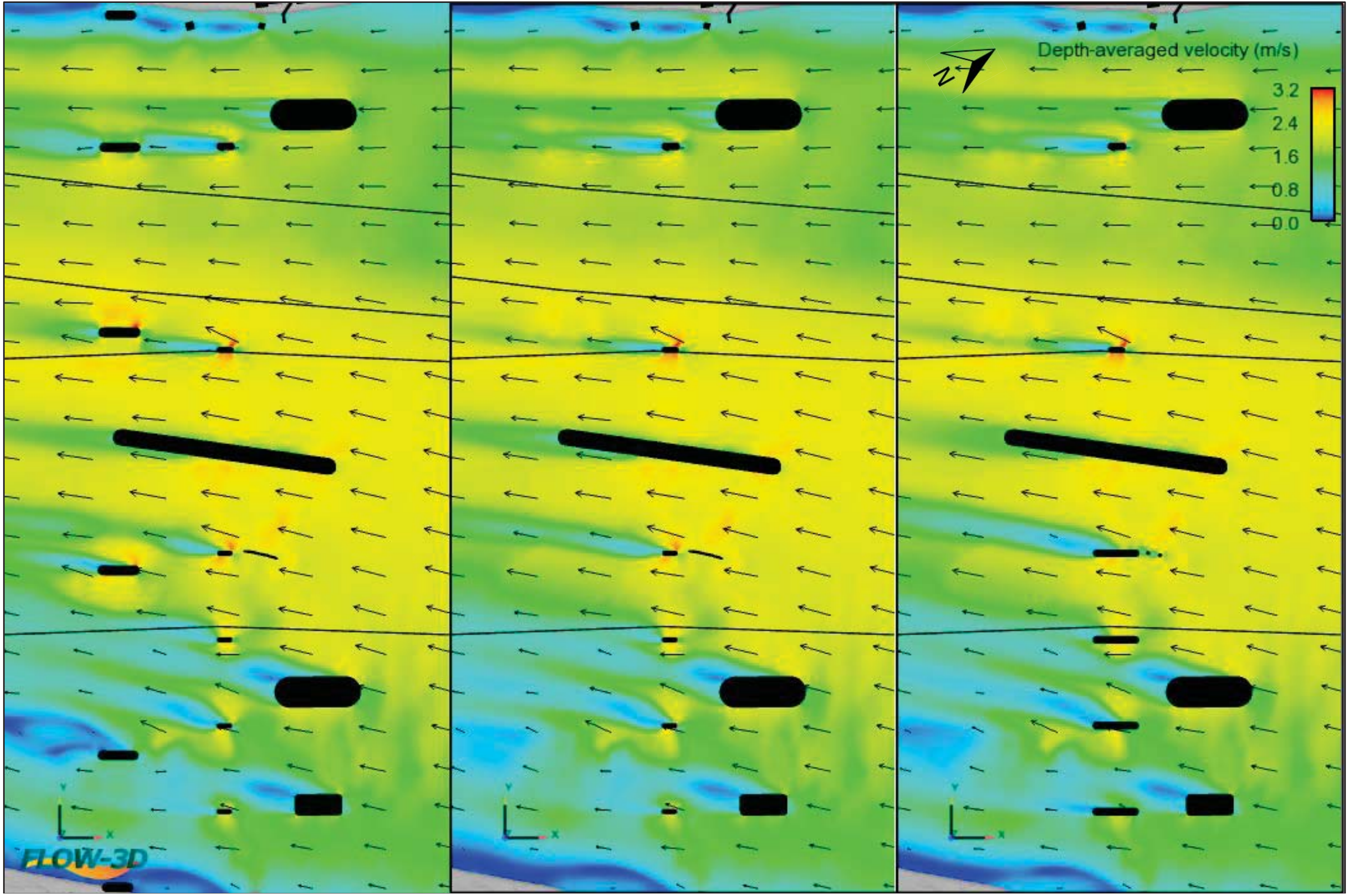


Figure A16. Typical Freshet Flow (Q = 13,215 m^3/s) Depth-Averaged Velocity


Existing Configuration + Reference Concept piers

Existing demolished + Reference Concept piers

Existing demolished, NWR pier upgrades + Reference Concept piers

Figure A17. Typical Freshet Flow (Q = 13,215 m^3/s) Velocity Transects (looking east)

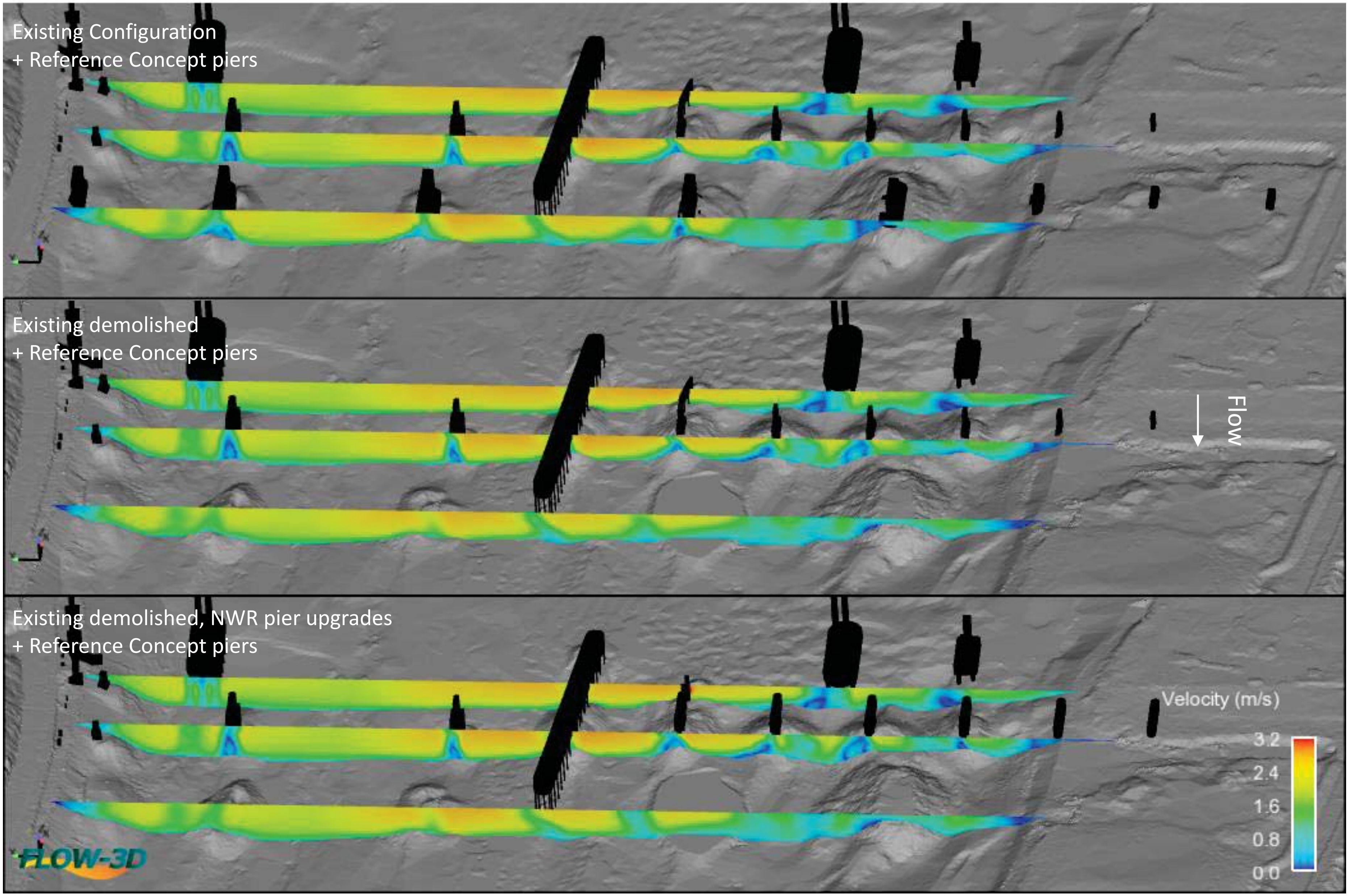


Figure A18. Winter Flood Tide (Q = -8,311 m³/s) Depth-Averaged Velocity

Existing Configuration
+ Reference Concept piers

Existing demolished
+ Reference Concept piers

Existing demolished, NWR pier upgrades +
Reference Concept piers

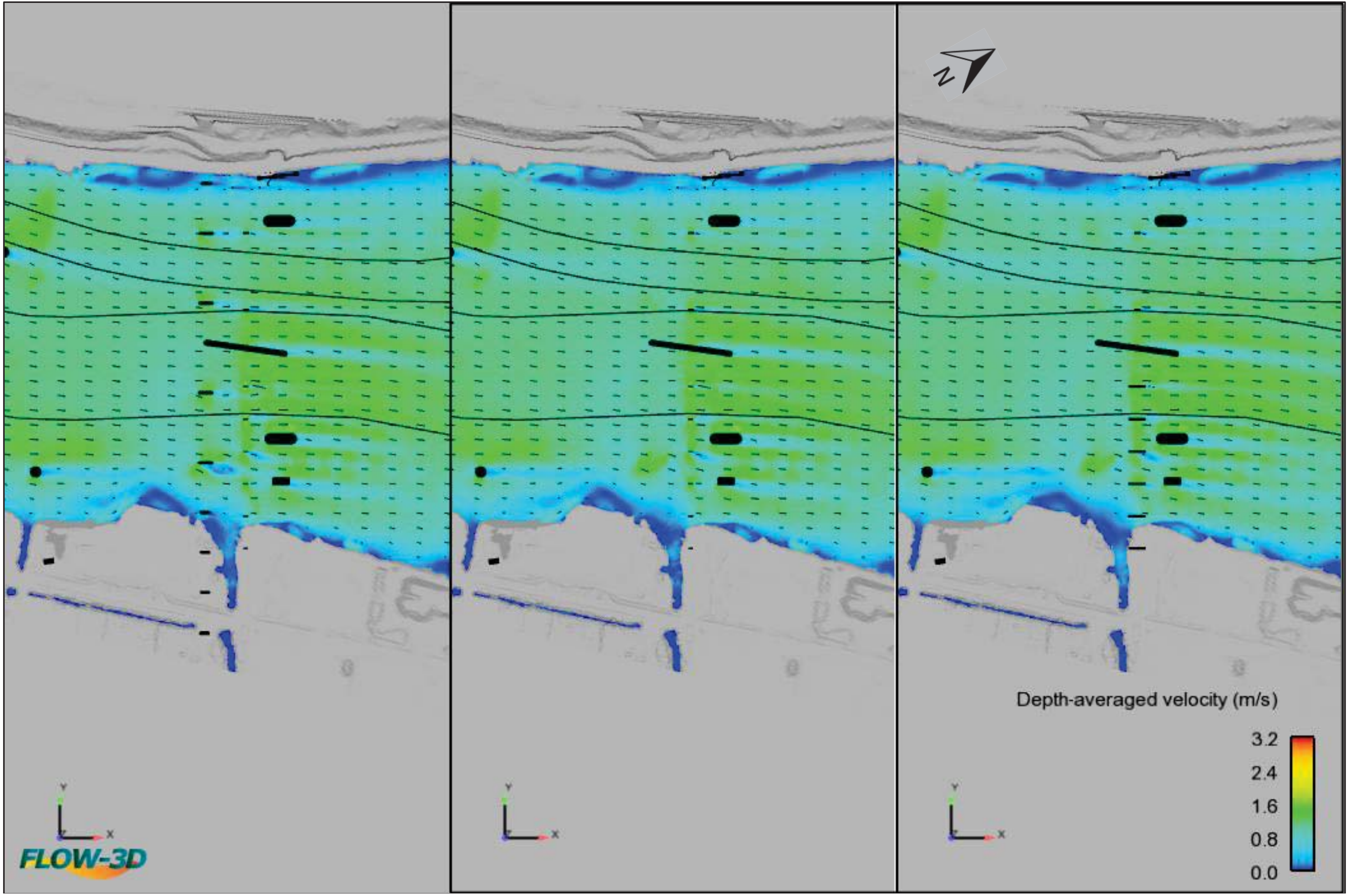
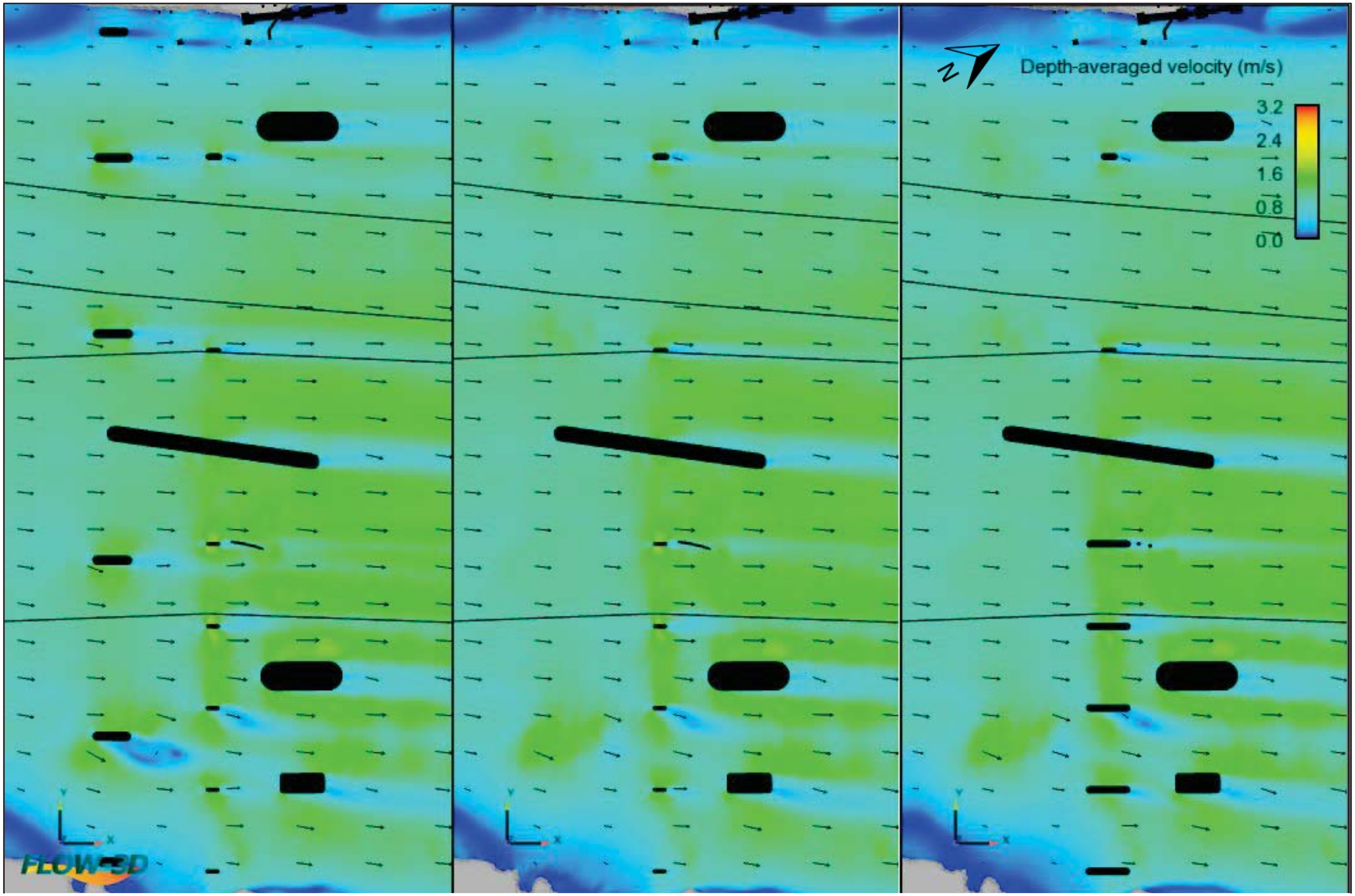


Figure A19. Winter Flood Tide (Q = $-8{,}311$ m^3/s) Depth-Averaged Velocity

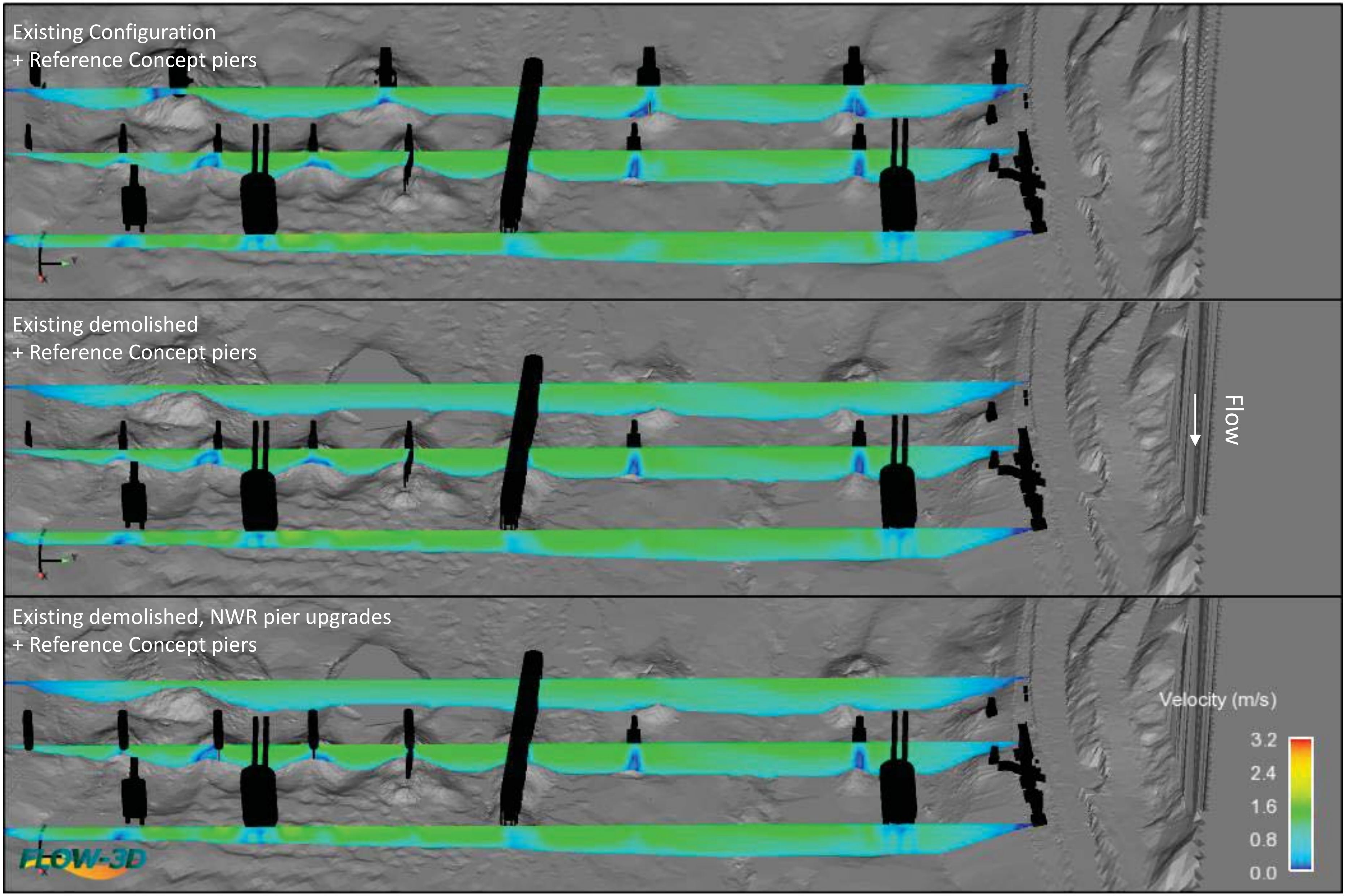


Existing Configuration + Reference Concept piers

Existing demolished + Reference Concept piers

Existing demolished, NWR pier upgrades + Reference Concept piers

Figure A20. Winter Flood Tide (Q = -8,311 m^3/s) Velocity Transects (looking west)



APPENDIX B: MORPHODYNAMIC MODEL

1 INTRODUCTION

1.1 Background

This Appendix describes the development, calibration, validation and detailed results from a morphodynamic model in support of technical studies to assess river hydraulics and morphological changes associated with TransLink's Pattullo Bridge replacement project. The appendix accompanies NHC's main report "River Hydraulics and Morphology-Draft Technical Report", which synthesizes results from this appendix as well as results from Computational Fluid Dynamics Modelling (Appendix A) and mobile bed physical modelling (Appendix C).

1.2 Reference Bridge Concept

Translink proposes to replace the existing Pattullo Bridge with a new four-lane bridge (Reference Concept) which will be located just upstream of the existing bridge. The project will also include decommissioning of the existing bridge. The locations of the Reference Concept piers in relation to the existing CN Rail bridge and existing Pattullo Bridge are shown in **Figure 1**.

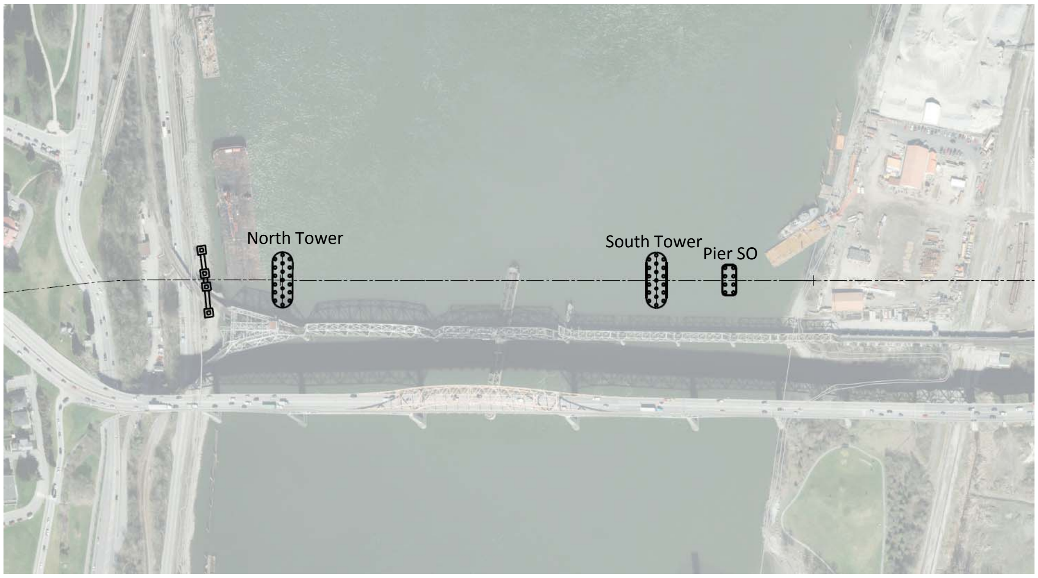


Figure 1. Reference Concept piers – reproduced from Parsons Drawing: SK-S-028

1.3 Purpose of Morphodynamic Model Study

The Reference Concept piers (as well as the subsequent decommissioning of the existing Pattullo Bridge) are expected to modify the local hydraulic flow conditions and could potentially alter the local sediment transport characteristics near the site. The changes to local river morphology could potentially lead to changes in maintenance dredging requirements and cause alterations to habitat in regions further away from the Reference Concept piers. Key sites identified by Port of Vancouver (POV), Metro Vancouver and the PBRep archaeology team are shown in the main body of the report (Figures 5 – 7 and Tables 2 – 3). The morphodynamic model has been developed as a tool to assess the potential changes in Fraser River morphology in these sites due to the Reference Concept piers.

2 METHODOLOGY

2.1 Model Description

Potential changes in sedimentation patterns associated with the Reference Concept piers were evaluated using the TELEMAC SYSTEM, a suite of finite element computer programs developed by the Laboratoire National d'Hydraulique et Environnement (LNHE), a department of Électricité de France (EDF)'s Research and Development Division. The various TELEMAC SYSTEM modules use high-capacity algorithms based on the Finite-Element method. All TELEMAC SYSTEM modules were developed in accordance with the quality assurance procedures followed in EDF's R&D Division. The equations and model descriptions are provided in detail in (Hervouet, 2007). Two TELEMAC modules were applied to compute the physical processes of tidal and river currents (TELEMAC-3D) and sediment transport (SISYPHE). Brief descriptions of these modules are provided below.

2.1.1 TELEMAC-3D - hydrodynamic model

TELEMAC-3D is a three-dimensional (3D) model that solves the Reynolds-Averaged Navier-Stokes equations in unstructured meshes obtained by superimposition of two-dimensional (2D) meshes of triangles. Its main outputs, obtained at each point in the resolution mesh in 3D, are velocity in all three directions and the concentrations of transported quantities. TELEMAC-3D's can represent the following processes:

- Influence of temperature and/or salinity on density;
- Bottom friction;
- Influence of the Coriolis force;
- Influence of weather elements: air pressure and wind;
- Sources and sinks for fluid moment within the flow domain;
- Dry areas in the computational domain: tidal flats.

When drying occurs, the water depth falls to zero and the planes collapse to a zero inter-layer spacing. Finite-volume style numerical techniques are used to ensure that both water and a tracer can be well-conserved in the presence of drying and subsequent re-wetting.

2.1.2 SISYPHE – Sediment Transport model

SISYPHE is the sediment transport and bed evolution module of the TELEMAC SYSTEM. SISYPHE can be used to model complex morphodynamic processes in diverse environments, such as coastal, rivers, lakes and estuaries, for different flow rates, sediment size classes and sediment transport modes. In SISYPHE, sediment transport processes are grouped as bed load, suspended load or total load, with an extensive library of bed load transport relations. SISYPHE is applicable to non-cohesive sediments that can be uniform (single-sized) or non-uniform (multiple-sized), cohesive sediments (multi-layer consolidation models), as well as sand-mud mixtures.

A number of physically-based processes are incorporated into SISYPHE, such as the effect of bed slope associated with the influence of gravity, bed roughness predictors, and areas of non-erodible bed, among others.

2.1.3 Model Framework

For this study, TELEMAC-3D and SISYPHE are internally coupled to simulate tidal and river currents, and local bed scour and deposition. The current field is first simulated by the hydrodynamic model TELEMAC-3D. TELEMAC-3D then transfers the current velocity values and water depths to the morphodynamic model, SISYPHE, to compute scour and deposition of the riverbed. The new bed elevation computed by SISYPHE is fed back into TELEMAC-3D to re-compute the flow hydrodynamics. The model coupling flow diagram is shown in **Figure 2**.

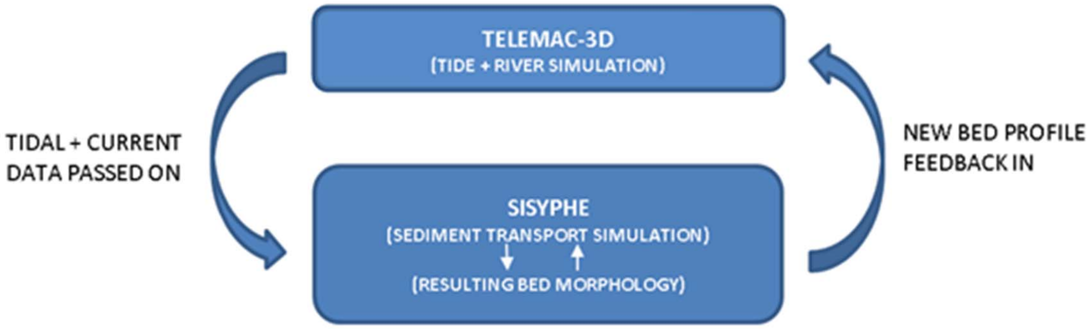


Figure 2. TELEMAC model coupling flow diagram

The time step of the SISYPHE sediment transport model was the same as the time step of the TELEMAC-3D model. This allows the hydrodynamic variables to be transferred to SISYPHE at each time step, which in turn, sends the updated bed elevation back to the hydrodynamic model for the next time step.

2.2 Model Setup

The model domain extends from Douglas Island at its eastern (upstream) boundary to Annacis Island at its western (downstream) boundaries (**Figure 3**). The model mesh consists of approximately 50,000 nodes, 96,000 elements and 8 levels in the vertical. The element lengths vary from approximately 40 m near the open boundaries and to about 2 m near Pattullo Bridge. The small element length is required to better resolve the hydraulics associated with the bridge piers near Pattullo Bridge. The model elevations in Geodetic Datum (GD) were derived using the following datasets:

- Bathymetric survey data collected by NHC on May 14, 2014 (survey extending approximately 50 m upstream and 500 m downstream of Pattullo Bridge).
- 2014 Public Works and Government Services Canada (PWGSC) bathymetric surveys and 2005 Fraser Basin Council LiDAR.

