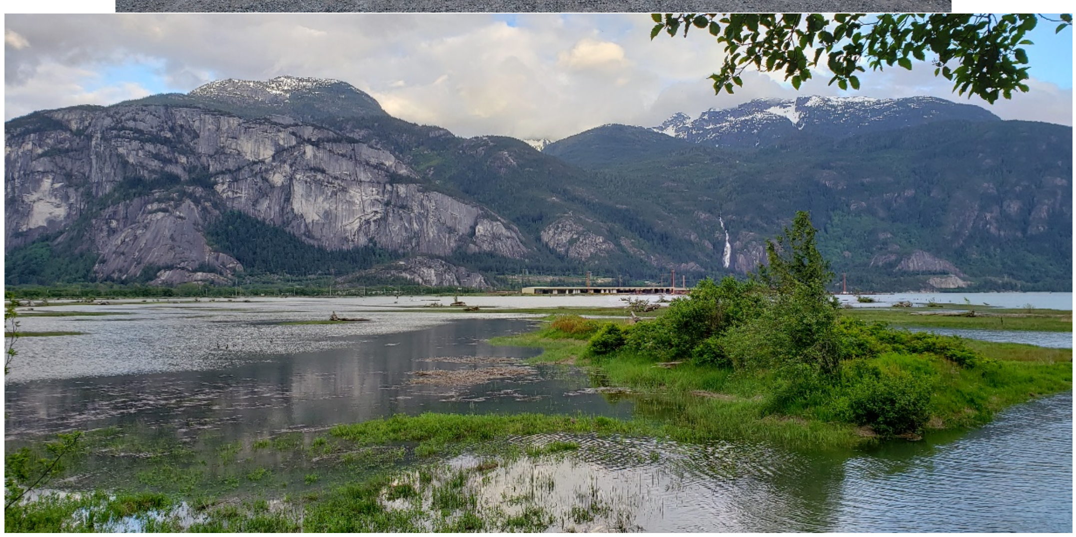
Squamish Training Berm Removal – Phase 2

Squamish River Watershed Society

Final Report



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Executive Summary

The Squamish River Watershed Society (SRWS) has been implementing restoration and enhancement works in the Squamish estuary. The SRWS plans to remove part of a coastal structure built in the 1970's (Squamish Training Berm) within the fish and wildlife structure area and therefore support the Central Estuary Restoration Project (CERP). The removal is aimed to preserve and restore the integrity of the Squamish River watershed, improving access and habitat in the Estuary for juvenile chinook.

SNC-Lavalin (SNCL) was retained by SRWS to conduct a comprehensive hydrodynamic and sediment transport model investigation to forecast the sedimentation process during a specific condition and to provide a comparative assessment between the current condition and a berm removal scenario. This study assesses the impacts of training berm removal to navigation (current speed), water levels, and sedimentation in the regionals adjacent to the existing berm. SNCL developed a hydrodynamic and sediment transport model coupled with wave modelling using the Delft3D Suite for the existing and future scenarios. The model was run for both scenarios for a period of fourteen days that included one typical storm event and an average winter river discharge. The model used for this study was developed in a triple-nested configuration to account for the complexity of the area. The coarse model has a resolution of 100x100 m and covers Howe Sound and provides boundary conditions of wave climate and tidal induced currents to the 20x20 m nested model at Squamish Estuary. The Squamish Estuary 20x20 m model in turn provides boundary conditions to a fine resolution, 5x5 m Squamish Model. The bathymetry data was developed based on a compilation of the available and most recent surveys.

The effects of tidal oscillations, Squamish River discharge, wave climate and storm surge were incorporated into the model. The model was validated comparing the modelled water level with measured water levels at a Lower Estuary station. SNCL also calibrated the modelled current speeds with measured current data provided by Squamish Terminals.

The results show that the berm removal could result in larger currents and slightly larger waves in the upper central channel and in the Squamish Terminal area. The berm removal also allows currents and waves to carry sediments from the Squamish river into the upper central channel area which leads to deposition to the east and over the top of the remaining removed berm surface.

The following summarizes the model results:

- Currents: The Removal scenario leads in higher currents at the east side of the berm while the currents at the west side of the berm reduce from 0.8 m/s for the Existing scenario to 0.2 m/s for the Removal scenario. Overall, the Removal scenario leads to lower currents at the Squamish River delta compared to the Existing scenario.
- Waves: There is no significant change in significant wave height between the existing and removal scenarios except for the east side of the berm where the wave height increased from 0.5 in the Existing scenario to 0.7 m in the Removal scenario. This is a predictable change since the training berm is providing shelter for the immediate east area. The removal of the berm allows the wave to propagate into the central channel and results in larger waves at the upper section of the channel adjacent to the berm.
- Sedimentation/Erosion: For the removal scenario, results in overflowing of the removed berm and subsequent sedimentation from the Squamish River into the upper central channel area and deposition near the berm on both sides as well as on top of the remove berm.

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1. Introduction

1.1 Background

The Squamish River Watershed Society (SRWS) retained SNC-Lavalin to assess the impacts of the training berm removal from the Squamish River as part of the Central Estuary Restoration Project (CERP). The CERP has the purpose of restoring and preserving the integrity of the Squamish River watershed as well as improving access and habitat in the central estuary for juvenile chinook.

SNC-Lavalin conducted a preliminary wave impact study for two berm removal scenarios considering existing extreme event and water levels (see previous report Ref [1]). The bathymetry used in the wave model for the removal scenarios was estimated based on available information and previous hydrodynamic and sediment transport models for the region.

In the present study, the initial model bathymetry was updated by incorporating more recent survey data.

A comprehensive hydrodynamic and sediment transport model to forecast the sedimentation process during the studied events was conducted to provide a comparative assessment between the current condition and the preferred berm removal scenario. This study assesses the impacts of training berm removal to navigation (current speed), water levels, and sedimentation in the regional proximal to the berm.

1.2 Scope

The scope of this assessment was to conduct a comparative hydrodynamic and sediment transport model, coupled with wave modelling, for the present (existing) scenario and a potential future scenario, for the training berm removal. The model was run for both scenarios for a 14-day interval that included one storm event. This document describes the hydrodynamic and sediment transport related modelling and comparison results for the scenarios with and without the training berm (removed from the “Yellow Gate” for 1.1 km). The results are focused on comparison of the operational conditions only, with and without the training berm.

The initial scope was to run two different operational conditions, with duration of approximately 14 days each. However, due to a scope change, only one condition was considered in this study. A scenario for a for high flow discharge (freshet) from Squamish River and ambient wave conditions was eliminated from the scope of this current assignment. The current scope considered only operational conditions and on comparative results.

1.3 Modelling Approach

The hydrodynamic / sediment transport model, coupled with the wave model, is used to simulate short term hydrodynamic and metocean conditions. Model details are described in Section 2. The general approach for modelling is as follow:

- Update model bathymetry by incorporating the following dataset.

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- Canadian Coast Guard Aid to Navigation Waterways Management for Squamish Terminal project 2017 (Ref [2]);
- Terminal Berth and Seabed Condition Survey Ref [3] provided by Canadian Survey Inc.;
- CCOM - Center for Coastal and Ocean Mapping 2019 Ref [4]; and
- Squamish River Bathymetry 2007 survey: conducted and provided by BC Hydro.

› Update wind data analysis detailed in Appendix A and Ref [6].

› Conduct measured water level data analysis and comparison between available stations.

› Conduct historical river discharge data analysis and associated sediment flux at the upstream boundary. Historical data and literature were used to define sediment flux.

› Conduct model validation and calibration using tidal stations from Environment Canada as well as Lower Estuary Station water level measurements. Currents speeds were validated using Acoustic Doppler Current Profiler (ADCP) current data from February 16, 2017(Ref [5]), provided by the Squamish Terminals.

› Selection of a representative 14-day period for the model runs, in consultation with the SRWS.

› Comprehensive hydrodynamic and sediment transport modelling, coupled with the wave model, to forecast the sedimentation process and impacts of the proposed berm removal.

The hydrodynamic and sediment transport model was conducted for two scenarios (with and without the training berm), with a run duration of approximately 14 days each. The berm removal scenario includes a 1.1 km long berm removal, keeping the south end of the berm in place. Table 1 summarises the general run parameters. The following describes the general model inputs:

› Winds measured at Pam Rocks station was input to model to represent the sea state at Howe Sound. The measurements from the Squamish Windsports Society (SWS) station were used in nested model grids to represent more local conditions.

› River discharge was defined based on the available period of measured discharge from Water Survey of Canada at Squamish River - near Brackendale hydrometric station 08GA022. .

› The bathymetry assumed for the training berm removal scenario considered that the south end of the structure (170 m -Wind Sports Society) would not be removed (Figure 2).

› The range of extreme seasonally variable combinations of events that could occur (for instance a severe storm in the late spring, in combination with a late freshet or intense rainfall event in the watershed) are considered to be beyond the scope of the present investigation. The current scope of work focused on a more operational condition as a first identification of the removal consequences.

› This study considered a short duration model run to identify, by comparison, the effects of the training berm removal. The selected period reflects an operational condition with one typical storm event occurred at mid-winter (February 1st) – see Ref [6] for data analysis.

› The expected wave conditions (as a result of local wind generation) are incorporated through the coupling of the hydrodynamic and sediment model with a wave model using non-stationary wind input (minor storm and operational) as defined above.

› Sea level rise is not considered. This assignment is not intended to address the long-term effects of the proposed works.

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- The period of runs was selected based on the following criteria:
  - Operational conditions include one typical storm. An extreme storm was not selected because the intention was to evaluate results for operational conditions and more representative navigation conditions. A short-duration (ie: 14 days) model run, with extreme wind/waves/flow, would not give representative results for sediment transport, because the fourteen-day duration is not enough time for the system to recover. The sedimentation and erosion impact would likely be overestimated.
  - A minor local southerly wind storm is included within the operational run. The higher winds were measured at the Pam Rocks and SWS stations.

Table 1 Summary of scenario runs

Parameter	Scenario A	Scenario B
Flow and sediment discharge	Average winter flow and sediment discharge	Average winter flow and sediment discharge
Sea Level Rise allowance	0.0 m (current)	0.0 m (current)
Length of berm removal	None	Removal of 1.1 km from Yellow Gate to SWS
Wind conditions	Operational wind Including one storm Peak (19.0 m/s)	Operational wind Including one storm Peak (19.0 m/s)

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2. Numerical Modelling

The modelling for this study used the open source Delft 3D- Flow numerical model. Delft3D-Flow is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. Source and sink terms are included to model discharges and withdrawals. For the present application, the simulations were conducted in 2D model (depth-averaged) using Cartesian grid co-ordinates.

Delft3D-Flow supports several kinds of boundary conditions such as astronomical constituents, water levels, velocities, combinations of water levels and velocities and discharges.

The Delft3D-Flow program has the following standard features:

- Tidal forcing
- The effect of the Earth's rotation (Coriolis force)
- Density driven flows (pressure gradient terms in the momentum equations)
- Advection-diffusion solver included to compute density gradients with an optional facility to treat very sharp gradients in the vertical
- Space and time varying wind and atmospheric pressure
- Advanced turbulence models that account for vertical turbulent viscosity and diffusivity based on the eddy viscosity concept. Four turbulence model options are provided: k ε, k L, algebraic and constant models
- Time varying sources and sinks (e.g. river discharges)
- Simulation of thermal discharge, effluent discharge and the intake of cooling water at any location and any depth
- Drogue tracks[1]
- Robust simulation of drying and flooding of inter-tidal flats.

The Delft3D Flow model was coupled with the Simulating WAves Nearshore (SWAN) wave numerical model to investigate the morphologic changes of the Squamish estuary system due to physical processes and sediment exchange between Squamish River and the open coast. Delft3D-Flow forms the core of the model system; simulating water motion due to tidal and meteorological forcing by solving the unsteady shallow-water equations in two (depth-averaged) dimensions. The wave model SWAN was applied in a non-stationary computational mode to propagate waves from the offshore boundaries of the model to the estuary, generating wind-induced waves within Howe Sound. SWAN models the effects of wind-wave generation, refraction, shoaling, dissipation by bottom friction, white capping, nonlinear wave-wave interactions, and ambient currents on the wave properties. It is recommended that a phase-resolved wave model should be used to properly include detailed wave reflection and diffraction near coastal structures before project implementation.

Two scenarios were modelled, with berm (existing scenario) and without berm (1.1 km removal scenario) to investigate the sedimentation transport pattern and its impact on the wave conditions. The initial

[1] track floating particles

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bathymetry considered for the model is described above; however, seasonal variability of the bathymetry was not considered.

2.1 Reference system

The horizontal coordinates and vertical reference datum used in this analysis are given in Table 2. The vertical elevations or depths are referenced to either the Canadian Geodetic Vertical Datum from 1928 (CGVD 28) or the Chart Datum (CD) for the area, as noted in the report. Horizontal reference is UTM Zone 10N (NAD 1983).

