Pacific Northwest LNG
British Columbia, Canada

Supplemental Modelling Report

For

3D Modelling Update

H345670-0000-12-124-0013
Rev. 0
November 10, 2015

Pacific Northwest LNG
3D Modelling Update

Supplemental Modelling Report

2015-11-06	0	Final	L. Absalonsen R. Arbuckle T. Cheng C. Day C. Monfort F. Salcedo C. Wheeler	S. Fenical O. Sayao	C. Mealing	
Date	**Rev.**	**Status**	**Prepared By**	**Checked By**	**Approved By**	**Approved By**
HATCH						**Client**

Safety • Quality • Sustainability • Innovation

Table of Contents

Safety • Quality • Sustainability • Innovation

List of Tables

List of Figures

Safety • Quality • Sustainability • Innovation

Safety • Quality • Sustainability • Innovation

List of Appendices

Executive Summary

Description of Project

Pacific NorthWest LNG is a proposed natural gas liquefaction and export facility on Lelu Island which is located within the District of Port Edward and on land administered by the Prince Rupert Port Authority (PRPA). The proposed project includes a marine export terminal located offshore of Lelu Island, in the naturally deep waters of Chatham Sound.

The proposed marine structures include a long span suspension bridge and piled trestle and berths. The bridge spans approximately 1600 m along the northwest edge of Flora Bank from Lelu Island to Agnew Bank, supported by two isolated in-water supporting structures – the Southwest Tower and Southwest Anchor Block. The trestle and berths are generally composed of widely spaced pile bents supporting a traffic deck. In hydrodynamic terms, the proposed structures consist of two isolated individual “islands” of approximately 0.2 ha each located along the north edge of Flora Bank, and an extended field of sparse support piles located between approximately 50 to 500 m north of Flora Bank.

About this Report

This report summarizes results of modelling efforts conducted subsequent to the May 5, 2015 3D Modeling report (Hatch, 2015), including continued refinement of previous hydrodynamic and morphology efforts using Delft3D, extensive new high resolution modelling efforts to closely examine behaviour in the immediate vicinity of the proposed tower and anchor block, and additional supporting analysis. Although this report supplements previously completed work, the analytical and modelling efforts to date, taken in combination with works by others (incl. SedTrend, 2015ab), have yielded a strong understanding of the coastal processes acting on Flora Bank and its environs, providing further confidence that the predicted impacts of the marine structures are well understood.

Project Site and Environment

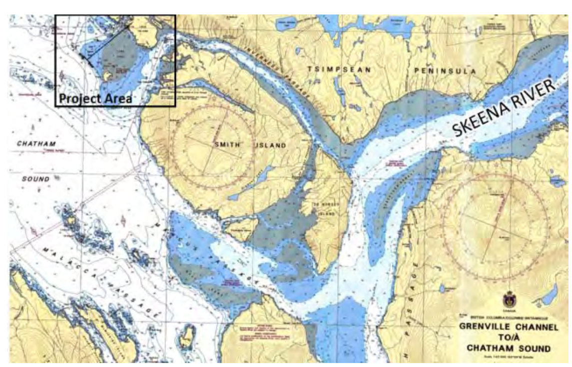
Flora Bank is large, flat, inter-tidal area, roughly 2 km by 1.7 km (325 ha in area) above lowest normal tide elevation (0 m Chart Datum or -3.8 m Mean Sea Level). Due to a relatively large tidal range, water depth varies to a maximum of approximately 7 m.

Flora Bank is believed to be a glacial relict formed during the most recent glacial retreat roughly 8,000 years ago. The shape and extent of Flora Bank has not changed significantly over a period of many years, and appears to be very stable.

Flora Bank sediments consist of fine to medium sands (SedTrend, 2015b), which are distinct from the clays and silts found on the deeper waters of Agnew and Horsey Banks, and the clays and fine to medium silts found in the deeper troughs of Chatham Sound. Sediment grain sizes and the SedTrend (2015b) analysis indicate that sediment transport and erosion/deposition patterns are spatially variable in this area of Chatham Sound, which includes many depositional deeper-water areas that likely receive fine sediments from the Skeena River plume.

The combination of coarser sandy material and very wide and flat configuration, results in very gradual dissipation of wave and current energy (which are relatively low at the site), infrequent sediment transport due to mild conditions and exposure at low tide, low levels of net transport off of Flora Bank, and finally low levels of bed erosion or deposition. The low levels of transport and erosion/deposition are consistent with the results of the SedTrend (2015) analysis, which was unable to discern any transport trends over the vast majority of Flora Bank.

Eel Grass coverage of Flora Bank varies from year to year, but typically is found over an area of approximately 35-45 ha, or approx. 10-15% of the extent of Flora Bank.



Agnew Bank is a sub tidal flat located on the west side of Flora Bank, with elevations ranging from 0 to -5 m(CD). Agnew Bank differs greatly from Flora Bank in that it is generally deeper and does not become exposed at low tide. It is also different in that it is a depositional environment, with much finer surficial sediments than found on Flora Bank. Most of Agnew Bank is relatively flat and slopes gradually to the offshore, with the exception of the southwest side which slopes more quickly to deeper water near the proposed tanker LNG carrier berths, and along its boundary with Porpoise Channel.

Modelling Inputs / Modelling Efforts

A series of modelling efforts have been undertaken to develop an understanding of Flora Bank. Several tools have been utilized in a range of broadly parallel efforts, in order to fully explore the various processes relevant to understanding both Flora Bank and the potential effect of the proposed structures on hydrodynamics and morphology. Numerical modelling was performed to simulate coastal processes on both a large/regional scale (hundreds of kilometers down to tens of meters) and a highly localized scale (meters) to ensure accurate simulation of relevant physical processes.

These efforts build on previous work undertaken over the course of the project development to date, and have directly incorporated a wide range of relevant data sources, including Environment Canada and National Oceanic and Atmospheric Administration (NOAA) wind and wave data; data collected directly by PNW LNG; and sediment data and resulting analysis developed by SedTrend (2015b). Results from numerical modelling and supporting analyses have been compared with results of SedTrend (2015ab) and indicate broad consistency.

The Delft3D (Deltares 2014ab) coastal processes modelling system has the capability to simulate all coastal processes mentioned above, and pre-eminence in the coastal engineering industry for accurate simulation of morphological change under complex coastal conditions. Delft3D simulates wave growth and transformation, and 3D hydrodynamics, salinity transport, sediment transport, and morphological change. The Delft3D far-field model domain stretches beyond the west coast of Haida Gwaii, while the nested domain encompasses an area of approx. 80 x 80 km centered at the project site, including the lower 20 km of the Skeena River.

The MORPHO modelling system (Kolomiets et al 2014) was selected to simulate fine-scale physical processes around the proposed SW Tower and SW Anchor Block. MORPHO is an unstructured, finite volume coastal processes modelling system that simulates fully nonlinear depth-averaged hydrodynamics, sediment transport and morphological change. The scale of the processes simulated in the MORPHO model spanned from hundreds of meters down to meter-scale resolution around the structures. The MORPHO model domain is approximately 3 x 3 km, centred on Flora Bank, and the MORPHO models were driven using Delft3D-generated velocity and water level input conditions, but generate independent results.

Range of Conditions Examined

Many coastal processes play a role in the hydrodynamics, transport and morphology of Flora Bank. Coastal processes evaluated at the project site and incorporated into the 3D regional scale modelling effort include:

- Tides (water levels);
- Tidal currents;
- Winds and wind-driven currents;
- Local wind-driven waves;
- Offshore waves (swells);
- Salinity; and,
- Skeena River discharge.

Additionally a range of frequent, seasonal and extreme events were considered in order to evaluate relative contributions of these processes in varying circumstances, including:

- Typical "daily" conditions over extended durations within a typical year;
- Key seasonal periods (for example the stormier winter months, and the Skeena River freshet season); and,
- Extreme (large and infrequent) storm events, including 50- and 100-year return period events.