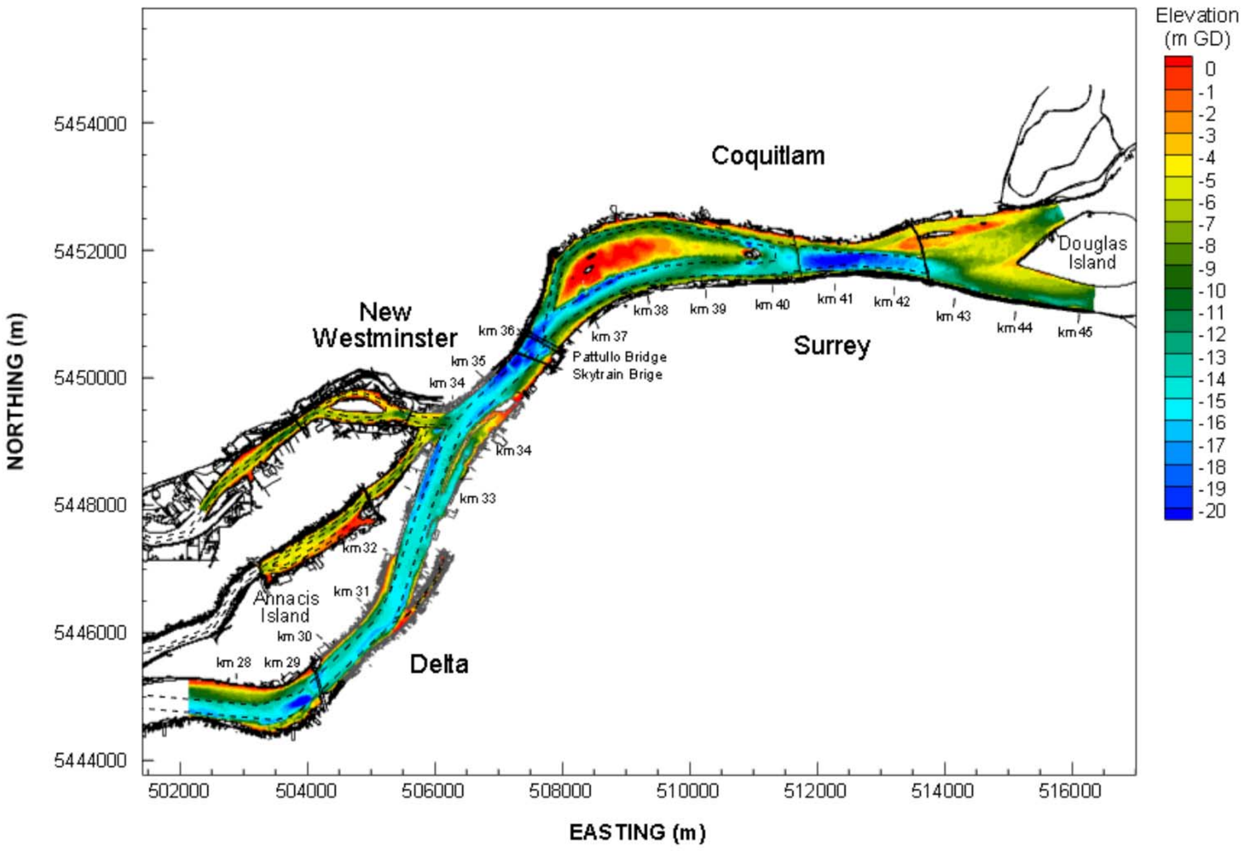


Figure 3. TELEMAC Fraser River model mesh extent

2.2.1 Model Hydraulic Conditions

Inflows to the Fraser River at Douglas Island and water levels at the downstream ends were computed using a hydraulic model of the Fraser River that uses the MIKE11 one-dimensional hydrodynamic software developed by the Danish Hydraulic Institute. NHC prepared the Fraser River MIKE11 model for Fraser Basin Council in 2006 (NHC, 2006) and updated it for BC Ministry of Environment two years later (NHC, 2008).

The morphodynamic model was used to simulate the 2012 freshet. The year 2012 was selected because of the availability of data for model calibration and because of its relatively large freshet flow (about 1:20 year return flow). The 2012 Fraser River flow at Hope is shown in **Figure 4**. The freshet period during which the Hope flows were greater than 6,000 m^3/s (the approximate threshold for significant bed material motion in the Fraser River), was chosen for the sedimentation analysis. For the 2012 freshet, this period extended between May 26th and July 27th.

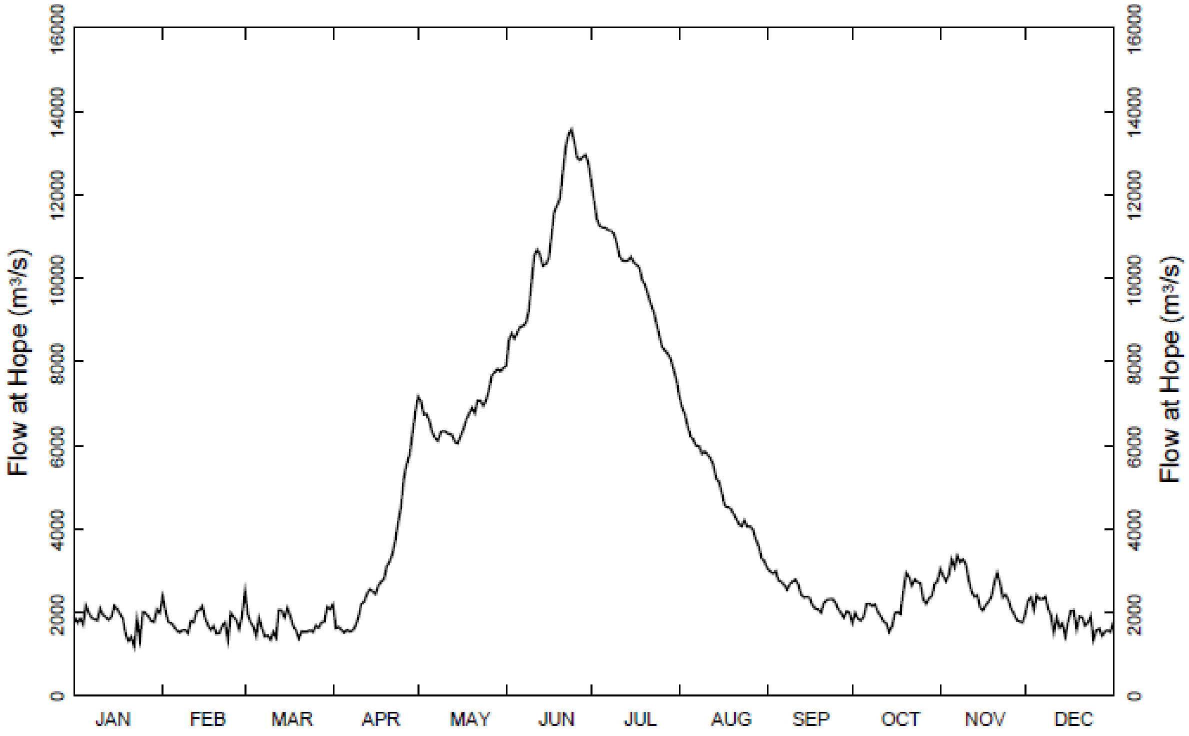


Figure 4. **2012 Fraser River daily flow at Hope**

2.2.2 Model Sediment Data and Transport Equation

Total sediment transport load in the Lower Fraser River includes both bed material load and wash load. Most transported sediment in the Lower Fraser River is fine “wash load” (mainly clay, silt and very find sand) which is derived from erosion in the upper reaches of the watershed, and is flushed through the river system without affecting the morphology of the main channel. The bed material load represents the portion of sediment load that is derived from entrainment and erosion of the sediments making up the main channel of the river and is directly linked to the channel's morphology. The bed material load can be transported both as bedload and as suspended material.

The model incorporates transport of suspended bed materials as well as bedload. Sediment sizes in the model were based on known characteristics of Fraser River bed materials. Model sediment consists of a D_{50} (median diameter) of 0.32 mm based on surface samples collected by McLaren and Ren (McLaren and Ren, 1995) in the lower Fraser River between February 9 and April 7, 1993.

The van Rijn formula (van Rijn, 1993) was used to compute bedload and suspended bed material transport. The formula distinguishes between sediment transport below the reference height which is treated as bedload transport and that above the reference height which is treated as suspended bed material load. Sediment is entrained in the water column by imposing a reference concentration at the reference height. The reference height is a function of effective roughness height, dune/ripple height and water depth.

Equilibrium sediment concentration was prescribed at the upstream model boundary. This modelling approach allows the sediment load entering through the boundary to be near-perfectly adapted to the local flow condition, limiting accretion and erosion near the model boundary.

2.2.3 Model Limitations

Although the model represents the "state of the art" for predicting morphodynamic processes, there are a number of limitations with the tool. For example, the model cannot represent meandering evolution or lateral channel (planform) changes. However, since most of the banks along the lower Fraser River have been fixed by riprap or training walls, this issue is relatively unimportant in this case. The model does not include the finer wash load sediments (clay, silt and fine sand), which are generally flushed through the main channel without depositing. However, some of this material may deposit (at least temporarily) in slack water areas such as sloughs or highly sheltered areas along the shoreline. This processes will not be captured in the simulations.

Sediment transport predictions are subject to considerable uncertainty due to complex interaction between the turbulence in the flow, shear stress near the bed and the presence of bedforms. There are no up to date measurements of bed material transport rate to calibrate the model predictions. This limitation was overcome by conducting a sensitivity analysis to demonstrate the effect of changing various assumed parameters on the predictions.

The geology of the Fraser River has a substantial influence on the sediment transport process in the river. The bed and banks of the river occasionally contain non-alluvial materials such as bedrock, glacial tills, and deposits of silt and clay. In some locations (such as near the Alex Fraser Bridge), Pleistocene-age cobble, boulders, and gravels locally constitute a less- erodible layer or armour which slows or limits the rate of channel scour. The armour is commonly covered by 1.5 – 3 m of sand deposited during the falling limb of the freshet (Tamburi, 1976). Holocene age estuarine deposits (silt and clay) may also locally decrease the erodibility of the present bottom (Nelson et al. 2017). A detailed mapping of the sub-surface geological features under the channel generally only available at major infrastructure such as bridges and pipeline crossings. An armour layer was used in the model to limit erosion in areas believed to be geologically controlled or protected by riprap.

2.3 Model Validation

A numerical hydrodynamic and sediment transport model requires adequate field data to validate the model. For this study, both the hydrodynamic and the morphodynamic components of the model were validated using observed datasets collected from the study area.

2.3.1 Water Levels

Water Survey of Canada (WSC) operates a water level gauge along the Fraser River near Port Mann Bridge. In addition, Canadian Hydrographic Service (CHS) operates a tide gauge at New Westminster along the Fraser River. The water levels from these two stations were used to calibrate the Fraser River hydrodynamic model. **Figure 5** shows the location of these two stations and **Table 1** lists the corresponding station information.

Table 1. Water level gauges used for model calibration.

Station	Latitude	Longitude	Station ID	Type
New Westminster	49° 12' 00" N	122° 54' 37" W	7654	CHS
Port Mann Pumping Station	49° 13' 04'' N	122° 49' 37'' W	08MH126	WSC

CHS – Canadian Hydrographic Service
WSC – Water Survey of Canada

Figure 5. Location of water level gauges used for model calibration

Observed and modelled hourly water levels between May 25th and June 25th 2012 at New Westminster and Port Mann Pump Station are compared in **Figure 6**. The results indicate good agreement between observed and modelled water levels at the two stations. The model reproduced the tidal range variability from spring to neap tidal cycles and the daily high and low waters level elevations. The root-mean-squared error (RMS) values between predicted and modelled water levels at Port Mann Pump Station and New Westminster are 0.19 m and 0.14 m respectively. Since flow rates are not measured at Port Mann, the model inflow was obtained from predictions using NHC's Fraser River Mike11 model (NHC, 2008). There are uncertainties associated with estimating the tributary flows entering the Fraser River between Hope and Port Mann. Despite this limitation the results show that the observed and modelled water levels at the two stations generally agree.

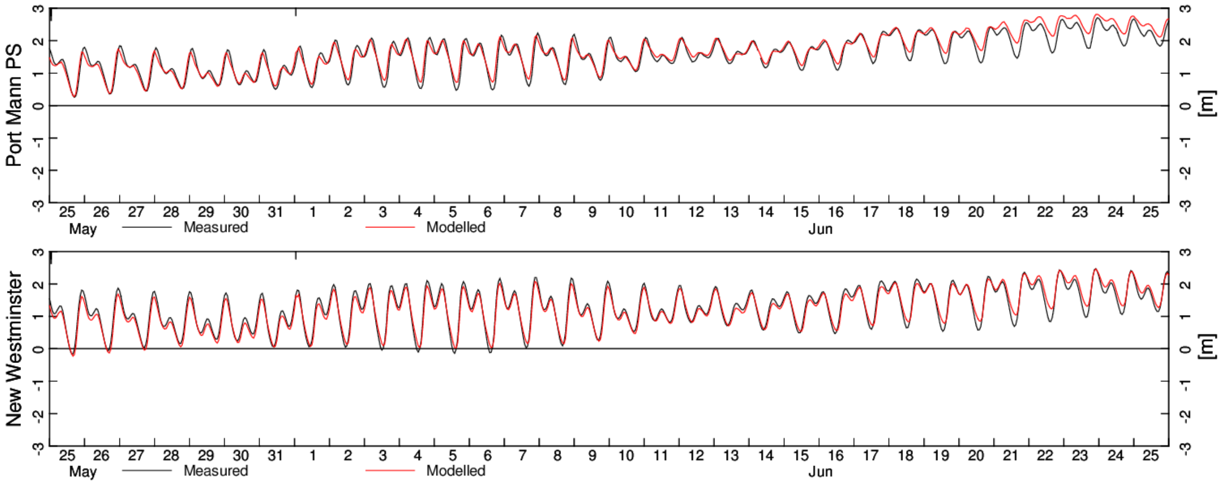


Figure 6. Observed and computed water levels – May 25th to June 25th, 2012

2.3.2 Velocity

An ADCP survey was conducted on June 15, 2016 near Pattullo Bridge along several transects (**Figure 7**). The Fraser river flow varied between 7,680 and 8,070 m^3/s and the water level at New Westminster varied between 0.11 m and 0.57 m.

Velocity measurements from the ADCP survey were used to confirm model's ability to reproduce velocity distribution across the river channels (**Figure 9**). At each transect, the three-dimensional ADCP velocity measurements were depth-averaged over the water column. Depth-averaged transverse velocity profiles were extracted from the model results at the same locations and times as the ADCP measurements. The measured and computed velocities generally compared well, with the model tending to slightly under-predict velocities. The underestimate in velocity is likely a result of the underestimation in discharge imposed at the upstream boundary, predicted by the MIKE11 model as discussed in **Section 2.2.1**.

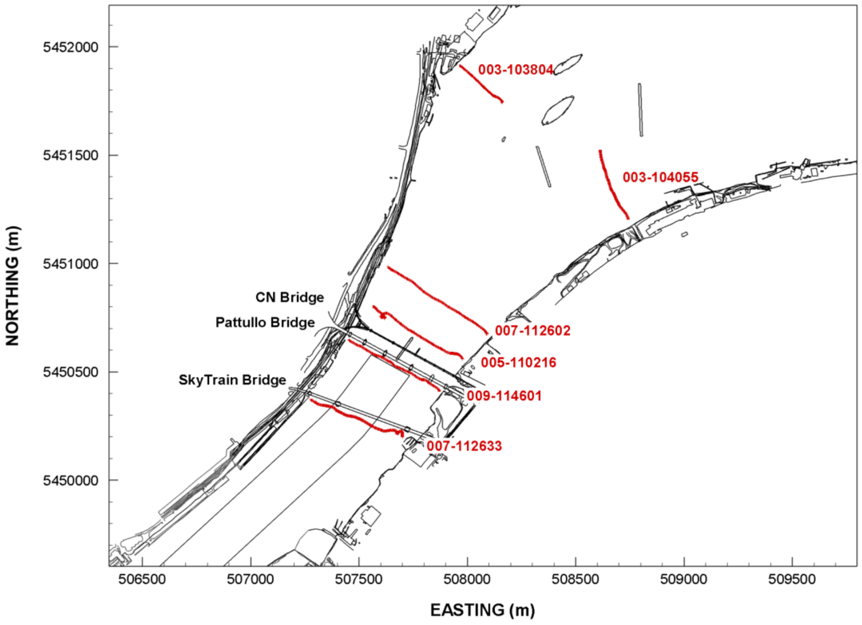


Figure 7. June 15, 2016 ADCP transect locations

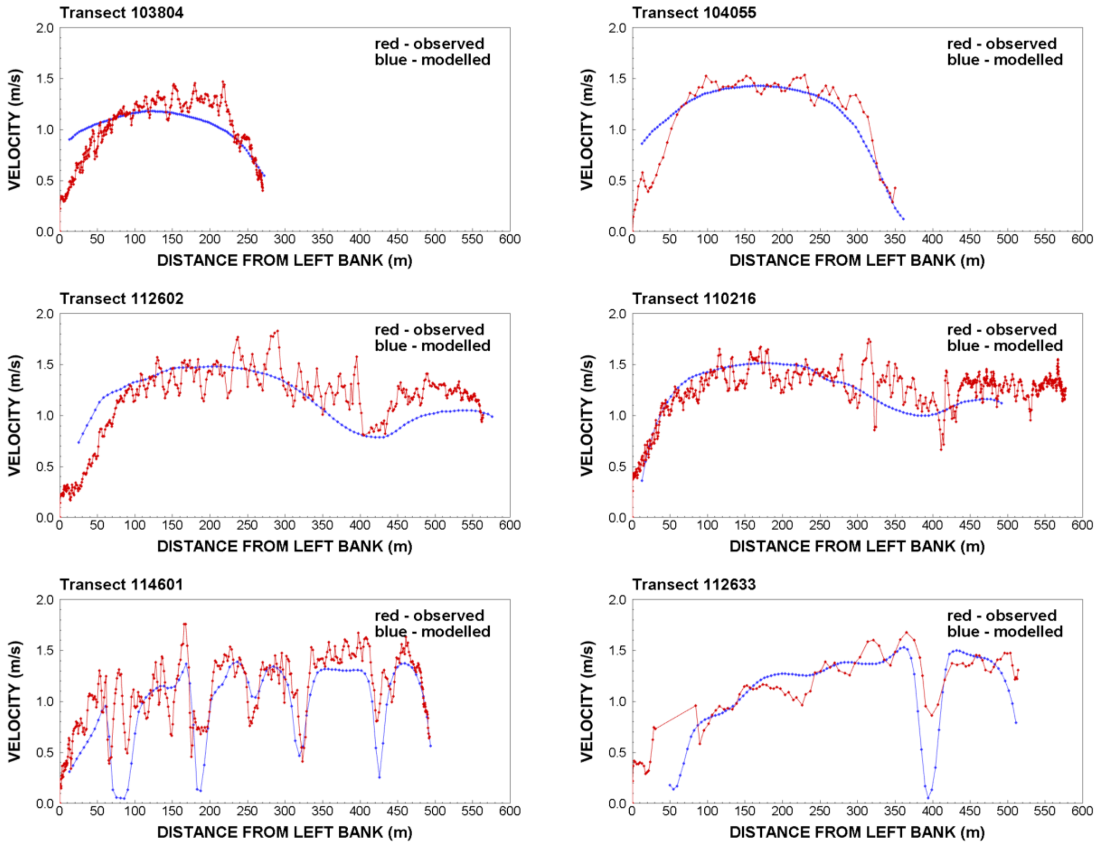


Figure 8. **Modelled and observed velocity comparison**

2.3.3 Flow Split

Flow splits occur upstream and downstream of Pattullo Bridge. At the upstream end, the Sapperton V-dyke bifurcates the flow into Queens Reach and Sapperton Reach. At the downstream end, a series of structures at New Westminster trifurcates the upstream into North Arm, Annacis Channel and South Arm. ADCP transects were also conducted on June 15th and used to confirm model's ability to compute the distribution of flow at trifurcation. Measured and computed flow splits are compared in the table below.

Table 2. **Modelled and measured flow split at Sapperton V-Dyke – June 15, 2016**

	Queens Reach	Sapperton Channel
Measured	70%	30%
Modelled	68%	32%
Difference	2%	-2%

Table 3. **Modelled and measured flow split at trifurcation – June 15, 2016**

	North Arm	Annacis Channel	South Arm
Measured	12%	10%	78%
Modelled	11%	9%	80%
Difference	1%	1%	-2%

The results show that there is good agreement between measured and computed flow splits at Sapperton V-dyke and at New Westminster Trifurcation. The flow split results confirm that the model accurately distributes the flow around islands and training structures in the system.

2.3.4 Sediment Transport

The coupled hydrodynamic–morphodynamic model results were compared to observed datasets to validate the morphodynamic component of the model. The morphodynamic model validation includes comparing the modelled results to measured sediment loads, sedimentation patterns, and shoaling rates on the lower Fraser River.

Sediment loads on the lower Fraser River were measured by Water Survey of Canada (WSC) at Hope, Agassiz, Mission, and Port Mann during the period 1965 to 1986. Based on that data, the bed material load at Mission averaged 2.9 million tonnes/year, and ranged from 1.2 million to 8.9 million tonnes/year (NHC, 2002).

Modelled sediment input over the course of the freshet period (May 26 to July 27) was 3.7 million tonnes. This value is larger than the long-term average bed material load of 2.9 million tonnes/year and falls within the 1.2 million to 8.9 million tonnes/year range. The 2012 freshet was a large event with a return period of about 20 years at Hope (WSC gauge 08MF005) and would have had a higher than average sediment load. The year 1976 has comparable freshet characteristics as 2012 as shown **Figure** 9. The estimated bed material load for 1976 is 5.1 million tonnes (NHC, 2002) which is higher than the modelled sediment input for the 2012 freshet. One factor that could account for this difference is because the flows during the falling limb of the 1976 freshet remained greater than 6,000 m^3/s for a longer period of time than during 2012. Under controlled laboratory studies the van Rijn sediment transport equation typically ranged from 0.5 to 2.0 times the observed sediment loads. Given the more complex physical setting on the Fraser River and the inherent errors in measuring bed material load, the agreement is better than might be normally expected.

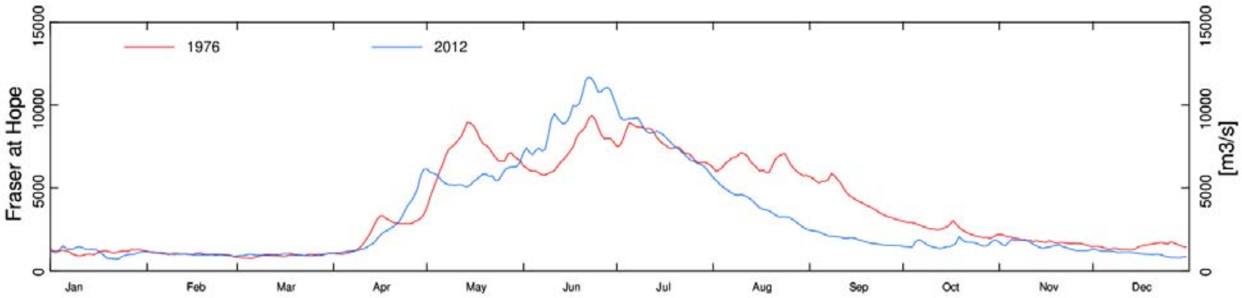


Figure 9. Fraser River daily discharge at Hope (WSC 08MF005) for the years 1976 and 2012

2.3.5 Bed Level Changes

The model was validated by comparing observed sedimentation patterns on the lower Fraser River. The validation run began with 2014 PWGSC bathymetry (conditions as of March 2014) and used the 2012 freshet hydrograph. **Figure 10** shows the modelled sedimentation pattern from the Fraser River model at the end of the simulation period under the existing conditions. The blue shading indicates regions of scour and yellow and red shadings represent regions of deposition. Another approach undertaken to validate the morphodynamic model is through examining the shoaling rate in the system. Accurate shoaling rates for the lower Fraser River are expensive and time consuming to determine because of the necessity to conduct hydrographic surveys on a regular basis over an extended period of time. When no data on shoaling rates are available, it may be possible to substitute with dredge records. However, comparing the modelled dredge volume with the available dredge record from the Port of Vancouver (PV) can be problematic. The PV data are based on the dredging activity that takes place over the course of the standard calendar year (January to December), whereas the modelled dredge volume accounts for the volume required to be removed from the river in order to meet the design grade over the course of the dredging year (mid-June to mid-March). Spot dredging also takes place over the course of the freshet to keep the channel safe, but is not accounted for in the model simulation.

Despite the difficulties inherent in comparing the model results with the dredge record, the comparison is useful; if the model's sediment transport module is producing valid results, the modelled volume of sediment deposited in the navigation channel should be similar to the required maintenance dredging volume. Comparison of modelled and actual dredging volumes in St. Mungo's Bend and Annieville Channel is shown in **Table 4**. Required maintenance dredging volume was computed by comparing the bed surface elevation at the end of the model simulation to the dredge design grade. The modelled maintenance dredging volume[1] for 2012 was similar, providing confidence that the model adequately captures the sediment dynamics in the system.

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[1] The current deep-sea shipping channel in the Fraser River is designed to accommodate vessels with a maximum draught of 11.5 m. Required maintenance dredging volume is computed by comparing the bed surface elevation at the end of the simulation to the design grade - the minimum dredge depth that allows an 11.5 m draft vessel to safely transit under the lowest high tide. If the modelled bed surface elevation is shallower than the design grade, then dredging is required.

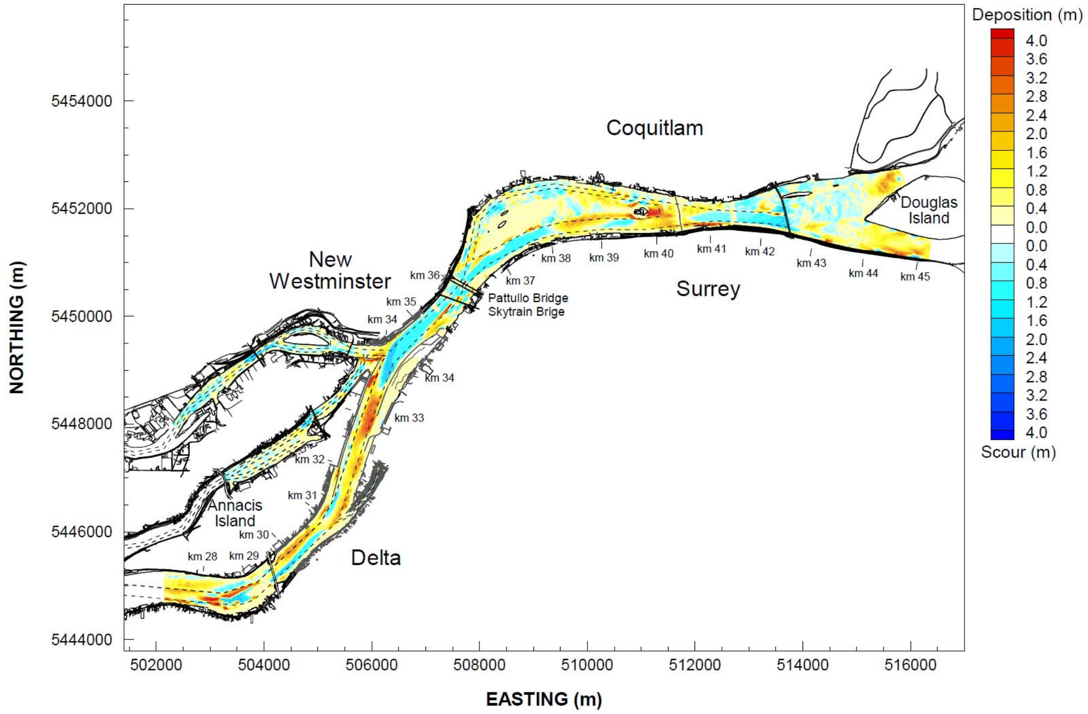

Figure 10. Predicted sedimentation pattern – existing conditions

A sensitivity analysis was conducted to evaluate the effect of selected model sediment size on predicted maintenance dredging volume. Bed material D_{50} of 0.32 mm resulted in the best match with the reported maintenance dredging volume.

The hindcast sedimentation pattern shows a reasonable agreement with the established deposition regions in the lower Fraser River which requires annual dredging, including deposition on the outer bank of St. Mungo's Bend between km 27 to km 30, and deposition at the Fraser Surrey Dock at km 33.

Table 4. Maintenance dredging volume

Reach	Km	Dredge record (m^3)	Modelled (m^3)	Difference (m^3)
St. Mungo's Bend	27 to 29	176,900	210,200	33,300
Annieville Channel	32 to 34	567,200	605,800	38,600
Total	-	744,100	816,000	71,900

3 MODELLING ANALYSIS

3.1 Model Scenarios

Three scenarios were modelled for the analysis:

1. Existing conditions
    - existing Pattullo, NWR and Skytrain bridge piers

2. Reference Concept
    - Reference Concept piers plus existing Pattullo, NWR and Skytrain bridge piers

3. Decommissioning
    - Reference Concept plus existing NWR and Skytrain bridge piers. Pattullo bridge instream piers were removed and the riprap cones were truncated to El. -10 m in the secondary navigation channel, and to El. -14.35 m in the primary navigation channel. In practice this resulted in removal of Piers 2 – 6 and truncation of the riprap at Pier 4 to El. -14.35; other pier protection was below the maximum elevation or outside the navigation channels.

The model meshes near Pattullo Bridge for the three geometries are shown the figures below.