Table 2 Horizontal and vertical references specifications

Parameter	Value
Horizontal datum	UTM Zone 10 N
Vertical datum	CGVD 1928 / Chart Datum

At Squamish, Chart Datum (CD) is 3.08 m below CGVD 28. This is the same difference considered for the Designated Flood Level Studies –Ref [7] and Ref [8]). In Howe Sound and in the approaches to the Squamish Estuary, CD is 3.1 m below the 0 m (CGVD) contour. For computational purposes, depths are positive, referencing Chart Datum as the vertical datum.

2.2 Grids

The model grids were developed using the bathymetric dataset presented in Table 3. Three grids were generated to account for the complexity of the area. Figure 1 shows the limits of each grid.

- Coarse Grid (100 x 100 m)
- Nested1 Grid (20 x 20 m)

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› Nested2 Grid (5 x 5 m)

Figure 1 Model grids boundaries

2.3 Bathymetry

The bathymetry data is a compilation of surveys shown in Table 3 and the previous model bathymetry used by SNC-Lavalin in Ref [8].

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Table 3 Summary of bathymetric datasets

Source	Original Reference System	Comments
CCOM - Center for Coastal and Ocean Mapping (2019)	WGS84 / CD	Provided by John Hughes Clark
Terminal Berth and Seabed Condition Survey (2018)	NAD83 (UTM Zone 10) / CD	Contour intervals 5 m CRA Canada Survey Inc. provided by Squamish Terminals
Canadian Coast Guard (2017)	NAD83 (UTM Zone 10) / CD	-
SNC-Lavalin IFHMP Bathymetry (2015)	NAD83 (UTM Zone 10) / CD	Compilation of datasets – See Ref [7]
Squamish River (2007)	NAD83 (UTM Zone 10) / CD	Survey was conducted and provided by BC Hydro.

An initial review of the recent bathymetry datasets indicated that differences between the 2015 SNC-Lavalin bathymetry grid and the more recent surveys were mostly around the Squamish Terminals, south of the training berm, and within the Squamish River delta. Changes in bathymetry are typically related to dredging scheduled by the Terminals or the results of foreslope instabilities; which are likely to continue to occur in the future in an episodic manner.

Figure 2 shows the bathymetry defined by the three model grids. The following changes were considered for the model bathymetry.

- The bathymetric data upstream of the Squamish River (survey provided by BC hydro 2007) was added to the datasets.
- Bathymetry at the south and west of the Squamish training berm was updated using CCOM 2019, as there was a discrepancy (at some locations more than 10 m) between 2015 SNC-Lavalin and CCOM 2019 bathymetric data.
- CCOM 2019 bathymetry also provided more detailed information at the downstream part of Squamish River and further to the south of the Squamish estuary.
- The bathymetric data at Squamish terminals was updated with the Terminals Berth and Seabed Condition Survey (2018) and the Canadian Coast Guard (2017) data, both provided by the Squamish Terminals. This information was more recent and has higher resolution comparing to SNC-Lavalin 2015 data.
- The training berm bathymetry was adapted to represent a removal scenario. More than 20 sections were considered from the tip of the berm (SWS) to the remaining island beyond the existing “Yellow Gate”. The seabed elevation across each section was digitally modified to match the existing level at each side of the training berm. Wherever the difference between the elevation on each side of the training berm was significant, a linear interpolation was used between them. The bathymetry adjacent to the remaining island/berm was left as defined by the reference survey data.

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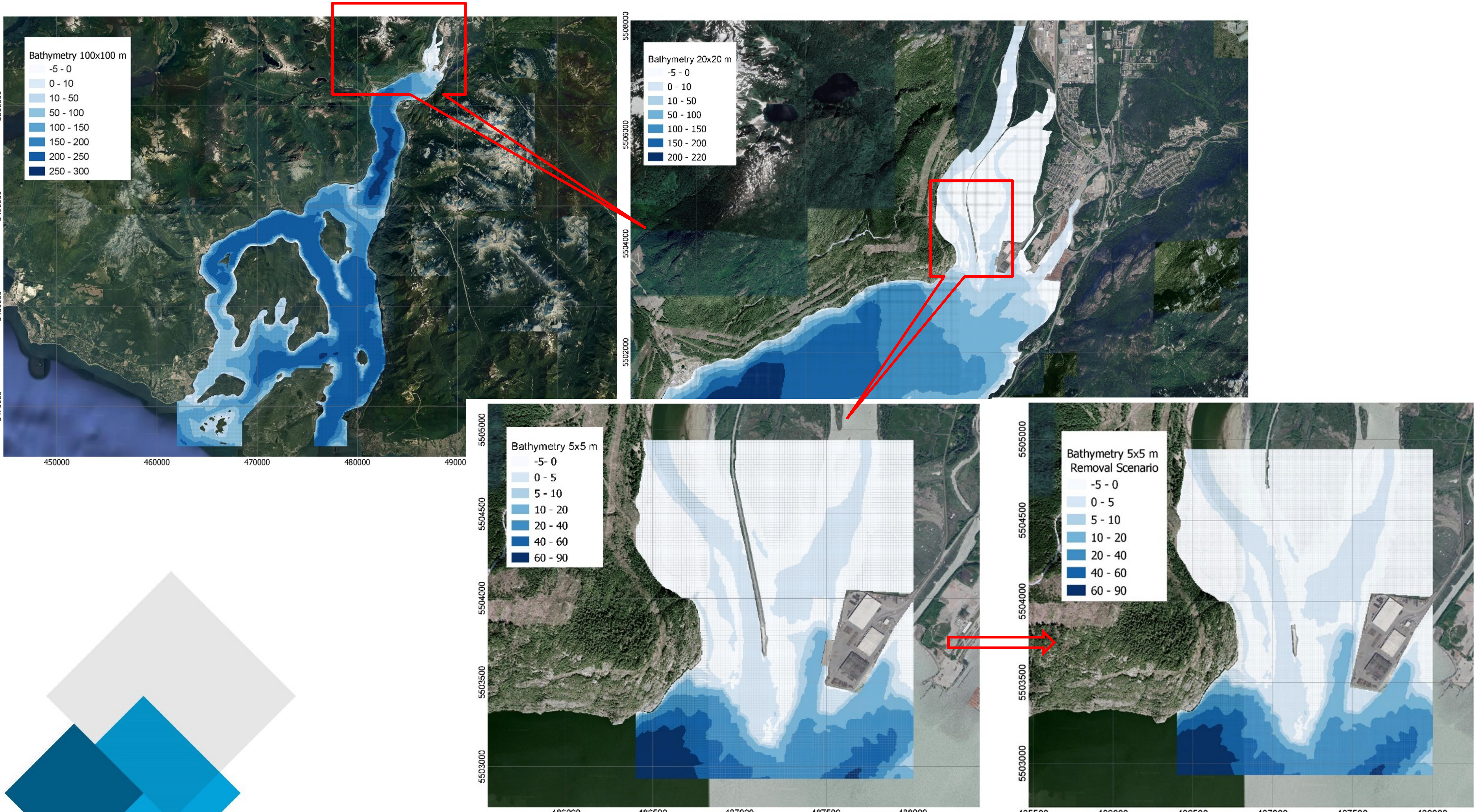

Figure 2 Model bathymetry for 100x100 m, 20x20 m, and 5 x 5 m grids - existing (left) and removal scenario (right)

2.4 Model input

This section describes the metocean parameters used as input for selected period modelled. General metocean data analysis, conducted previous to the selection of the modelled period, is presented in Appendix A and Ref [6].

The selected period generally consisted of operational metocean conditions, it is a typical storm event that occurred on February 1st. The selection was made based on the measured data at SWS and Pam rocks stations. The data was analyzed to capture highest winter wind events. Based on literature review and previous study (Ref [7]), southerly winds in Howe Sound are expected to be stronger in the north Howe Sound and Squamish Harbour area than they are in the southern end of the Sound. The significance of southerly winds in this study is because of their longer fetch will impact the wind climate at the Squamish estuary. SNC-Lavalin assessed all southern storm events longer than three hours and selected one that showed the peak winds at Pam Rocks Station and the SWS station at a similar time. The local wind data recorded at SWS station was used to define the selected storm period. SNC-Lavalin filtered out wind storm events with duration shorter than three hrs and ranked them from highest to lowest at SWS station. The selection of the designated storm period was made if the selected period met all of the following conditions:

- Available of water level measurement at Lower Estuary station
- Storm peak at the similar time at both SWS and Pam Rocks
- Ensure that the corresponding river flow discharge measurements are similar to average winter flow discharge

For the selected period, the average winter flow discharge for the Squamish river was considered with the peak flow occurring at the same time as the wind storm. Water levels ranged between spring (tidal range of approximately 4.2 m) and neap tides (tidal range approximately of 2.0 m). The selected period of simulation started from 2020-01-24 19:00 PM and finished at 2020-02-09 12 AM. The computational time step was three seconds.

2.4.1 Water Levels

The tidal conditions are based on the water level information for the Point Atkinson reference port (Station ID 7795) and the Lower Estuary station shown in Figure 3. The total available period of measurements at the two stations was from June 2018 to March 2020.

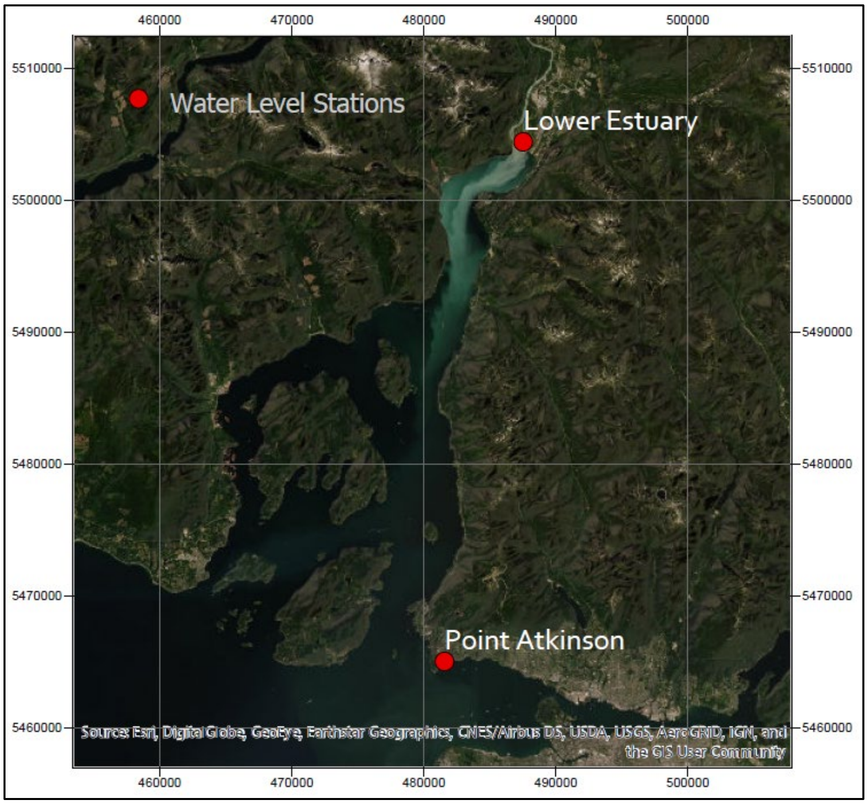

Figure 3 Water level measurements locations

The water levels time series used as input at Point Atkinson and Lower Estuary are shown in Figure 4. The run started during a spring tide (tidal range approximately 4.2 m) and continued during neap tide (tidal range approximately 2.0 m) happening on February 1st, 2020 (during the storm) and finished by another spring tide at the end of the simulation period (February 9^{th}, 2020).

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The tides at Point Atkinson together with the external storm surge for the wind storm event were input into the coarse grid. For nested grids (20x20 m and 5x5 m), the timeseries of measured water level data at Lower Estuary gauge were input as a representative of tidal level, external and internal storm surge.