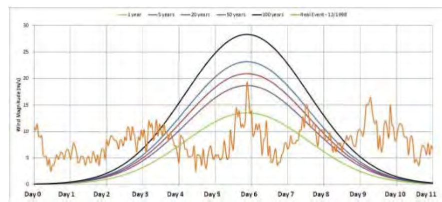
Inputs for typical modelling conditions utilize time histories of hindcast information from a combination of measurements and predictions as is typical in the industry. Extreme storm events, in contrast, are typically not reflected in available data (due to their highly infrequent occurrence) and were synthetically generated, typically by scaling appropriate measured events. Recent efforts have included synthesized extreme events which are significantly more conservative (larger in magnitude and duration) than are probable at a given return period based on actual measured events shown in available data.

5 Key Questions

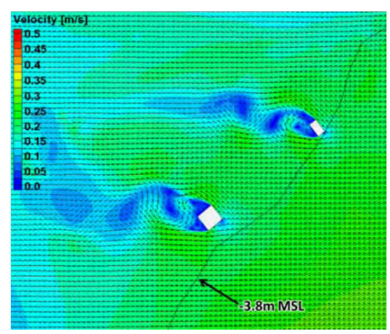
A key focus of recent efforts has been to further refine these modelling efforts in order to respond to a set of key concerns expressed by CEAA and relevant Federal Agencies, including:

1. Refinement of wind and wave inputs to account for spatial variability of the wind fields (gridded winds) and offshore waves (gridded offshore waves), to determine whether variability of offshore inputs results in improved predictions of waves at the project site. Analysis indicates that predictions of local and offshore waves at the project site (as compared with on-site measurements) are not appreciably affected by inclusion of the refined inputs.

2. Modifying representation of extreme storm events to include synthetic longer-duration events, from a broader range of directions. The refined modelling efforts have included development and modelling of extended duration, unidirectional storms with intensities appropriate for the relevant return periods, which will likely amplify modelled hydrodynamics and transport in comparison to “natural” records. Results indicate that Flora Bank remains stable due to significant attenuation of waves and currents; that the majority of the morphology changes arising during storms are driven by sediment transport only under strong wave attack. Results show that the proposed structures have only a modest, and mildly attenuating, effect on the predicted changes due principally to a modest reduction in wave energy from westerly and northwesterly waves.



3. Improved representation of the larger marine structures and their local effects. Significant additional modelling of local effects has been conducted in the vicinity of the proposed SW Tower and SW Anchor Block structures. This work has included development of a new high-resolution model driven by results from the regional Delft3D model, and examination of hydrodynamic and transport effects of these structures during typical, seasonal and extreme storm conditions. This effort has yielded further insights into the dominant natural flow conditions, which are broad, relatively uniform and mild (low current velocities that are below threshold of sediment motion most of the time). Modelling of the proposed structures shows modest local increases in current in the immediate vicinity of the structures as well as typical eddying effects downstream of the structures. Generally speaking the additional high-resolution modelling has confirmed the presence of local, transient current variations in the immediate vicinity of each of the proposed structures, and confirmed that the structures induce limited local erosion and



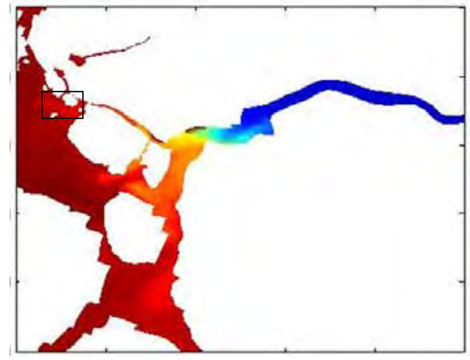
deposition patterns within an area located within tens of metres away from the structures themselves.

4. Performance of longer-period simulations with real continuous inputs (no input data averaging). A wide range of time-series simulations have been completed with continuous data inputs and without any morphological acceleration (MORFAC=1) in order to supplement insights gained through previously conducted time series studies and the extensive MORFAC=13.5 results presented previously. Continuous time-series analysis have been completed for circumstances including both typical daily and seasonal periods, and for the full range of extreme events discussed above, and over a series of extended time periods up to 1 year in duration covering the full annual cycle. While this effort has supported significant additional understanding of Flora Bank under a wide variety of conditions, the refined modelling approach continues to support the conclusion that Flora Bank is a highly dissipative feature and morphologically stable environment. Except as noted otherwise, all discussions within this report are based on continuous time-series modelling runs.

   "MORFAC" runs can utilize time-averaged inputs and discrete time intervals to represent longer time periods, allowing efficient estimation of effects over long-time periods (i.e. 5-years). "Continuous time series" runs, in contrast, update the wind and wave input conditions on an hourly or near-hourly basis (i.e. at the frequency available in the available wind and wave data sets), while the model itself calculates changes on a continuous basis (10-second time steps), uninterrupted over the modelled time period (i.e. a complete 11 day extreme storm cycle, or over an extended 12-month time period).

   The continuous time-series runs undertaken in recent months typically incorporate the full range of refined input parameters explained above, extended over an modelled domain of approximately 8000 km^2, resulting in a comprehensive simulation of the existing conditions.

5. Improve the presentation of results to better convey coastal processes being simulated. Significant efforts have been undertaken to quantitatively review and present model results, particularly sediment flux and net sediment transport across a wide range of modelled conditions. In general, the additional analysis and presentation results has been helpful in displaying the level of transport occurring for each sediment size, directions and magnitudes of net transport. Modelling results indicate large, wide and extremely homogeneous fields of transport (of primarily the finer materials) over Flora Bank which provide a very clear indication as to why Flora Bank experiences little bed elevation change. The extremely low gradients in wave heights and current speeds results in low gradients in transport, and hence little bed elevation change.



In addition, recent modelling efforts have refined a range of other inputs, including Skeena River freshwater discharge and salinity to further enhance the detail with which the Skeena river inputs to the site area are represented in the model. Efforts have included doubling the vertical resolution of the modelling domain, extending the model's initial salinity "spin-up" periods, and careful review of salinity variation in the model results. Additionally, the use of continuous time series modelling ensures that the full freshwater discharge and sediment load from the Skeena River are considered in the model. Based on extensive modelling efforts it is evident that the Skeena River freshwater discharge plays only a limited role in physical processes at the project site, owing principally to the distance to the site and the limited flow through Inverness Channel, and to the fact that only extremely fine sediments – too fine to influence morphology at the site - are present in the Skeena River plume.

Results: Conditions at Flora Bank

The analysis results confirm that the coastal processes surrounding Flora Bank are dominated by tidal currents, wind driven waves and storm events. Due to shelter provided by Haida Gwaii, ocean swells and offshore waves are significantly attenuated and have only a modest presence at Flora Bank. Flora Bank is located within the Skeena River estuary, but due to the significant distance from the mouth of the Skeena (approximately 18 km) and the intervening channel geometry, the annual Skeena freshet cycle has very limited effect on the morphology of Flora Bank.

Tidal currents are generally mild, with flood and ebb current velocities typically less than 0.25 m/s (0.5 knots). Significant wave heights under typical conditions are usually less than 0.3 to 0.5 m, as wave heights are gradually attenuated during approach to and travel over Flora Bank. Limited wave breaking occurs on Flora Bank except during extreme events and during a small range of low water levels.

Direct sediment transport analysis using multiple methods (mobility analysis, 1D profile modelling and 3D Delft3D modelling) indicates that sand on Flora Bank is typically mobilized where current velocities exceed approximately 0.3 m/s and/or wave action is significant. Given both the relatively low duration of most periods when these conditions are exceeded and the large flat extents of Flora Bank, transport distances are generally limited with relatively little material transported off of Flora Bank.