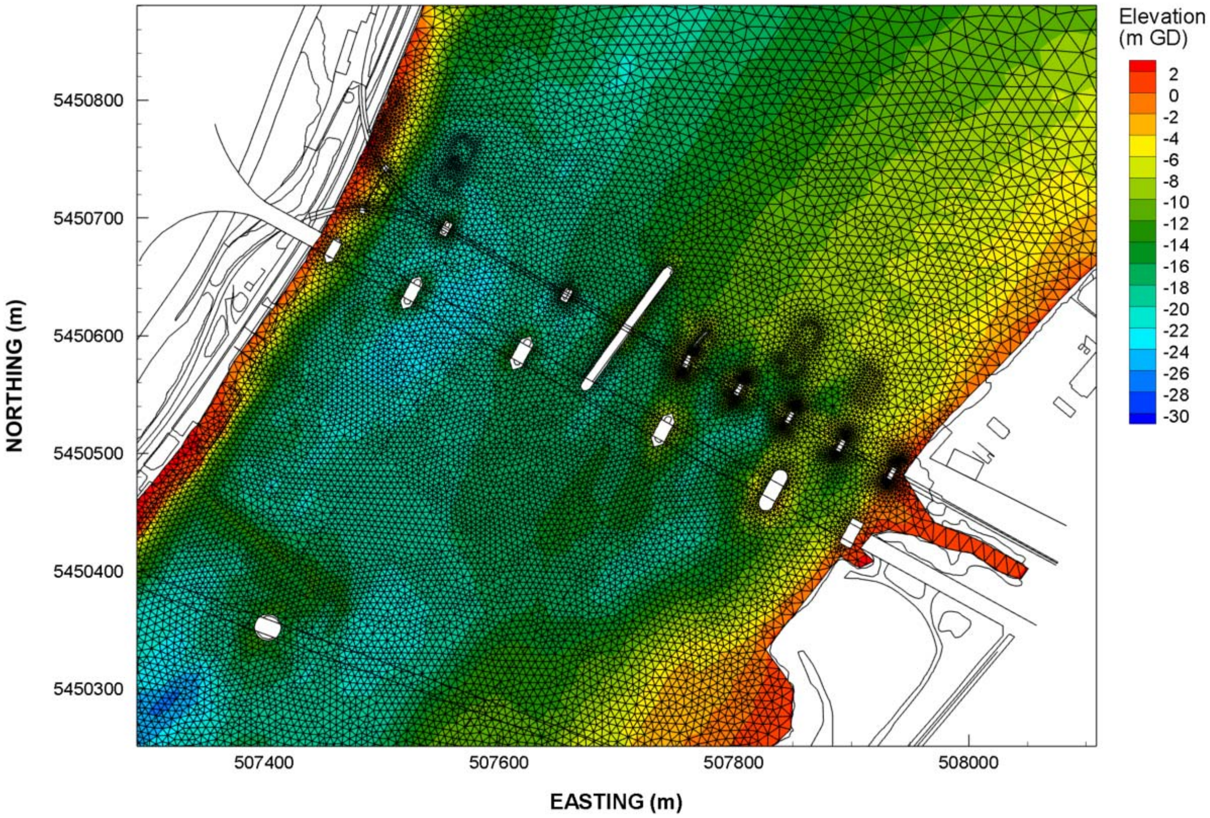

Figure 11. Existing conditions mesh

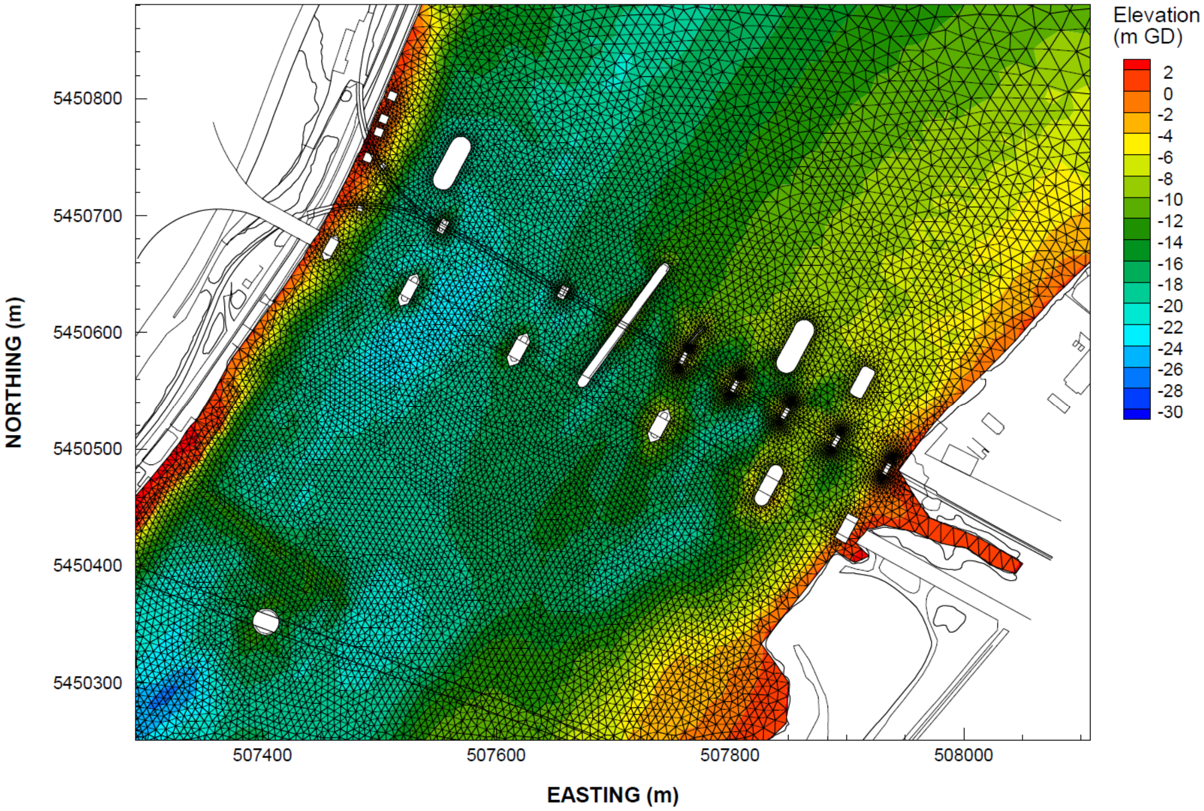

Figure 12. **Reference Concept mesh**

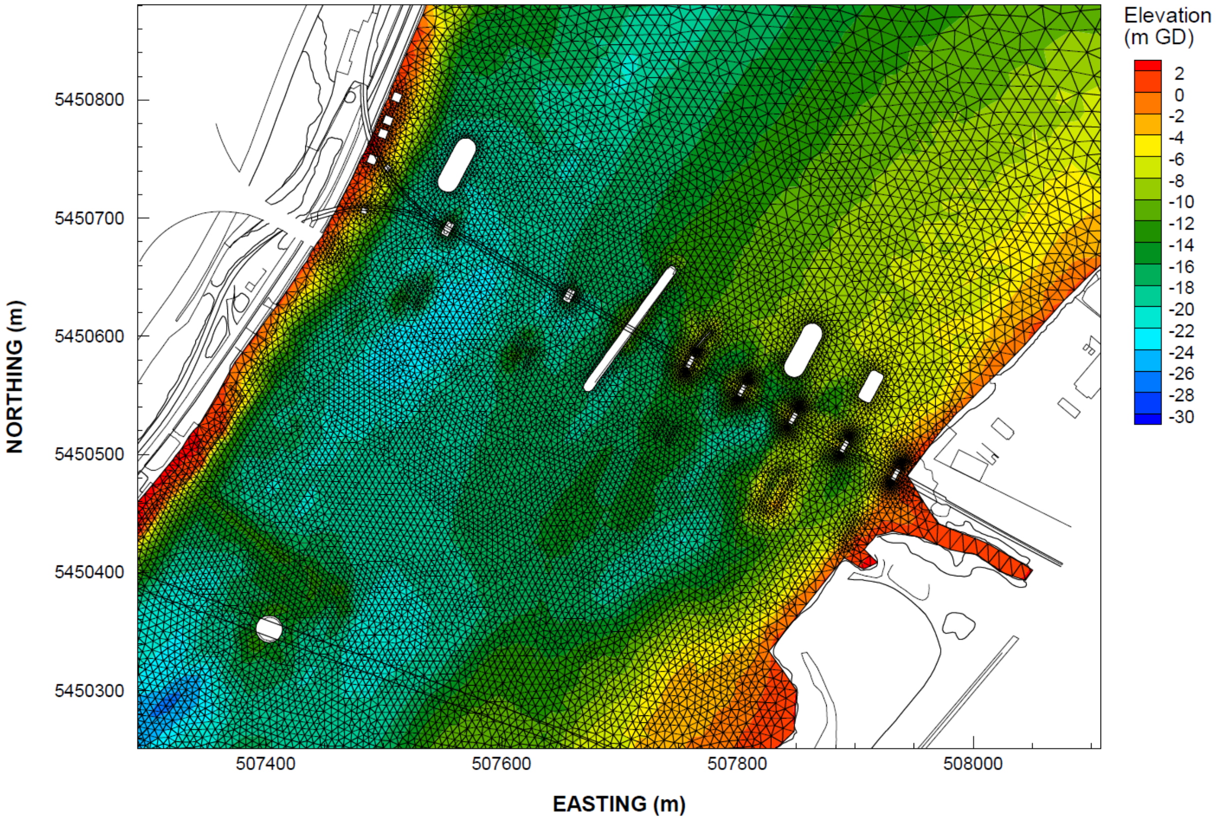

Figure 13. Decommissioning mesh

3.2 Model Results- Hydrodynamic Analysis

To evaluate the potential hydraulic and sedimentation impact of Reference Concept and Decommissioning in the lower Fraser River, current distributions during the high discharge summer freshet period were first evaluated. **Figure 14**, **Figure 15** and **Figure 16** show the modelled depth-average velocity on June 25, 2012 when the river discharge Port Mann Bridge was about 12,000 m^3/s. The contour colouring indicates the flow velocity.

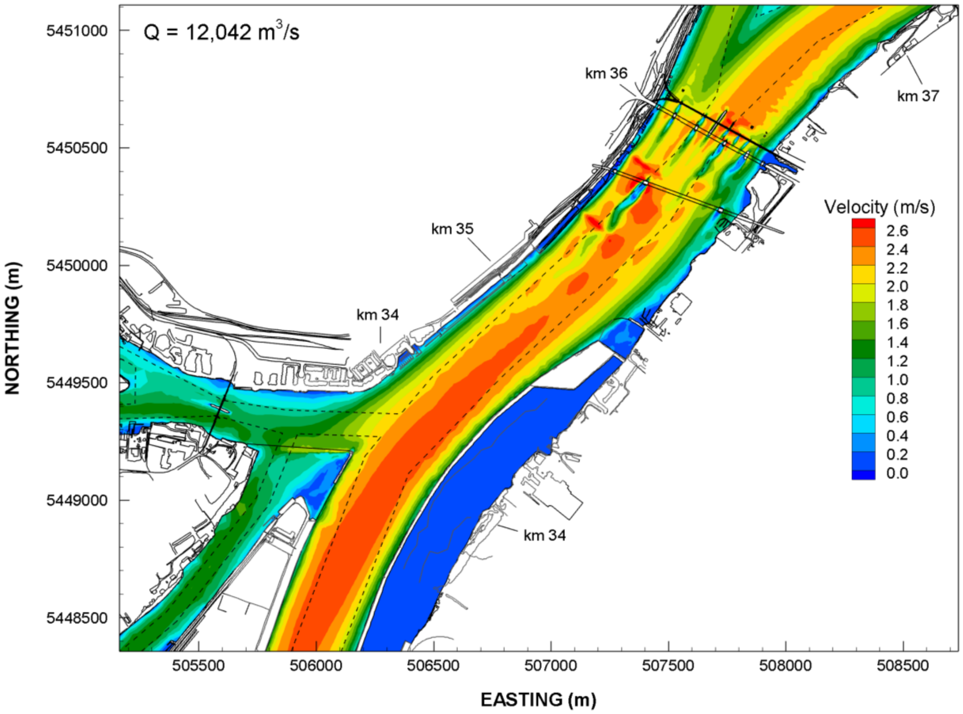

Figure 14. Depth-average speed distribution – Existing conditions

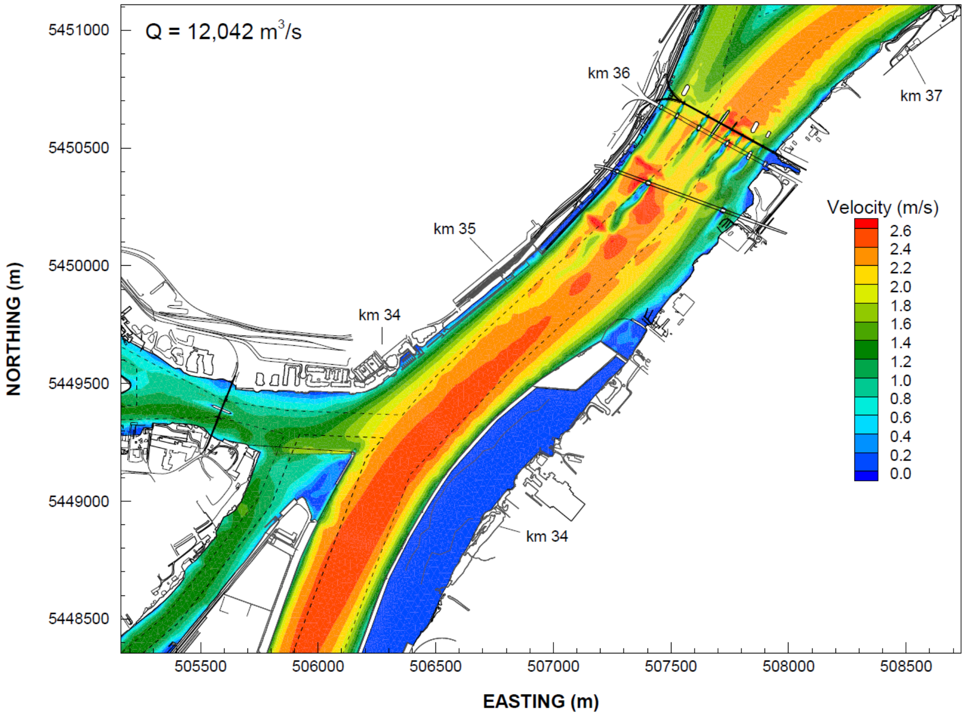

Figure 15. **Depth-average speed distribution – Reference concept**

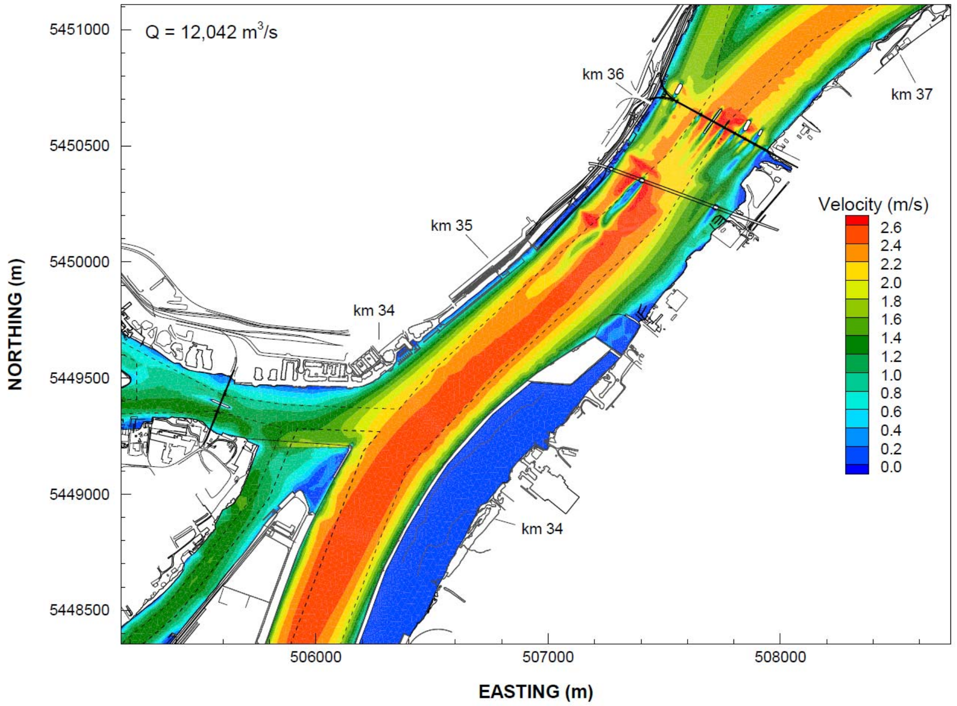

Figure 16. **Depth-average speed distribution – Decommissioning**

To better visualize the difference between the existing conditions and the two proposed conditions, velocity difference maps were prepared and presented in **Figure 17** (Reference Concept minus existing conditions) and **Figure 18** (Decommissioning minus existing conditions). The yellow and red shading indicates regions experiencing velocity increase under the proposed conditions and the blue shadings represent regions experiencing velocity decrease.

The figures show that with the Reference Concept and Pattullo Bridge in place:

- Small increases in velocity are expected between the new bridge piers and across most of the NWR Bridge alignment. This is a result of reduction in cross-sectional flow area at the bridge crossings.

- Small reductions in velocities are expected downstream of the Reference Concept piers.

- Velocities will increase near the south bank south of Pier S0, between Pattullo Piers 5 and 6, and extending down to the Skytrain Bridge alignment.

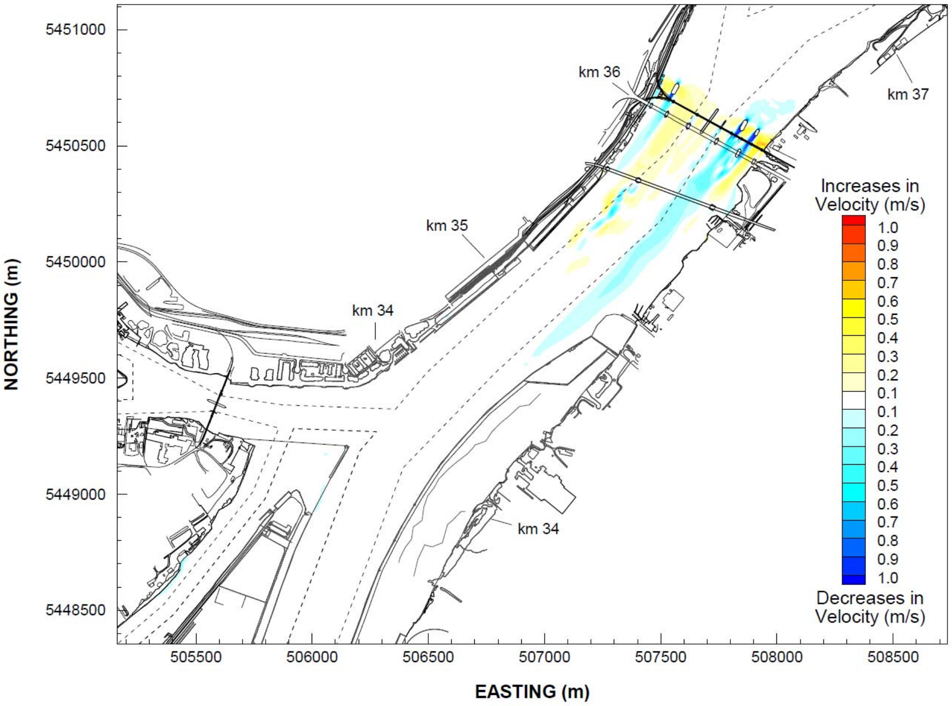

Figure 17. Difference in depth-average speed distribution – Reference Concept minus Existing Conditions

Following decommissioning of the Pattullo Bridge:

- The increase in cross-sectional flow area downstream of NWR will result in lower velocities.
- The low velocity regions behind where Pattullo Bridge piers will experience faster velocity with the bridge decommissioned.

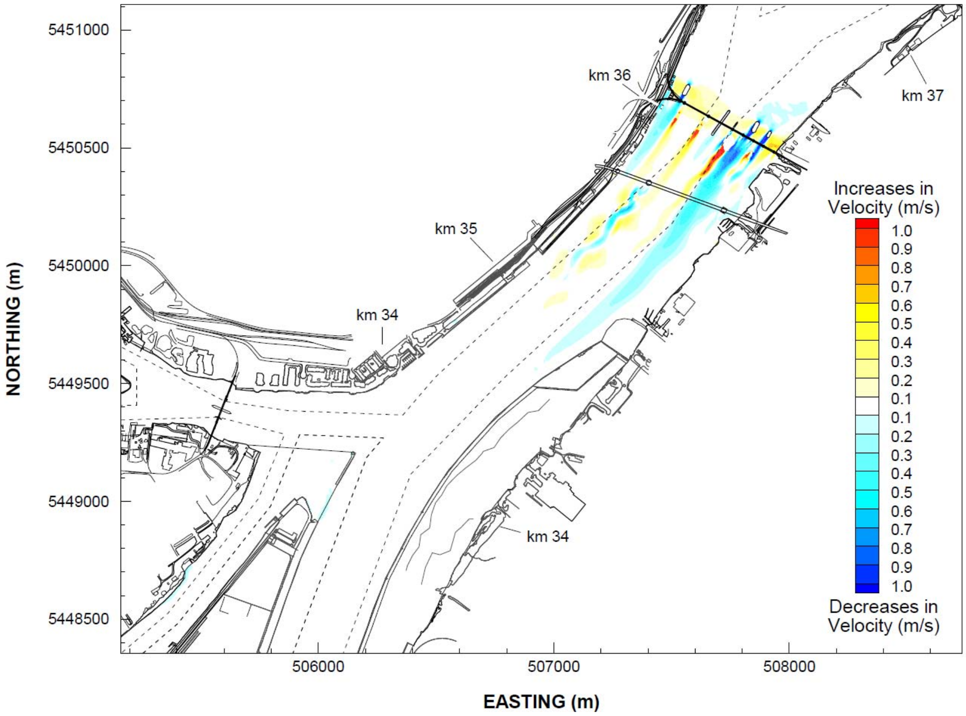

Figure 18. Difference in depth-average speed distribution – Decommissioning minus Existing Conditions

3.3 Model Results - Sedimentation Analysis

3.3.1 Overview

The sedimentation analysis involved simulating the Reference Concept scenario (with the existing Pattullo Bridge still in-place and the scenario of the Reference Concept with the existing Pattullo Bridge decommissioned. The simulations were made for the 2012 freshet period. Results from these runs are summarized in **Figure 19** and **Figure 20**, respectively. These results were then compared with the simulation of the existing conditions (shown in Figure 10). Bed level difference maps were prepared to illustrate the apparent changes at the end of the 2012 freshet. These plots are summarized in **Figure 21** and **Figure 22** respectively. Areas shaded blue indicate regions of scour and yellow and red shadings represent regions of deposition. It should be noted that the changes are representative of conditions for a 2012 freshet, which is a relatively large event (20-year return period). The actual pattern and magnitude of bed changes will be affected by the freshet size and duration of high water.

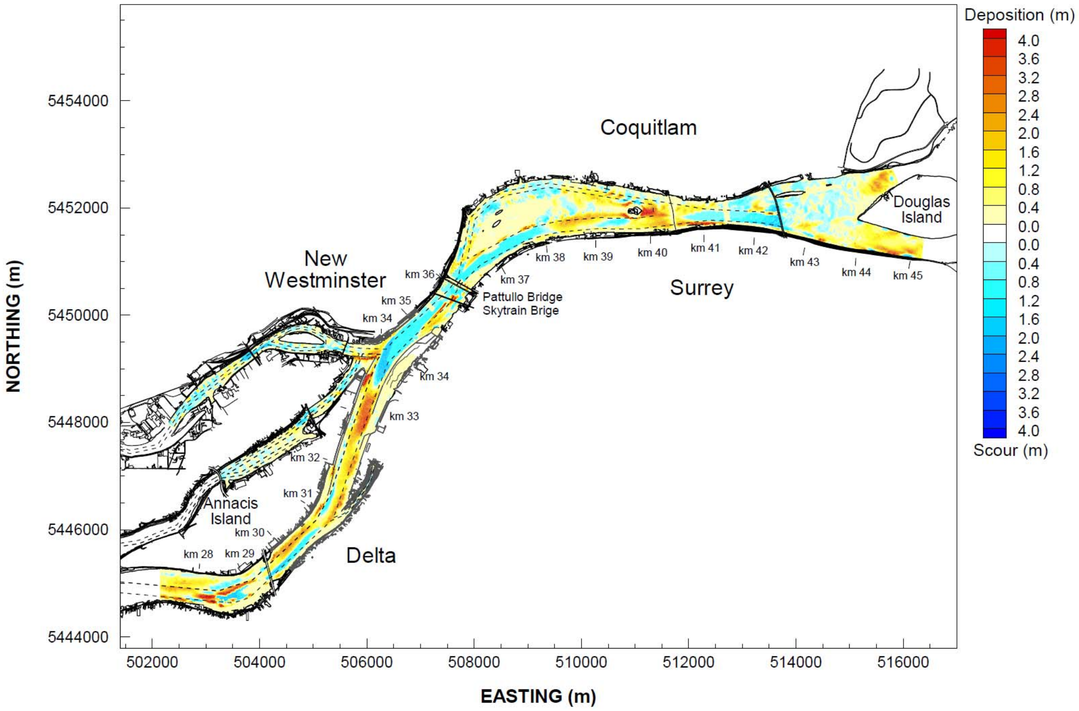

Figure 19. **Sedimentation pattern after 2012 freshet - Reference Concept**

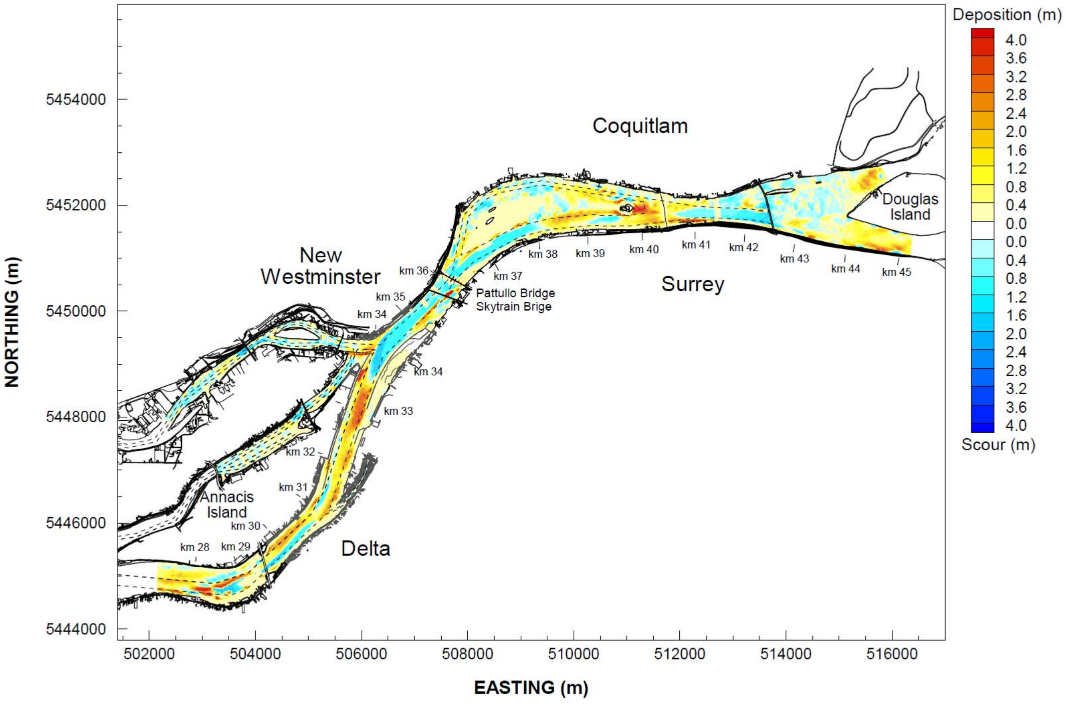

Figure 20. **Sedimentation pattern after 2012 freshet – Reference Concept with existing Pattullo Bridge decommissioned**

3.3.2 Effects of the Reference Concept Piers

A bed difference map (**Figure 21**) was prepared to visualize the effect of the Reference Concept piers on the sedimentation pattern. Bathymetry at the end of the existing conditions simulation was subtracted from the bathymetry at the end of the Reference Concept simulation. Positive values (represented by red shading) indicate that the bed elevation under the Reference Concept condition would be shallower than the bed elevation under existing conditions at the end of the freshet. Negative values (represented by blue shading) indicate that the bed elevation under the Reference Concept condition would be deeper than the bed elevation under existing conditions.

The results show that narrowing of the channel due to the Reference Bridge piers resulted in:

- 1-2 m of aggradation in the region upstream of the piers;
- 0.5 – 1.0 m of bed lowering in the main navigation channel upstream of the bridge crossings;
- about 1.5 m of bed lowering in the region between the South Tower and Pier S0;
- and about 1.0 m of bed lowering occurred between Pattullo Bridge Piers 5 and 6, extending upstream to between NWR Piers 9 and 10, and downstream for about 100 m.

The formation of low velocity regions behind the Reference Concept piers result in:

- 1 - 2 m of bed level aggradation downstream of the North Tower between the existing bridge and Skytrain bridge;
- 3-4 m of aggradation immediate downstream of the South Tower;
- 2 - 3 m of aggradation downstream of the South Tower between km 35 and km 36;
- and 1 - 2 m of aggradation downstream of Pier S0 between Pier S0 and existing bridge.

About 0.5 m of bed lowering is expected in the navigation channel downstream of the Skytrain Bridge. There is no notable difference in flow velocities here, so the bed lowering is believed to be a result of less available sediment due to the deposition along the margin of the navigation channel.

Bed lowering of 0.5 – 1.0 m near the upstream end of the Phase III Trifurcation Training Wall is expected to occur. This is a result of a sediment deficit caused by upstream deposition in the wake of the South Tower between km 35 and km 36.

At the New Westminster Trifurcation, the model showed about 0.5 m of bed lowering in Annieville Channel along the Annieville Dyke, and 0.5 - 1.0 m of lowering downstream of the sheet pile wall at the tip of Annacis Island. Lowering in these areas is believed to be a result of a sediment deficit due to the upstream deposition.

The impact to the area of interest are summarized in Table 5.