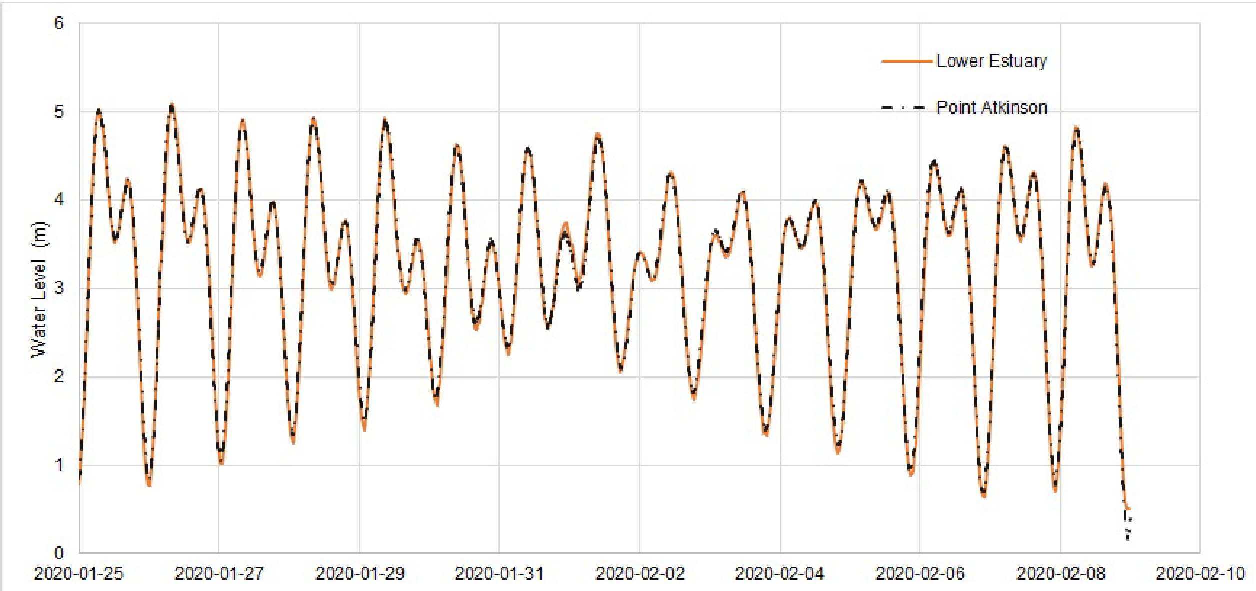

Figure 4 Water levels at Point Atkinson and Lower Estuary

2.4.1.1 External Storm Surge

External storm surge was input to the model based on the measured residual water level data at Point Atkinson. The water l2evel residuals[2] measured at Point Atkinson station is shown in Figure 5 during the modelled period of time. The maximum water level difference was approximately 0.48 m.

Figure 5 Water level residuals at Point Atkinson

[2] Water level residuals are the difference between measured and predicted water levels

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2.4.1.2 Local Storm Surge Effects

Local storm surge effects, resulting for inflow and convergence effects in Howe Sound and Squamish Harbour, were estimated by comparison of water level measurements between the stations Lower Estuary and Point Atkinson.

Figure 6 shows the water level difference between the measurement from Point Atkinson and Lower Estuary during the run period. The maximum water level difference of the series (approximately 0.32 m) occurred in January 8th.

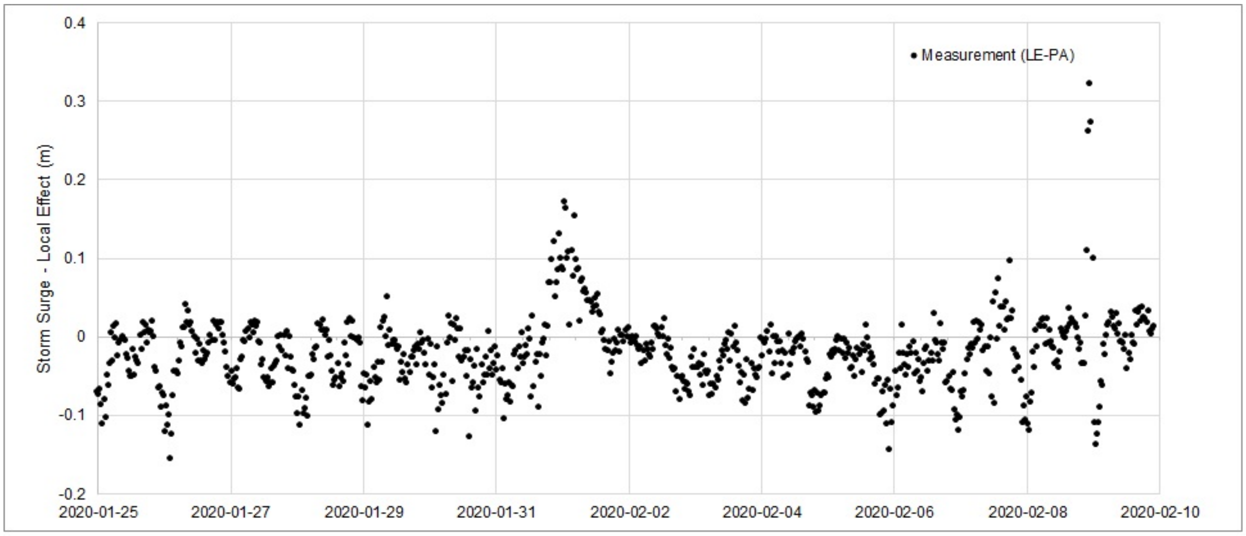

Figure 6 Water level difference between Lower Estuary and Point Atkinson during the modelled period

2.4.2 Wind

The calculation of the sea state at the Squamish estuary requires a reliable estimate of the overwater winds both within Howe Sound in general but especially within the upper (north) reaches of Howe Sound.

Wind data measured from three stations were analysed: Squamish Airport, Squamish Wind Sports (SWS), and Pam Rocks. The wind speeds at the Squamish Airport station are consistently lower when compared to Pam Rocks or the Squamish Wind Sport (SWS) site, mainly because the station is inland. Even though the Squamish Airport wind data is the longest measured time series, it was not considered as a reliable source for this study purpose (Ref [6]). Wind data from SWS station was considered the most representative of local wind.

Figure 7 shows the wind time series input to the model. The wind measured at Pam Rocks was input to grid (100x100 m). The measurements from SWS stations were used in nested model grids (20 x 20 and 5 x 5 m) to represent local conditions.

The selected storm at SWS station was fourteen hours long (2020-02-01 2:00 AM to 2020-02-01 4:00 PM) with a maximum southeasterly wind speed of 19 m/s on 2020-02-01 9:00 AM. The wind measurements at Pam Rocks showed local southerly and southwesterly wind from 2020-02-31 5:00 PM to 2020-02-01 4:00 AM with a peak of 15.3 m/s on 2020-02-01 12:00 AM.

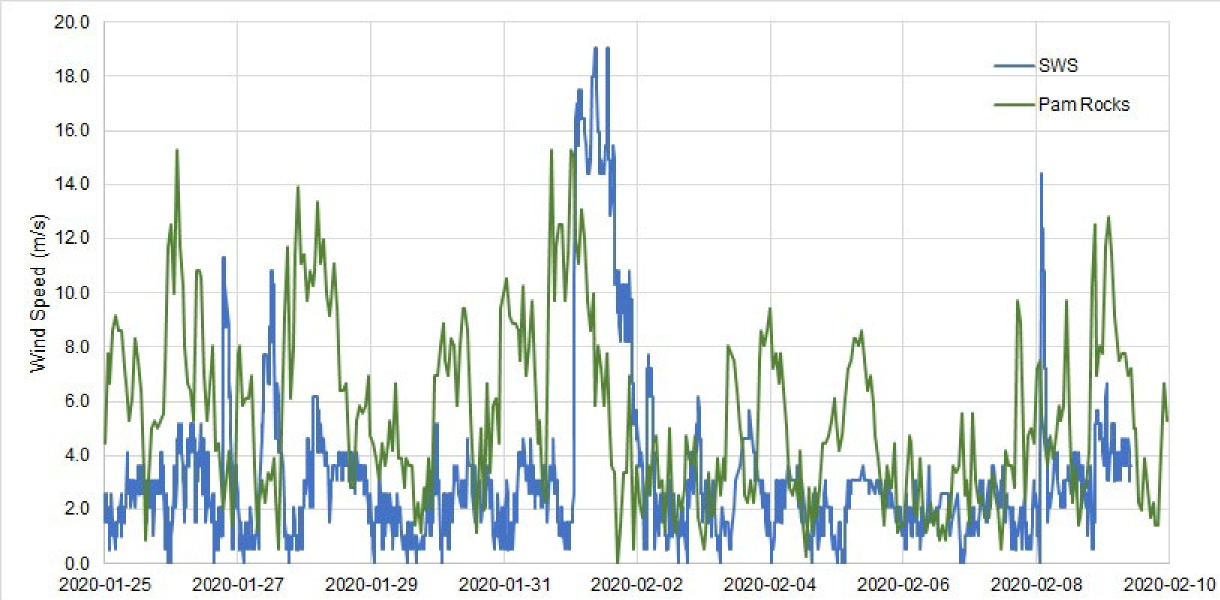

Figure 7 Wind Input to the Model

A time-varying wind field that incorporated the winds measured at the Pam Rocks and SWS stations was prepared as a model input. For the coarse grid (100 x 100 m) at Howe Sound, Pam Rocks wind field is provided as an input to consider the longer fetch defining the wave climate. For the nested models (20 x 20 and 5 x 5 m), SWS time-varying wind field was provided as it is more representative of local wind effects.

2.4.3 Currents

The input waves and tides were used in the 100x100 m grid to obtain the wave and tidal induced currents for the nested grids. Details on the current validation are presented in Ref [6].

2.4.4 Sediment Transport

An overview of previous studies on sedimentation transport patterns, sediment characteristics and sediment grain size at Squamish estuary and Squamish River can be found in Ref [6].

2.4.5 River Discharge and Sediment Influx

The model input for river discharge during the period consisted of measured hourly data from the Squamish river near Brackendale hydrometric station (08GA022) over the 14-day interval of simulation. The suspended sediment flux input was obtained using a rating curve that shows the correlation between the sediment influx concentration and the river discharge, Ref [6]. The time series of the selected river discharge input is presented in Figure 8. The Squamish River discharge and sediment flux peaked (peak to peak) at 743 m^3/s and 280 mg/L respectively, at the same time as the wind storm peaked at the SWS site (2020-02-01 9:00 AM).

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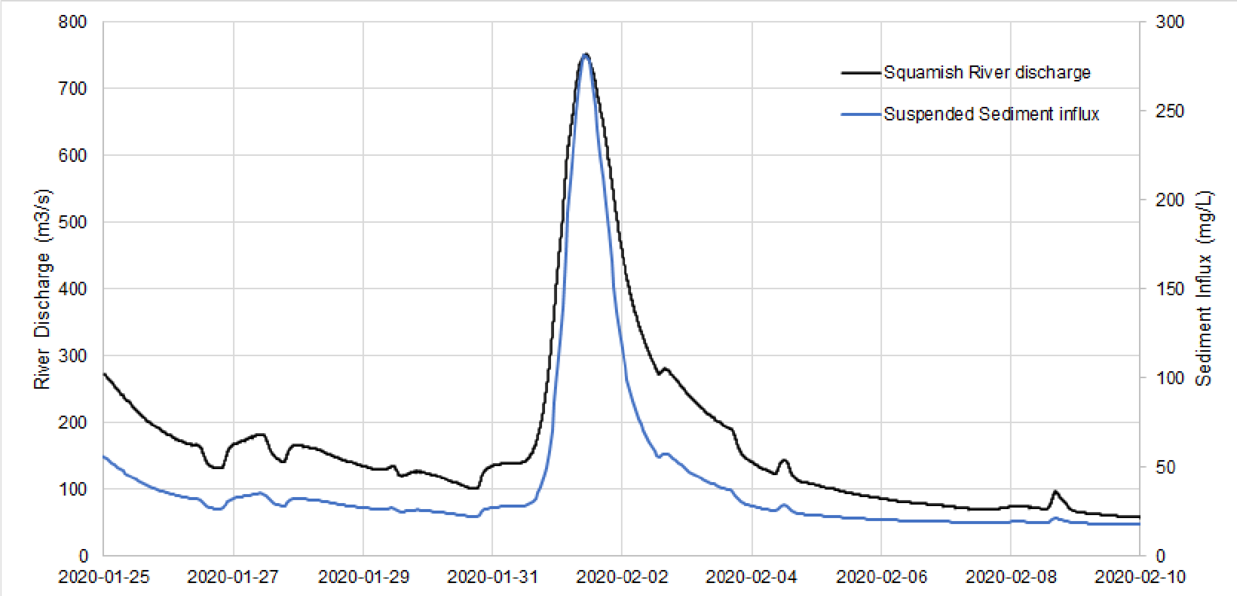

Figure 8 Time series of River discharge and sediment influx for Squamish River

2.5 Model Validation / Calibration

The model was validated by comparing the water level at the Lower Estuary Station and the results from the 5 x 5 m grid. The model was also calibrated using the current speed measurements provided by the Squamish Terminals on February 16, 2017 between 14:25 and 15:00 h (Ref [**5**]). The model input for validation consisted of measured water levels from Point Atkinson, river discharge from Squamish River, wind speeds from Pam Rocks and local winds from SWS. More details on the model validation can be found in Ref [6].

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3. Model Results

The model results for the existing and removal scenarios are presented at the peak of the storm - on February 1st, 2010 at 10 AM. Figure 9 and Figure 10 show the spatial distribution for depth averaged velocity and significant wave height (during storm peak). The cumulative sedimentation/erosion patterns are presented in Figure 11 for February 9th (end of 14 days of simulation).

Selected points of interest (see Figure B - 1 Appendix B) were defined for comparison purposes and overlaid on each map for each scenario. More information on site specific results is presented in Appendix B.