A range of extreme storm events have also been analysed to understand the effect of infrequent large events on Flora Bank. Generally, patterns evidenced in typical conditions are amplified by extreme events (since "typical" conditions include smaller storms), though even in very large events actual bed changes occur only during a portion of the storm and transport of fine to medium sand off Flora Bank is limited.

Safety ● Quality ● Sustainability ● Innovation

Owing in large part to the combination of coarser sediments, flat and gradual configuration and relatively benign typical coastal conditions, sediment transport on Flora Bank occurs principally during storm events. The synthetic extreme events that were created here represent an exaggeration of what typically occurs during real extreme events, and even within the synthetic storm events, changes in bed elevation are not likely to be measurable in the field.

Effect of Structures

Generally speaking the effects of the proposed structures within the environment discussed above are best understood by stepping progressively outward from the structures.

The direct physical footprint of the structures includes the footprint of the proposed SW Tower and SW Anchor Block, the trestle and berth support piles, and an allowance for scour protection intended to prevent seabed erosion immediately adjacent to the structures. The potential for local scour is well understood, and the extent of likely protection has been estimated in previous studies. The direct footprint of the proposed structures is approximately 2.15 ha.

High-resolution modelling has permitted examination of local currents and vortex shedding (eddying) effects arising in the immediate vicinity of the structures, under both typical conditions and extreme storm events. Model results evidence vortex formation and dissipation consistent with established literature, and localized and transient instantaneous velocity changes in the vicinity of the structures. This result is consistent with known processes around relatively small (relative to the flow field) and isolated structures in relatively homogeneous flow conditions.

Peak current velocities during both ebb and flood conditions typically remain below 0.3 m/s, and are of the same order as transient current velocities evidenced elsewhere on Flora Bank during typical tidal conditions. Over extended periods local hydrodynamic effects are likely to gradually develop local bedform changes within the immediate vicinity of the structures, but the predicted erosion and deposition around the structures remains remote from the extents of mapped eel grass habitat. Elevated levels of TSS within the water column are found only over very short periods of time, and only shortly after construction while the local erosion and deposition patterns develop.

Hydrodynamic effects that generate erosion and deposition, or TSS changes, dissipate within tens of meters away from the structures. High-resolution modelling has been performed using conservative, rectangular-shaped structures that have not benefited from future design refinement. A preliminary sensitivity analysis using larger, but circular, structures indicates that a substantial reduction in the predicted hydrodynamic and erosion/deposition effects is likely following subsequent design refinement.

Regional-scale modelling was performed using the continuous time-series simulations within the refined Delft3D model for the full range of conditions described above. Analysis results indicate that in all circumstances evaluated, the structures have a limited effect on the background coastal conditions, and generally evidence a mild attenuating effect on the predicted erosion and deposition patterns. This is primarily due to the trestle pile field's slight wave attenuation effects during west and northwest winds.

Neither the modelling results nor previous work undertaken by SedTrend evidence significant transport of fine to medium sand onto or off of Flora Bank. This indicates that for sand similar to that found on Flora Bank, there are limited natural sediment transport processes on and around Flora Bank that can be appreciably affected by the proposed marine structures.

Quantification of Flux and Transport

Analysis of the modelling results has included additional efforts to quantify sediment transport using several approaches, including both review of sediment transport spatial gradients, and volumetric analysis of bed elevation changes over defined areas. Generally these efforts evidence little net (residual) transport of material onto or off of Flora Bank under a range of conditions, and small differences between cases with and without the marine structures. Even in larger extreme storm events, the marine structures have only a mild attenuation effect, with the vast majority of the structure-induced changes being either a reduction in natural erosion, or reduction in natural deposition, that occurred during the event.

Generally speaking, analysis of the results indicates that bed elevation changes due to the marine structures are within or near the limits of the Delft3D model's error bands. That is to say that although the analysis of extreme events has validated the capability of the model to produce reasonable morphological changes, the scale of the morphological changes under typical and even extreme event conditions remains relatively low, reinforcing the conclusions that:

- The evident long-term stability of Flora Bank is a result of limited change under benign conditions; and,
- The relative effect of the proposed structures within this environment is marginal.

Analysis of modelling results indicates that Flora Bank is very stable, highly dissipative and only experiences bed elevation changes during strong perturbations, all behaviours which are in agreement with long-term observations. Measurable bed elevation changes are only likely during very rare extreme events. Therefore, measurable differences in bed change on Flora Bank that are attributable to the marine structures are also only likely to occur during extreme events, and only likely to occur in the form of a mild reduction in erosion and deposition, with the exception of the immediate vicinity of the SW Anchor Block and SW Tower.

Long-Term Analysis

Simulations have been performed covering a wide array of mild, typical and extreme coastal conditions. Some of these simulations were relatively short in duration, and some longer (up to 1 year) but all results provide information regarding the potential long-term impacts of the marine structures. In addition, important sensitivity testing simulations provide even more information about long-term effects.

Longer-term time series simulations that cover a complete year indicate the following:

1. Results of a range of simulations show consistent patterns;
2. Overall bed elevation changes predicted over a full year (absent the marine structures):
    a) remain moderate,
    b) are consistent with patterns/locations identified in other modelling results
    c) are concentrated in areas that make sense, for example erosion occurs in high-energy, high-elevation spots,
    d) continue to indicate that sand material moves around within Flora Bank
    e) show no evidence of divergence or instability over time even with exaggerated morphological changes
3. Relative bed elevation changes for cases with and without the marine structures:
    a) remain consistent in location/pattern/magnitude,
    b) show similar patterns of moderate bed change attenuation (reductions in both erosion, and deposition),
    c) show no evidence of increasing divergence or instability, and
    d) show no evidence of materially altering natural long-term trends.

Pathways

Evaluation of the modelling results in the context of potential impacts to fish and fish habitat has been strongly guided by efforts to articulate a set of key pathways connecting effects to potential impacts.

Key pathways may be broadly summarized as:

- Direct impacts: These are well understood relative to the present state of marine structures design, and conservatively accounts for scour protection. Total direct footprint is estimated at 2.13 ha.
- Erosion or deposition induced by marine structures that potentially affect eelgrass habitat: Modelling analysis indicates moderate direct effects on the bedform in the immediate vicinity of the bridge structures arising from localized tidal flow changes around the two bridge obstacles. Changes on Flora Bank are expected to be local (near the two bridge structures), and eroded sediments during tidal flow and wave action will be deposited nearby.
- Changes in currents around the southwest anchor block and southwest tower: modelling results indicate that localized current changes and eddies in the local vicinity of the proposed SW Tower and SW Anchor block (within tens of metres of the structures) are evident, but are transient, mobile and of limited magnitude.
- Changes in total suspended solids (TSS) relative to background levels are similarly focused around the SW Anchor Block and SW Tower, consistent with the localized current changes and eddies in the local vicinity. TSS variances are transient, mobile and of limited magnitude.

More generally, modelling results support continuing understanding of the coastal processes at work and support continuing confidence that Flora Bank is robust and stable, both prior to and following construction of the proposed marine structures. Analysis efforts have identified no potential for a fundamental state change impacting fish and/or fish habitat, as well as no evidence of divergent or run-away effects. This is principally due to the moderate, broad flow fields within which the structures are located.

1. Introduction

This report provides an update on the hydrodynamic, sediment transport, and morphology modelling efforts which evaluate the potential effects of proposed marine terminal infrastructure on fish and fish habitat on Agnew Bank and Flora Bank.

This report supplements recent modelling efforts broadly described in "Pacific Northwest LNG Updated 3D Modelling Work Plan" and builds upon previous modelling efforts documented in Hatch's May 5 2015 Report "Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation" (Hatch, 2015).

Recent modelling and related analysis efforts have been undertaken in part to address the comments raised by CEAA and the federal experts contained in correspondence from CEAA (Canadian Environmental Assessment Agency) to PNW LNG dated June 2, 2015, which in turn referenced review comments from Natural Resources Canada (NRCan letter, May 29) and Fisheries and Oceans Canada (DFO letter, May 29; and DFO Science Technical Review, May 20). CEAA provided further feedback to PNW LNG in a slide deck presented June 4, 2015.