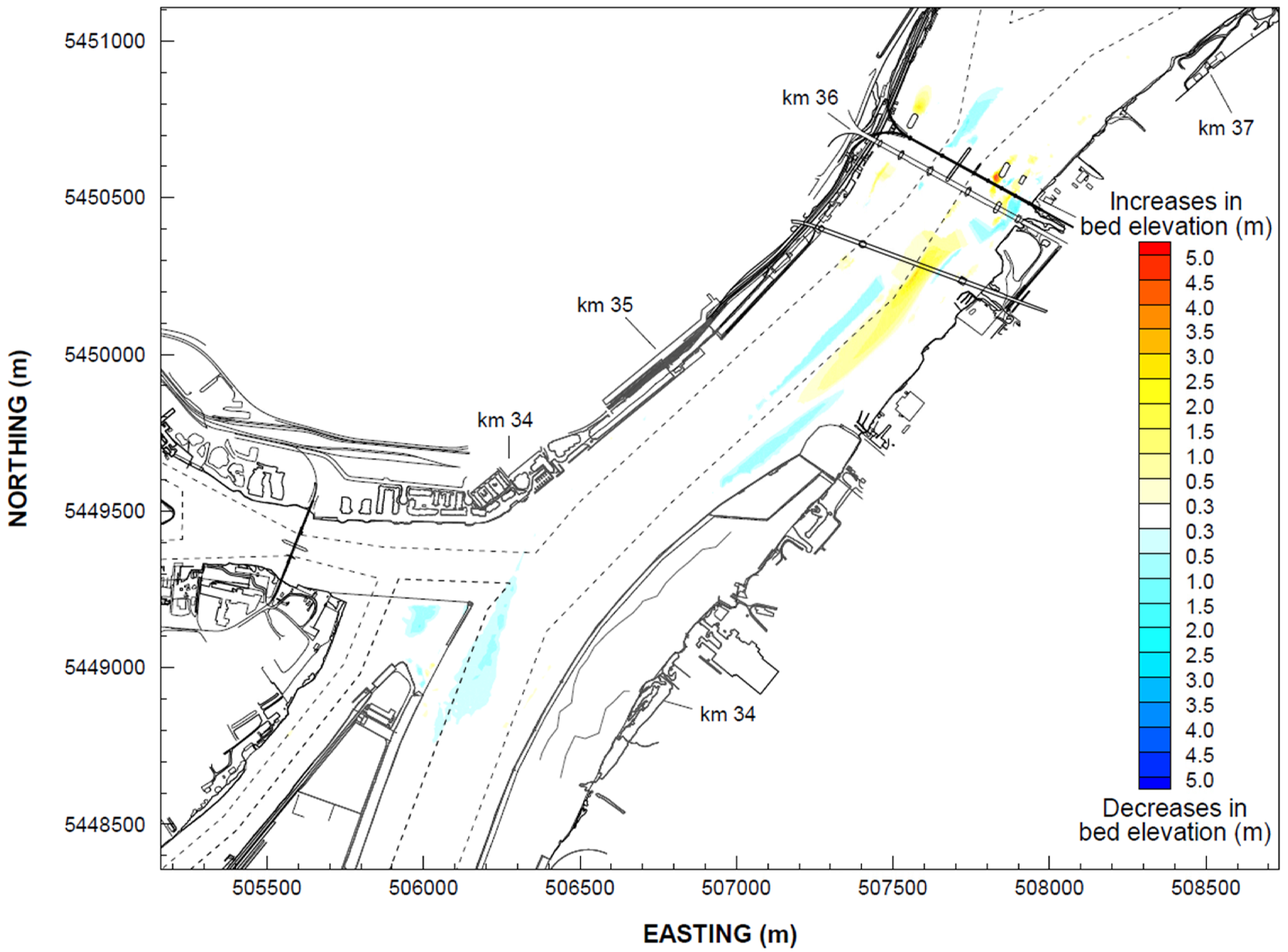

Figure 21. **Bed difference map – Reference Concept minus existing conditions**

3.3.3 Effects of Pattullo Bridge Decommissioning

A similar difference map (**Figure 22**) was prepared to examine the effects of the long term scenario with the Pattullo Bridge piers decommissioned. The bathymetry at the end of the existing conditions simulation was subtracted from the bathymetry at the end of the Decommissioning simulation.

Changes in river bed levels in the Decommissioning scenario were similar to the Reference Concept scenario, with a few following notable differences:

- Removal of the Pattullo piers and truncation of the riprap cone at Pier 4 eliminated the bed lowering that occurred between Piers 5 and 6 in the Reference Concept Scenario.
- Deposition downstream of the South Tower increased from 3-4 m in the Reference Concept scenario to 4-5 m with the Pattullo Bridge decommissioned. The extent of the deposition area also increased from 25 m x 200 m to about 75 m x 225 m. This is believed to be due to the removal of Piers 4, 5 and lowering of the riprap cone around this pier. With the piers and riprap in place, flow accelerates around the riprap mound; after decommissioning this flow acceleration is reduced, allowing more of the sediment in the water column to deposit closer to the crossing.
- Further downstream the deposition in the wake of the South Tower is attenuated to approximately 1 m, but encroaches slightly into the navigation channel.
- The elimination of low velocity regions behind the existing bridge piers resulted in bed lowering of 1 – 2 m in the main navigation channel downstream of Pier 4.
- Bed lowering around the flow splitter at the upstream end of Annacis Island was reduced under the Decommissioning scenario.
- About 0.5 m of aggradation is predicted in the navigation channel in Annieville Channel around km 34.

The Port of Vancouver (POV) identified areas of interest in regards to hydrotechnical effects of the project. The effects of the Project on these areas are summarized in **Table 6**.

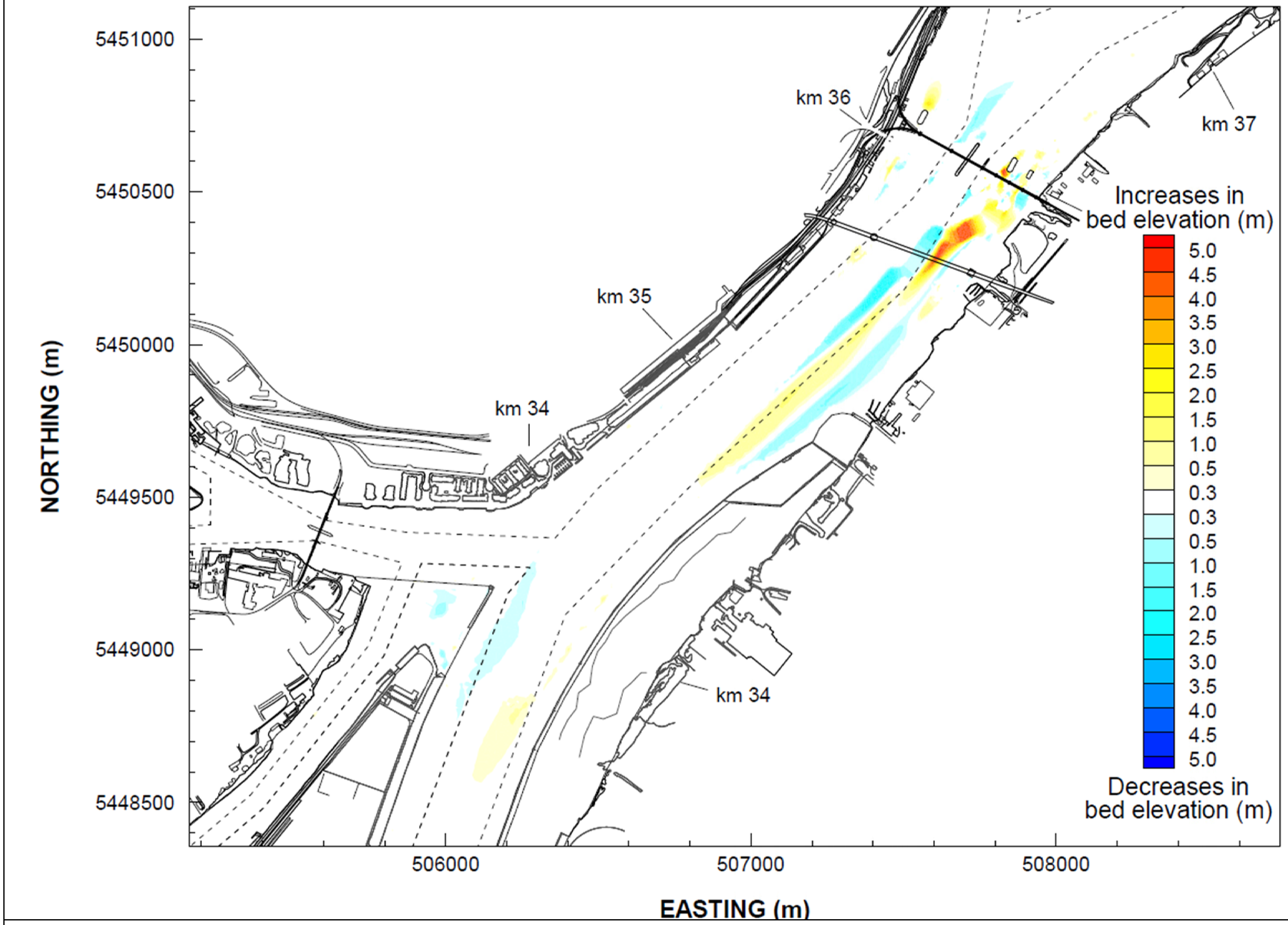

Figure 22. **Bed difference map – Decommissioning minus existing conditions**

Table 5. Modelled morphological changes at sites of interest for Reference Concept scenario.

No.	ID	Type	Site/Area	Expected Bed Level Changes
1	FRMA-1	Navigation Channel - Main	Main Navigation Channel - Near Bridge	▪ 0.5 – 1 m lowering upstream of the Reference Concept alignment ▪ 0.5 - 1 m lowering downstream of Skytrain Bridge
2	FRMA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Near Bridge	none
3	FRMA-3	Navigation Channel - Main	Main Navigation Channel - Queens Reach	none
4	FRMA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Sapperton Channel	none
5	FRMA-11	Infrastructure	Existing Pattullo Bridge Piers (during construction phase)	▪ about 1 m lowering between Pattullo Piers 5 and 6 ▪ about 1 m aggradation downstream between Piers 1 and 2 ▪ 2-3 m aggradation downstream of Pier 4 between Skytrain piers
6	FRMA-12	Infrastructure	NWR Bridge Piers	▪ about 1.5 m lowering upstream of NWR Pier 8 ▪ 0.5 – 1 m lowering between NWR Piers 9-10 ▪ 3-4 m aggradation between NWR Piers 7-9 and downstream of Ref Concept South Tower
7	FRMA-13	Infrastructure	Skybridge Piers	2-3 m aggradation between Skytrain piers downstream of Pattullo Pier 4
8	FRMA-14	Infrastructure	Sapperton V-Dyke	none

9	FRMA-15	Infrastructure	Sapperton Wing Walls	none
10	FRMA-16	Infrastructure	New West Board Walk	none
11	FRMA-17	Infrastructure	New West Submerged Weir 1	none
12	FRMA-18	Infrastructure	New West Submerged Weir 2	none
13	FRMA-19	Tenant	Valley Towing Site	none
14	FRMA-20	Tenant	Amix Sites (Upriver and Downriver of Bridge)	none
15	FRMA-21	Tenant	Schnitzer	none
16	FRMA-22	Tenant	Lehigh Hanson	none
17	FRMA-23	Tenant	Seaspan Barge Tie-Up	none
18	FRMA-24	Tenant	Mill & Timber Site	none
19	FRMA-25	Tenant	Harken Log Storage Areas	none
20	FRMA-26	Tenant	Cathedral Ventures Basin	none
21	FRMA-27	Infrastructure	Transmountain Pipeline	none
22	FRMA-28	Infrastructure	Gas Pipeline	none
23	FRMA-30	Infrastructure	Metro Vancouver Utilities - Port Mann	none
24	FRNA-1	Navigation Channel - Secondary	Secondary Navigation Channel - North Arm	none
25	FRNA-11	Infrastructure	MV Utilities - Annacis Main # 3	none
26	FRNA-12	Infrastructure	MV Utilities - Annacis Main # 3	none
27	FRNA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Poplar Channel	none
28	FRNA-29	Infrastructure	Metro Vancouver Utilities - Downriver of Queensborough Rail Bridge	none
29	FRNA-30	Infrastructure	Metro Vancouver Utilities - Upriver of Queensborough Rail Bridge	none
30	FRSA-1	Navigation Channel - Main	Main Navigation Channel - Annieville Channel	none
31	FRSA-2	Deep-Sea Berth & Approach	Fraser Surrey Docks - Upriver Berths	none

32	FRSA-3	Deep-Sea Berth & Approach	Fraser Surrey Docks - Downriver Berths	none
33	FRSA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Annacis Channel	none
34	FRSA-4	Deep-Sea Berth & Approach	WWL - Berths	none
35	FRSA-11	Infrastructure	Trifurcation Phase 1 Wall	none
36	FRSA-12	Infrastructure	Trifurcation Phase 2 Wall	none
37	FRSA-13	Infrastructure	Trifurcation Phase 3 Wall	about 0.5 m lowering near Trifurcation Phase 3 wall, between Harken log storage areas and Skybridge Piers
38	FRSA-14	Infrastructure	Flow Splitter	▪ about 0.5 m lowering upstream of flow splitter ▪ 0.5 – 1 m lowering downstream of flow splitter
39	FRSA-15	Tenant	Annacis Marine Base	none
40	FRSA-16	Infrastructure	MV Utilities - Annacis Main # 2	none
41	FRSA-17	Infrastructure	MV Utilities - Annacis Main # 3	none
42	ZCCG-1	Infrastructure	CCG Nav Aids (Upriver and Downriver of Bridge)	none

Table 6. Modelled morphological changes at sites of interest for Decommissioning scenario.

No.	ID	Type	Site/Area	Expected Bed Level Changes
1	FRMA-1	Navigation Channel - Main	Main Navigation Channel - Near Bridge	▪ 0.5 – 1 m lowering upstream of the Reference Concept alignment ▪ 1.5 - 2 m lowering downstream of Skytrain Bridge ▪ about 1 m aggradation along margin of navigation channel between Harken log storage and Skytrain Bridge ▪ about 0.3 m aggradation along Trifurcation Phase 3 wall at km 34.
2	FRMA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Near Bridge	none
3	FRMA-3	Navigation Channel - Main	Main Navigation Channel - Queens Reach	none
4	FRMA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Sapperton Channel	none
5	FRMA-11	Infrastructure	Existing Pattullo Bridge Piers (during construction phase)	▪ 2 m aggradation downstream between Piers 1 and 2 ▪ 4-5 m aggradation downstream of Pier 4 between Skytrain piers
6	FRMA-12	Infrastructure	NWR Bridge Piers	▪ about 1.5 m lowering upstream and downstream of NWR Pier 8 ▪ 1 m lowering between NWR Piers 9-10

				▪ 4-5 m aggradation between NWR Piers 7-9 and downstream of Ref Concept South Tower
7	FRMA-13	Infrastructure	Skybridge Piers	4-5 m aggradation between Skytrain piers downstream of Pattullo Pier 4
8	FRMA-14	Infrastructure	Sapperton V-Dyke	none
9	FRMA-15	Infrastructure	Sapperton Wing Walls	none
10	FRMA-16	Infrastructure	New West Board Walk	none
11	FRMA-17	Infrastructure	New West Submerged Weir 1	none
12	FRMA-18	Infrastructure	New West Submerged Weir 2	none
13	FRMA-19	Tenant	Valley Towing Site	none
14	FRMA-20	Tenant	Amix Sites (Upriver and Downriver of Bridge)	none
15	FRMA-21	Tenant	Schnitzer	none
16	FRMA-22	Tenant	Lehigh Hanson	none
17	FRMA-23	Tenant	Seaspan Barge Tie-Up	none
18	FRMA-24	Tenant	Mill & Timber Site	none
19	FRMA-25	Tenant	Harken Log Storage Areas	none
20	FRMA-26	Tenant	Cathedral Ventures Basin	none
21	FRMA-27	Infrastructure	Transmountain Pipeline	none
22	FRMA-28	Infrastructure	Gas Pipeline	none
23	FRMA-30	Infrastructure	Metro Vancouver Utilities - Port Mann	none
24	FRNA-1	Navigation Channel - Secondary	Secondary Navigation Channel - North Arm	none
25	FRNA-11	Infrastructure	MV Utilities - Annacis Main # 3	none
26	FRNA-12	Infrastructure	MV Utilities - Annacis Main # 3	none
27	FRNA-2	Navigation Channel - Secondary	Secondary Navigation Channel - Poplar Channel	none

28	FRNA-29	Infrastructure	Metro Vancouver Utilities - Downriver of Queensborough Rail Bridge	none
29	FRNA-30	Infrastructure	Metro Vancouver Utilities - Upriver of Queensborough Rail Bridge	none
30	FRSA-1	Navigation Channel - Main	Main Navigation Channel - Annieville Channel	none
31	FRSA-2	Deep-Sea Berth & Approach	Fraser Surrey Docks - Upriver Berths	none
32	FRSA-3	Deep-Sea Berth & Approach	Fraser Surrey Docks - Downriver Berths	none
33	FRSA-4	Navigation Channel - Secondary	Secondary Navigation Channel - Annacis Channel	none
34	FRSA-4	Deep-Sea Berth & Approach	WWL - Berths	none
35	FRSA-11	Infrastructure	Trifurcation Phase 1 Wall	none
36	FRSA-12	Infrastructure	Trifurcation Phase 2 Wall	none
37	FRSA-13	Infrastructure	Trifurcation Phase 3 Wall	▪ 1 m lowering near Trifurcation Phase 3 wall, between Harken log storage areas and Skytrain Bridge
38	FRSA-14	Infrastructure	Flow Splitter	▪ about 0.3 m lowering upstream of flow splitter ▪ about 0.5 m lowering downstream of flow splitter
39	FRSA-15	Tenant	Annacis Marine Base	none
40	FRSA-16	Infrastructure	MV Utilities - Annacis Main # 2	none
41	FRSA-17	Infrastructure	MV Utilities - Annacis Main # 3	none
42	ZCCG-1	Infrastructure	CCG Nav Aids (Upriver and Downriver of Bridge)	none

4 CONCLUSIONS

We evaluated potential changes in sedimentation patterns associated with the Project using the TELEMAC SYSTEM, a 3-dimensional morphodynamic model. Three scenarios were modelled for the analysis, including existing conditions, the Reference Concept, and a Decommissioning scenario. The existing conditions includes the existing Pattullo, NWR and Skytrain bridge piers. The Reference Concept scenario incorporates these existing piers plus the proposed Reference Concept piers. The Decommissioning scenario includes the proposed new piers, existing NWR and Skytrain Bridge piers; the Pattullo bridge instream piers were removed and the riprap cones were truncated to El. -10 m in the secondary navigation channel, and to El. -14.35 m in the primary navigation channel.

The model results indicate that changes to sedimentation process due to the construction of the Reference Concept piers and decommissioning of the existing Pattullo Bridge will be mostly confined within one kilometre downstream of the Pattullo Bridge. For the most part, the changes are within the range of natural variability in the river bed at the Project site. Bed lowering is expected near the south bank between Pattullo Piers 5 and 6. Significant deposition is expected on the margins of the navigation downstream of the South Tower. Sedimentation changes in the Reference Concept scenario are believed to result from increased velocities at the bridge crossings due to reduction in cross-sectional flow area, and formation of low velocity regions behind the Reference Concept piers.

Riverbed changes in the Decommissioning scenario were generally similar to the Reference Concept scenario, with some notable differences. Bed lowering in the area between Pattullo Piers 5 and 6 was eliminated. Deposition downstream of the South Tower increased to a maximum of 4-5 m, and further downstream the deposition of about 1 m encroached slightly into the navigation channel. A small amount of deposition occurred in the navigation channel in Annieville Channel. Sedimentation changes due to the Decommissioning conditions were believed to be due to increased velocities at the bridge crossings, reduced in velocities where the existing Pattullo Bridge piers are located, and increased velocity in the region behind where the existing Pattullo Bridge piers were located.

The predicted changes are representative of a relatively large flood, having a return period of 20 years (at Hope). The magnitude of bed level changes will be affected by the peak freshet flow and the duration of highwater.

5 REFERENCES

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APPENDIX C: PHYSICAL MODEL

1 INTRODUCTION

1.1 Model Objectives

A comprehensive physical hydraulic model, integrating the key elements at the project site, was constructed for use as a hydraulic design-aid tool. The objective of the physical model study was to evaluate near-field effects of the Project on river hydraulics and morphology at the crossing. Potential effects include changes to flow distribution, scour at the existing and proposed bridges, de-stabilization of the bed slope between New Westminster Rail and Pattullo bridges, velocity and flow pattern changes affecting navigation, and sedimentation affecting navigation and high-value habitat along channel margins.

2 MODEL DESCRIPTION

2.1 Similitude and Scale

Selecting the scale for a physical hydraulic model study involves identifying the primary force relationship to accurately simulate prototype[1] conditions, then selecting a model scale to minimize scale effects. Inertial and gravitational forces are the dominant forces that define the hydrodynamic flow patterns for free-surface flow such as that of a river. As a result, for reproducing hydraulic processes, the Froude number[2] is the key force ratio that must be equal in both the model and prototype. The model scale should also be large enough to allow flow visualization, accurate measurements of water levels and velocities, and to provide sufficient dimensional control to ensure the model study objectives can be met.

The need to reproduce alluvial channel processes such as sediment transport and scour impose additional conditions. The model should adequately reproduce the general sediment transport regime in the river (bed mobility and sediment suspension). Sediment mobility is normally described in terms of the Shields Parameter (ϴ).

$$\theta = \frac{\tau}{\rho g(s-1)D} \qquad \text{(Eq. 1)}$$

where tis the bed shear stress, ρ is the density of water, g is the gravitational constant, s is the specific gravity of the sediment and D is the sediment size.

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[1] 'Prototype' refers to the full-scale or 'real world' structure.

[2] Froude Number is the ratio inertial force to gravitational force

Initiation of sediment movement typically begins when the Shields Parameter exceeds approximately 0.03 to 0.045. During floods on the sand-bed reach of the lower Fraser River, the Shields Parameter commonly ranges from 0.5 to 1.5.

Light weight sediments are commonly used in hydraulic models to improve the representation of bed mobility. For example, replacing natural sand (s=2.65) with a light weight sediment such as walnut shell (s=1.3) increases the effective sediment mobility by a factor of 55 (for the same size of sediment). Another common approach to increase bed mobility is to use a distorted model (horizontal and vertical model scales are not the same). However, past experience has shown that the model must be undistorted (horizontal and vertical scales the same) in order to reproduce secondary currents, local scour processes and the launching behaviour of the riprap protection at the piers (Jansen et al, 1979[3]).

Based on the above similitude requirements, NHC built and tested a 1:80 scale undistorted mobile bed model using light weight sediment to reproduce scour and sedimentation processes in the Fraser River. The model was operated in adherence to the Froude criterion for dynamic similarity, leading to the following scale ratios.

Table 2.1 Model Scale Relationships

Parameter	Relationship	Value
Length, Pressure	L_r	1 : 80
Area	L_r^2	1 : 6,400
Time, Velocity	$L_r^{1/2}$	1 : 8.94
Discharge	$L_r^{5/2}$	1 : 57,200

It is unlikely that the time scale ($L^{1/2}$) is directly applicable to the geomorphological time scale; in other words, the Froude time scale does not necessarily represent the time required for scour to reach equilibrium in the river. For consistency, however, prototype time based on the Froude criterion is used throughout model study reporting. These characteristics and limitations are not believed to significantly affect the applicability of key model findings to prototype conditions.

2.2 Model Layout

The physical hydraulic model represented the full width of the main channel of the Fraser River from the downstream end of Sapperton Bar to downstream of the Skytrain bridge, which is approximately 1 km upstream to 1 km downstream of the existing Pattullo Bridge, as outlined on Photo 2.1. The limits for the physical model boundary were established to allow for adequate entrance and exit channel length to accurately represent flow patterns in the vicinity of the bridge crossings. The model incorporated the bathymetry and topography up to El. 8.0 m (NAD83 UTM Zone 10) along with the details of the piers and riprap supporting the bridges (New Westminster Rail Bridge, existing Pattullo Bridge, Skytrain Bridge,

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[3] Jansen, P., van Bendegom, L., van den Berg, J., de Vries, M. and A. Zanen, 1979: Principles of River Engineering, the Non-Tidal River, Pitman, London.

and proposed Pattullo Replacement Bridge), and the submerged river training sills on the north bank. Figures 2-1 through 2-30 illustrate the physical model layout including pier dimensions.

The river bed bathymetry along the modelled reach and the topography of the river banks and overbank areas were simulated using available survey contour information[4]. The river bed at both the upstream and downstream end of the model was placed as a fixed surface and then gradually transitioned into mobile bed material in order to allow flow entering the model to develop prior to affecting the mobile portion of the model river channel. A lightweight model sediment was selected for the mobile-bed to match mobility of the bed load sediments that are present in the river (refer to Section 2.3 for further detail). The river banks were placed as fixed surfaces in the model using roughened concrete. The geotechnical stability of prototype soil conditions of the bank were not simulated in the model. The existing and proposed bridge piers were fixed to the bottom of the model and constructed in accordance with the best available drawings, as provided by Parsons Corporation[5].

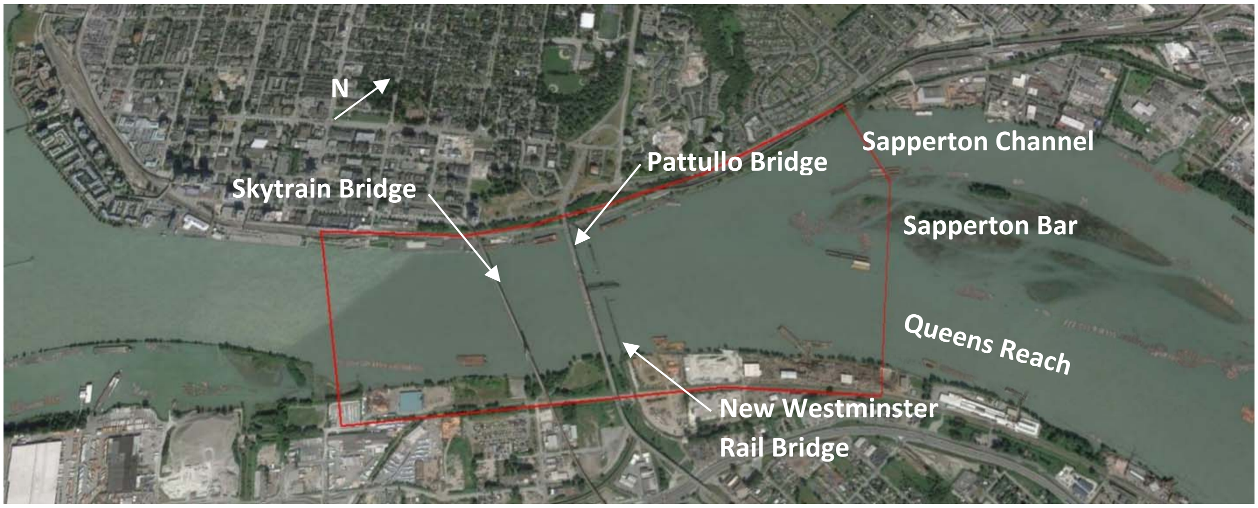

Photo 2.1 Approximate extents of the physical model

Flow was supplied to the upstream boundary of the physical model and adjusted using baffles during model calibration to closely match prototype velocities and flow patterns approaching the bridges. The lightweight model sediment was supplied at the upstream end of the model during testing to simulate

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[4] Contours were derived from a TIN created from 2014 bathymetric data in the main channel, 2011 bathymetric data in the Pattullo Sapperton Channel; 2014, May CRA Multibeam around bridges and 2005 LiDAR (FBC) for the bank elevations; 2017 Pattullo Bridge Monitoring Freshet Summary by Northwest Hydraulic Consultants Ltd. All data were prepared using ArcGIS 10.3 or 10.4. Coordinate system: UTM Zone 10, NAD 83, metres.

[5] New Westminster Rail Bridge was sourced from Translink 2002-09-18 as-built drawings in TIF files: 49742, 60204, 60704, 49785, 49813, 49913-225, 49803, 49814, 49800, 49785, 49786, 49940, 60187, 60188, 60744, 49921, 49924, and 60418. Also, from McElhanney 2016-0601 Mapping Info – Lidar & Ortho Plan

Pattullo Bridge sourced from Translink 2002-09-18 as-built drawings in DWG files: 09330101A and BC Public Works historical drawings from April 1935 (Drawings 101805 to 101813) and proposed Pier 5 pressure grouting drawing (No. 933-19) from January 1957.

Skytrain Bridge sourced from Translink 2016-07-14 PDF file CN130.

sediment that would be actively transported as bed load and in suspension during high flows in the Fraser River. The water surface elevation was set at the downstream end of the model by adjusting a tilting tailgate. An overflow weir was used in lieu of the tailgate for the test conditions when the flow was reversed to represent a low winter flow with a large flood tide.

2.3 Model Sediment

The PBRep mobile bed model is intended to represent local scour, not reproduce the full mobility of the Fraser River. Although scaling relations have been developed theoretically for selecting scales in mobile bed models, in practice these are difficult to apply to sand-bed rivers. This is partly due to uncertainties over bed-form dimensions and associated form resistance. For the case of a sand-bed river, exact sediment transport similarity cannot be fully achieved in a physical model without introducing other distortions that will compromise the accuracy of the results. However, local scour processes are mainly governed by the geometry of the structures and general mode of sediment transport. Scour depth at structures such as piers, bridge abutments or guidebanks is relatively insensitive to the sediment transport intensity once general mobility is achieved [6]. Essentially, the magnitude and extent of the local scour is not highly dependent on the shear stress or absolute magnitude of the bed mobility once the bed becomes sufficiently mobile to generate dunes and sediment suspension.

The size of the model bed sediment was selected based on experience from similar testing on the lower Fraser River and by comparing the critical velocity for initiating sediment transport to the model velocities. The bed sediment of the Fraser River, which is sand with a median grain size of 0.3 mm, cannot be geometrically scaled in the model since the resulting sediment would be clay and silt that would likely exhibit cohesive properties. For that reason, a light-weight sediment was required to represent the river bed material. A narrowly graded crushed walnut shell with a median diameter of approximately 0.68 mm (20/40 processed walnut shell) was selected to simulate the 0.35 mm sand. The selected material has a specific gravity of 1.33 (compared to 2.65 for sand), which makes it sufficiently mobile to reproduce dunes and to transport sediment in suspension during flood flows.

The selected model material (processed walnut shell) has been used successfully in a number of mobile bed models of sand-bed rivers, including models used to assess scour and sediment movement behaviour on the Fraser river such as the existing Pattullo Bridge (NHC, 2009)[7], the Port Mann Bridge Replacement (NHC, 2009)[8], the Golden Ears Bridge (NHC, 2006)[9] and the Skytrain Bridge (NHC, 1985)[10]. In addition, validation testing was conducted in the physical model to confirm that the walnut shell

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[6] Breusers and Raudkivi, 1991. Scouring, Hydraulic Structures Design manual, No. 2, IAHR, Balkema, 143pp, 1991.

[7] NHC, 2009. Pattullo Bridge Functional Design Preliminary Hydrotechnical Assessment Final Report. Prepared for Delcan Corporation by Northwest Hydraulic Consultants Ltd. September 2009. NHC 35179. North Vancouver, BC.

[8] NHC, 2009b, Port Mann Bridge Hydrotechnical Assessment and Design Scour and Scour Protection Final Report. Prepared for T.Y. Lin International (Olympia, WA) by Northwest Hydraulic Consultants Ltd. June 2009. North Vancouver, BC.