3.1 Current

Comparison of the currents[3] for the existing and removal scenarios show that the currents at the upper central channel (S7) and the Squamish terminal berth are higher during the removal scenario. For the remaining observation points, currents are reduced or remain at the same intensity. Site specific sea state results for the indicated observation points are summarized in Table 4.

The specific results show that for the Existing scenario (Figure 9 – upper panel) the current velocity is approximately 1.2 m/s at the river upstream boundary. Currents flow downstream without passing over the berm. By the time the currents reach to the Squamish delta, the velocity is reduced to 0.5 m/s. The current speed at the Squamish Berth, channel, point S7(east side of the berm), Squamish estuary and District of Squamish (DoS) vary between 0.1 to 0.2 m/s.

Figure 9 (bottom panel), shows the current pattern for the Removal scenario. Unlike the Existing scenario, the currents diverge toward the Squamish Berth and wrap around the remaining Windsports island. This results in stronger currents at the Squamish terminal berth (approximately 0.4 m/s). The current at points S22, DoS and Channel remain the same as the existing scenario.

The Removal scenario leads in significantly higher currents (0.6 m/s) at the east side of the berm (S7) while the currents at the west side of the berm (S4) reduce from 0.8 m/s for the Existing scenario to 0.2 m/s for the Removal scenario. Overall the Removal scenario leads to lower currents at the Squamish River delta compared to the Existing scenario.

[3] Currents in this study represent the depth averaged velocity and includes waves Stokes drift velocity. High speed current can induce navigational hazards to the vessels sailing toward and from Squamish Terminal.

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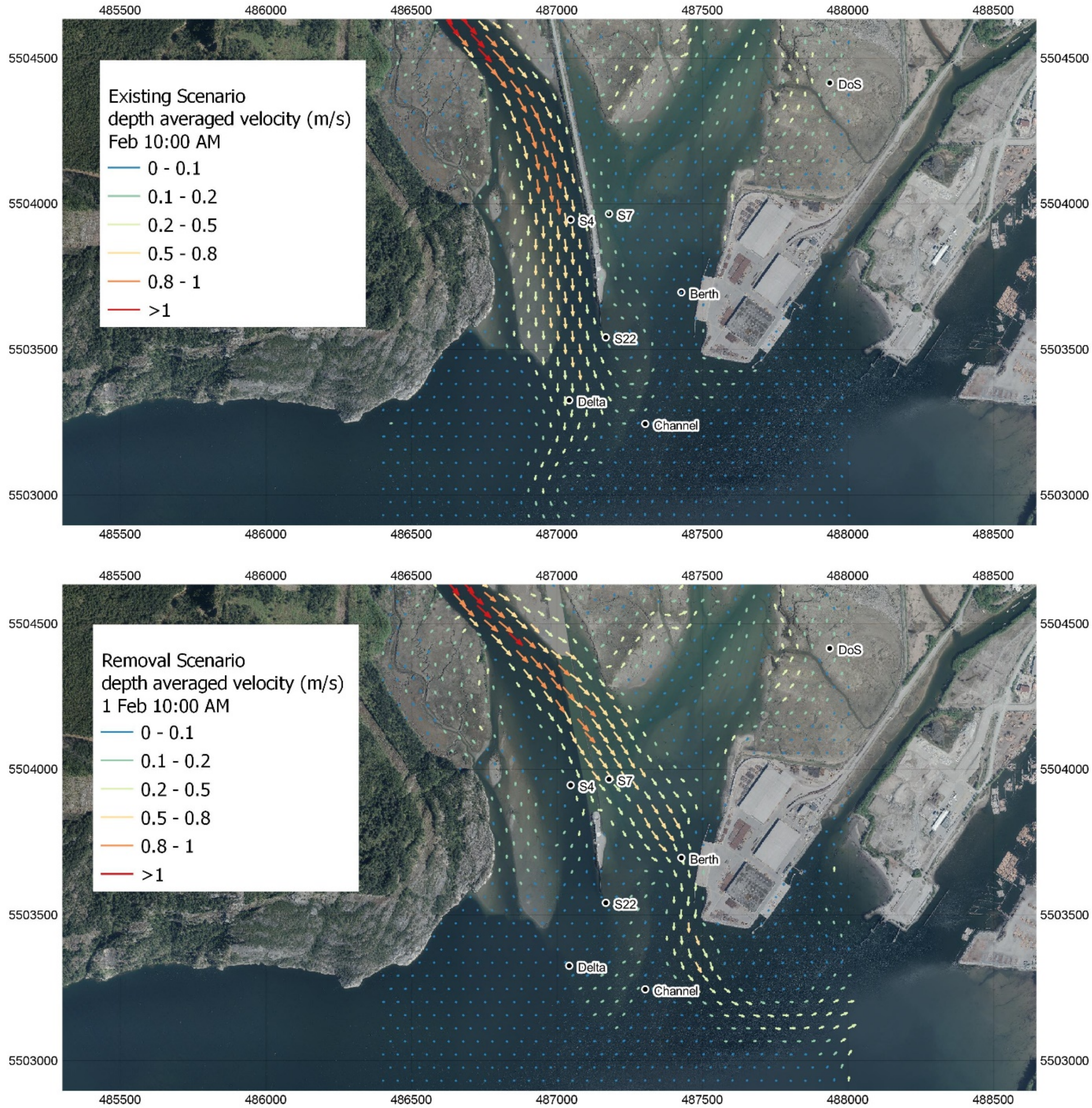

Figure 9 - Depth averaged velocity (m/s) on February 1st, 2020 10 AM (during Storm) -Existing Scenario (top) and Removal Scenario (bottom)

3.2 Wave Height

Figure 10 shows the special distribution of significant wave heights for the Existing and Removal scenarios at the storm peak. For the Existing scenario, significant wave height is approximately 0.9 m at the Squamish River delta and as it propagates toward the river upstream, reduces its intensity. The significant wave height at the vicinity of the Squamish terminal, point S22 and Channel is approximately 0.8 m. The significant wave height on the west side of the berm (S4) is approximately 0.8 m and is reduced to 0.5 m on the east side (S7). The significant wave height at the DoS point is insignificant for this storm.

For the Removal scenario, the significant wave heights are approximately the same around all the observation points with magnitude of approximately 0.7 m. As the sea state propagates towards the upstream portions of the estuary heights are reduced.

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When the berm is removed, waves diffract around the south island, providing shelter in the areas behind the island. The sea state adjacent to the berm remains the same on both sides. Wave heights are still insignificant around the DoS point.

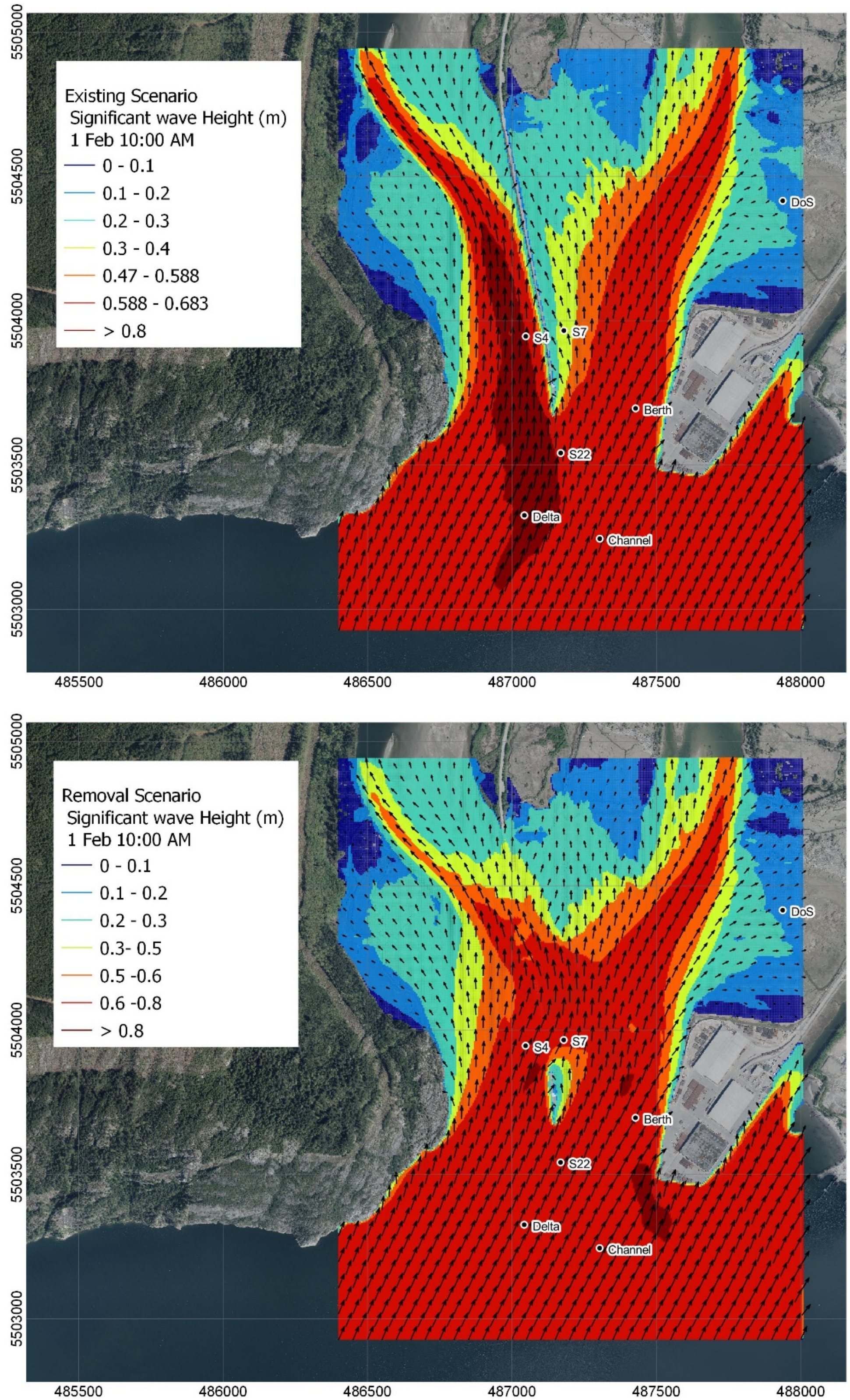

Figure 10 – Significant wave height on February 1st 10 AM (during Storm) -Existing Scenario (top) and Removal Scenario (bottom)

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3.3 Sedimentation/Erosion

Figure 11 shows the sedimentation and erosion at the end of the two modelled scenarios. For the Existing scenario sedimentation is more intense at the river upstream and reduces around the river delta, confirming the previous studies findings that the Squamish River is the main source of the sedimentation in the Squamish estuary (Ref [9] and (Ref. [10]). No significant sedimentation/erosion took place around the other points of interest: Channel, Squamish Terminals, S22, and DoS.

For the Removal scenario, as waves and currents flowed over the removed berm, they carried sediment to the east of the berm. Deposition occurred at the top of the removed berm. On the west side of the berm, there is scour next to the remaining toe of the berm and slight additional deposition. It is important to note that the removal scenario considered that the remaining berm material is larger than the sediments around the berm, making the removed berm area less erodible. This assumption was taken considering that even though the berm will be removed, part of the core of the structure close to the natural seabed will be remaining.

The remaining south section of the berm (SWS island) blocks the sediment transport in that specific area and no changes are observed on the west side of the island.