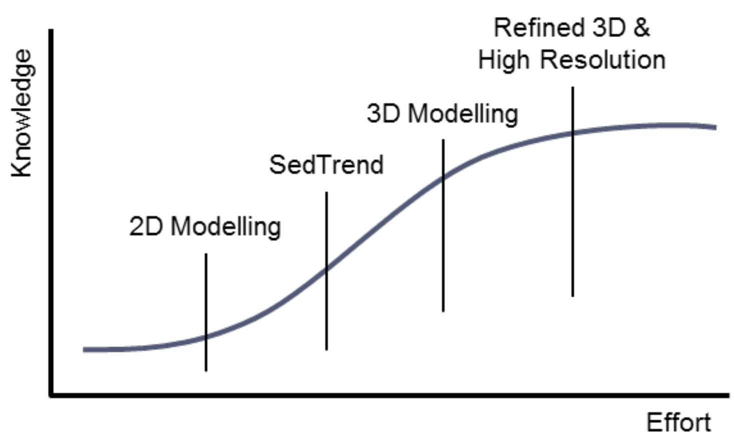


Figure 1-1: Development of Understanding over Time

These recent efforts build upon and supplement a growing body of knowledge regarding the hydrodynamic and morphological behaviour of Flora and Agnew Banks which has been informed by a series of efforts, including:

- Hatch Marine Structures Scour Analysis (Hatch, 2014b);
- Hatch 2D Modelling (Hatch, 2014a);
- SedTrend Sediment Trend Analysis of Prince Rupert Harbour and its Surrounding Waters (SedTrend, 2015a, 2015b);

- Hatch 3D Modelling (Hatch, 2015); and
- Various Fish and Fish Habitat studies undertaken by Stantec (Stantec, 2015a).

While this report specifically addresses key concerns raised by CEAA and supporting federal experts, the broader objective is to provide an integrated overview of modelling efforts intended to understand the coastal processes acting on Flora Bank. These processes effect the hydrodynamics, sediment transport, and morphology under natural conditions, and provide an baseline context for understanding the effects anticipated to arise from the construction of the proposed marine infrastructure. These results incorporate recent refinements to previous 3D modelling efforts related to input conditions, modelling approach and quantification of results intended to support further confidence in the modelling results.

The current modelling efforts are intended to develop understanding of Flora Bank and the probable effects of the proposed structures in order to allow regulators and project stakeholders to complete the assessment stage with confidence. Refinement of analysis, modelling, and design will continue though the permitting and detailed design phases in a continuous effort to optimize the design and minimize impacts.

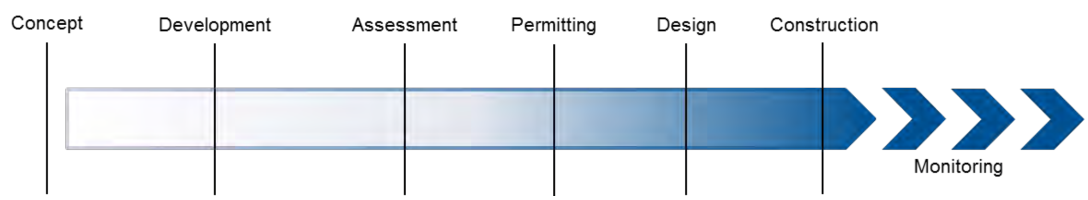


Figure 1-2: Project Cycle

This report presents an overview of the current findings in regard to the effects of the proposed structures developed from both refined 3D regional modelling efforts, as well as from recent additional high resolution modelling of hydrodynamics and sediment transport local to the proposed Southwest Tower and Southwest Anchor Block structures.

1.1 Workplan

- This report summarizes efforts articulated in a work plan, provided in Appendix J, prepared in order to guide further modelling and related analysis efforts intended to address the comments raised by CEAA and the federal experts.
- Although described in a sequential manner as an aid to visualizing the process, many of these efforts have been undertaken in parallel, in order to further improve:
  - Confidence that the baseline model appropriately represents the hydrodynamic and sediment transport behaviour of Flora Bank (i.e. through refinement of the Skeena River discharge parameters) at the level of detail necessary to substantiate conclusions regarding potential impacts of the marine structures;

    - Confidence that the potential effects of the new structures on the hydrodynamics and sediment transport are appropriately represented (i.e. through improvements to the modelling of the anchor block, etc.); and,
    - Confidence that any potential adverse effects of the new infrastructure have been determined, particularly when comparing the relative effects of relevant extreme storm events, and relative long-term erosion/deposition trends.
- The work plan explicitly has guided efforts to address CEAA's five key concerns while continuing to refine the overall understanding of the behaviour of Flora Bank. The principal objectives of the work plan are to:
    - Evaluate and further refine selected inputs to the modelling analysis, including review and as appropriate refinement of the input of wind and wave fields in the model (CEAA concern #1);
    - Undertake additional modelling runs using time series (MORFAC = 1), in order to further refine the understanding of the model response to daily and seasonal effects and the potential impacts of the marine structures, supported by additional runs refining understanding of the long-term morphology and potential impacts of the marine structures (CEAA concern #2); and
    - Review the scaling and directionality of the extreme events and amend the model approach as appropriate (CEAA concern #3);
    - Refine the representation of the proposed bridge infrastructure in the model(s) (CEAA concern #4); and,
    - Refine the presentation of output data resulting from both of the above efforts and using data already available from previous efforts in order to allow greater insight, validation and quantification of observed trends (CEAA concern #5).

Recent efforts have made significant progress on all five of the objectives summarized above, and have additionally provided even greater insight into the fundamental context and dynamics of the site.

Most particularly recent efforts have completed refinements to various input parameters in the Delft3D model, and have principally focused on new high-resolution modelling of the SW Tower and Anchor Block regions; on analysing the effects of extreme storms; and on time series modelling of various periods and over increasing durations. Long-duration time series modelling efforts have also provided further insight into the behaviour of Flora Bank both in natural conditions and with the proposed structures, as discussed herein.

1.2 Impact Pathways

Through ongoing consultation with DFO and CEAA, PNW LNG has identified four distinct pathways that may be induced by the marine infrastructure that could lead to adverse effects on fish and fish habitat, and which may be informed by the modelling results.

a) Direct loss of habitat on Agnew Bank from construction of the infrastructure and placement of scour protection and/or armouring of suspension bridge substructures, trestle pile bents and the berths for erosion control;

b) Potential loss or alteration of eelgrass habitat due to induced erosion and/or deposition on Flora Bank;

c) Potential for an increase in total suspended solids (TSS) beyond existing levels that may directly affect fish or limit a fish's ability to feed; or

d) Potential for a material increase in currents around the SW Tower and SW Anchor Block that affects the ability of CRA species to move through the water and use the habitat.

This report also considers potential material alteration to the overall Flora Bank morphology.

As a guideline to understanding the potential for loss of eelgrass habitat due to induced erosion and/or deposition on Flora Bank, a general threshold of 5 cm/year has been established (note: scientific literature indicates that eelgrass may be negatively affected at deposition or erosion levels > 6.5 cm/year therefore 5 cm/year is a precautionary threshold).

These pathways descriptions provide a qualitative mechanism through which the many technical aspects of the modelling and analytical efforts may be synthesized to support understanding of their relevance to the potential effects of the proposed structures on fish and fish habitat.

1.3 About this Report

This report summarizes recent modelling and analytical efforts which build upon a range of efforts completed to date. To assist in placing these recent efforts in the context of the full body of knowledge available to date, this report endeavours to provide a comprehensive summary of our understanding of the project area conditions and effects of the marine structures.

This report is structured as follows:

Section 1 gives the introductory remarks about the report.