[9] NHC, 2006, Golden Ears Bridge Hydrotechnical Investigation Final Report. Prepared for Golden Ears Crossing Constructors Joint Venture by Northwest Hydraulic Consultants Ltd. May 2009. NHC 33992. North Vancouver, BC.

[10] NHC, 1985. ALRT Fraser River Crossing Hydraulic Model Study of Alternative 1 Pier Designs Final Report. Prepared for Bush, Bohlman – Reid, Crowther Ltd. Consulting Engineers (Vancouver, BC) by Northwest Hydraulic Consultants Ltd. February 1985. NHC 31359. North Vancouver, BC.

adequately simulates local scour expected in the prototype, and provide a reasonable approximation of sediment movement paths and areas of sediment scour and deposition that can be expected in the prototype. The approximate flow rate and water level for incipient motion of the model material was appraised during startup of each model test to confirm that sediment mobility remained relatively similar throughout the testing phase. Sediment transport measurements collected at Mission[11,12,13] were extrapolated to determine an estimate of the sediment feed rate[14] for the physical model tests, then model validation testing was conducted to refine the feed rate appropriately.

2.4 Model Riprap

Due to its much larger size, riprap can be geometrically scaled, since it can be represented as gravel-sized sediment. There were two key gradations identified in the as-built drawings of the 2008 protection upgrades and Skytrain Bridge as-built drawings: 400-mm nominal size and 600-mm nominal size. The model riprap consisted of crushed quartz gravel having a specific gravity of between 2.65 and 2.75. NHC selected Bird's Eye and a 1/2" crush gravels to represent the prototype 400 mm and 600 mm respectively (Table 2.2 Table 2.3).

Table 2.2 Riprap 400 mm nominal size

Particle Size Distribution	Type "B" Skytrain (BC Transit, 1986)	Sieve Analysis (Metro Testing, 2016) Bird's Eye	
	Prototype (mm)	Model (mm)	Prototype (mm)
D_{100}	400 to 550	9.5	760
D_{85}	350 to 550	8.3	664
D_{50}	300 to 400	5.5	440
D_{15}	100 to 200	3.0	240

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[11] McLean D.G., Church M., Tassone B., 1999. "Sediment Transport along lower Fraser River – measurements and hydraulic computations" Water Resources Research, Vol. 35, No. 8, pg 2533-2548.

[12] McLean D.G., Tassone B., 1988. "A sediment budget of the Lower Fraser River ", 5th Inter-Agency Sedimentation Conference, Las Vegas, Nevada.

[13] McLean D.G., Church M. 1986. "A re-examination of sediment transport observations in the Lower Fraser River, Water Resources Branch, Sediment Survey Section, Environment Canada, Report IWD-HQ-WRB-SS-86-6, 52 p.

[14] 'Sediment feed rate' refers to the volume and timing that model sediment is added at the upstream end of the model over the duration of a test.

Table 2.3 Riprap 600 mm nominal size

Particle Size Distribution	2008 Riprap Protect Upgrades (NHC, 2008)	Sieve Analysis (Metro Testing, 2016) 1/2" Crush	
	Prototype (mm)	Model (mm)	Prototype (mm)
D_{100}	900	12.5	1000
D_{80}	700	9.4	744
D_{50}	600	7.4	592
D_{20}	300	5.4	432
D_{5}	100	3.1	248

2.5 Model Instrumentation

Physical model study measurements included:

- Model inflow regulated by a valve and measured with an ultrasonic meter (accuracy of approximately ±2 percent).
- Water levels measured using staff gages located on selected bridge piers and at key locations within the model (accurate to ±0.5 m prototype).
- Water levels near the Skytrain crossing measured using a point gauge (accurate to ±0.1 m prototype).
- Bed elevations measured using a high-speed 3D laser scanner to generate a detailed point cloud of the entire physical model bed. Contour maps were then created in AutoCAD Civil 3D by sampling the data on a 3 m grid throughout most of the model and on a 1 m grid (prototype units) in the vicinity of the bridge crossings (accurate to ± 0.3 m vertically and 0.4 m horizontally in prototype units). In addition, manual bed elevation checks were made for all tests using a staff gage and laser level (accurate to ±0.5 m prototype).
- Mid-depth velocities recorded along channel transects and points near the bank using a one-dimensional miniature propeller velocity probe (resolution of 0.1 m/s prototype; minimum recordable velocity of 0.5 m/s). Velocity measurement locations are shown in Figure 3-1.
- Visual aids such as coloured dye injected at key locations in the model were used to qualitatively assess changes in the flow patterns.
- Velocity and current directions at the water surface were obtained by tracking small light-emitting diodes mounted on floats (drogues) with a high-resolution video imaging system (VIS). The cameras were calibrated in position and LabVIEW software was customized to distinguish lateral position of individual drogues over time to calculate the current direction and velocity(resolution of 0.2 m/s prototype).

- Digital photographs and video footage were taken throughout the test program to provide visual documentation of the model study progress and key results.

3 TEST PROGRAM

The testing program was divided into the following phases: calibration and validation testing, baseline testing, and replacement concept testing. For the purposes of the physical model study, the proposed bridge replacement concepts are referred to as the Stage 1 Reference Concept and the Short-Span Option; the Project reference concept has since been further refined. Flows and water levels for the test scenarios were estimated using MIKE 11 river modelling of the Lower Fraser River (NHC 2006b, 2008; BC MFLNRO 2014, 2014b)[15,16,17,18] and were selected based on the flow and water level that resulted in the highest average flow velocity. A steady flow rate and water level were maintained throughout each test duration. For all tests, the model river bed was set in accordance with the June 2016 bathymetric survey[19], but without the scour details at the structures.

3.1 Model Calibration and Validation

A calibration test was conducted in the PBRep physical model to adjust the model inflow distribution to match field observations of channel velocities and flow distribution. The flow distribution was verified by measuring velocities along two transects upstream of the New Westminster Rail Bridge and one transect downstream of the Skytrain Bridge, and comparing the results to paired velocity-discharge Acoustic Doppler Current Profiler (ADCP) measurements collected by NHC on May 24, 2014[20] at an approximate river discharge of 6,400 m^3/s, and an approximate water level of El. 0.0 m at the Skytrain Bridge. Adjustments were made to the model inflow and outflow conditions by adding and adjusting perforated plates and baffles in the headbox at the upstream end of the model and tailbox at the downstream end until the desired flow distribution was obtained.

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[15] NHC, 2006b. Lower Fraser River Hydraulic Model, Final Report. Report prepared for Fraser Basin Council.

[16] NHC, 2008. Fraser River Hydraulic Model Update, Final Report. Report prepared for BC Ministry of Environment.

[17] BC MFLNRO, 2014. Fraser River Design Flood Level Update - Hope to Mission, Final Report by Flood Safety Section.

[18] BC MFLNRO, 2014b. Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios, Final Report by Flood Safety Section.

[19] NHC, 2017. Pattullo Bridge Monitoring 2017 Freshet Summary – DRAFT. Northwest Hydraulic Consultants Ltd. Project 300016 North Vancouver, BC. 2017-09-06.

[20] NHC, 2014. Pattullo Bridge Seismic Upgrade, Factual Report for Bathymetric Survey and ADCP Measurements – Revision 1. Prepared for B&T by Northwest Hydraulic Consultants Ltd. June 19, 2014. NHC 300320. North Vancouver, BC.

Table 3.1 Summary of calibration and validation test scenarios.

Description	Test No.	Discharge at Pattullo Bridge (m^3/s)	Water Level at Skytrain Bridge (m)	Direction of Flow
Calibration Test (May 24, 2014)	CV1	6,400	El. 0.0 m	South
Validation Test (2012 flood freshet)	CV2	15,815	El. 1.5 m	South

Once this was accomplished, a validation test was conducted to confirm the response of the model bed sediment compared to river bed topography observed in the field. It is standard practice to verify a mobile bed physical model before testing design options. Generally, a known flood event is used in the model to confirm that the model reproduces certain phenomenon that are known to have occurred in the field, such as particular scour or deposition patterns or particular flow patterns. These tests serve to confirm that the model can reliably represent the prototype conditions. For the PBRep model validation test, the discharge was first increased incrementally to determine the approximate discharge when the model sediment begins to move (incipient motion). Then, the discharge was increased to 15,815 m^3/s (2012 flood freshet) and an approximate water level of El. 1.5 m at the Skytrain Bridge for the validation test. The 2012 freshet was selected because it was the largest freshet event on the river since 1972, with an annual return period of approximately 20 years based on long-term records upstream at Hope, BC. Also, detailed multi-beam monitoring surveys were available at the site, with the surveys conducted on June 18 2012, four days before the freshet peak. The resulting bed levels, local scour patterns at the bridge piers, and dune characteristics that developed in the physical model were compared to the 2012 freshet bathymetric survey (NHC, 2013) [21].

3.2 Baseline Testing

Baseline testing was conducted for comparison with the Stage 1 Reference Concept and Short-Span Option test results. The flow condition for baseline tests was the 1894 flood of record, which has a return period of approximately 500 years at Hope[22], and a corresponding discharge at the Pattullo Bridge of 21,200 m^3/s. The 1894 flood has been adopted by agencies as the standard design flood event for most large river protection and flood control projects on the Lower Fraser River.

Three baseline tests were conducted; they are summarized in Table . Tests B1 and B2 did not produce acceptable river bed results, and adjustments were made to achieve more realistic bed conditions in Test B3. As a sensitivity analysis for test duration, the length of the first baseline test (B1) was doubled

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[21] NHC, 2013. Pattullo Bridge Monitoring 2012 Winter Monitoring Summary - Draft. Northwest Hydraulic Consultants Ltd. Project 300016 for Translink. February 7, 2013. North Vancouver, BC.

[22] NHC, 2008. “Fraser River Hydraulic Model Update”. Report prepared by Northwest Hydraulic Consultants for the BC Ministry of Environment, 2008.

to 11 hours (4 days in prototype) compared to the selected test duration of 5.5 hours (2 days prototype) to confirm that enough time was provided in the model to reach equilibrium.

Table 3.2 Summary of baseline test scenarios.

Description	Test No.	Discharge at Pattullo Bridge (m^3/s)	Water Level at Skytrain Bridge (m)	Direction of Flow
Baseline – Long Duration (1894 flood of record)	B1	21,200	El. 3.5 m	south (downstream)
Baseline – Normal Duration (1894 flood of record)	B2		El. 3.5 m	
Baseline – Normal Duration; Low Tide Level (1894 flood of record)	B3		El. 2.8 m	

3.3 Stage 1 Reference Concept and Short-Span Option Testing

Three flow scenarios were used to evaluate the Stage 1 Reference Concept and the Short Span Option, as summarized in Table 3.3. Testing for these design options was conducted with the existing Pattullo Bridge piers and rock mounds in place to represent the condition when the new bridge has been constructed and the existing bridge has not yet been removed.

Table 3.3 Model Testing Flow Scenarios

Description	Test Number	Discharge at Pattullo Bridge (m^3/s)	Direction of Flow	Water Level Downstream of SkyTrain Bridge (m GD)
1894 Flood of Record (500 year return period)	RC1 / SS1	21,200	south (downstream)	2.8
200 year Winter Flow with Large Ebb Tide	RC2 / SS2	16,000	south (downstream)	1.4
Low Winter Flow with Large Flood Tide	RC3 / SS3	8,300	north (upstream)	0.0

4 TEST RESULTS

4.1 Calibration and Validation

4.1.1 Velocities

The velocities measured in the calibrated configuration of the physical model compared well to the results from the field surveys (smoothed ADCP data) at a river discharge of 6,400 m^3/s during flood tide conditions (Calibration Test). As shown in Figure 4-1, the general trend of the velocity distribution was replicated, and the velocities showed good agreement to the smoothed ADCP data. The average velocity at each transect measured in the model was approximately 1 m/s. The velocity data were confirmed in the model after further modifications were required to the model headbox during baseline testing; also included in Figure 4-1.

Flow velocities were also measured for the validation test. The average velocity at each transect was approximately 2 m/s, and exhibited a similar distribution to the velocities recorded at the calibration test flow rate. The velocity distribution across the channel agreed closely with the predictions from NHC's hydrodynamic model of the reach used as part of the work for PBRep (Figure 4-2). For the validation test, which simulated the 2012 freshet, water covered most of the Sapperton bar, but did not exceed the river banks. There was observable flow separation and eddy shedding from the bridge piers, which was also apparent during monitoring of the 2012 freshet.

4.1.2 Mobile Bed

At the beginning of the calibration and validation tests, the discharge was increased incrementally in order to determine the approximate hydraulic conditions (flow depth and flow velocity) when the model sediment begins to be transported as bedload (incipient motion). The critical velocity for incipient motion (v_c) was estimated to be between approximately 0.7 and 1.0 m/s (0.07 and 0.11 m/s model) at a water depth of about 15 m. The test scenarios that have been selected to evaluate the replacement concepts for the new Pattullo Bridge are predicted to have a mean velocity that ranges between 2.1 m/s to 2.4 m/s near the Bridge Piers with the exception of the test at low winter flow with large flood tide, which has an estimated mean velocity of 1.3 m/s. The mobility of the model material is expected to be slightly lower than the Fraser River based on established relations between scour depth and dimensionless velocity (v/vc) [4], which is the ratio between the mean approach velocity (v) and the critical velocity to initiate motion (v_c), but the model tests are within a reasonable range for providing realistic local scour predictions at the structures.

Validation testing also included evaluation of local scour at a single pile to determine if the amount of scour classically observed around a single pile was reproduced with the selected model sediment. Two sizes of cylinders, a 9.3 m diameter and a 6.1 m diameter test cylinder, were installed in a relatively straight, uniform section of the model downstream of the Skytrain Bridge. The scour depth measured in the physical model at the end of the validation test were compared to estimated scour depth using four different established empirical methods (Laursen 1962[23], Melville 1997[24], Richardson and Davis 1995[25], IAHR [26]). The results are summarized in Table 4.1. The measured scour at the model test cylinders was typically less than the design guidelines, but considered a reasonable approximation of the typically conservative empirical formula.

Table 4.1 Validation Test - Scour at a Single Pile

Method	9.3 m Diameter Test Cylinder		6.1 m Diameter Test Cylinder	
	Scour Depth (m)	Scour Elevation (m)	Scour Depth (m)	Scour Elevation (m)
Physical Model Results	11.6	-29.0	8.0	-24.2
Richardson and Davis, 1995	12.9	-30.3	10.5	-26.7
Breusers and Raudviki, 1991	15.1	-32.5	10.4	-26.6
Laursen, 1962	17.3	-34.7	12.6	-28.8
Melville, 1997	22.4	-39.8	14.6	-30.8

One of the primary objectives of the validation test was to evaluate how well the physical model represented the scour and sediment deposition patterns documented in the field. The model sediment was transported as bed load and in suspension during freshet conditions. Dunes were well developed throughout the model at the end of the validation test. The average trough to peak dune height in the main channel at the upstream end of the model was approximately 1.7 m. Near the Pattullo and New Westminster Rail (NWR) Bridge, the dunes in the model were typically between 2.4 m and 3.8 m. Downstream of the first rock weir, where flow velocities tend to be lower, the dunes were approximately 1.3 m high. The model dunes are representative of prototype dunes that have been documented previously in the Fraser River at Mission and in Annieville channel during freshet conditions.[27] [28] The results confirm that the model can reproduce dunes similar to those observed in this reach of the Fraser river.

The overall bed formations and bed levels that resulted from the validation test in the physical model were generally within ±5 m of the 2012 and 2016 bathymetric surveys, which is considered to be in good agreement. Figures 4-3 to 4-8 show the resulting bed elevations recorded in the physical model, and the 2012 and 2016 bathymetric surveys. The validation test also resulted in many of the same general trends as observed in the field, and the model sediment was shown to reasonably simulate the river bed material. In the physical model, the protective aprons around most of the piers were fully launched by the end of the test, and a pronounced mound or 'cone' due to the development of "horseshoe" vortices

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[23] Laursen, E.M., 1962. *Scour at Bridge Crossings*. Trans. ASCE, v.127 part 1.

[24] Melville, B.W. 1997. *Pier and Abutment Scour: Integrated Approach.* Jour. Hydraulic Engineering (ASCE), 123, 2, 125-136.

[25] Richardson, E.V. and Davis S.R., 1995. *Evaluating Scour at Bridges*. Hydraulic Engineering Circular 18 (3rd Edition), Federal Highway Administration, McLean, Virginia.

[26] Breusers and Raudkivi, 1991. *IAHR Monograph Hydraulic Structures Design Manual 2*, Chapter 5 .

[27] McLean, D. 1990: The Relation Between Channel Instability and Sediment Transport on Fraser River, PhD dissertation, University of British Columbia.

[28] NHC 2016: Overview of Fluvial Geomorphology at Project Site, Annacis Island WWTP Transient Mitigation and Outfall Project, prepared by Northwest Hydraulic Consultants Ltd. for CDM Smith and Metro Vancouver, 11 January 2016.

on the upstream side of the pier. This pattern was also observed during the 2012 freshet. No significant scour or unravelling of the protection at Piers 2 and 3, or unusual bed lowering in the channels between the piers was evident.

The following differences from the surveyed levels were noted for the validation test:

- Downstream of Sapperton Wingdam No. 1, scour was significantly exaggerated by the flow conditions at the entrance to the model.
- The model bed levels were up to approximately 7 m lower than the bathymetric survey levels at the flow convergence downstream of Sapperton Bar.
- The steep slope from the NWR bridge down toward the Pattullo Bridge Piers 4 and 5 did not develop in the model, nor did the scour between Piers 4 and 5.

Based on the validation testing results, modifications to the model headbox flow distribution, Wingdam No. 1 porosity, the extent of the non-mobile reach in the model, and the model bed near Pattullo Piers 4 and 5 were implemented prior to baseline testing in order to correct the scour downstream of Wingdam No. 1, and to improve simulation of the river bed behaviour in the vicinity of Pattullo Piers 4 and 5.

4.2 Baseline

4.2.1 Preliminary Baseline Testing

In general, the bed shape at the end of baseline tests B1 and B2 were found to be reasonable in comparison to the June 2016 bathymetric survey. In addition, the normal duration baseline test (Test B2) resulted in bed levels that were generally within ± 3 m to the long duration test (Test B1) indicating that a 5.5 hour (model) test duration was adequate to reach equilibrium bed levels. Nonetheless, additional refinements to the model were required prior to the final baseline test, B3, in order to eliminate unrealistic scour in the model along the left bank, and to produce more representative scour patterns in the vicinity of Pattullo Piers 4 and 5. The changes to the model included: additional baffling at the model headbox; extension of the non-mobile materials in the main channel to allow the flow from the model headbox to expand and develop upstream of the mobile material; the addition of two flow vanes at the model headbox; modifications to porosity of Wingdam No. 1; adjustment of model sediment feed rate and distribution for the main channel; and lowering of the water level for the flood of record test to the low tide level (El. 2.8 m at the Skytrain bridge) while maintaining the peak discharge of 21,200 m^3/s. In addition, the elevation of the riprap sill connecting the aprons for NWR Bridge Piers 6 to 10 was adjusted to better match what was shown in the previous model study report (NHC, 2008b)[29], which were consistently 2 m higher than the minimum elevations recorded during the June 2016 survey. The height of the sill in the 2008 study was based on previous surveys and diver inspections that inferred that a weir-like apron of rock is likely present under the CN

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[29] NHC, 2008b. Pattullo Bridge Scour Protection – Conceptual Design Report. Northwest Hydraulic Consultants (NHC) Project 34765 for Translink Greater Vancouver Transport Authority. June 2008. North Vancouver, BC.

Rail Bridge, which results in deep scour around Pattullo Piers 4 and 5 when flow plunges over the apron during freshet. In the 2008 model study, high flow velocities over the sill were observed to increase the turbulent energy and enhance the local scour between the Pattullo piers.

4.2.2 Baseline Test Results (Test B3)

4.2.2.1 Velocities

Water covered most of the Sapperton bar, but did not exceed the river banks. There was observable flow separation and eddy shedding from the bridge piers. Mid-depth velocities typically ranged between 1.0 and 3.5 m/s. Velocities were higher (3.5 to 4.5 m/s) south of the Primary Navigation channel. Surface velocities typically ranged from 2 to 3 m/s. As shown from the velocity vectors in Figure 4-15, the angle of pier skew of Pattullo Piers 4 and 5 was approximately 15 degrees to the approaching flow, which agrees with previous observations (NHC, 2008).

4.2.2.2 Mobile Bed

As expected for the flood of record, the model sediment was transported as bed load and in suspension. Bed levels, local scour patterns at the bridge piers, and dune characteristics were documented for later use as a baseline for comparison to the Stage 1 Reference Concept and Short Span Option test results. Dunes were well developed throughout the model at the end of the baseline test, as shown in Photo Plate 4-1. The trough to peak dune height typically ranged from 1.5 to 6.0 m.

The model bed levels along the NWR Bridge lowered by approximately 5 m between Piers 1 through 6, and up to 5 m of deposition occurred between NWR Piers 6 and 10. There was development of “horseshoe vortex” induced scour on the upstream side of the NWR bridge piers. An approximately 1V:4H slope developed in the model from the NWR bridge down toward the Pattullo Bridge between Pattullo Piers 4 and 5.

The protective aprons around most of the Pattullo piers were fully launched by the end of the test, and the large mounds at the piers were established in the model bed. No unusual bed lowering in the channels between the piers was evident. The channel bed between Pattullo Piers 1 and 2 lowered by 4 m to El. -24 m. The bed lowered by approximately 8 m to El. -30 m in the channel between Piers 2 and 3, which is considered reasonable for the flood of record. There was no significant scour or unravelling of the protection at Pattullo Piers 2 and 3. NWR Bridge Pier 5 extends between Pattullo Piers 3 and 4, and the bed lowered by a maximum of 5 m along the Pattullo bridge alignment between Piers 3 and 4. The bed level between Pattullo Piers 4 and 5 lowered to approximately El. -20 m. The lowest bed elevations observed between Pattullo Piers 4 and 5 as part of the monitoring program was -28 m, observed during the 2011 Freshet survey. Launching of toe apron material around Piers 4 and 5 was identified. The shape of the contours suggests a relatively uniform slope. General bed levels on the south side of Pattullo Pier 5 were similar to the 2016 surveyed bed levels with a maximum bed lowering of about 1 m.

4.3 Stage 1 Reference Concept and Short Span Option Results

The Stage 1 Reference Concept includes a pylon on the south bank, and a pylon and two smaller piers in the north side of the channel (Figures 2-25 to 2-27). The Short Span Option includes a pylon on the south bank, two pylons in the channel, and a portal pier on the north side of the channel (Figures 2-28 to 2-30).

4.3.1 Velocities and Flow Patterns

When comparing the results between the Baseline, Stage 1 Reference Concept, and the Short Span Option the overall effects on velocities were limited. For the Stage 1 Reference Concept, changes in flow patterns and velocities were generally limited to local effects around the piers. Table summarizes the typical ranges of mid-depth and surface velocities for each test. Figures 4-9 to 4-14 present a comparison of the mid-depth velocities between the Stage 1 Reference Concept and the Short Span Option. Figures 4-16 to 4-18 provide the resulting surface velocity vector plots for testing of the Stage 1 Reference Concept, and Figures 4-19 to 4-21 provide the resulting surface velocity vector plots for the Short Span Option tests.

The surface flow at the downstream end of NW Rail Pier 5, between the two navigation channels, was angled slightly more to the south for both the Stage 1 Reference Concept and the Short Span Option when compared with the baseline condition. The Short Span Option resulted in an increase of 0.5 m/s in surface velocities along the sides of NW Rail Pier 5 (swing span) at the Flood of Record and along the south side of NW Rail Pier 5 for the 200-year winter flow. In contrast, surface velocities within the southern edge of the Primary Navigation channel were between 1.0 to 2.5 m/s lower in the shadow of Pylon SS3 of the Short Span Option when compared to velocities in that area for both the baseline and the Stage 1 Reference Concept.

At the flood of record and the 200-year winter flow, the Short Span Option resulted in a 0.5 m/s increase in the surface velocities between Piers 4 and 5, which remained outside of the south limit of the Primary Navigation Chanel. There was also an increase in mid-depth velocities of about 0.5 to 1.0 m/s between Pattullo Piers 4 and 5 for the Short Span Option.

At the flood of record and the 200-year winter flow, mid-depth velocities for the Short Span Option were generally 0.25 to 0.5 m/s higher in the Secondary Navigation Channel when compared to both the baseline and the Stage 1 Reference Concept, and 0.25 to 0.75 m/s higher within the Primary Navigation Channel downstream of the Skytrain Bridge.

The direction and magnitude of the surface vectors for the Short Span Option were similar to those for the Stage 1 Reference Concept at the low winter flow with large flood tide. Flow patterns for the low winter flow test are not comparable to the other two tests scenarios, since flows are reversed for this condition.

Point velocities were collected near the shoreline downstream of the Pattullo Bridge at key locations of interest (Series 8 velocity data). At the four locations selected on the north side of the river, velocities were typically reduced with either the Stage 1 Reference Concept or the Short Span Option installed when compared to baseline measurements with velocities being the lowest at these locations for the Stage 1 Reference Concept. The exception was at one point (8F) downstream of Pattullo Piers 1 and 2, where the velocity increased slightly (by 0.2 m/s) with the Stage 1 Reference Concept installed when compared to the baseline. On the south side of the river, the point velocities were similar between the baseline, Stage 1 Reference Concept and Short Span Option, except at one point (8B) upstream of Skytrain Pier S1, where the velocity increased by 1 m/s when the Stage 1 Reference Concept Bridge was in place.

Table 4.2. Summary of typical mid-depth and surface velocities

Test Number	Scenario	Flow Condition	Mid-depth Velocities (m/s)	Surface Velocities (m/s)
B3	Baseline	Flood of record	1.0 – 3.5	2.0 - 3.5 3.5 - 4.5 south
RC1B	Stage 1 Reference Concept	Flood of record	1.0 – 3.5	2.0 - 3.5 3.5 - 4.5 south
SS1	Short Span Option	Flood of record	1.0 – 3.5	2.0 – 3.5 3.5 – 4.5 south (further south than RC1B and B3)
RC2B	Stage 1 Reference Concept	200-year winter flow with large ebb tide	1.5 – 2.5	1.5 – 3.0 3.5 – 4.5 south
SS2	Short Span Option	200-year winter flow with large ebb tide	1.5 – 2.75	1.5 – 3.0 3.5 – 4.0 south
RC3	Stage 1 Reference Concept	Low winter flow with large flood tide	0.5 – 1.5	1.0 – 2.0
SS3	Short Span Option	Low winter flow with large flood tide	0.5 – 1.5	1.0 – 2.5

4.3.2 Scour and Sedimentation

Generally, bed levels along the replacement bridge alignment were similar at all three flow scenarios for both the Stage 1 Reference Concept (Tests RC1B, RC2B, and RC3) and the Short Span Option (Tests SS1, SS2 and SS3) with up to 5 m of bed lowering through the reach from the replacement bridge to the Pattullo Bridge. However, the Short Span Option resulted in bed levels that were generally 1 to 2 m lower along the south side of the river in the vicinity of the bridge crossings when compared to the baseline and the Stage 1 Reference Concept (Figures 4-33 to 4-35,4-44 and 4-53). The locations noted as having less scour for the short span option when compared with the baseline and the Stage 1 Reference Concept, included north of the Secondary Navigation Channel and within the Secondary Navigation Channel. The reduced scour may be attributable to slight differences in the flow patterns across the river due to the presence of the short span bridge piers. In addition, there was less constriction in this area of the Short Span Option when compared to the Stage 1 Reference Concept. Figures 4-27 to 4-30 provide comparisons of sections of the resulting model bed between the starting bed, Baseline, Stage 1 Reference Concept and Short Span Option at the flood of record. Figures 4-40 to 4-43 and 4-49 to 4-52 provide comparisons of sections of the resulting model bed between the starting bed, Stage 1 Reference Concept and Short Span Option at the 200-Year winter flow and the low winter flow, respectively. Photo Plates 4-2 to 4-4 and Photo Plates 4-5 to 4-7 include selected photos from each test of the Stage 1 Reference Concept and the Short Span Option, respectively.

Stage 1 Reference Concept

Flow constriction between the north pylon N0 and the north bank resulted in scour along the bridge alignment. The deepest scour at the Stage 1 Reference Concept piers occurred downstream of the north pylon N0, between N0 and NW Rail Pier 4, at the flood of record. The bed between N0 and NW Rail Pier 4 scoured to El. -39 m (up to 18 m lower than the baseline bed level) and caused collapse of the rock mound at NW Rail Pier 4. At the 200 year winter flow, the deepest scour along the Stage 1 Reference Concept alignment was El. - 27 m, which occurred between Piers N0 and N1. Scour between N0 and NW Rail Pier 4 reached El. -25 m, which resulted in launching of the rock at NW Rail Pier 4. The deepest scour at the low winter flow with large flood tide reached El. -25.5 m at the north pylon, N0. Scour may have been 3 to 5 m deeper within the pile group.

The maximum scour at Stage 1 Reference Concept Pier N1 was El. -29 m at the nose, and El. -26.5 m at the nose of Pier N2 at the flood of record. Scour between N2 and NW Rail Pier 3 extended to El. -26 m at both the flood of record and the 200 year winter flow and caused launching of the existing protection on north-east (right) side. Scour at Piers N1 and N2 at the low winter flow, reached El. -23 m and El. -24 m, respectively.

The toe of the slope at the south pylon, S0, was scoured by about 3 m at the flood of record and the low winter flow, but by about 10 m to El. -15 m at the 200 year winter flow. Minor riprap launching occurred, but the piles were not exposed.

Short Span Option

Along the Short Span Concept alignment, the deepest scour occurred between Pier SS1 and the north bank at the flood of record, reaching a depth of El. -34 m, which is about 14 m lower than the baseline bed levels and about 8 m lower than the Stage 1 Reference Concept bed levels. However, the level of scour in this area may be exaggerated in the model due to proximity with the non-mobile model bank. For the 200 year winter flow, the scour at Pier SS1 reached a maximum of El. - 23.0 m at the downstream end of the pier.