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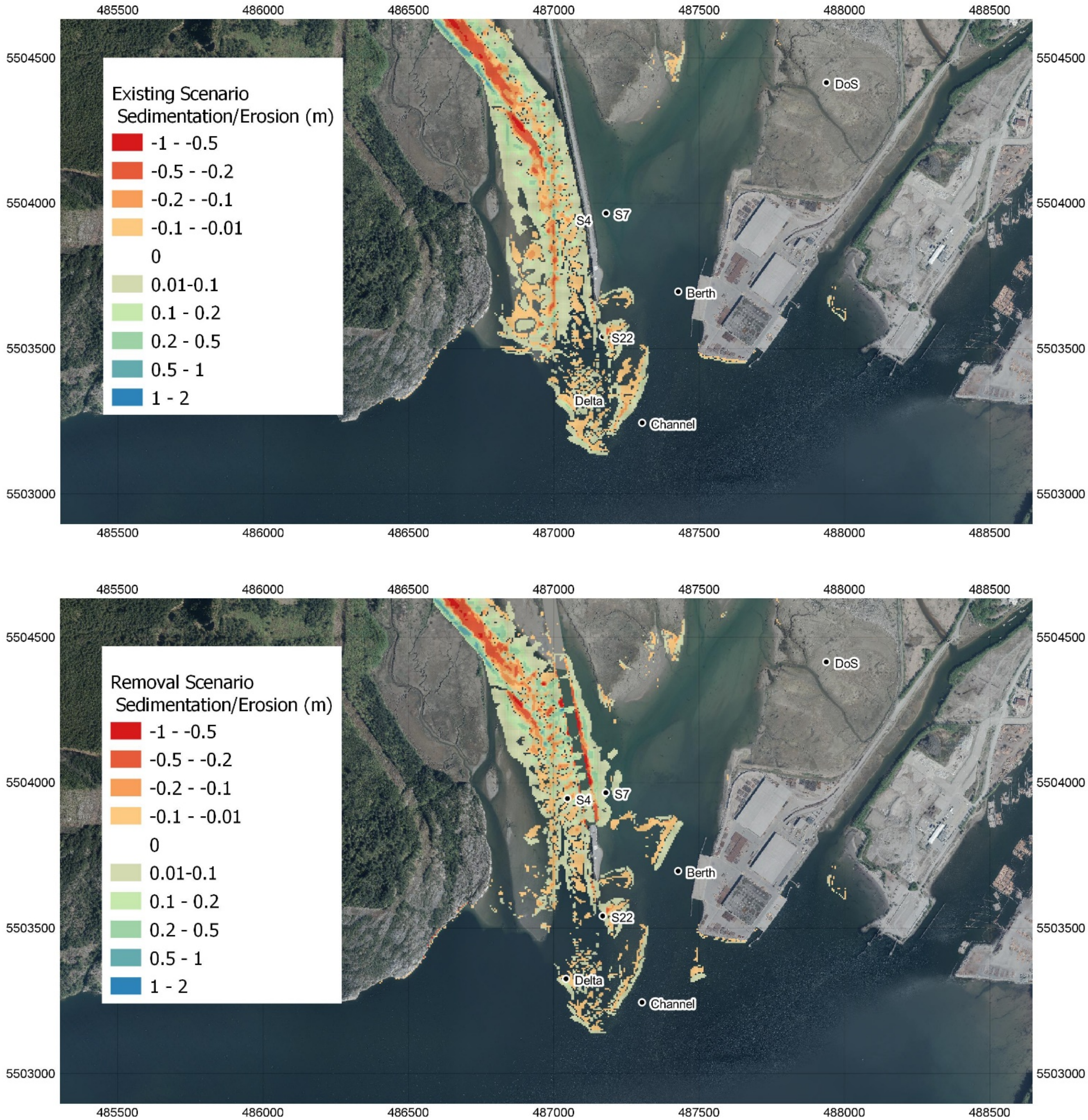

Figure 11 – Sedimentation/Erosion at the end of the simulation on February 9th at 12 AM -Existing Scenario (top Panel) and Removal Scenario (bottom Panel)

Site specific results for the various observation points indicated in each map above are summarized in Table 4. Deposition is shown as positive and scour as negative sign. Increases of significant wave heights, sedimentation, current speeds are highlighted in red, while points with the same results for the different scenarios are highlighted in green.

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Table 4 Comparison between the existing and removal scenarios for currents, significant wave height and water level on February 1st at 10:00 AM, for sediment thickness at the end of the simulation, February 9th at 12:00 AM

Output Points	Sediment Thickness (m)		Currents (m/s)		Significant Wave Height (m)	
	Existing	Removal	Existing	Removal	Existing	Removal
S4	-0.19	-0.14	0.8	0.2	0.8	0.7
S7	0	+0.01	0.1	0.6	0.5	0.7
S22	0	0	0.2	0.1	0.8	0.7
Delta	-0.1	-0.06	0.5	0.1	0.9	0.7
Berth	0	0	0.1	0.4	0.8	0.7
Channel	0	0	0.1	0.1	0.7	0.7
DoS	0	0	0.2	0.2	0.2	0.1

There is no significant change in significant wave height at the observation areas, except for the east side of the berm (S7) where the wave height increased from 0.5 in the Existing scenario to 0.7 m in the Removal scenario. This is a predictable change since the training berm is providing shelter for the immediate east area. The removal of the berm allows the wave to propagate into the central channel and results in larger waves at the upper section of the channel adjacent to the berm.

Comparison of the currents for the two scenarios show that the currents at the upper central channel (S7) and at the Squamish Terminal berth are higher during the Removal scenario. For the remaining observation points currents were reduced or remained at the same intensity.

The time series for all points of interest for the duration of the runs is presented in Appendix B.

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4. Conclusions and Recommendations

The removal of the 1.1 km section of Squamish training berm is part of SRWS plans to restore the Squamish estuary. The objective of this study was to investigate the effect of the removal on the sedimentation processes in the area and provide a comparative assessment between the existing situation and the preferred berm removal scenario. This study also assessed the impacts to navigation (current speeds), wave heights and sedimentation in the study area.

The results show that the Removal scenario could result in generally higher currents and larger waves at the upper central channel and in the Squamish Terminal area. The Removal scenario also allows currents and waves to carry sediments from the Squamish river into the upper central channel area which leads to deposition to the east and over the top of the remaining removed berm surface.

The results of this study show likely expected changes to the sediment transport, hydrodynamics and wave conditions for a relatively short period of time and for the modelled Removal Scenario.

The following summarizes the key comparison results of this study:

› Current velocities increase in upper central channel and near the Squamish terminal berth, but decreases or remain the same in other parts of the estuary.

› Wave heights increase in parts of the upper central channel and the Squamish Terminal area, but overall the waves are smaller.

› For the existing scenario, sedimentation is higher at the river upstream and reduces around the river delta. The presence of the berm confines the sedimentation to the west side of the berm. However, a gradual sedimentation formed around the south of tip of the berm and slightly at southeast.

› For removal scenario, currents and waves are able to flow over the removed berm and carry sediments from the Squamish River into the upper central channel area. This leads to deposition near the berm on both sides and on top of the remove berm.

› The indicated increases in current velocity and wave height are not expected to significantly impact navigation or sedimentation in the areas of interest (ie: the Squamish Terminal berth area or the shoreline along the District of Squamish dikes) for the modelled period.

This study presents the likely impacts of training berm removal on operational conditions. It represents a typical storm event and average winter river discharge. It is recommended that a sediment transport analysis to evaluate long term effects of severe storms or river discharges is undertaken prior to final design of any implementation process. It is also likely that further optimization of the Removal scenario could be considered, such as different lengths of berm removal.

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5. References

Ref [1] "Squamish Training Berm Realignment - Wave Impact Assessment", SNC-Lavalin, January 2020.

Ref [2] "Squamish Terminal Project, Drawing: Sounding with color banding bounding surface for terminal and approach" Canadian Coast Guard Aid to Navigation Waterways Management, March 2017

Ref [3] "Drawing : Bathymetric Contour Plan of Squamish Terminals Squamish, BC", Squamish Terminals Ltd. surveyed by CRA Canada Survey Inc. 10/15/2018

Ref [4] "Center for coastal and ocean mapping/joint hydrographic center", http://ccom.unh.edu/",2019.

Ref [5] "Squamish Terminals Hydrodynamic and Sediment Transport Modelling", Tetra Tech, 4 July 2017.

Ref [6] "Squamish Training Berm Removal – Phase 2, Model Criteria and Progress Report", SNC-Lavalin, June 2020.

Ref [7] Integrated Flood Hazard Management Plan, Background Report, KWL, September 2017.

Ref [8] "District of Squamish Integrated Flood Hazard Management Plan", SNC-Lavalin, (Document 618897-3000-41EB-0001), 12/02/2015.

Ref [9] "Squamish Estuary Qualitative Sediment Transport Assessment", KWL, December 2018.

Ref [10] "First wide-angle view of channelized turbidity currents links migrating cyclic steps to flow characteristics." Clarke, J.E.H., 2016., Nature communications, 7(1), pp.1-13.

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6. Revision Index and Signatures

Issue Code	Rev. No	Date (yyyy-mm-dd)	Description of Changes	Initials
RR	PA	2020-11-27	Issued for Internal Review	GMJ
RR	PB	2020-12-09	Issued for Client Review	GMJ
RI	R0	2021-02-11	Final	GMJ

Issue Codes:

RC Released for Construction
RD Released for Design
RF Released for Fabrication
RI Released for Information
RP Released for Purchase
RQ Released for Quotation
RR Released for Review and Comments

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Appendix A

Wind Assessment Summary[1]

[1] This is a summary of the Wind Assessment conducted for the document "Model Criteria and Progress Report, SNC-Lavalin 2020"

The calculation of the sea state at the Squamish estuary requires a reliable estimate of the overwater winds both within Howe Sound in general but especially within the upper (north) reaches of Howe Sound. Wind data measured from three stations were analysed: Squamish Airport, Squamish Wind Sports (SWS), and Pam Rocks. Figure A- 1 shows the locations where data was collected.

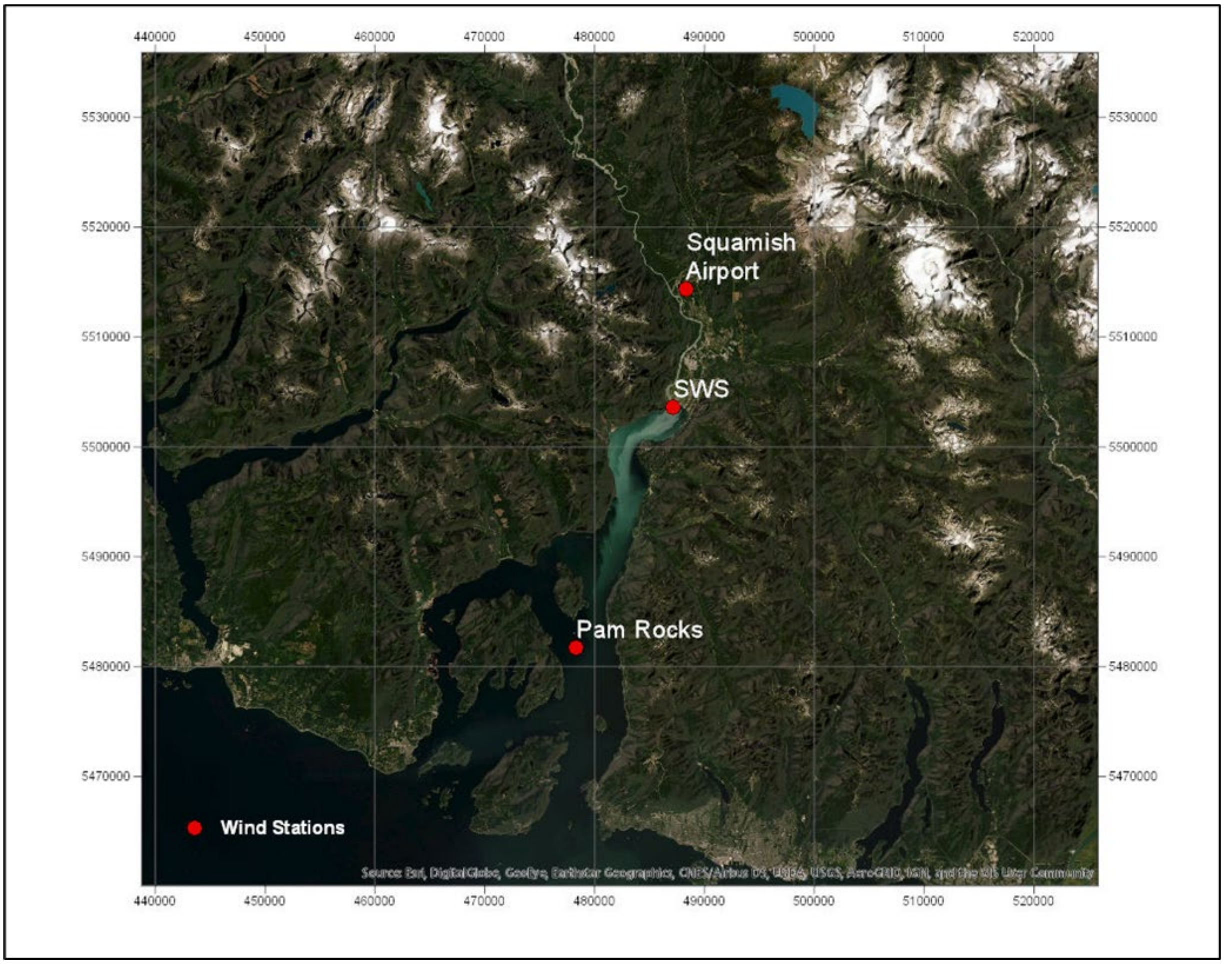

Figure A- 1 Location of wind stations

Table 1 shows the characteristics of each measured wind dataset. The Squamish Airport station has the longest period of measurements, followed by Pam Rocks and SWS stations. The wind comparison was focused on the last 10 years of data. Extreme wind analysis considered the entire series for each station.