Section 2 presents a brief description of the project and an overview of the proposed marine structures;

Section 3 provides an overall description of Flora and Agnew banks and summarizes the fundament coastal environment of the project site;

Section 4 gives an overview of the modelling approach, including a description of the regional 3D modelling and the recent high-resolution modelling efforts;

Section 5 provides an overview of modelling of key coastal processes and their effects on Flora Bank in its existing condition, and a summary understanding of the “baseline” conditions prior to construction of the proposed marine infrastructure;

Section 6 discusses both regional scale and high-resolution local scale modelling of the proposed structures.

Section 7 consolidates the modelling observations in the context of the possible impact pathways potentially affecting fish and fish habitat.

Section 8 provides the main findings obtained with the modelling study.

This report also includes a range of appendices which further detail the modelling and analysis efforts. The appendices are structured as follows:

Appendix A provides the Work Plan which was prepared to guide further modelling and related analysis efforts intended to address the comments raised by CEAA and the federal experts.

Appendix B describes the model setup for the regional (Delft3D) model and changes from previous efforts.

Appendix C and Appendix D provide information of the refinement of the wind and offshore wave input data for the regional (Delft3D) model, respectively.

Appendix E includes analysis of the vertical resolution and the modelling of stratification in the regional (Delft3D) model.

Appendix F demonstrates the calibration and validation of both the Delft3D wave and flow model.

Appendix G provides background information on the development of the storm (extreme event) conditions.

Appendix H includes additional Delft3D modelling results.

Appendix I describes the efforts to model a continuous longer-term time series and lists the simulations conducted.

Appendix J describes the high resolution modelling including background model information, setup details, and results not included in the main body of the report.

Appendix K includes a desktop analysis of sediment mobility for the sediments typically found on Flora Bank.

Appendix L provides information on the direct impact calculations including local scour protection details around the marine structures.

Appendix M provides supplementary animations of the modelling results. Note that Appendix M consists of media files provided in electronic format.

As described in Section 1.1, an important component of this report is to address key technical aspects of the input and modelling issues raised by CEAA and the federal technical experts. Analysis addressing CEEA's 5 concerns are located within the report as follows:

Information on the review and refinement of the wind and wave inputs (CEAA concern #1) are included in Appendix C and Appendix D.

Longer-term time series runs (CEAA concern # 2) are included in Appendix I and in Sections 5.3 and 6.1.4.

Refinement of the scaling and setup of the extreme event conditions (CEAA concern #3) is included in Appendix G.

Representation of the proposed bridge infrastructure (CEAA concern #4) is provided in Section 4.1.6 and Appendix B.

Further refinement and quantification of the results (CEAA concern #5) is included throughout the report and additionally in Appendix H and Appendix I.

2. Project Description

Pacific NorthWest LNG is a proposed natural gas liquefaction and export facility on Lelu Island which is located within the District of Port Edward and on land administered by the Prince Rupert Port Authority (PRPA). The proposed project includes a marine export terminal located offshore of Lelu Island, in the naturally deep waters of Chatham Sound (Figure 2-1).

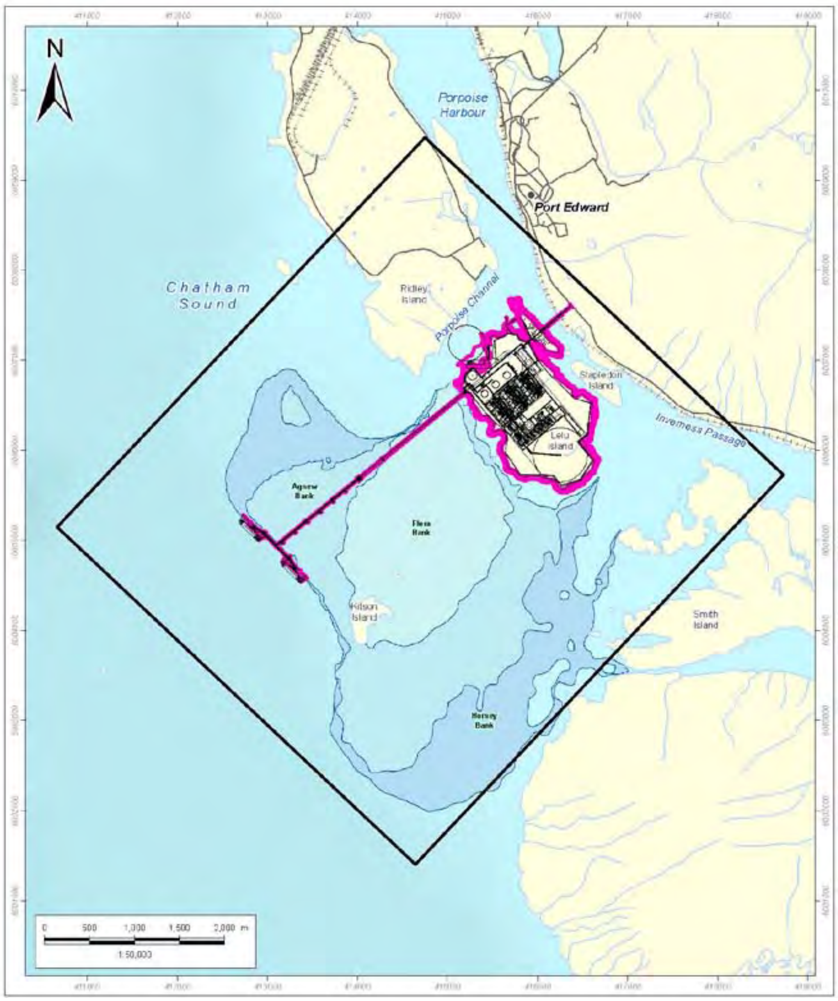


Figure 2-1: Project Site Location (Stantec, 2015)

The project site is located within Chatham Sound and is sheltered from offshore conditions by Haida Gwaii as well as locally by several islands. The site is also located in the outer extents of the Skeena River estuary and is separated from the mouth of the river by Smith Island and De Horsey Island (Figure 2-2).