The maximum scour at Pylons SS2 and SS3 was El. - 26 m and El. -23 m, respectively, at both the flood of record and the 200 year winter flow. This translates into approximately 8 m of scour at Pylon SS2 and approximately 13 m of scour at Pylon SS3. The maximum scour depth was typically located directly downstream of Pylons SS2 and SS3, or along the north side and downstream of the pier. For the low winter flow test, the deepest scour was measured to be El. -24.5 m in the north side of the river at Pylon SS2, and the maximum scour on the south side of the river developed near Pylon SS3, where the bed lowered to El. -19.5 m. The maximum scour depth was typically located directly downstream of the pier at the low winter flow. For the low winter flow, bed scour along the Short Span bridge alignment, typically ranged between 5 and 9 m from the south bank to NW Rail Bridge Pier 5.

The south bank in the vicinity of Pylon SS4 scoured by approximately 5 to 6 m and the scour exposed the sheet pile wall at Pylon SS4 to approximately El. - 7 m at the flood of record and to El. -6 m at the 200 year winter flow.

4.3.2.1 NW Rail Bridge

During the flood of record, both the Stage 1 Reference Concept and the Short Span Option induced significant scour to the NW Rail bridge which would require mitigation. Compared with the baseline, the Stage 1 Reference Concept resulted in 10 to 15 m deeper scour at NW Rail Piers 3 to 8 and Pier 6 protection. Scour reached a maximum of approximately El. -10 m at NW Rail Pier 7, Pier 8, and Pier 6 Protection. Riprap launched at all of these piers, and the piles were exposed at NW Rail Piers 7, 8 and Pier 6 protection. The deepest scour was to El. -28 m, on the downstream south side of NW Rail Pier 5. Compared with the Stage 1 Reference Concept, the Short Span Option at the flood of record resulted in 10 to 15 m less scour at NW Rail Pier 4, and up to 3 m more scour along both sides of NW Rail Pier 5. Scour reached a maximum of El. -8 m at Pier 6 Protection, El. -10.5 m at NW Rail Pier 7, and El. -12 m at NW Rail Pier 8, which exposed the piles at Piers 7 and 8 and launched the rock protection at NW Rail Pier 7. The deepest scour occurred between the north pylon N0 and NW Rail Pier 4, where the bed scoured to El. -39 m (up to 18 m lower than the baseline bed level) and caused collapse of the rock mound at NW Rail Pier 4.

For the 200-Year winter flow, scour effects at the NW Rail Bridge for both the Stage 1 Reference Concept and the Short Span Option were generally less severe than for the flood of record test. For the Stage 1 Reference Concept, scour at NW Piers 3 and 4 was similar to the flood of record, extending down to El. -26 and -27 m, respectively; riprap launched, but no piles were exposed. At NW Piers 5 to 8 and Pier 6 protection, the deepest scour with the Stage 1 Reference Concept installed was to El. -15 m between Pier 5 and 6. Riprap launched at all the NW piers to a lesser degree than in the flood of record test, and piles were not exposed. For the Short Span Option, there was scour down to El. -24 m along the north side of both NW Rail Pier 4 and Pattullo Pier 3, and scour to El. -26 m between the two piers (about 5 to 7 m of scour when compared to the 2016 bed levels). There was no significant launching of the rock mound at NW Rail Pier 4 nor at Pattullo Pier 3. The scour for the Short Span Option increased by 2 to 3 m on the north side of NW Rail Pier 5 (swing span) to NW Rail Pier 4 and Pattullo Pier 3 when comparing the Short Span Option to the Stage 1 Reference Concept. However, on the south side of NW Rail Pier 5 between NW Rail Piers 5 and 6, and further downstream between NW Rail Pier 5 and Pattullo Pier 4, there was up to 5 m less scour when compared to the Stage 1 Reference Concept results (Figure 4-44). Scour and deposition was minimal (±3 m) between NW Rail Piers 6 and 9 and the Pattullo Bridge with the Short Span Option installed when compared to both the Stage 1 Reference Concept and the 2016 bed levels.

For both the Stage 1 Reference Concept and the Short Span Option, scour at the NW Rail bridge was minimal at the low winter flow with little change observed in the north side of the river. For the Stage 1 Reference Concept, there was only minor scour near the piers in the south side of the river, and there was only 1 to 2 m of scour at the NW Rail Bridge in the south side of the river for the Short Span Option.

4.3.2.2 Pattullo Bridge

For the flood of record test, scour impacts to the Pattullo bridge with either the Stage 1 Reference Concept or Short Span Option installed were significant, but not as severe as those at the NW Rail bridge. Additional mitigation should be anticipated. For the Stage 1 Reference Concept, riprap at the nose of Pattullo Pier 2 launched, although the deepest scour near the pier remained steady at approximately -28 m. Bed levels on the south side of Pattullo Pier 5 lowered by about 5 m to El. - 16 m. Scour downstream between Pattullo Pier 4 and NW Rail Pier 5 increased by up to 10 m to El. -28 m. For the Short Span Option, scour increased by 3 to 5 m at NW Rail Pier 4 and Pattullo Pier 3 when compared to the Stage 1 Reference Concept. Riprap at the nose of NW Rail Pier 4 launched, but there was no significant unravelling of the protection at Pattullo Pier 3. Scour downstream between Pattullo Piers 4 and 5 increased by up to about 5 m. The bed on the south side of Pattullo Pier 5 scoured to El. -15 m, which was similar to the Stage 1 Reference Concept.

For both the Stage 1 Reference Concept and the Short Span Option, scour at the Pattullo bridge for the 200-Year winter flow test was similar to the flood of record test. For the Stage 1 Reference Concept, the deepest scour extended to El. -27 m, between Piers 2 and 3. Deep scour to El. -29 m occurred about 50 m downstream of Pier 5 on the south side, to El. -26 north of Pier 2, and to El. -25 downstream between Pier 4 and NW Rail Pier 5. There was minor launching of the apron at Pattullo Piers 2 and 4, and the existing apron was launching on north-east (right) side of Pattullo Pier 3 and the south side of Pattullo Pier 5. For the Short Span Option, maximum scour between Pattullo Piers 1 to 3 was about 5 m with the deepest scour at El. -26.5 m between Piers 2 and 3. There was minor launching of the rock protection on both sides of Pattullo Pier 2. From Pattullo Piers 4 and 5 to the Skytrain Bridge, scour increased by 3 to 6 m compared with the Stage 1 Reference Concept, but there was about 5 m less scour between Pattullo Pier 5 and the south bank.

At the low winter flow, both the Stage 1 Reference Concept and the Short Span Option resulted in scour along the Pattullo Bridge that was generally limited to 2 to 5 m in isolated locations across the river. The bed remained essentially unchanged between Pattullo Pier 3 and the north bank for both the Stage 1 Reference Concept and Short Span Option. Between Pattullo Pier 3 and NW Rail Pier 5 (swing span), the bed with the Short Span Option installed lowered to El. - 23.5 m, which is about 5 m below the original 2016 survey bed levels and the Stage 1 Reference Concept bed levels. The minimum bed level between Pattullo Piers 4 and 5 was El. -18.5 m, which is similar to 2016 bed levels and the Stage 1 Reference Concept. The maximum scour between the south shore and Pattullo Pier 5 was 2 m, with either the Stage 1 Reference Concept or Short Span Option bridge installed.

4.3.2.3 Navigation Channels

For the Stage 1 Reference Concept and the Short Span Option, differences in the bed levels within the navigational channels upstream of the bridges were minor. For both bridge options, the river bed lowered at the bridge crossings by between 0 and 5 m when compared to the starting bed levels (June 2016 survey).

Compared with the baseline results, significant bed level increases occurred in some areas within the Secondary Navigation Channel for the both the Stage 1 Reference Concept and the Short Span Option at the flood of record. For the most part, these represented reduced scour during the flood as opposed to sediment deposition (bed levels in these areas did not typically exceed the original 2016 bed level). For the Stage 1 Reference Concept, bed levels were up to 3 m higher within the Secondary Navigation Channel between Pattullo Piers 2 and 3, and up to 5 m higher upstream of the Stage 1 Reference Concept bridge between Piers N0 and N1, downstream of Pattullo bridge between Piers 4 and 5, and on the south side of the river along a distance of about 125 m downstream of Pattullo bridge. On the south side of the channel for approximately 300 m upstream of the bridges, bed levels were up to 5 m higher for the 200-Year winter flow than for the flood of record test, but remained well below 2016 bed levels.

There was minimal scour along the north bank and within the Secondary Navigation Channel for the Short Span Option at the flood of record and the 200-Year winter flow. Compared with the baseline and the Stage 1 Reference Concept, there was up to 5 m less scour north of the Secondary Navigation Channel and within the Secondary Navigation Channel with the Short Span Option installed. The exception was the river bed between SS1 and SS2 and NW Rail Piers 3 and 4 that was similar to the 2016 bed levels for the Short Span Option (including within the Secondary Navigation Channel), while it scoured by up to 7 m with the Stage 1 Reference Concept installed.

As for the Primary Navigation Channel, the baseline condition (flood of record) resulted in up to 5 m of deposition in a portion of the Primary Navigation Channel downstream of the Skytrain Bridge when compared with the starting bed levels in the model. However, this area was scoured by up to 6 m with the Stage 1 Reference Concept or the Short Span Option in place. Deposition of approximately 5 m above the original bed levels occurred in several locations on the south side of the river for the 200-Year winter flow, including within the Primary Navigation Channel downstream of NW Rail Bridge Pier 5, where bed levels reached up to El. -10 m. Deposition also developed on the south border of the Primary Navigation Channel downstream of the Pattullo Bridge extending almost to the Skytrain Bridge. For the Short Span Option at the flood of record and the 200-Year winter flow, deposition of up to 5 m over 2016 bed levels occurred in the Primary Navigation Channel downstream of Pattullo Pier 4, and this deposition extended from the Pattullo Bridge to the downstream end of the model for the 200-Year winter flow, as shown in Figure 4-43. This represented a bed level increase of up to 6 m compared with baseline conditions and up to 9 m compared with the Stage 1 Reference Concept.

Generally, resulting bed levels remained similar to the starting (2016 survey) elevations at the low winter flow with large flood tide test scenario.

5 CONCLUSIONS

Testing showed that changes in flow patterns and velocities were generally limited to local effects around the piers with either the Stage 1 Reference Concept or Short Span Option installed, while scour and sediment deposition effects were more pronounced. Minor differences noted in the flow patterns and velocities included:

- Flow at the downstream end of NW Rail Pier 5, between the two navigation channels, was angled slightly more to the south for both the Stage 1 Reference Concept and the Short Span Option when compared with the baseline condition. The Short Span Option resulted in an increase of 0.5 m/s in surface velocities along the sides of NW Rail Pier 5 (swing span) at the Flood of Record and along the south side of NW Rail Pier 5 for the 200-year winter flow.

- Surface velocities within the southern edge of the Primary Navigation channel were between 1.0 to 2.5 m/s lower in the shadow of Pylon SS3 of the Short Span Option when compared to velocities in that area for both the baseline and the Stage 1 Reference Concept.

- The Short Span Option resulted in a 0.5 m/s increase in the surface velocities and 0.5 to 1.0 m/s in mid-depth velocities between Pattullo Piers 4 and 5, which remained outside of the south limit of the Primary Navigation Chanel.

- At the flood of record and the 200-year winter flow, mid-depth velocities for the Short Span Option were generally 0.25 to 0.5 m/s higher in the Secondary Navigation Channel when compared to both the baseline and the Stage 1 Reference Concept, and 0.25 to 0.75 m/s higher within the Primary Navigation Channel downstream of the Skytrain Bridge.

The model reproduced bedload transport processes and bedforms in a realistic manner and provided useful insight into potential scour and deposition due to the Stage 1 Reference Concept and Short Span Option. Key findings included:

- Scour effects were generally most severe for the flood of record test when compared to the results from the 200-Year winter flow and the low winter flow with large flood tide test scenarios.

- Generally, bed levels between the replacement bridge alignment and the Pattullo Bridge lowered up to 5 m at all three test flow scenarios for both the Stage 1 Reference Concept and the Short Span Option. However, the Short Span Option resulted in bed levels that were generally 1 to 2 m lower along the south side of the river in the vicinity of the bridge crossings when compared to the baseline and the Stage 1 Reference Concept.

- The deepest scour at the Stage 1 Reference Concept piers occurred downstream of the north pylon N0, between N0 and NW Rail Pier 4, at the flood of record. The bed between N0 and NW Rail Pier 4 scoured to El. -39 m (up to 18 m lower than the baseline bed level) and caused collapse of the rock mound at NW Rail Pier 4. The maximum scour at Pier N1 was El. -29 m at the nose, and El. -26.5 m at the nose of Pier N2. Scour between N2 and NW Rail Pier 3 extended to El. -26 m and caused launching of the existing protection on north-east (right) side.

- For the Stage 1 Reference Concept, the toe of the slope at the south pylon, S0, was scoured by about 3 m at the flood of record and the low winter flow, but by about 10 m to El. -15 m at the 200 year winter flow. Minor riprap launching occurred, but the piles were not exposed.

- Along the Short Span Concept alignment, the deepest scour occurred between Pier SS1 and the north bank at the flood of record, reaching a depth of El. -34 m, which is about 14 m lower than the baseline bed levels and about 8 m lower than the Stage 1 Reference Concept bed levels. However, the level of scour in this area may have been exaggerated in the model for the flood of record test. For the 200 year winter flow, the scour at Pier SS1 reached a maximum of El. - 23.0 m at the downstream end of the pier. The maximum scour at Pylons SS2 and SS3 was El. - 26 m and El. -23 m, respectively. This translates into approximately 8 m of scour at Pylon SS2 and approximately 13 m of scour at Pylon SS3. The south bank in the vicinity of Pylon SS4 scoured by approximately 5 to 6 m and the scour exposed the sheet pile wall at Pylon SS4 to approximately El. - 7 m at the flood of record and to El. -6 m at the 200 year winter flow.

- Scour impacts to the NW Rail bridge at the flood of record with either the Stage 1 Reference Concept or the Short Span Option installed were significant, and would require mitigation. Compared with the baseline, the Stage 1 Reference Concept resulted in 10 to 15 m deeper scour at NW Rail Piers 3 to 8 and Pier 6 protection. Riprap launched at all of these piers, and the piles were exposed at NW Rail Piers 7, 8 and Pier 6 protection. The deepest scour was to El. -28 m, on the downstream south side of NW Rail Pier 5.

- Compared with the Stage 1 Reference Concept, the Short Span Option at the flood of record resulted in 10 to 15 m less scour at NW Rail Pier 4, and up to 3 m more scour along both sides of NW Rail Pier 5. Scour exposed the piles at Piers 7 and 8 and launched the rock protection at NW Rail Pier 7. The deepest scour occurred between the north pylon N0 and NW Rail Pier 4, where the bed scoured to El. -39 m (up to 18 m lower than the baseline bed level) and caused collapse of the rock mound at NW Rail Pier 4.

- Scour impacts to the Pattullo bridge were significant, but not as severe as those at the NW Rail bridge. Mitigation measures should be anticipated.

- For the Stage 1 Reference Concept, riprap at the nose of Pattullo Pier 2 launched, although the deepest scour near the pier remained steady at approximately -28 m. Bed levels on the south side of Pattullo Pier 5 lowered by about 5 m to El. - 16 m. Scour downstream between Pattullo Pier 4 and NW Rail Pier 5 increased by up to 10 m to El. -28 m.

- For the Short Span Option, scour increased by 3 to 5 m at NW Rail Pier 4 and Pattullo Pier 3 when compared to the Stage 1 Reference Concept. Riprap at the nose of NW Rail Pier 4 launched, but there was no significant unravelling of the protection at Pattullo Pier 3. Scour downstream between Pattullo Piers 4 and 5 increased by up to about 5 m. The bed on the south side of Pattullo Pier 5 scoured to El. -15 m, which was similar to the Stage 1 Reference Concept.

- Differences in the bed levels within the navigational channels upstream of the bridges were minor for both the Stage 1 Reference Concept and the Short Span Option, and the river bed lowered at the bridge crossings by between 0 and 5 m when compared to the starting bed levels (June 2016 survey).

- Compared with the baseline results, significant bed level increases occurred in some areas within the Secondary Navigation Channel for the both the Stage 1 Reference Concept and the Short Span Option at the flood of record. For the most part, these represented reduced scour during the flood as opposed to sediment deposition.

- For the Stage 1 Reference Concept, bed levels were up to 5 m higher than the baseline developed at some locations within the Primary and Secondary Navigation Channels and on the south side of the channel.

- Compared with the baseline and the Stage 1 Reference Concept, there was up to 5 m less scour north of the Secondary Navigation Channel and within the Secondary Navigation Channel with the Short Span Option installed. The exception was the river bed between SS1 and SS2 and NW Rail Piers 3 and 4 that was similar to the staring bed levels for the Short Span Option, but scoured by up to 7 m with the Stage 1 Reference Concept installed.

- Deposition of up to 5 m occurred in the Primary Navigation Channel downstream of Pattullo Pier 4 for the Short Span Option. This represented a bed level increase of up to 6 m compared with baseline conditions and up to 9 m compared with the Stage 1 Reference Concept. Protecting against scour at the bridges could potentially mitigate this deposition.

- The baseline condition resulted in up to 5 m of deposition in a portion of the Primary Navigation Channel downstream of the Skytrain Bridge at the flood of record, while this area was scoured by up to 6 m with the Stage 1 Reference Concept or the Short Span Option in place.

6 CLOSURE

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DISCLAIMER

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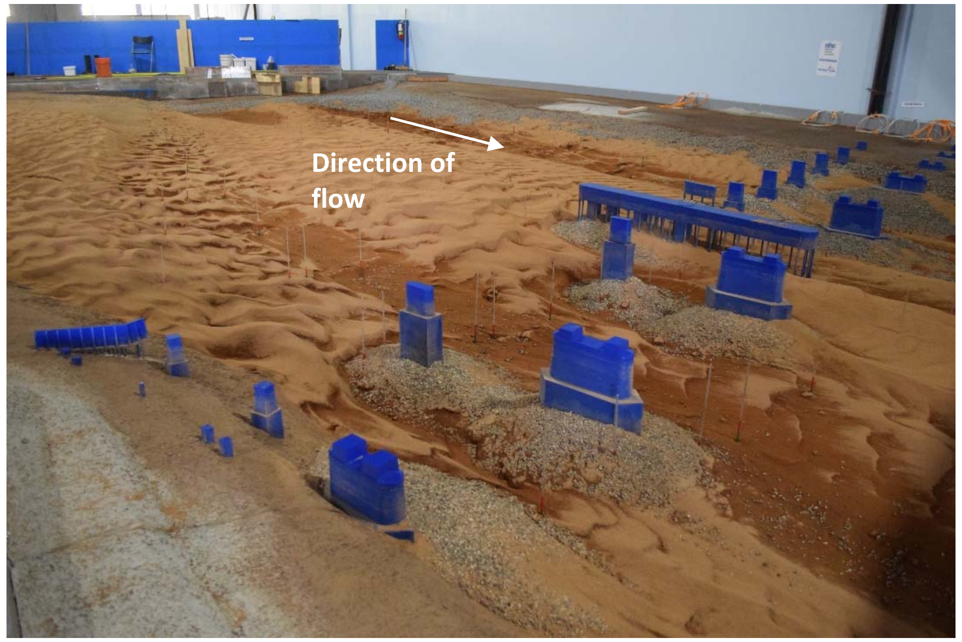
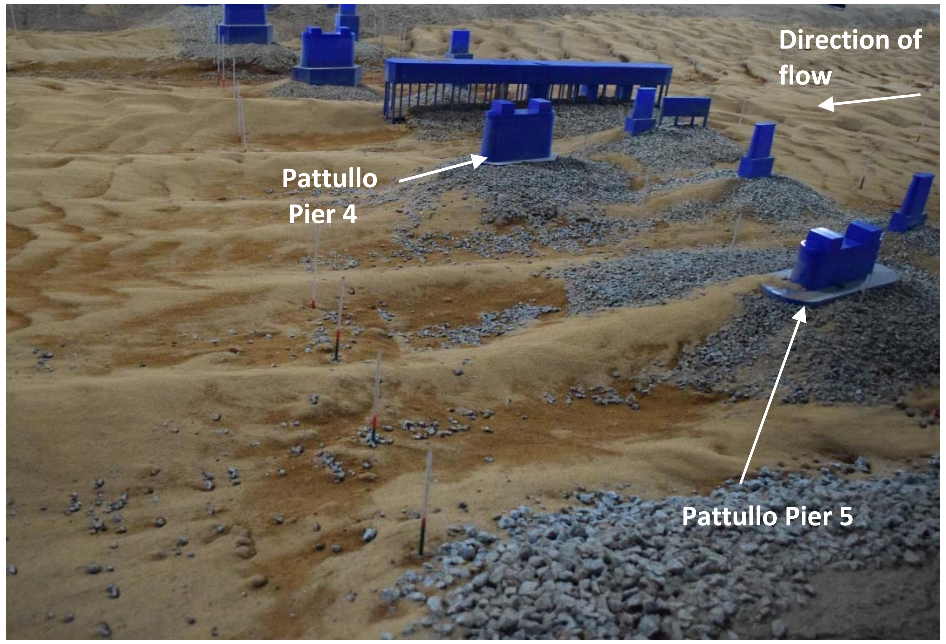
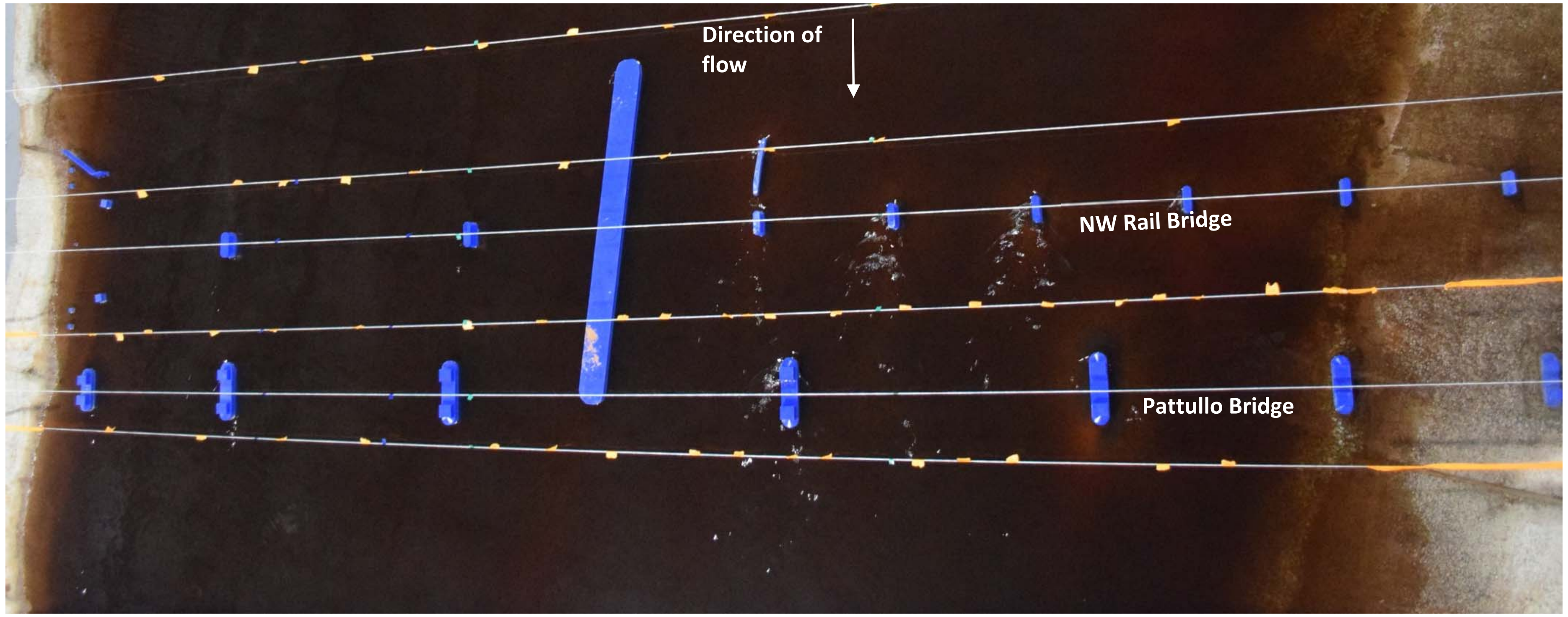


1) Oblique view from north side of river looking upstream at bed formations near the Pattullo and NW Rail Bridges after the Baseline test at the Flood of Record. (DSC 0921)



2) Oblique view from south side, looking upstream toward Pattullo Piers 4 and 5. (DSC 0974)

4) Overhead view of upstream reach of the physical model after the Baseline test at Flood of Record. (DSC 1009)

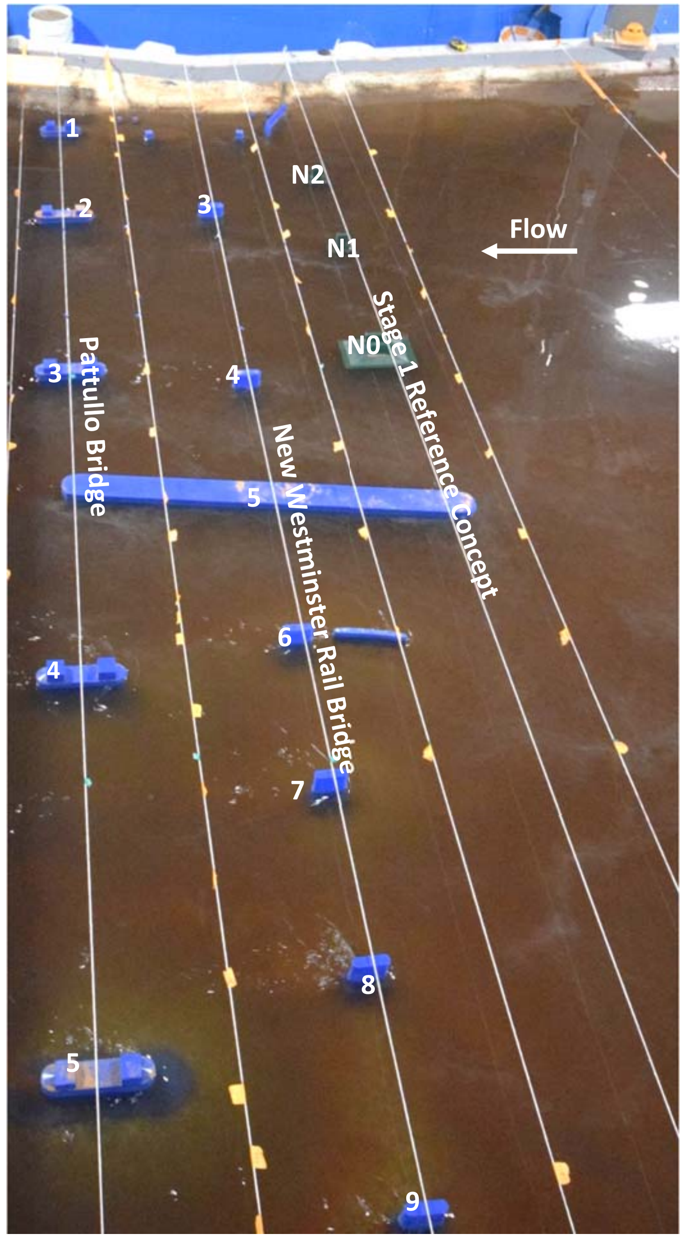


3) Overhead view of flow at bridge crossing during Baseline test. (DSC 0903)