Table 1 Summary of wind stations

Station Identifier	Station Name	Source	Location		Elevation (m)	Time Interval		
			Easting	Northing		Start	End	Total (years)
10476F0	Squamish Airport	EC	488341.5	5514368.5	54	1982-05-17	2020-03-31	38
-	SWS	Squamish Wind Sports Society	487145.5	5503615.2	-	2010-06-16	2020-03-30	10
10459NN	Pam Rocks	EC	478312.0	5481725.4	7.0	1994-02-01	2020-03-31	26

The wind speeds at the Squamish Airport station are consistently lower when compared to Pam Rocks or the Squamish Wind Sport (SWS) site, mainly because the station is in-land. Even though the Squamish Airport wind data is the longest measured time series, it was not considered as a reliable source for this study purpose. Based on literature review and previous study (Ref [8]), southerly winds in Howe Sound are expected to be stronger in the north Howe Sound and Squamish Harbour area than they are in the southern end of the Sound. Figure A- 2 and Figure A- 3 show the wind roses for the stations Pam Rock and SWS, respectively. The roses are for the same period of measurements from year 2010 to 2020.

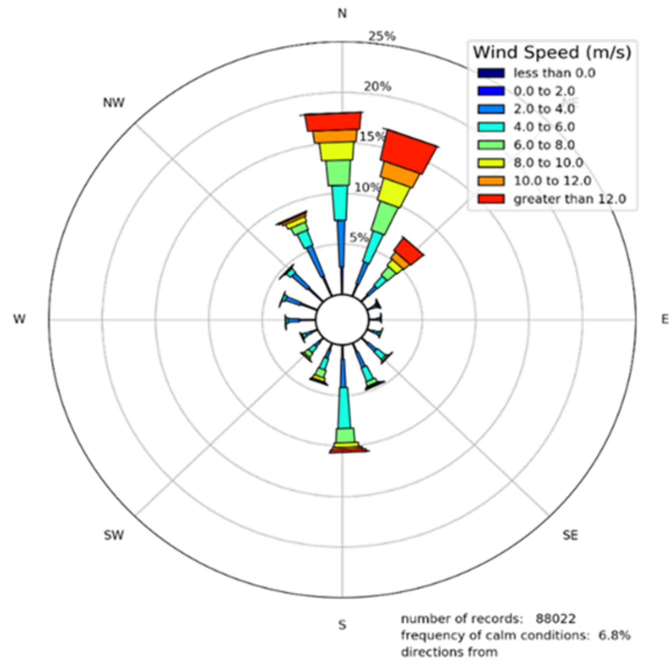

Figure A- 2 Pam Rocks wind rose (Date from 2010-2020)

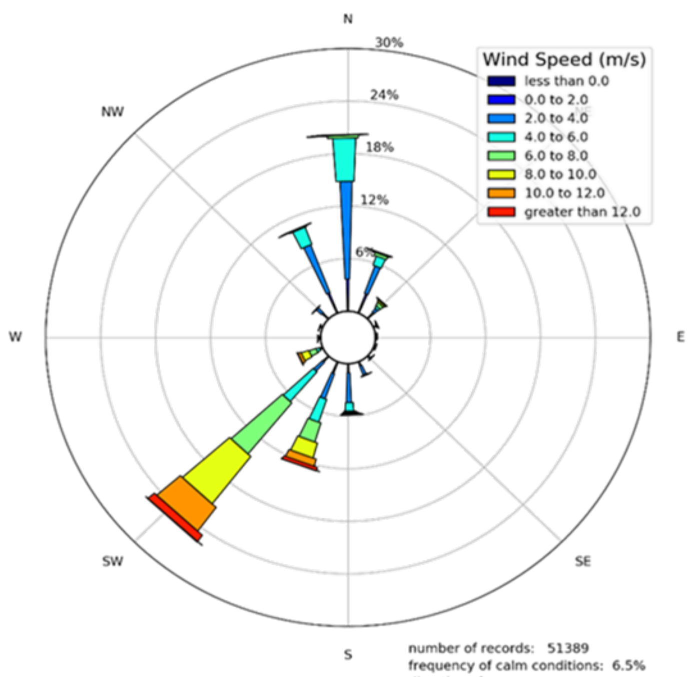

Figure A- 3 Squamish Wind Sport wind rose (Date from 2010-2020)

The predominant wind directions at Pam Rocks are northerly and north-easterly; However, southerly winds are more significant for this study as the longer fetch will impact the wave climate at the Squamish estuary. Winds measured at SWS station are predominantly and higher from southwest, compared to Pam Rocks.

During summer, there is a consistent higher occurrence of local strong wind events measured at SWS. These high winds are formed within the upper reaches of Howe Sound, and are not registered at the Pam Rocks station. These winds intensify as they funnel towards the Squamish estuary. Figure A- 4 shows the wind roses from 2010 to 2019 in a summer month (July). It is noted that the wind speeds at Pam Rock are more directionally distributed and pronominally from the south and north while at the SWS station, they are more frequent and higher from the SW direction. This difference supports the extreme popularity of Squamish Harbour as a wind surfing destination.

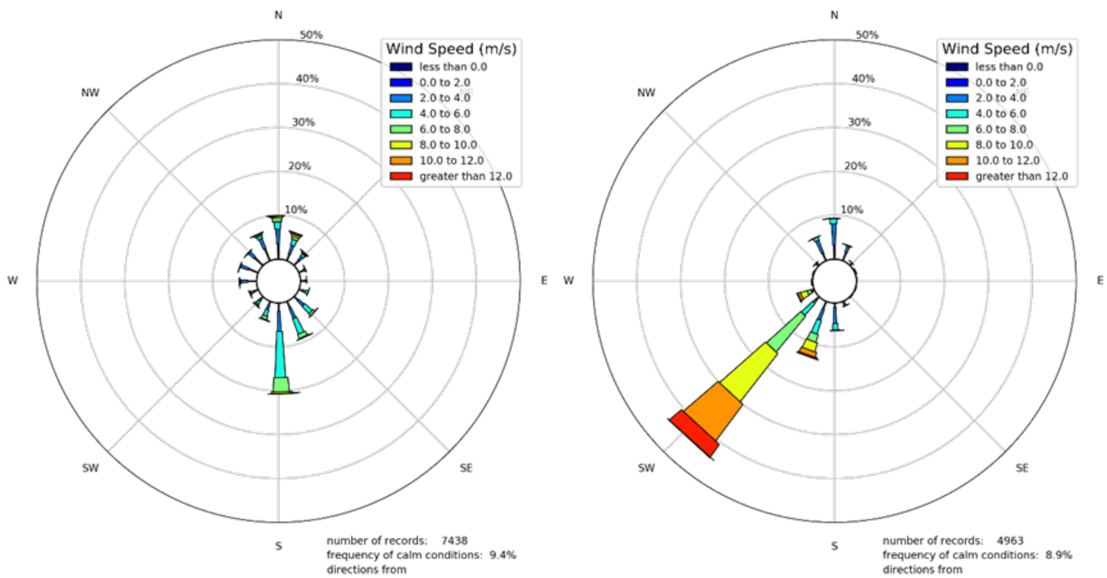

Figure A- 4 July wind rose 2010-2019 at Pam Rocks (left) and Lower Estuary (right)

During winter, there is high occurrence of storm events registered at the Pam Rocks station, these winds inflow into Squamish Harbour and are slightly lower than at Pam Rocks. These storm systems are controlled by the characteristics of the large-scale synoptic systems and associated fronts and are not influenced by the thermal conditions in the estuary area that define the summer characteristics.

Table 2 and Table 3 show the highest winter wind events during the recorded period at Pam Rocks and SWS, respectively. Only southern events longer than three hours were considered.

Table 2 Top wind events measured at Pam Rocks (1994-2019)

Pam Rocks			
Start Date & Time (UTC)	Duration (hours)	Wind Speed (m/s)	Direction
2010-01-18 11:00	3	24.2	150
1995-11-18 4:00	5	23.1	160
1999-01-29 6:00	11	23.1	160
2006-11-15 19:00	7	22.8	140
1997-03-31 0:00	9	22.8	150
2009-11-09 14:00	4	22.8	150
1997-01-01 10:00	7	22.2	150
2001-11-20 5:00	6	21.7	140
1998-11-25 5:00	4	21.7	180
2007-11-11 23:00	13	21.1	130
2016-10-14 22:00	3	20.6	160

Table 3 Top wind events measured at SWS (2010-2019)

Squamish Wind Sports			
Start Date & Time (UTC)	Duration (hours)	Wind Speed (m/s)	Direction (from deg T)
2015-11-17 20:00	3	21.1	182
2015-10-10 20:00	8	19.5	204
2016-03-10 16:00	7	19	211
2012-03-15 19:00	8	18.5	208
2018-01-18 12:00	4	18.5	225
2011-02-13 1:00	6	18	186
2014-01-11 15:00	6	18	182
2011-02-15 3:00	8	17.5	195
2012-01-04 23:00	9	17.5	213
2013-09-29 0:00	3	17.5	211
2017-10-17 13:00	6	17.5	203

Appendix B
Comparison Graphs

This Appendix presents the time series of site specific results for the observation points and comparing the results for exiting and removal scenarios. Figure B-1 shows the location of the observation points[1]. Figure B-2 to Figure B-8 show the time-series of currents, sedimentation/erosion and significant wave height for each observation point.

Figure B - 1 Location of observation points

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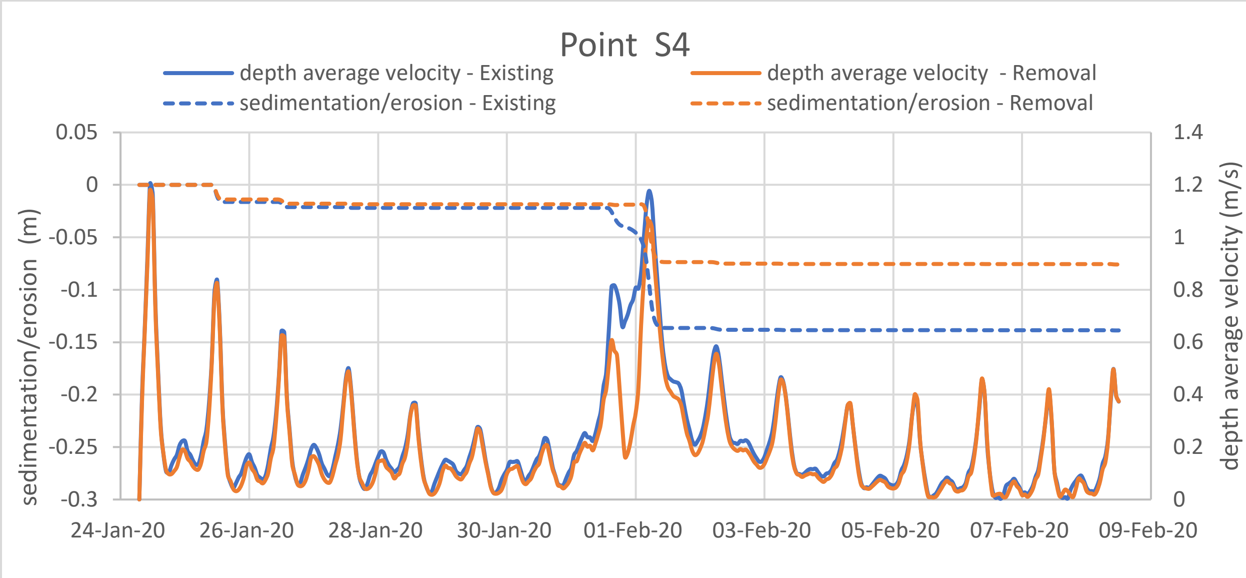
[1] DoS point was selected to represent the conditions at the District of Squamish. This point is close to the model boundary, so the location presented on the results of this Appendix (time series) were taken approximately 65 m west from the point shown in Figure B - 1 to neglect the boundary effects. This point is dry in low water level (satellite image), but it is wet throughout the selected simulation period.