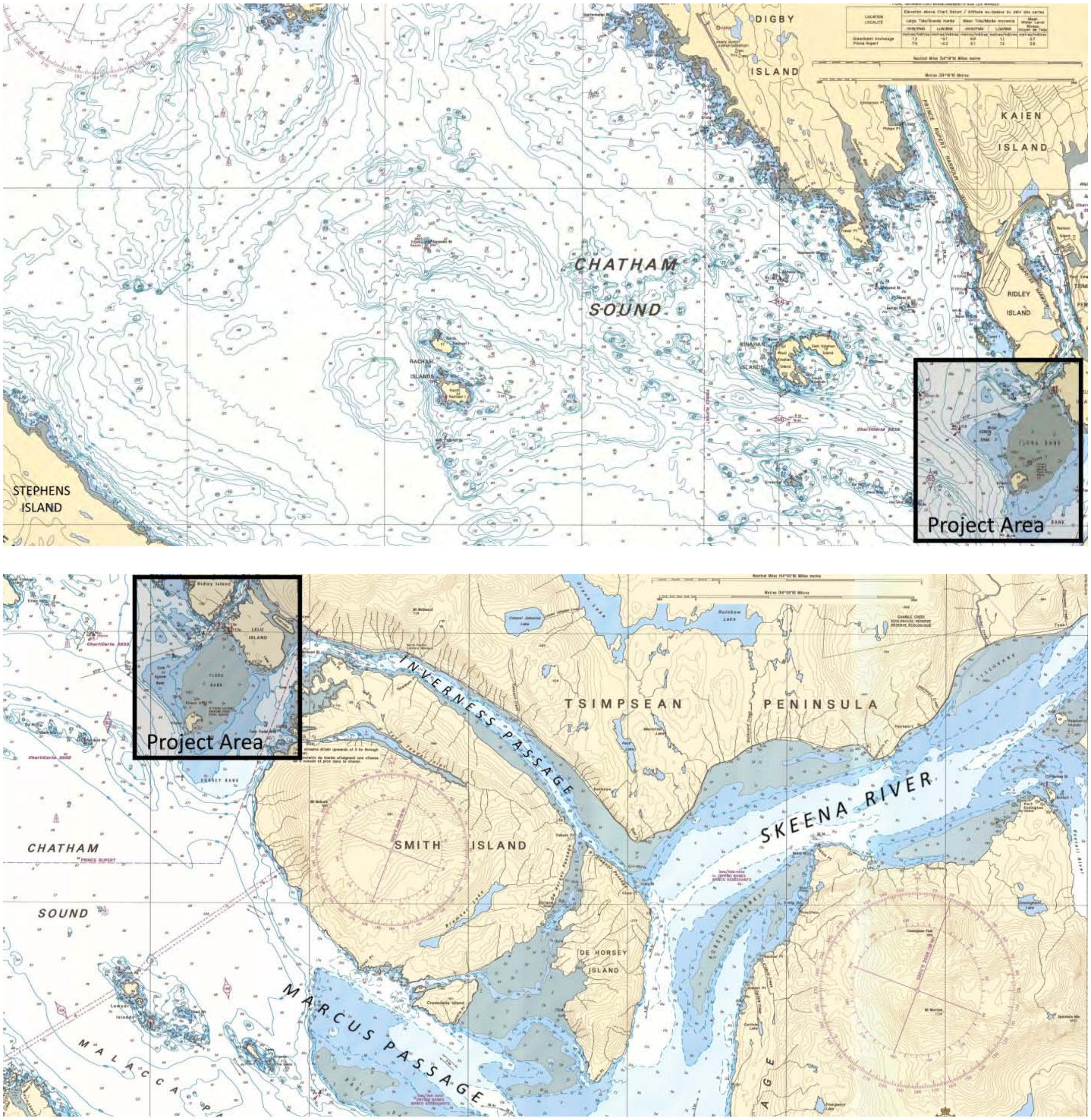


Figure 2-2: Project Area location within Chatham Sound (Top Panel) and Skeena River Estuary (Bottom Panel). Modified from CHS Charts 3957 and 3947.

The proposed marine structures include a long span suspension bridge and a piled trestle and berths. The bridge spans approximately 1600 m over the northwest edge of Flora Bank from Lelu Island to Agnew Bank (Figure 2-3).

Figure 2-3: Schematic of the Proposed Marine Structures

The in-water portion of the bridge consists of two support structures, the SW Anchor Block and the SW Tower, which are located on Agnew Bank. The trestle connecting the bridge to the berths is composed of a deck and widely spaced pile bents (a transverse row of piles), spanning approximately 1300 m to the location of the marine terminal berths in the deeper offshore area west of Agnew Bank. The alignment of the structures may be optimized vary slightly as the design progresses.

An elevation drawing of the proposed marine structures is shown in Figure 2-4. The dashed line shown in Figure 2-4 depicts the depth of the bedrock, and the solid line far above it depicts the mudline. The larger marine structures are located in very shallow water depths of approximately 4 to 5 mMSL.

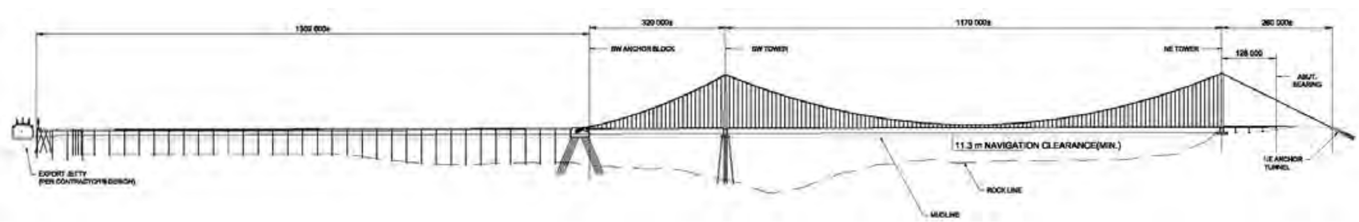


Figure 2-4: Elevation Drawing of the Proposed Marine Structures

The footprint on the SW Anchor Block is approximately 44 m x 45 m and the footprint of the SW Tower is approximately 20 m x 36 m. An elevation drawing of the proposed SW Anchor Block is shown Figure 2-5.

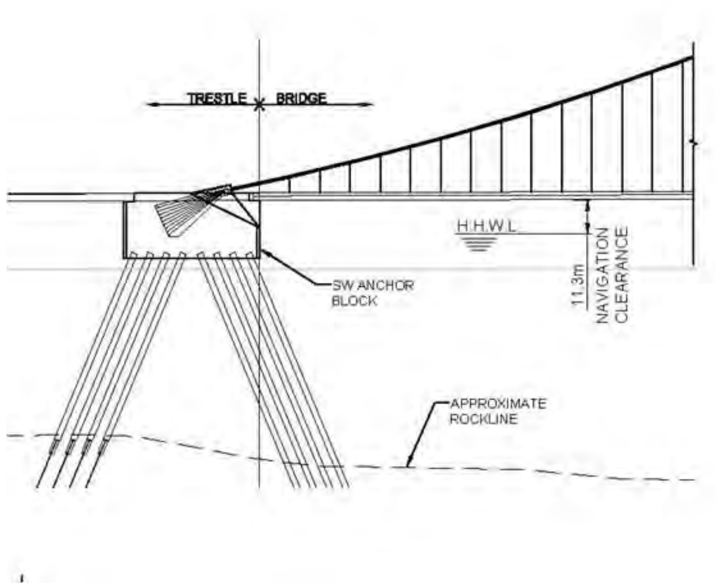


Figure 2-5: Elevation Drawing of the SW Anchor Block

The trestle vertical support piles are 1.2 m in diameter with bents consisting of 4 piles, with 4-m spacing. The pile bents are located 36 m on centre along the length of the trestle. With four piles at each bent and a large bent spacing, the in-water overall coverage of the piles (as measured in plan view) supporting the trestle is approximately 1-2% along its length.

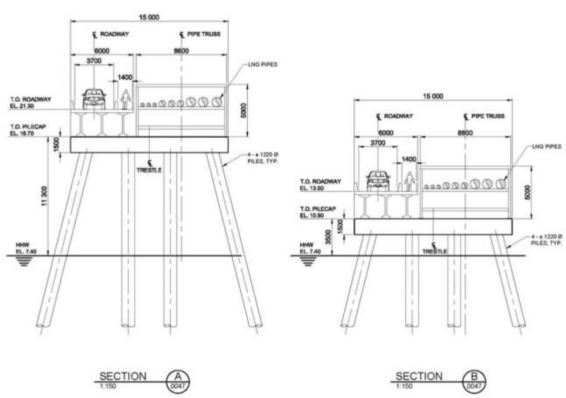


Figure 2-6: Typical Trestle Cross-Sections

The berths consist of a pile-supported deck system similar to the trestle, but aligned perpendicular to the trestle. Figure 2-6 shows the typical cross-sections of the trestle and Figure 2-7 shows the plan view of the proposed LNG berths.