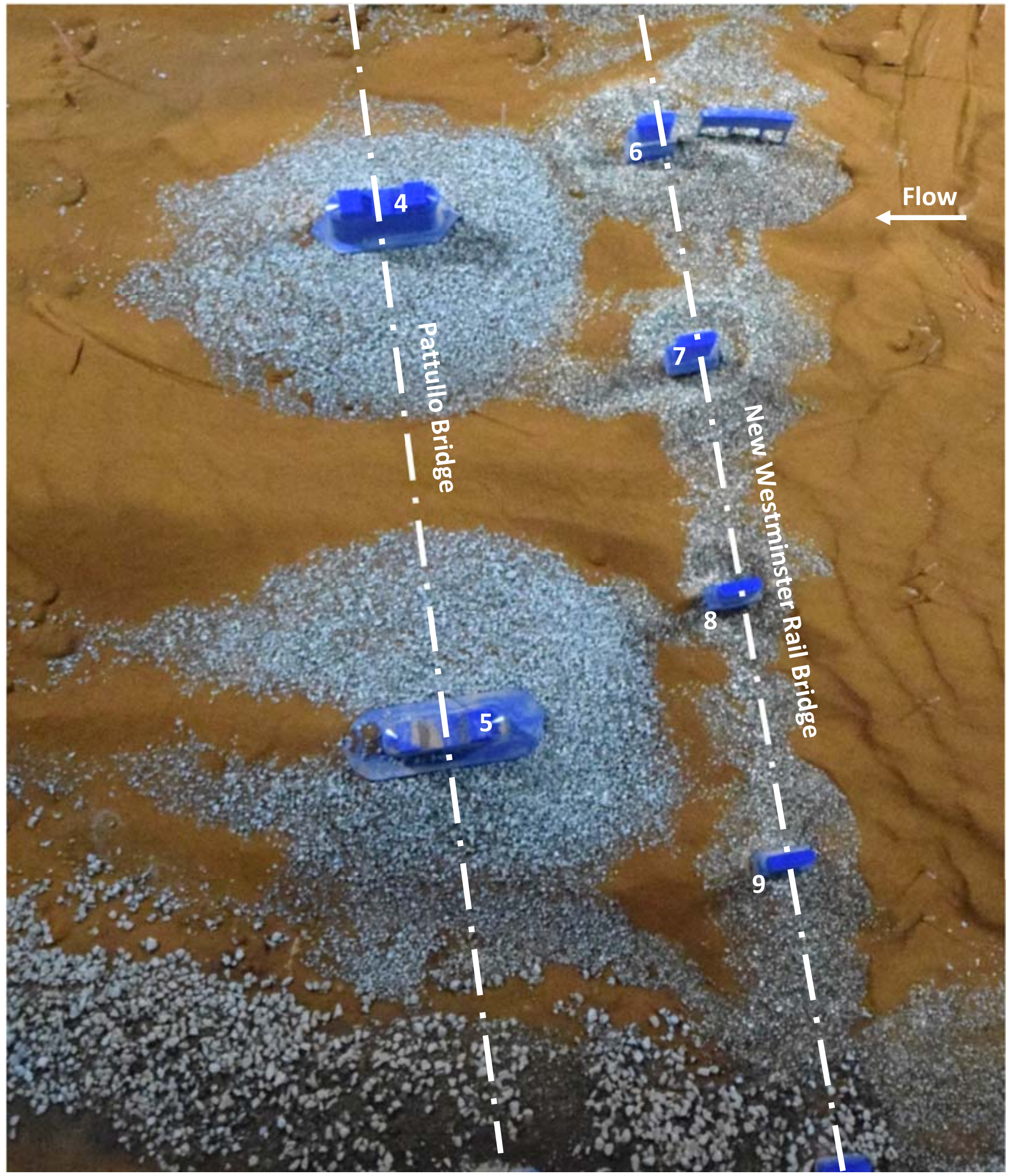
PATTULLO BRIDGE REPLACEMENT PROJECT
PHYSICAL MODEL STUDY

Baseline
Test B3: 21,200 m^3/s; El. 2.8 m

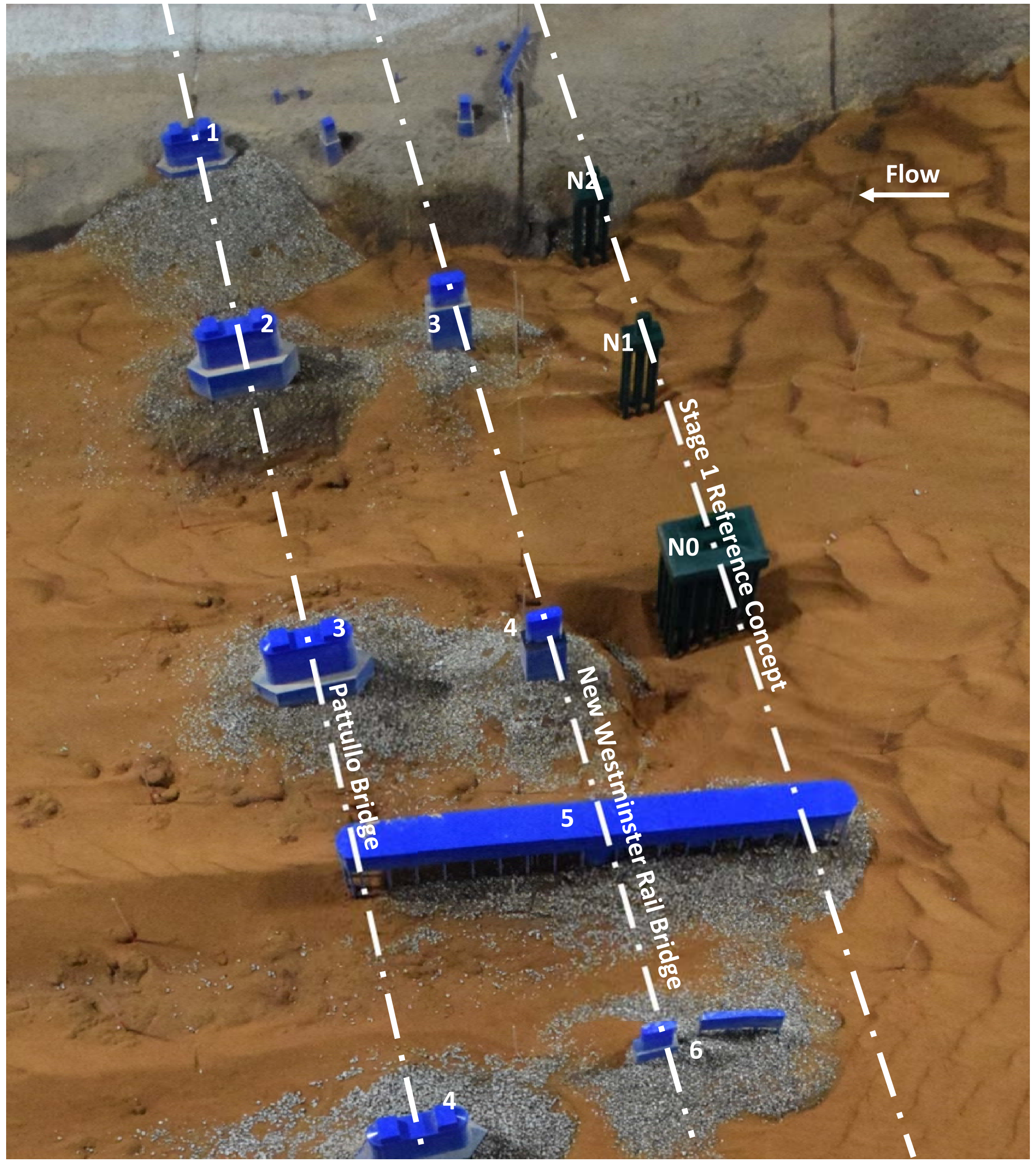
PHOTO PLATE 4-1



1) Overhead view of flow through bridge crossings at flood of record (DSC 1404)



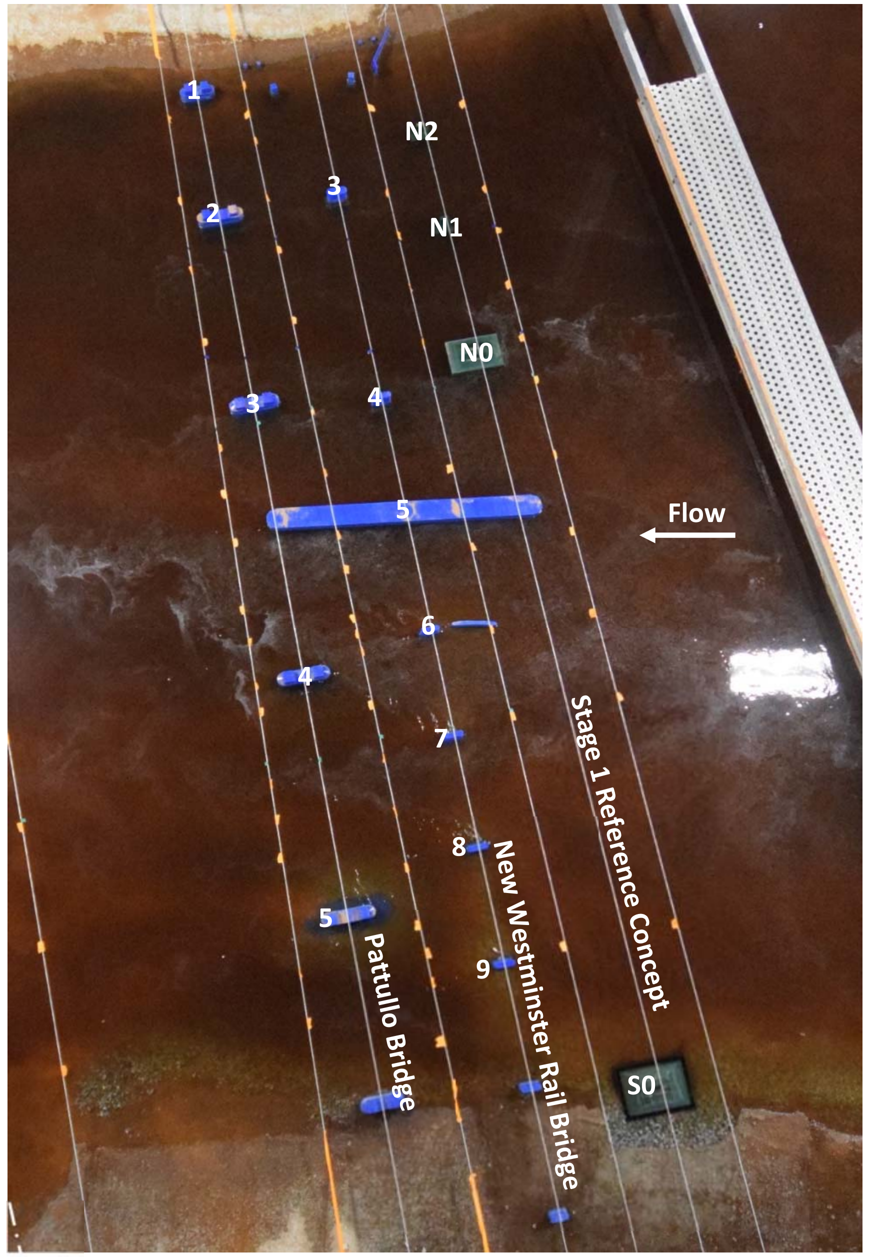
2) Overhead view of resulting bed formations on south side of river at Pattullo Bridge and NW Rail Bridge after flood of record test. (DSC 1442)



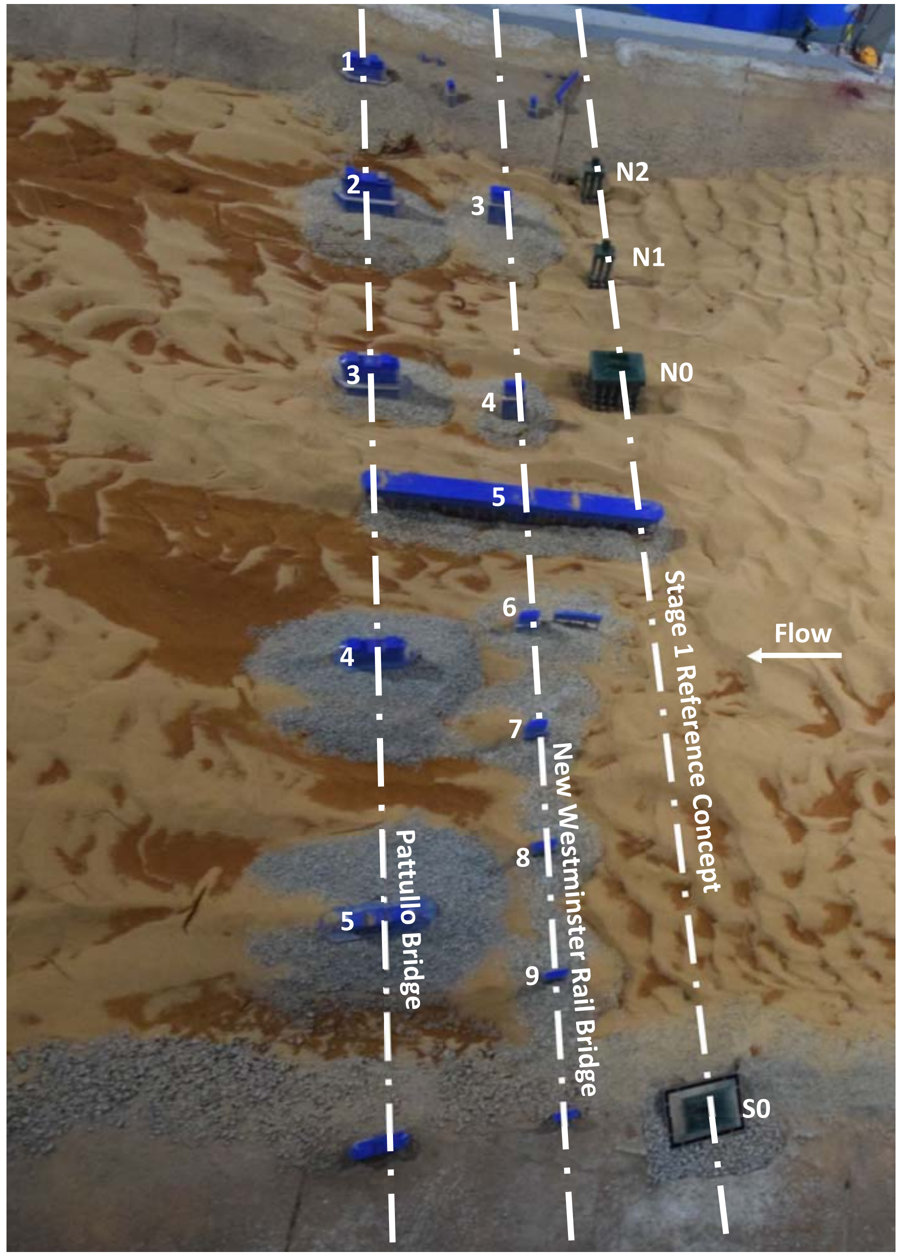
3) Overhead view of resulting bed formations on north side of river at Pattullo Bridge and NW Rail Bridge after flood of record test. (DSC 1231)

Stage 1 Reference Concept
Test RC1B: 21,200 m^3/s; El. 2.8 m

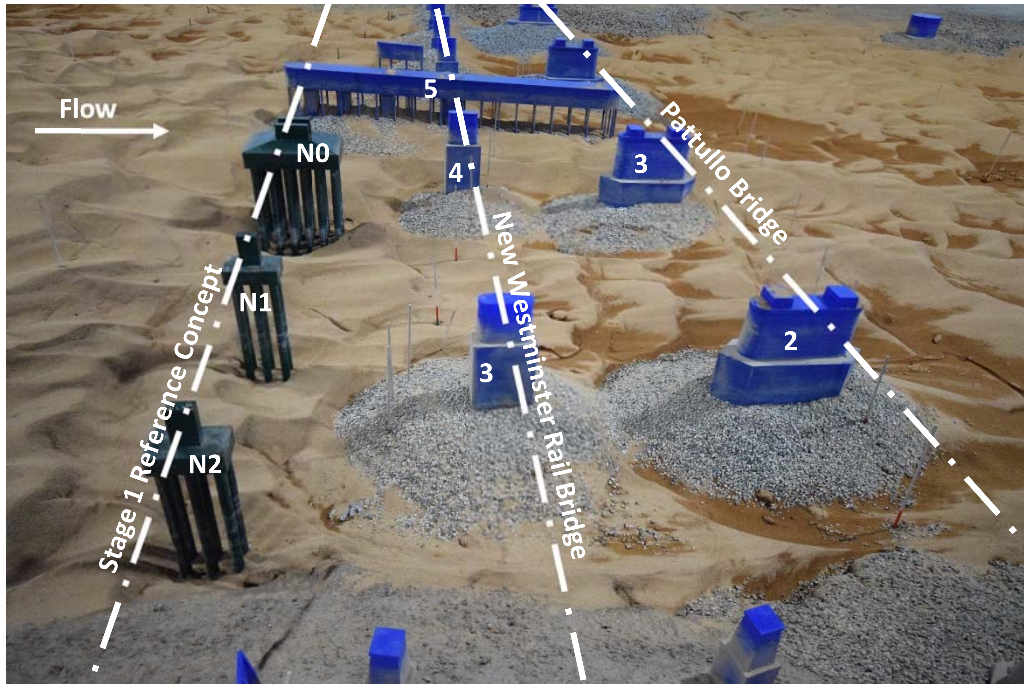
PHOTO PLATE 4-2



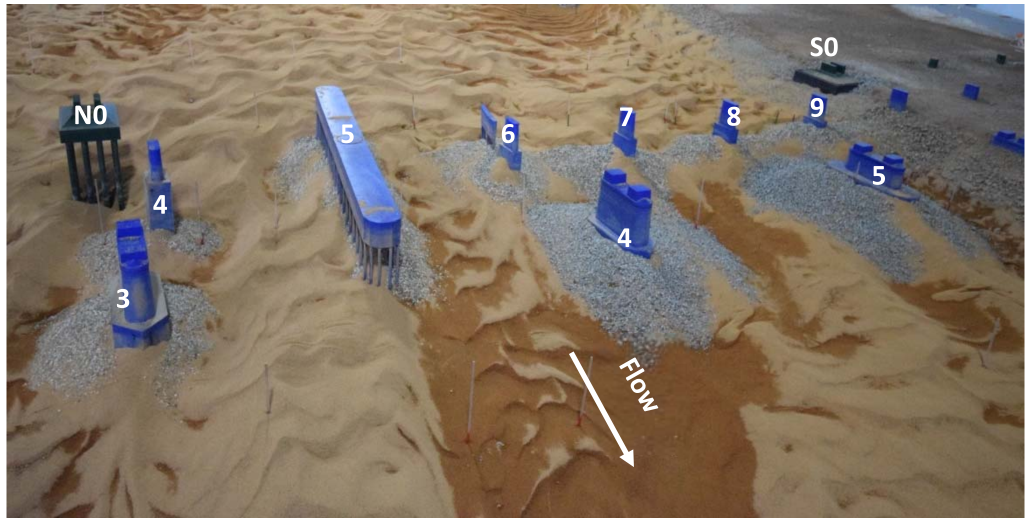
1) Overhead view of the model at the 200-year winter flow. (DSC 1601)



2) Overhead view showing the resulting bed at the bridge crossings. (DSC 1683)



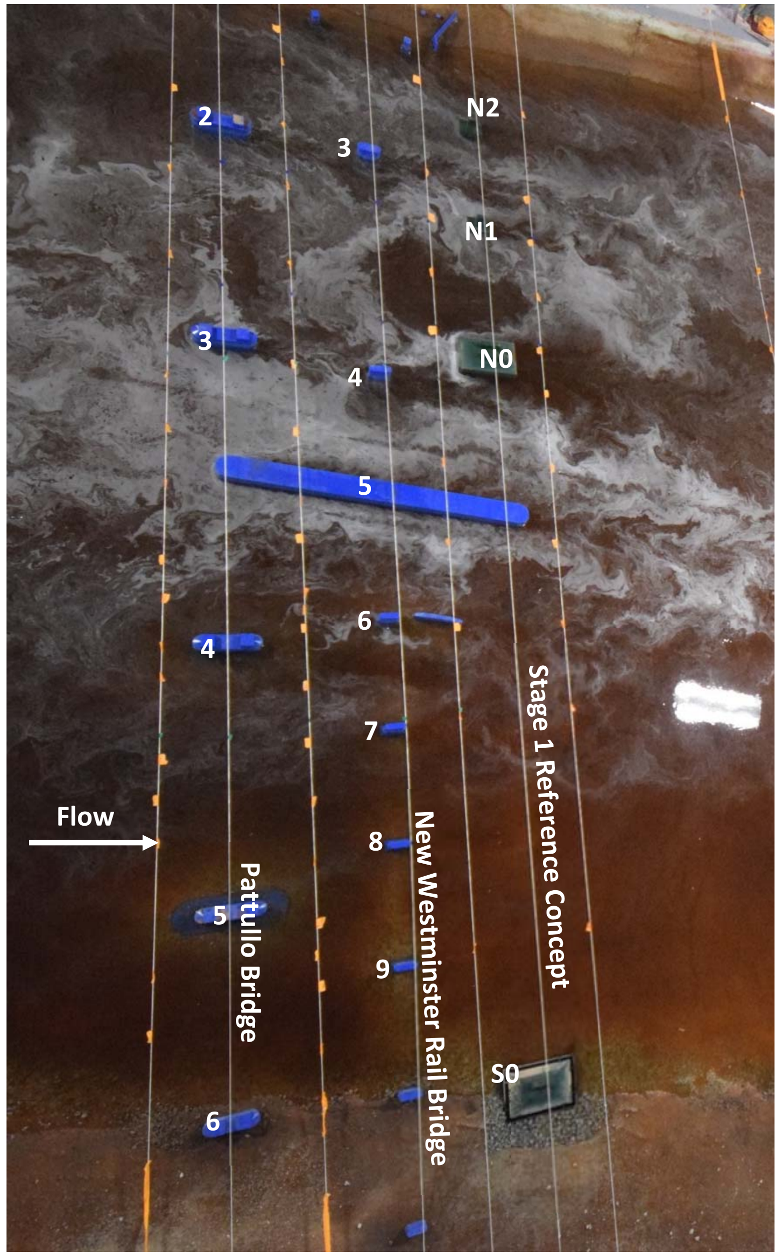
3) View looking south from New Westminster showing resulting bed on north side of river.(DSC 1661)



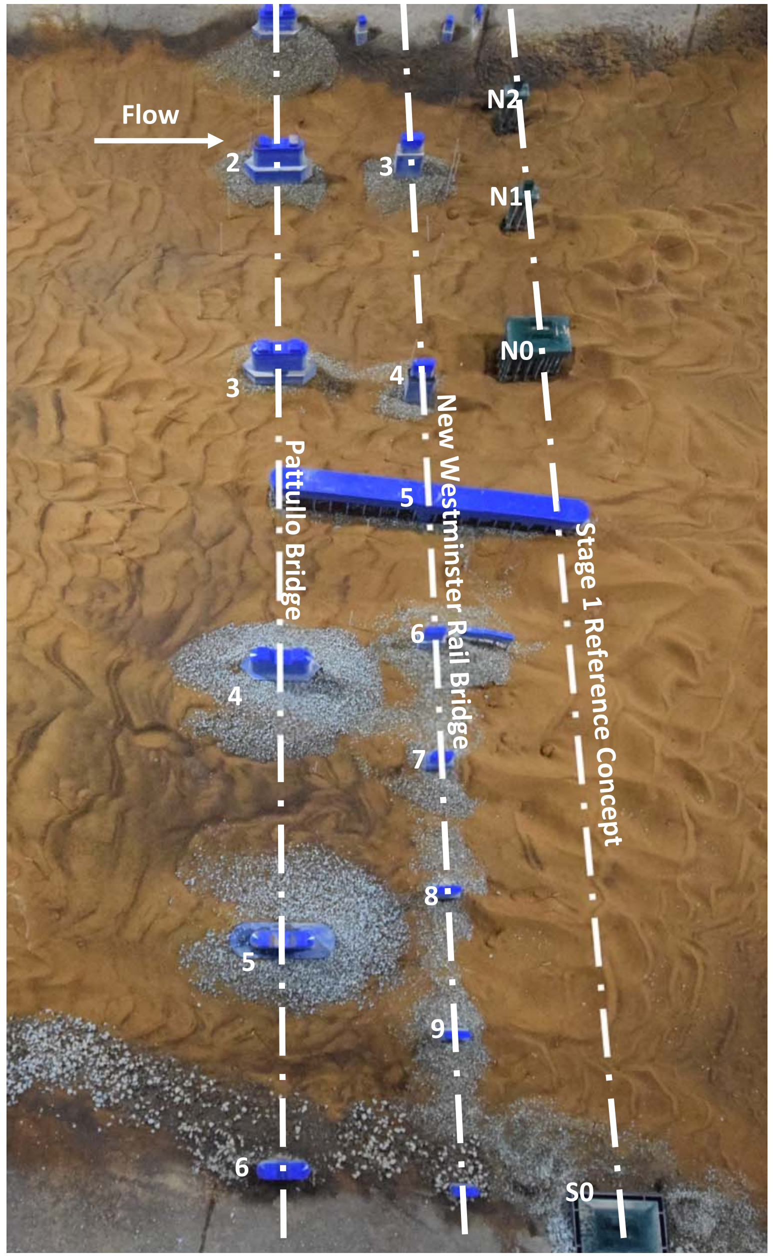
4) Resulting bed in model near bridge piers on south side of river. (DSC 1688)

Stage 1 Reference Concept
Test RC2B: 16,000 m^3/s; El. 1.4 m

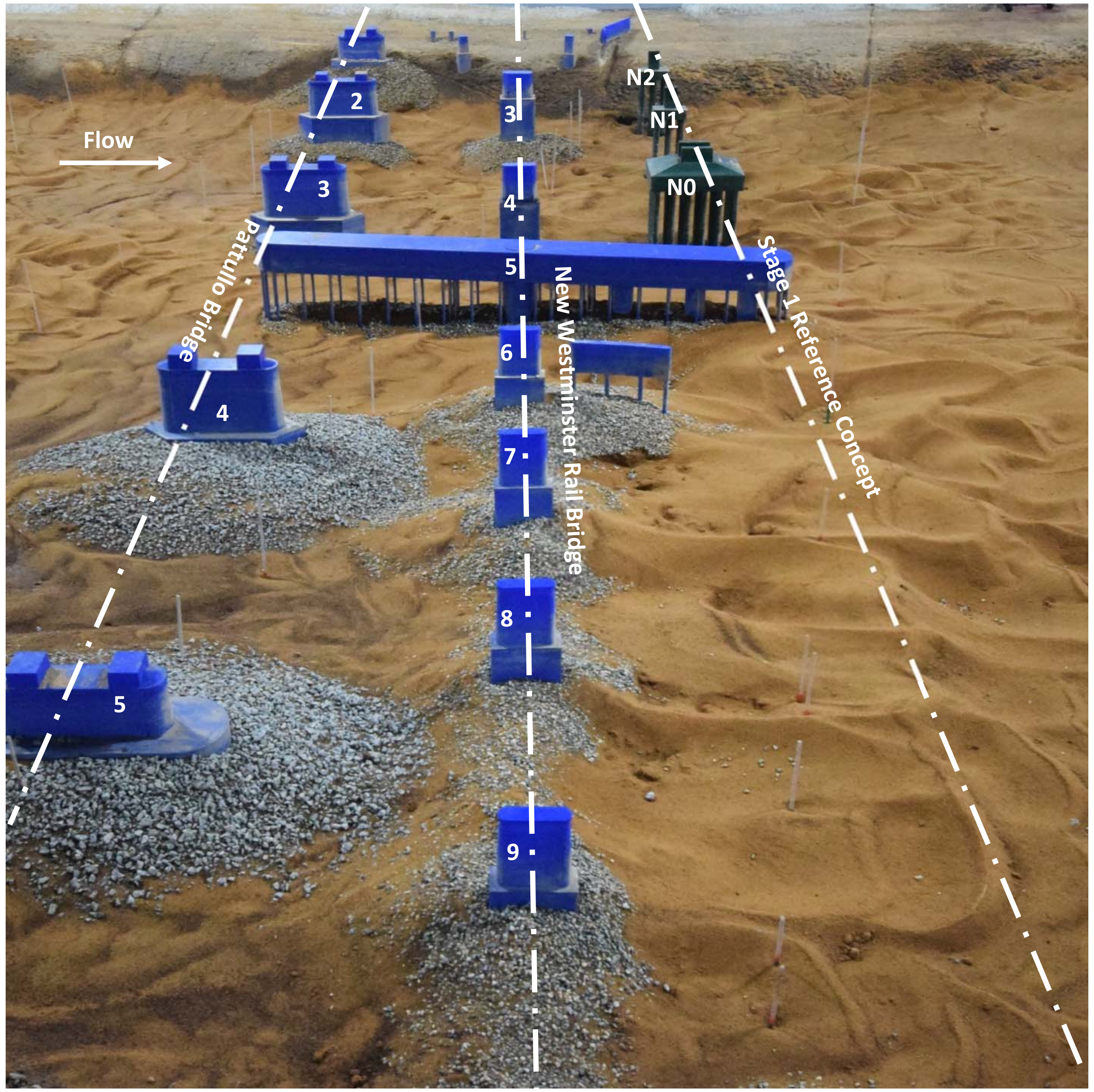
PHOTO PLATE 4-3



1) Overhead view of model at low winter flow. (DSC 1763)



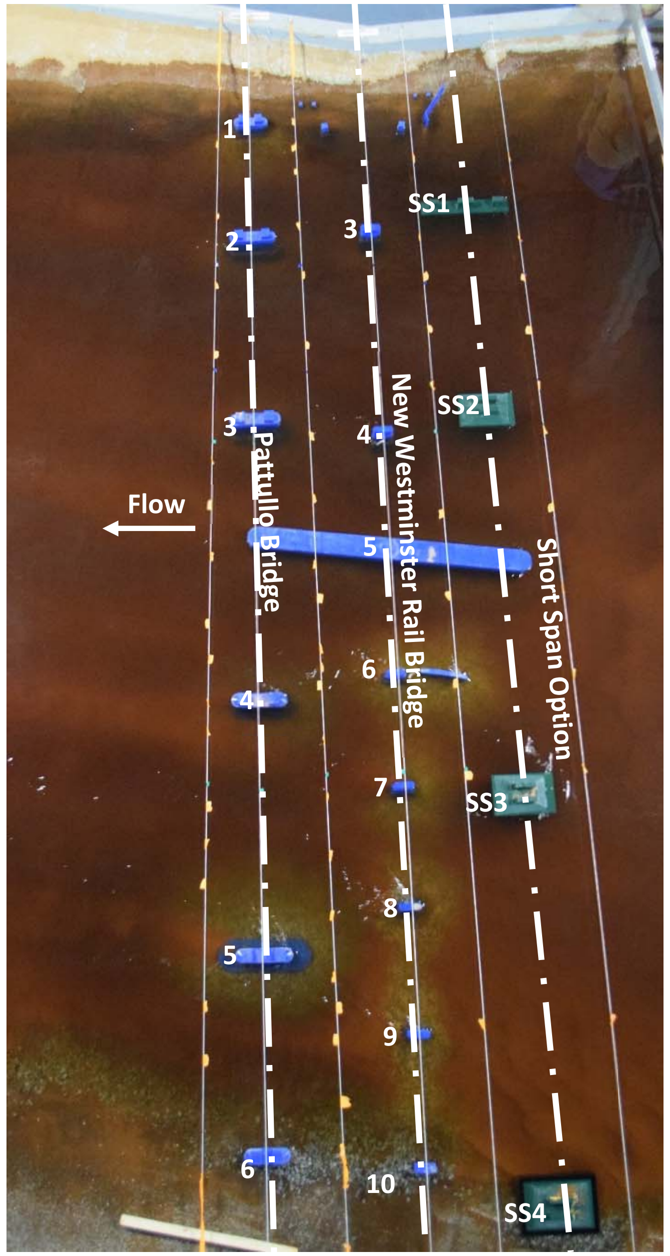
2) Overhead view showing bed levels after low winter flow test. (DSC 1771)