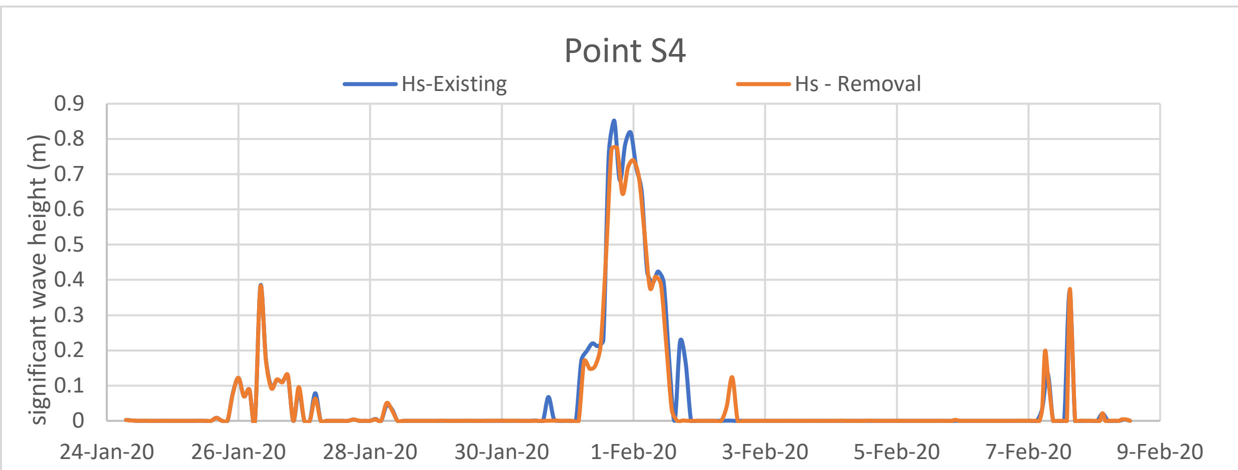
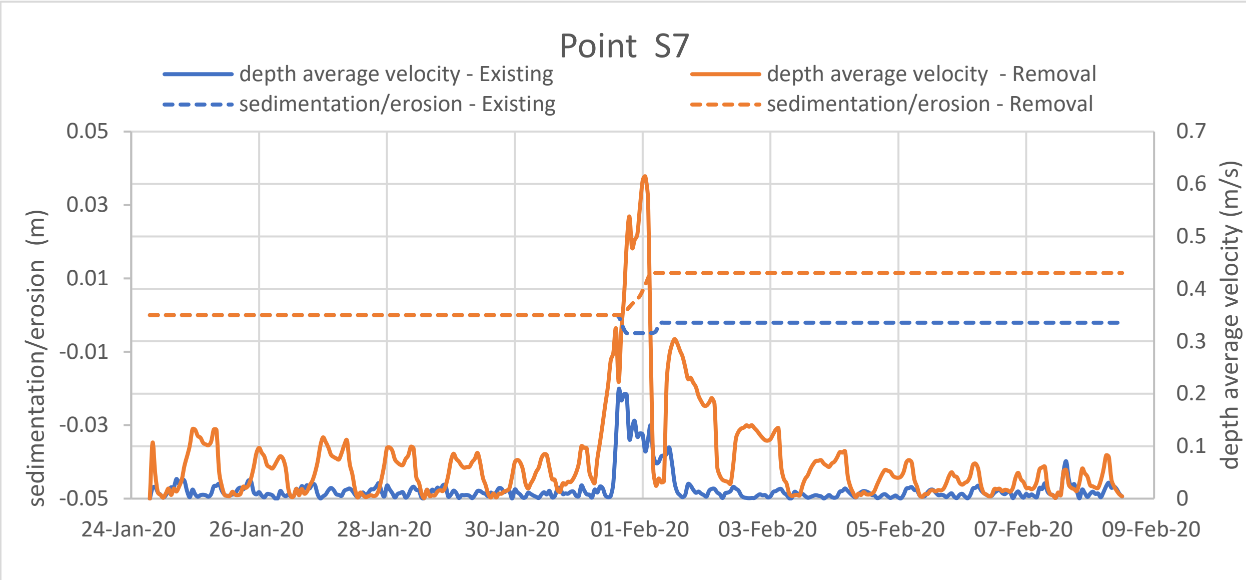


Figure B - 2 Time-series of depth averaged velocity (m/s), and sedimentation/erosion (m) at S4 -upper panel, Time-series of significant wave height (m) at S4 -bottom panel



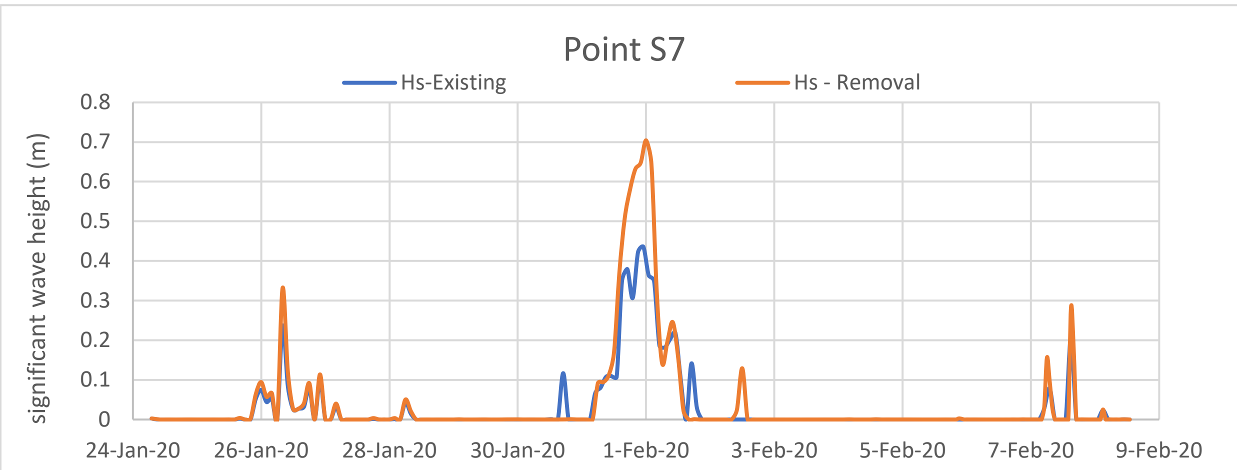
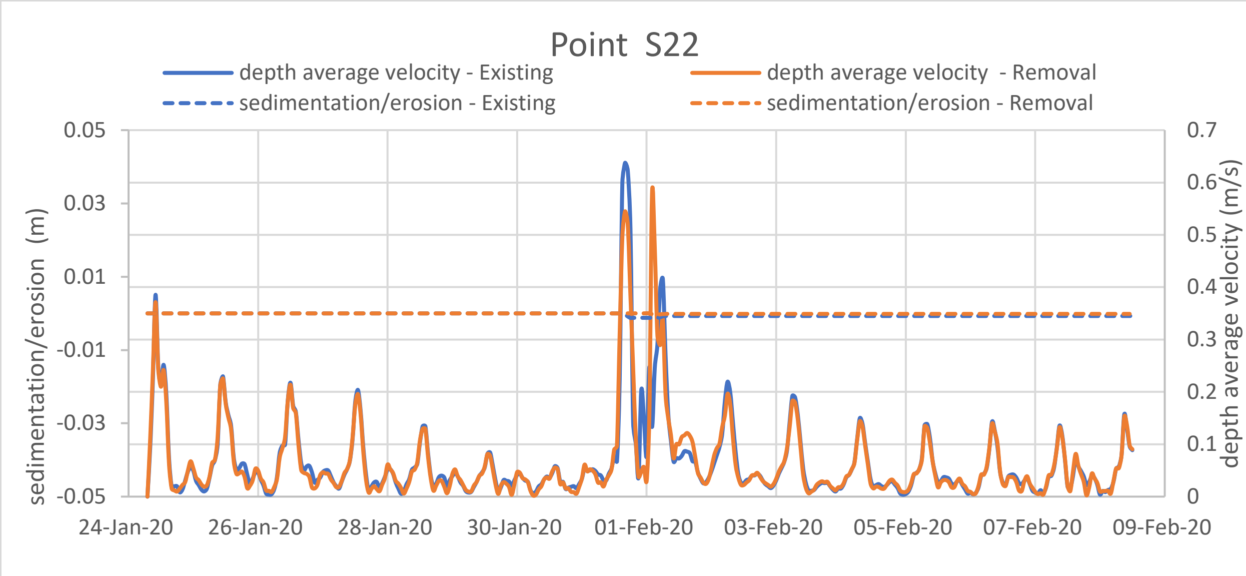


Figure B - 3 Time-series of depth averaged velocity (m/s), and sedimentation/erosion (m) at S7 -upper panel, Time-series of significant wave height (m) at S7 – bottom panel



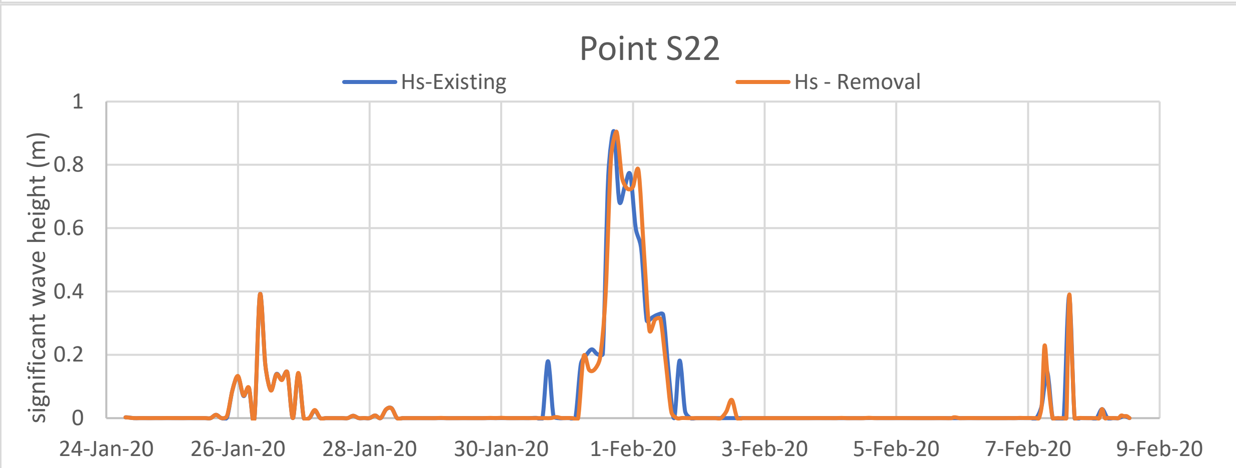


Figure B - 4 Time-series of depth averaged velocity (m/s), and sedimentation/erosion (m) at S22 -upper panel, Time-series of significant wave height (m) at S22 – bottom panel

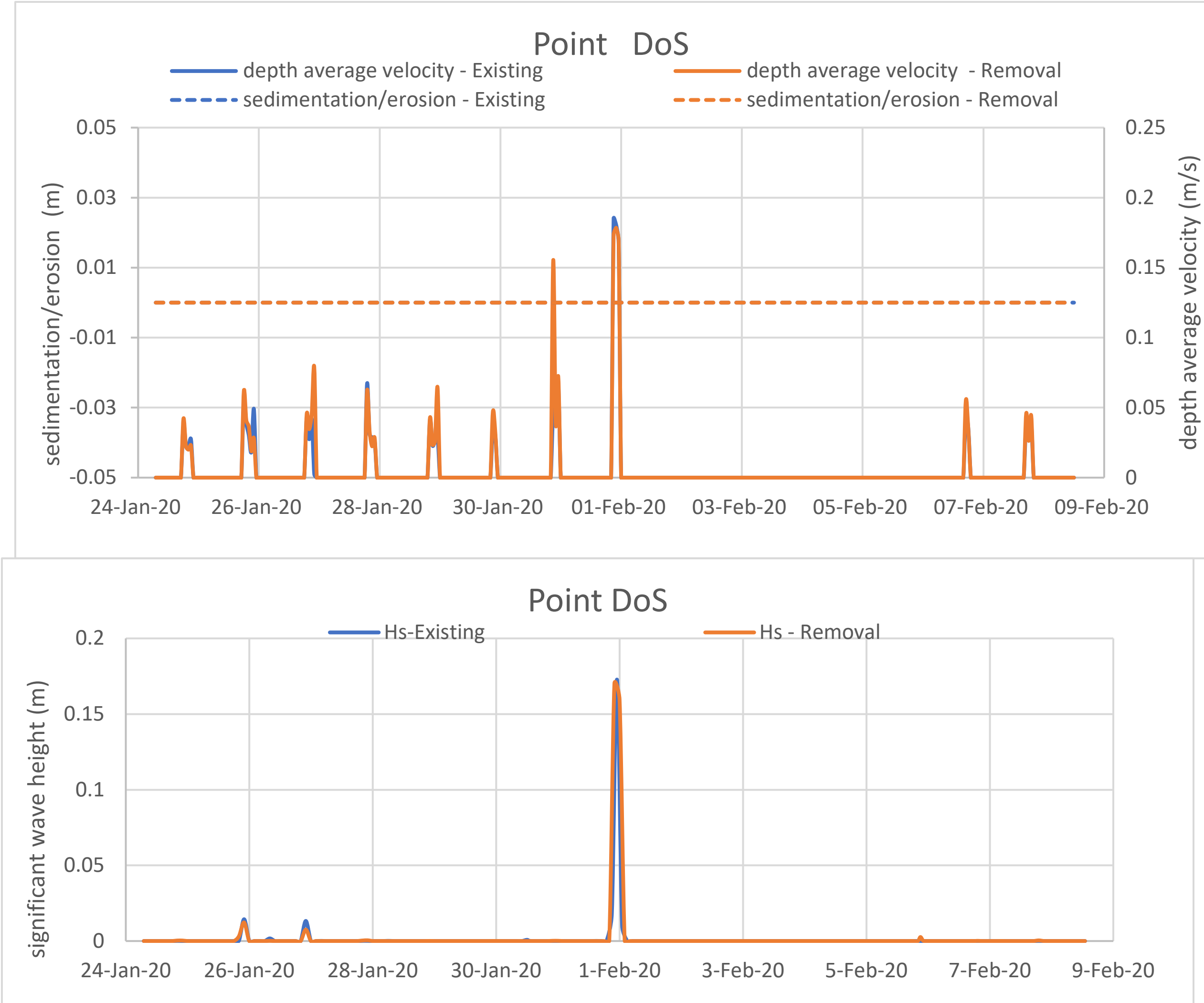


Figure B - 5 Time-series of depth averaged velocity (m/s), and sedimentation/erosion (m) at DoS -upper panel, Time-series of significant wave height (m) at DoS – bottom panel