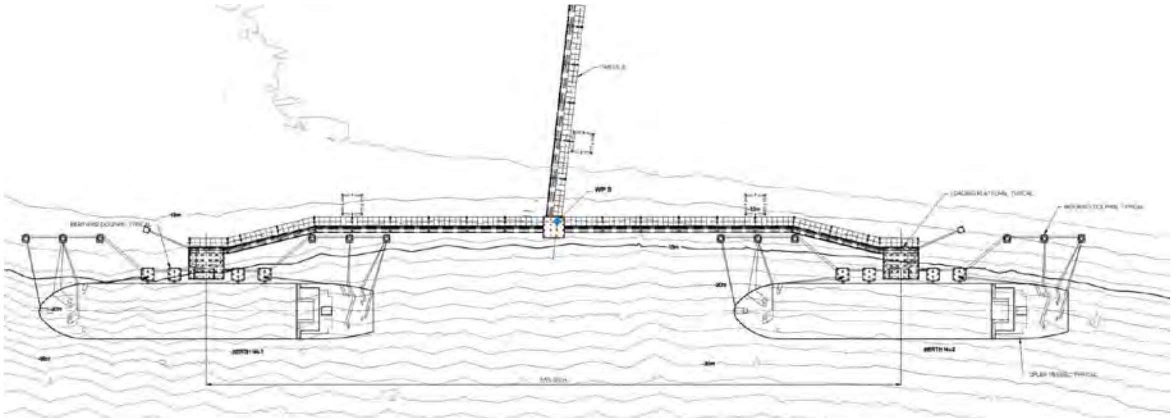


Figure 2-7: Proposed Berth Plan

Figure 2-8 shows the in-water view of marine structures and demonstrates the relatively small footprint of the proposed structures.

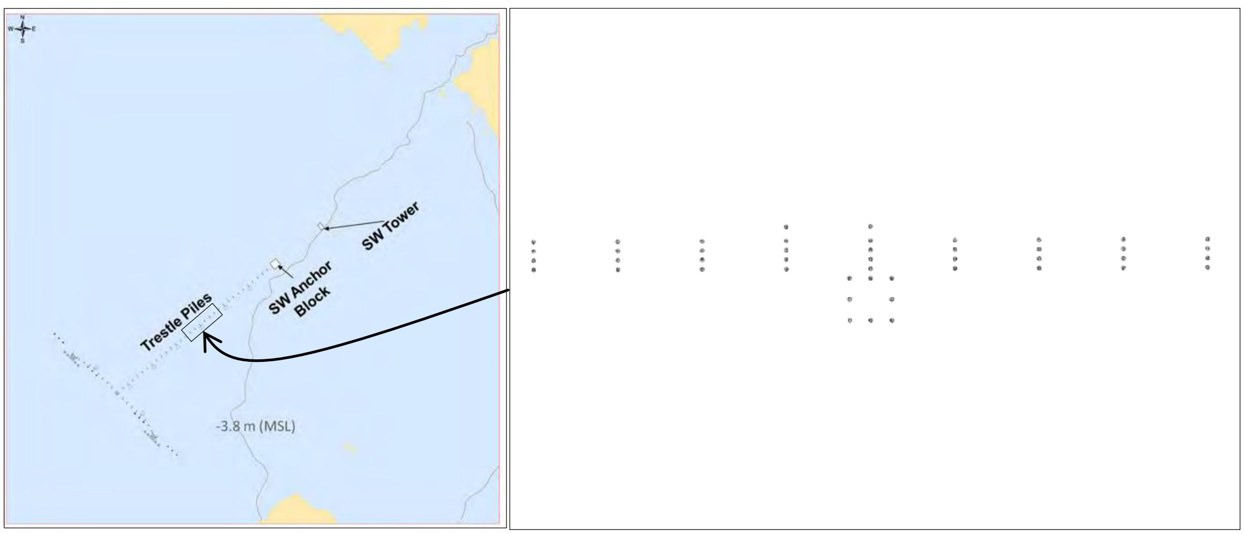


Figure 2-8: In-Water View of the Marine Structures Overall (left), and Closeup View of Trestle with Only In-Water Structures Shown

In the immediate vicinity of marine structures, scour protection will be installed to minimize the development of local scour surrounding the structures. The scour protection will likely consist of a 0.8 m thick rip-rap mat. Based on previous analysis of the local scour, 2 layers of approximately 0.4 m median diameter riprap will be used. The selected gradation ranges from 0.16 m to 0.6 m with no fines. The crest width of the local rip-rap mat will be 1.25 m around the individual piles, 10 m around the SW Tower, and 15 m around the anchor block (Hatch, 2014). Scour protection details are provided in Appendix K.

Based on the in-water footprint of the proposed structures and the proposed local scour protection footprint a direct impact footprint was calculated. Further details of the direct impact of the proposed structures is provided in Appendix L. The total direct impact of the marine structures, including scour protection, is approximately 2.15 ha (21,505 m^2).

Although the SW Anchor Block and SW Tower are the most significant proposed structures, they are located approximately 320 m apart, and each individually represents an area less than 0.6 ha (including scour protection), or less than approximately 0.2% of the area of Flora Bank above elevation -3.8 m MSL.

3. Site Description

This section describes the project area, including Flora and Agnew Bank (Figure 3-1), and the coastal processes in the project area which drive sediment transport and morphological change.

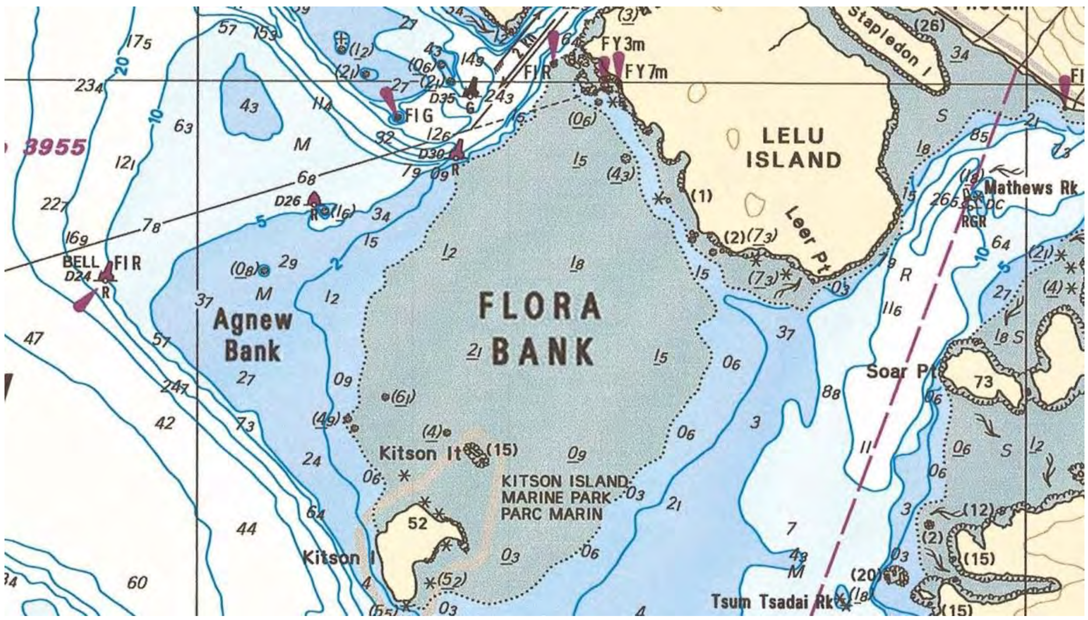


Figure 3-1: Flora and Agnew Bank (Modified from CHS Charts 3957)

3.1 Geological/Geotechnical Conditions Overview

The characteristics of the Pacific coastline reflect the effects of geological processes that have been occurring over hundreds of millions of years, with the primary process being plate tectonics that accreted the BC landmass to the North America block. Over geological time this has caused the complex tectonic uplift, faulting and folding of the crust that has given rise to the coastal mountain range. As a result, the rocks are generally highly fractured with two or more discontinuity sets. Sedimentary basins formed by the faulting and subsidence between the mountain ranges were subsequently infilled by sediments eroded from the highlands. The tectonic forces are still active today in the western margin and give rise to the seismic conditions along the coast. The rocks of the coastal belt are dominated by granite and metamorphic rocks, primarily Jurassic to Tertiary in age.

Over the last couple of million years, glaciation and associated processes have exerted a significant influence on the low-lying sediments and their distribution. A number of glaciations have occurred during the Quaternary Period, with the latest (Wisconsinan) generally reworking or obliterating the features of earlier events. The most recent glacial advance is termed the Fraser Glaciation, dated about 21,000 years before present, with rapid retreat occurring some 15,000 years BP.