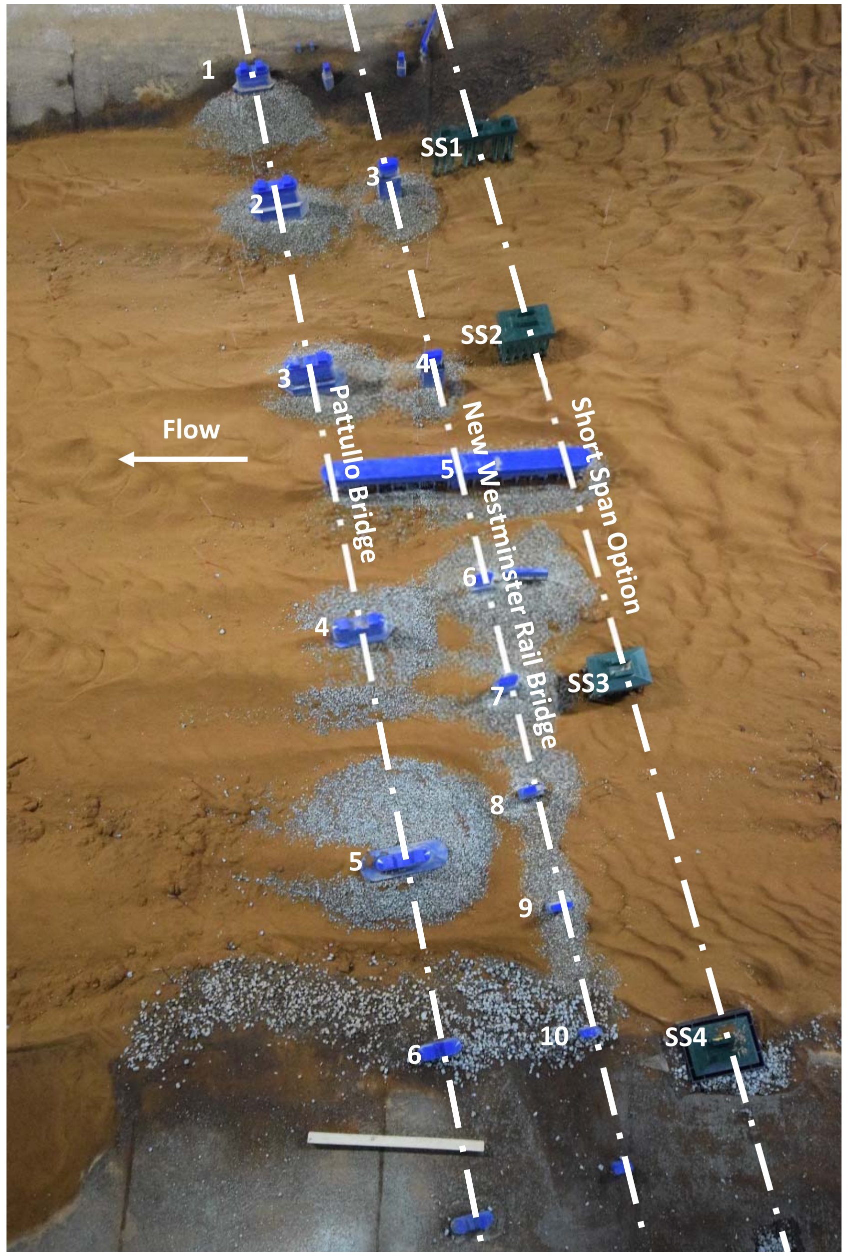
3) View from the south bank at the resulting model bed in the vicinity of the bridge crossings. (DSC 1761)

Stage 1 Reference Concept
Test RC3: 8,300 m^3/s; El. 0.0 m

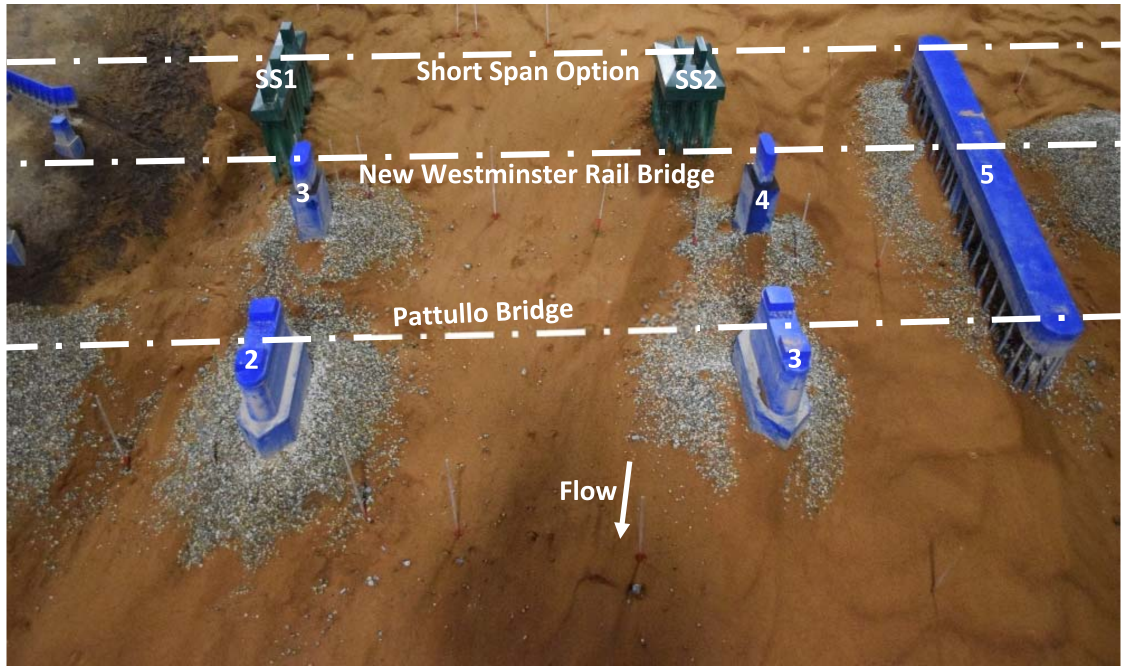
PHOTO PLATE 4-4



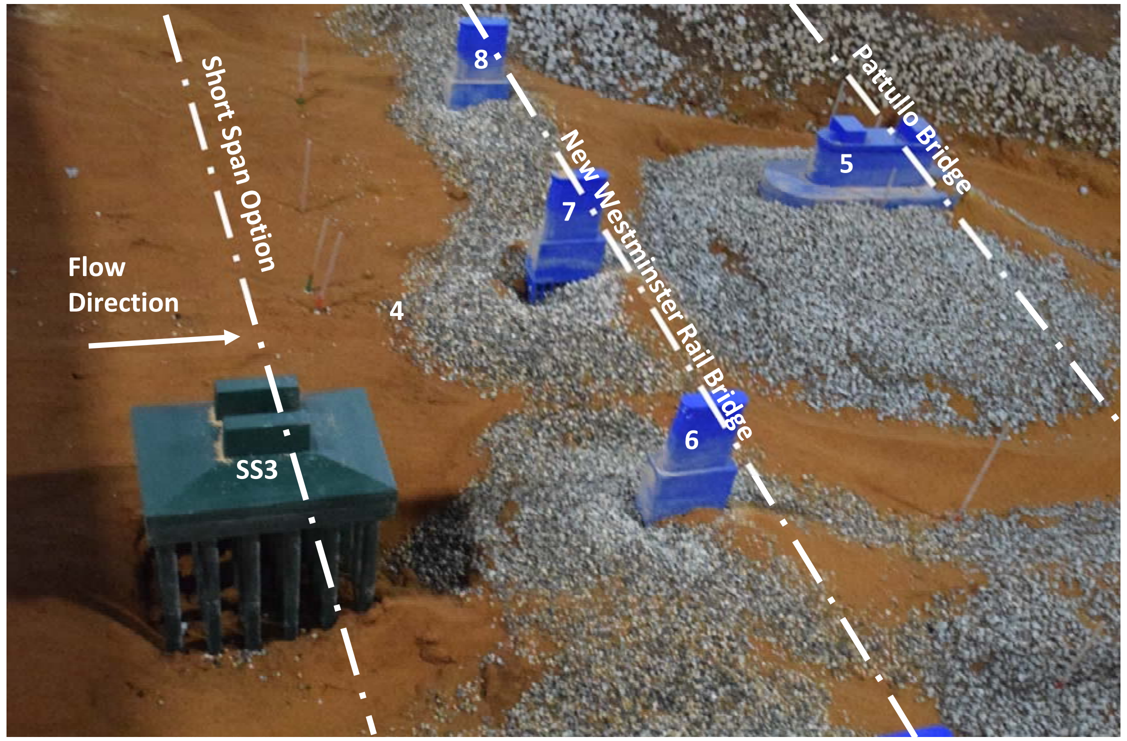
1) Overhead view of model flow through bridges at the flood of record. (DSC 2068)



2) Overhead view of resulting bed after flood of record test. (DSC 2072)



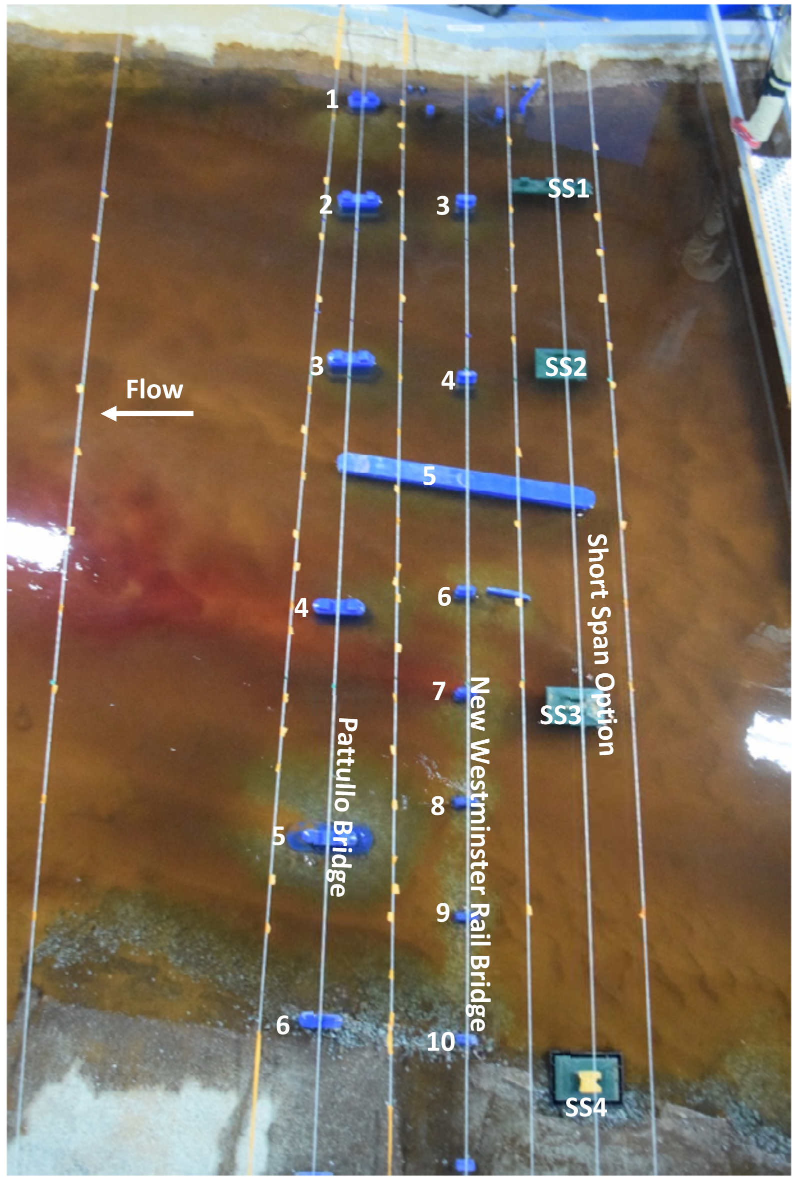
3) View looking upstream at resulting bed and bridge piers on north side of river. (DSC 2110)



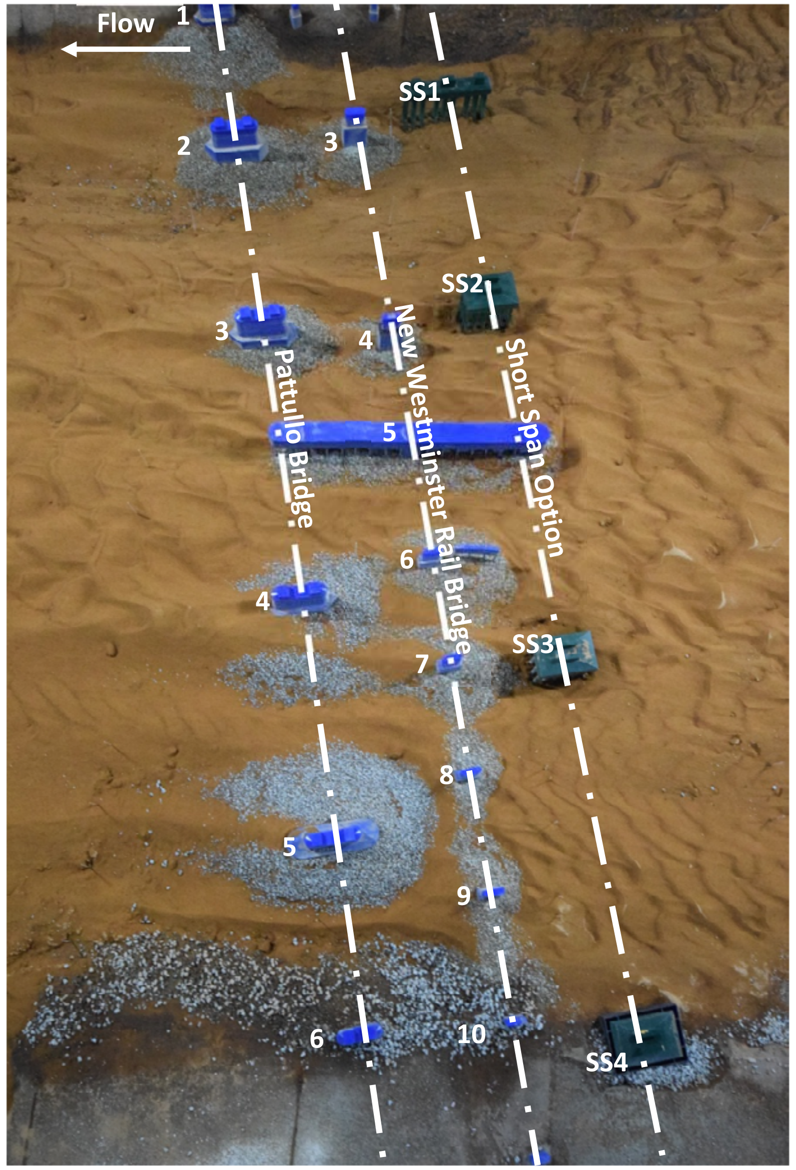
4) View from south bank of resulting bed and bridge piers on south side of river. (DSC 2131)

Short Span Option
Test SS1: 21,200 m^3/s; El. 2.8 m

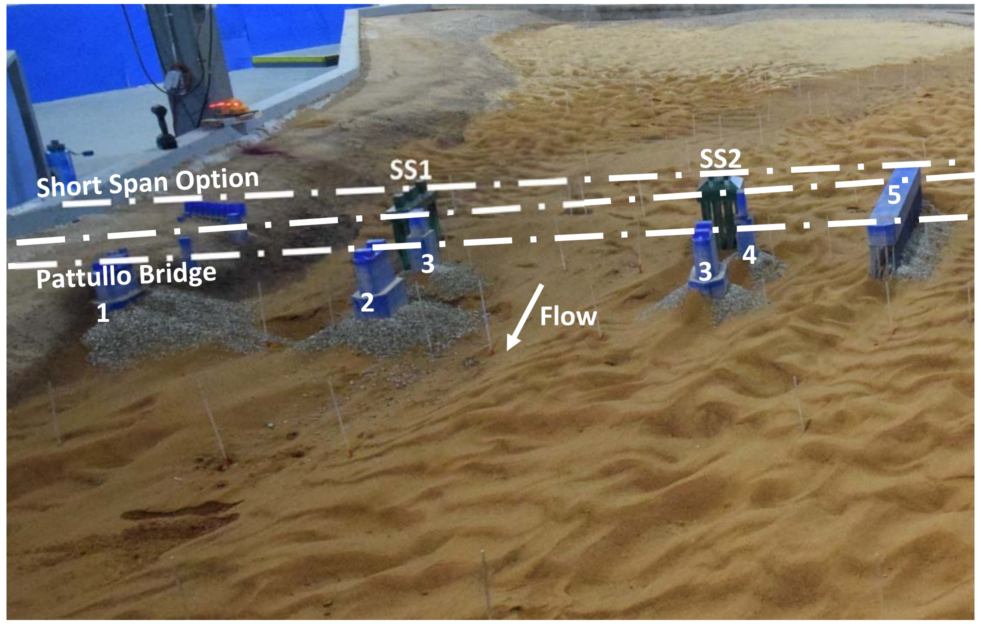
PHOTO PLATE 4-5



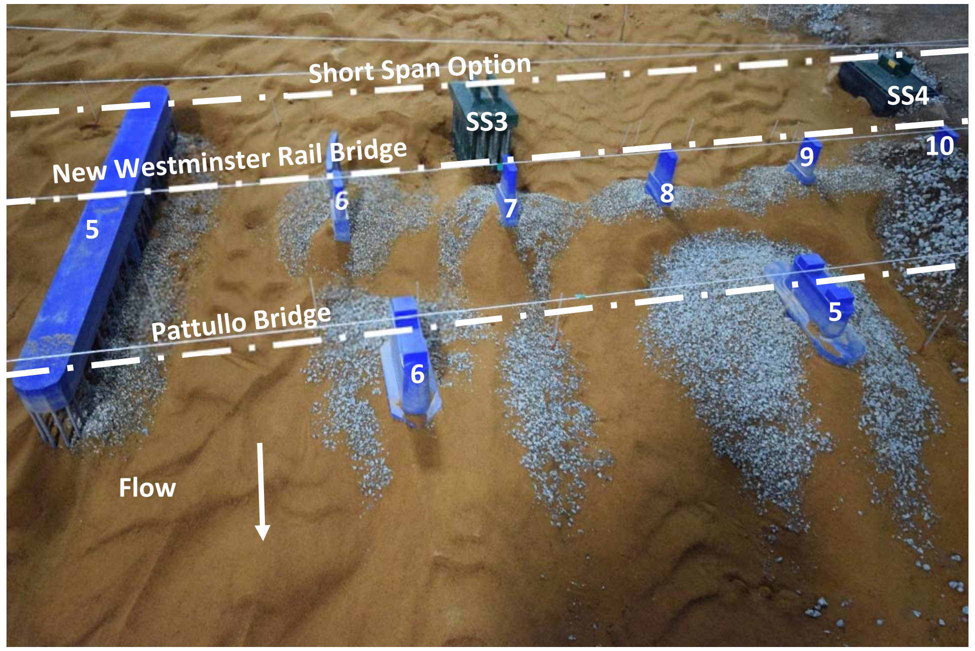
1) Overhead view of flow through model bridges at 200-Year winter flow. (DSC 1960)



2) Overhead view showing resulting bed after 200-Year winter flow. (DSC 2012)



3) View looking upstream of bridge piers and resulting bed on north side of river. (DSC 2015)

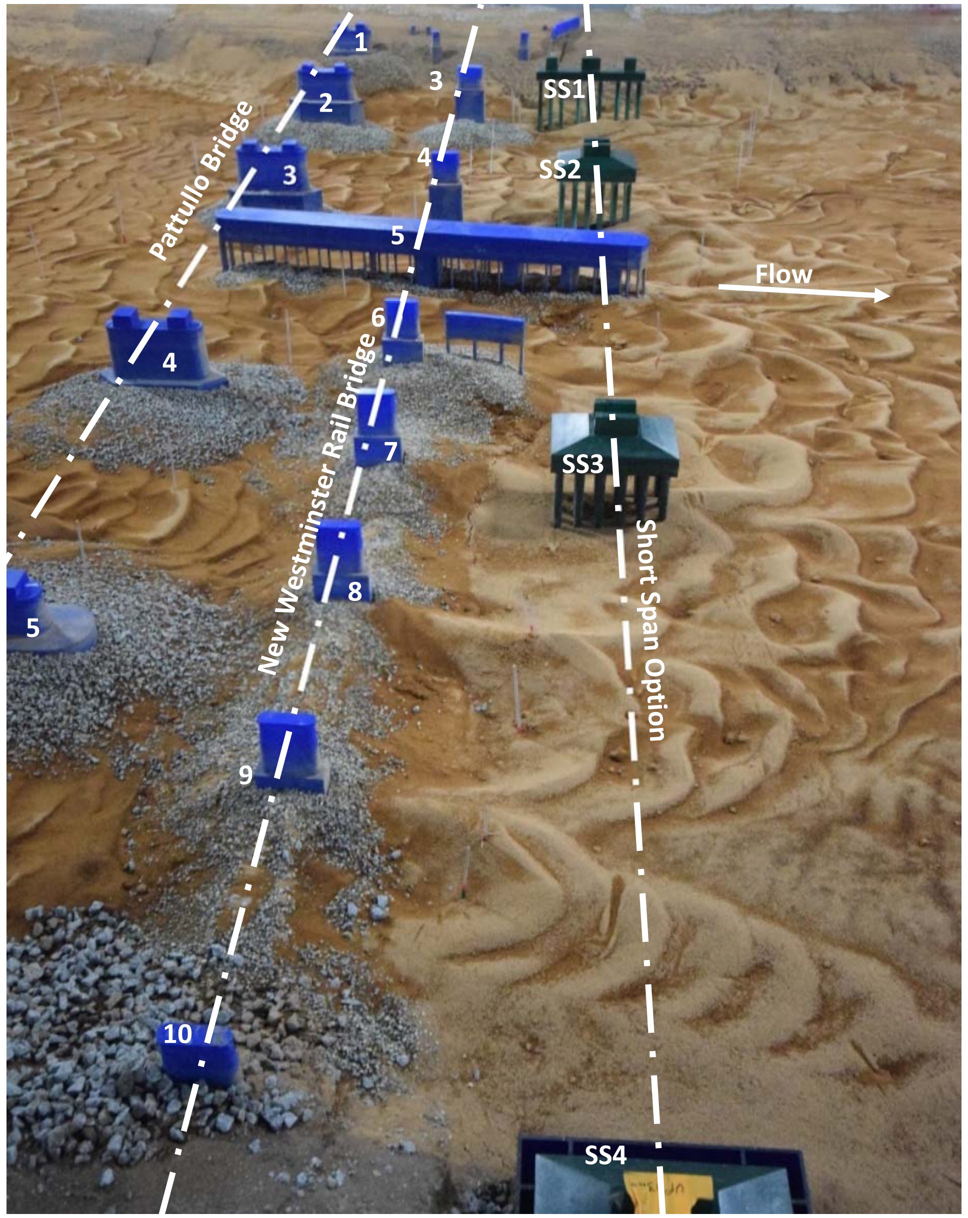


4) View looking upstream of bridge piers and resulting bed on south side of river. (DSC 1987)

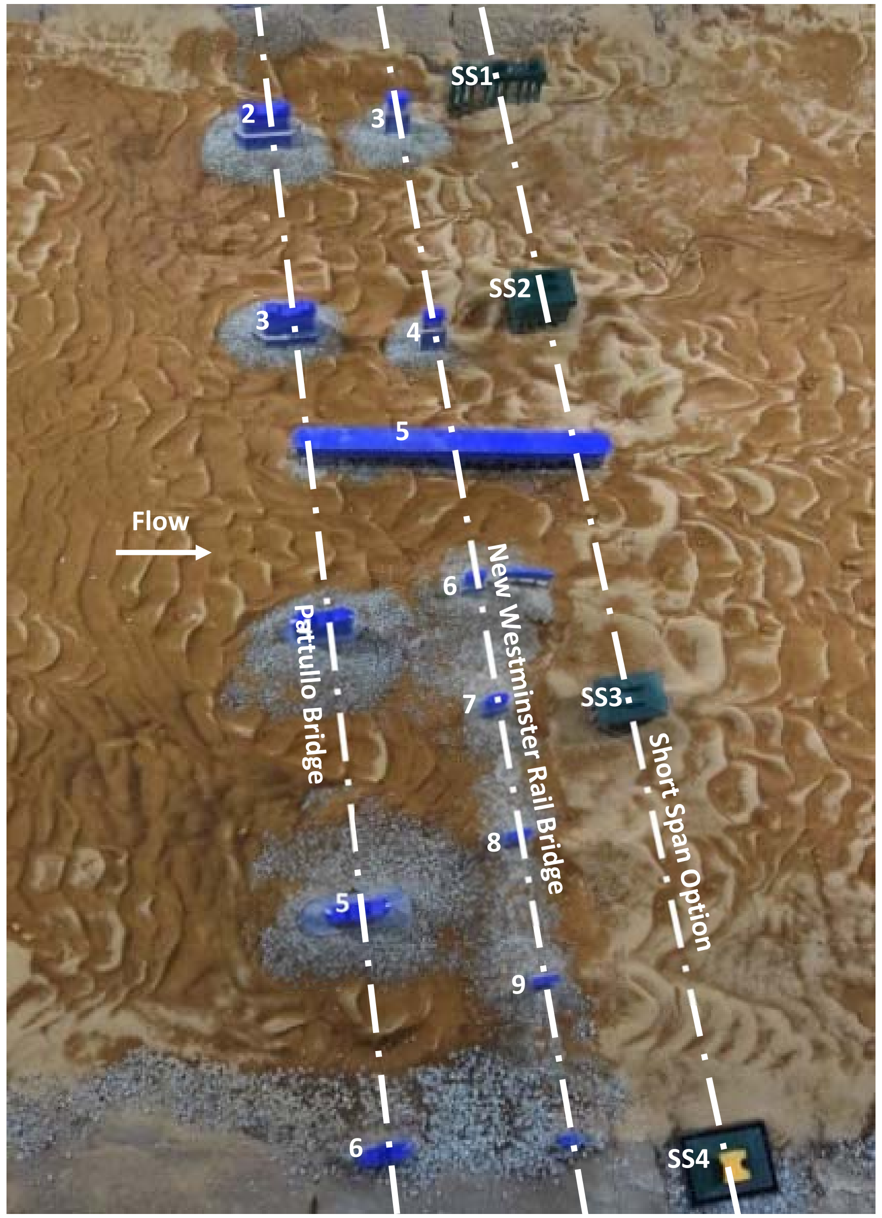
PATTULLO BRIDGE REPLACEMENT PROJECT
PHYSICAL MODEL STUDY

Short Span Option
Test SS2: 16,000 m^3/s; El. 1.4 m

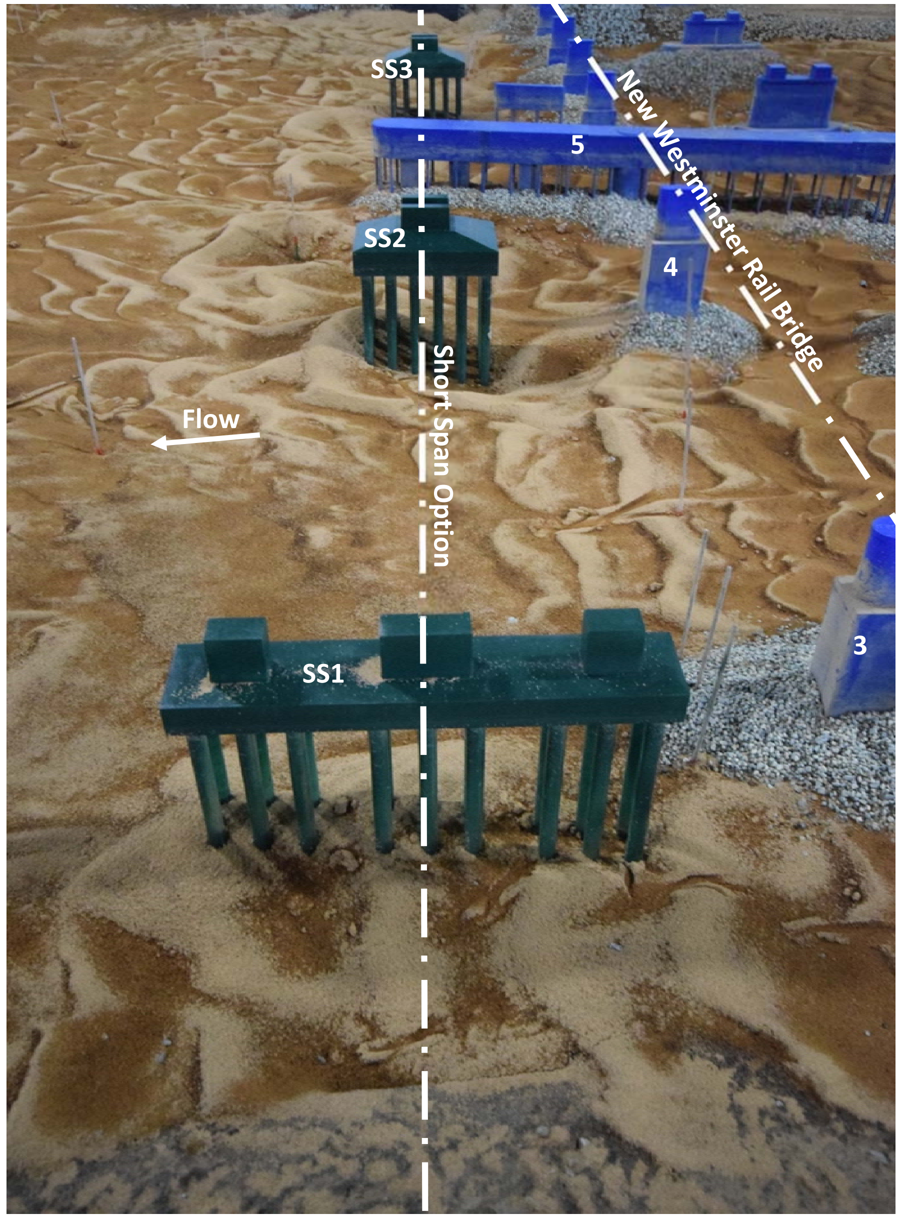
PHOTO PLATE 4-6



1) View from south bank of piers and resulting bed levels after low winter flow test. (DSC 1875)



2) Overhead view of piers and resulting bed levels after low winter flow test. (DSC 1880)



3) Resulting bed patterns at Pier SS1 and Pylon SS2. (DSC 1868)

PATTULLO BRIDGE REPLACEMENT PROJECT
PHYSICAL MODEL STUDY

Short Span Option
Test SS3: 8,300 m^3/s; El. 0.0 m

PHOTO PLATE 4-7