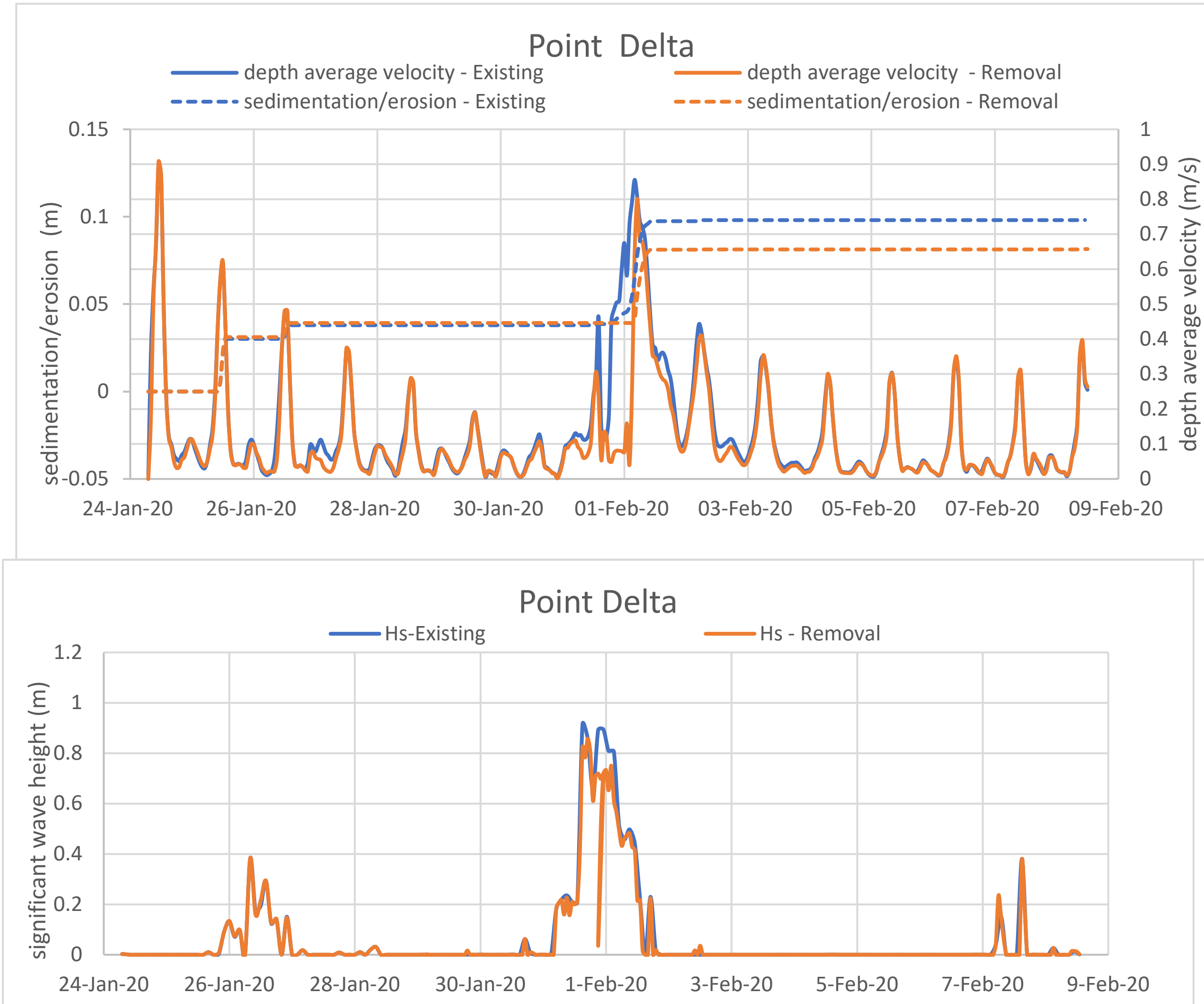
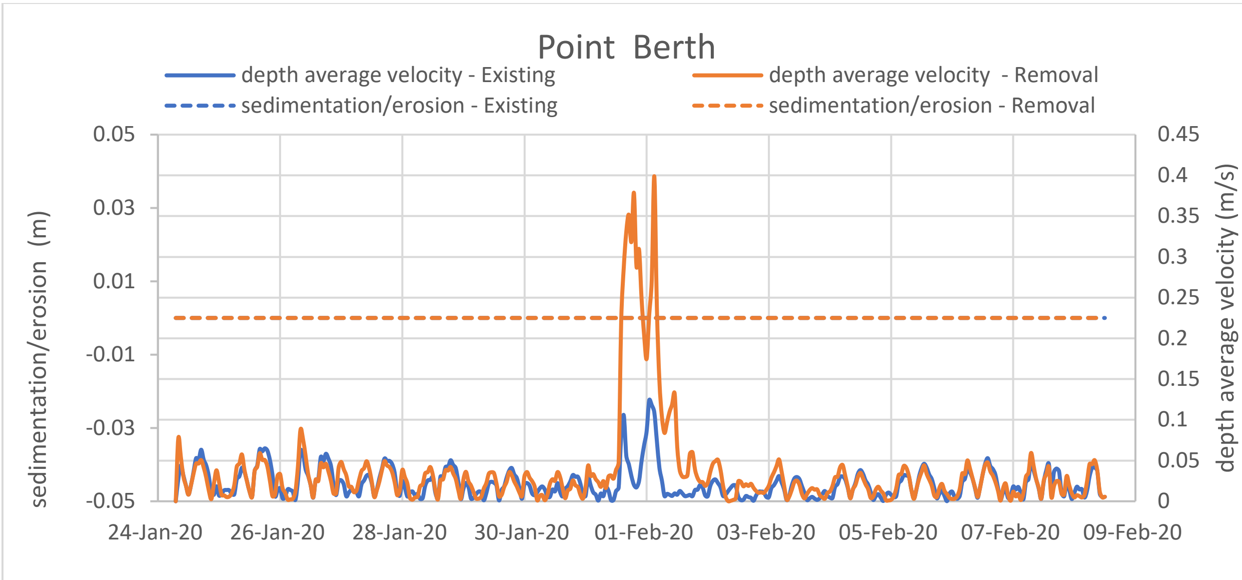


Figure B - 6 Time-series of depth averaged velocity (m/s), and sedimentation/erosion (m) at Delta -upper panel, Time-series of significant wave height (m) at Delta – bottom panel



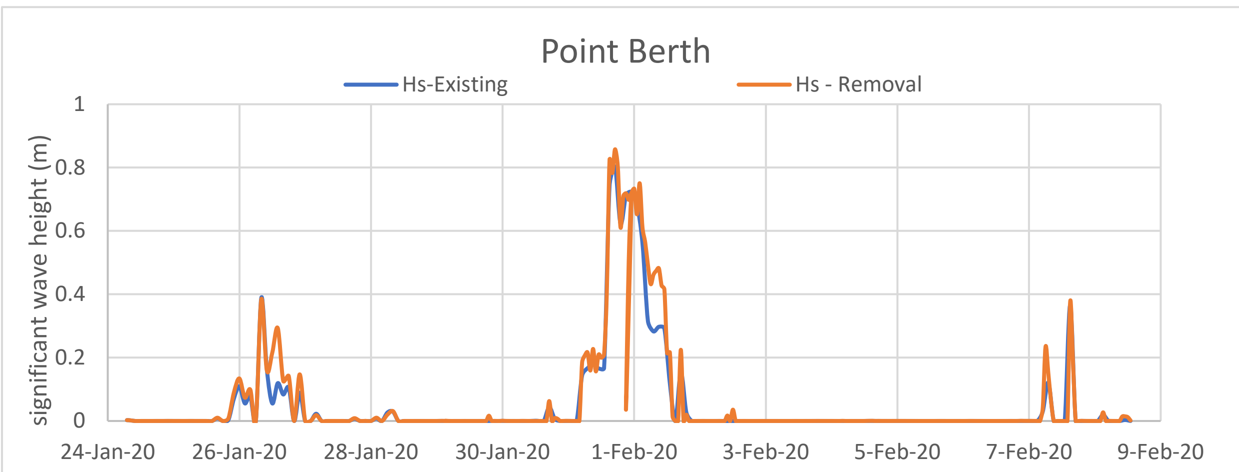


Figure B - 7 Time-series of depth averaged velocity (m/s), and sedimentation/erosion (m) at Berth -upper panel, Time-series of significant wave height (m) at Berth – bottom panel

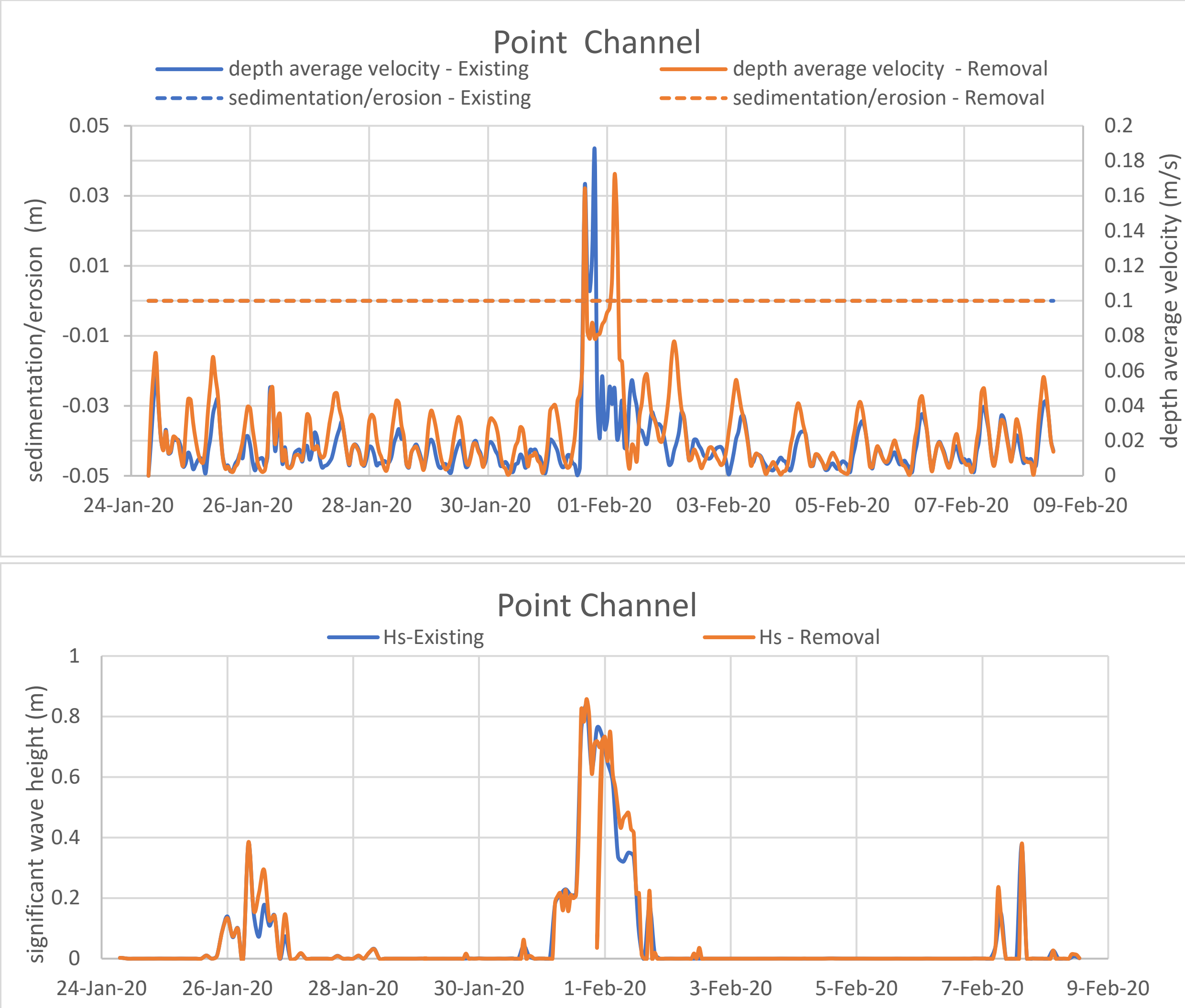


Figure B - 8 Time-series of depth averaged velocity (m/s), and sedimentation/erosion (m) at Channel -upper panel, Time-series of significant wave height (m) at Channel – bottom panel