Safety ● Quality ● Sustainability ● Innovation

Three broad physiographic features are present, one of which is the Coastal Trough, which includes the Hecate and Georgia depressions. Lelu Island is located in the Hecate Lowland of the Hecate Depression. Lelu Island is bordered by deep water in Porpoise Harbour (up to 25 m deep) to the northwest and Inverness Passage (up to about 15 m deep) to the southeast. Shallow water depositional areas to the west include Flora, Agnew and Horsey Banks. Flora Bank has a shallow eel grass bed and is exposed at low tide; Agnew and Horsey Banks are subtidal.

The area is generally low in sediment cover, partly due to the dominance of resistant rock types and partly due to the relatively few large rivers emptying into the coastal environment. What sediments are carried by the rivers settle out in the deep fjords or basins before reaching the coast. The main Hecate Trough is covered by glacial sediments up to about 100 m thick with a thin cover of very soft recent muds.

At Flora Bank, the typical profile of the marine sediments consists of a thin layer of fine to medium sand up to about 7 m thick, overlying a thick sequence of very soft to soft low plasticity clay/silty clay. The upper clay layer is up to 30 m thick, with thin layers of silt. The lower clay is of high plasticity and up to about 20 m thick. The clay is underlain by bedrock at around El. -60 m, but which varies between El. -40 m and El. >-90 m.

3.2 Descriptions of Flora Bank and Agnew Bank

3.2.1 Description of Flora Bank

Flora Bank is a wide and shallow tidal flat that becomes exposed at low tide. It is approximately 325 hectares in size and located directly offshore of Lelu Island. A small tidal passage separates Flora Bank from Lelu Island.

Flora Bank is a relatively flat shoal with approximate top elevation El. +1.0 m CD (chart datum), or -2.8 m MSL (mean sea level). At the SW end of Flora Bank, the seabed drops off with a gradient of about 10%, changing from El. -5 m to -50 m CD (-8.8 to -53.8 MSL) over a distance of about 500 m. The shape and extent of Flora Bank has remained visually similar over a period of many years.

As described by SedTrend (2015), Flora Bank appears to be composed of glacially-formed relict sediments which have been in place for thousands of years. The distribution of sediments is controlled by the glaciation features, sea level changes and the present-day wave/current regime. There is a clear trend for the fine-grained sediments to be located in deep troughs, with the coarser-grained sands and gravels to be concentrated on steep slopes or on the top of shallow banks, such as for Flora Bank.

Figure 3-2 shows an oblique aerial view of Flora Bank at low tide, and the surrounding islands and channels. The above mentioned tidal channel, Lelu Island Channel, as well as Porpoise Channel on the left side of the image and Inverness Passage to the right are depicted.

Figure 3-2: Photo of Lelu Island and Flora Bank

Figure 3-3 shows an elevation colour contour map of Flora Bank's bathymetry generated using the 2015 LiDAR data (Stantec, 2015c). The LiDAR data indicates that Flora Bank is relatively flat overall, but contains localized surface features such as dendritic drainage channels.

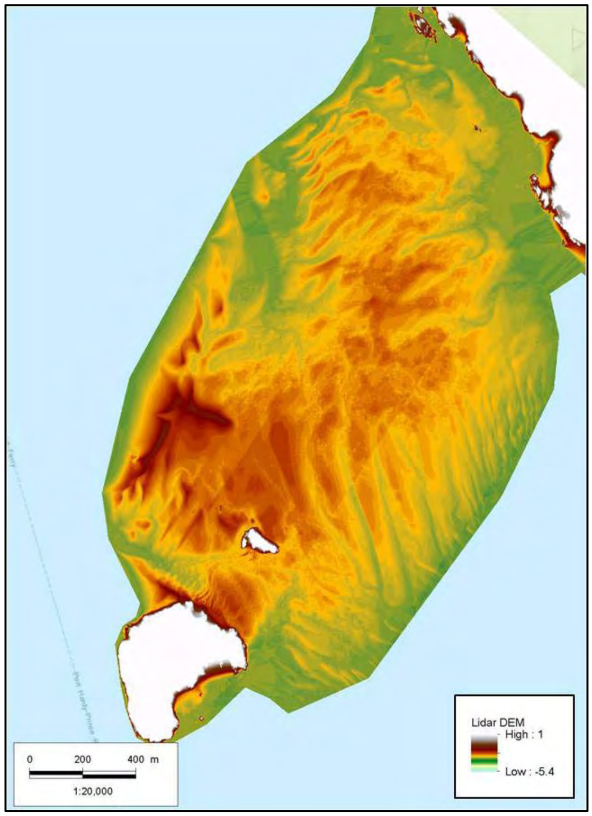


Figure 3-3: Flora Bank LiDAR DEM Colour Map June 18, 2015 (Stantec, 2015c)

The prominent drainage channel features appear relatively stable, as shown in Figure 3-4 which displays aerial photos of Flora Bank taken in 2009 (left), 5 years later in 2014 (middle), and 1 year later in 2015 (right). Figure 3-5 shows an overlay of the three aerial photos and highlights where the channels overlap. The approximate location and size of the drainage channels remains fairly consistent over the 5-year period, further demonstrating Flora Bank's stability. It is assumed that these are drainage channels because they do not align with primary ebb or flood tidal current directions.

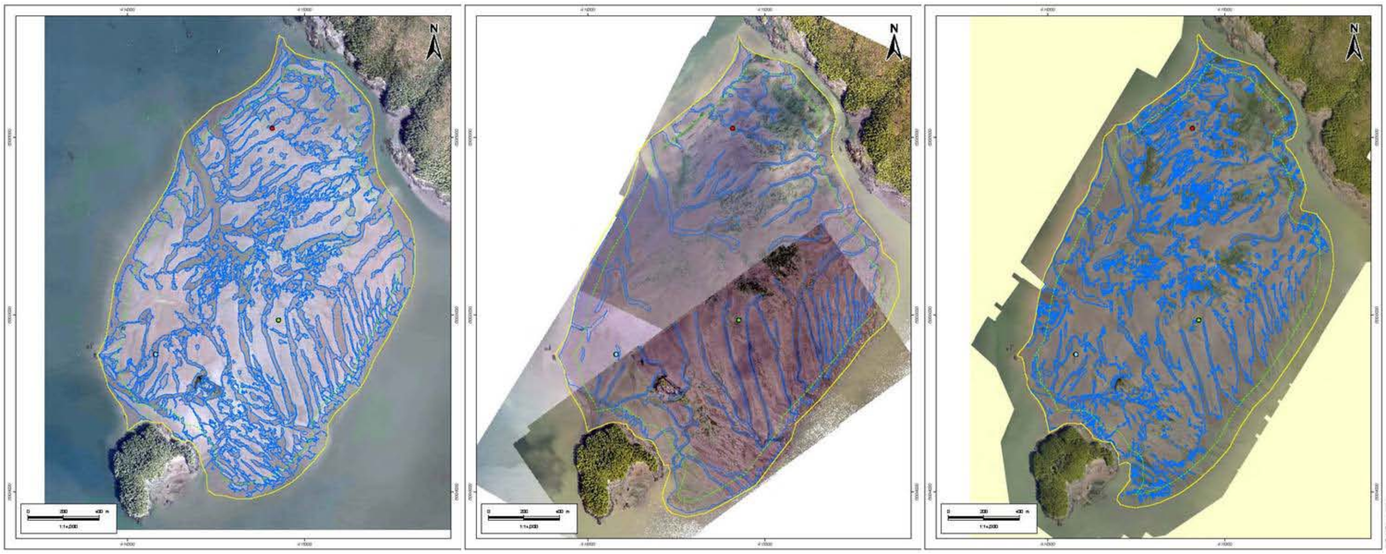


Figure 3-4: Aerial Images of Flora Bank in 2009 (left), 2014 (middle), and 2015 (right) (Stantec, 2015b)

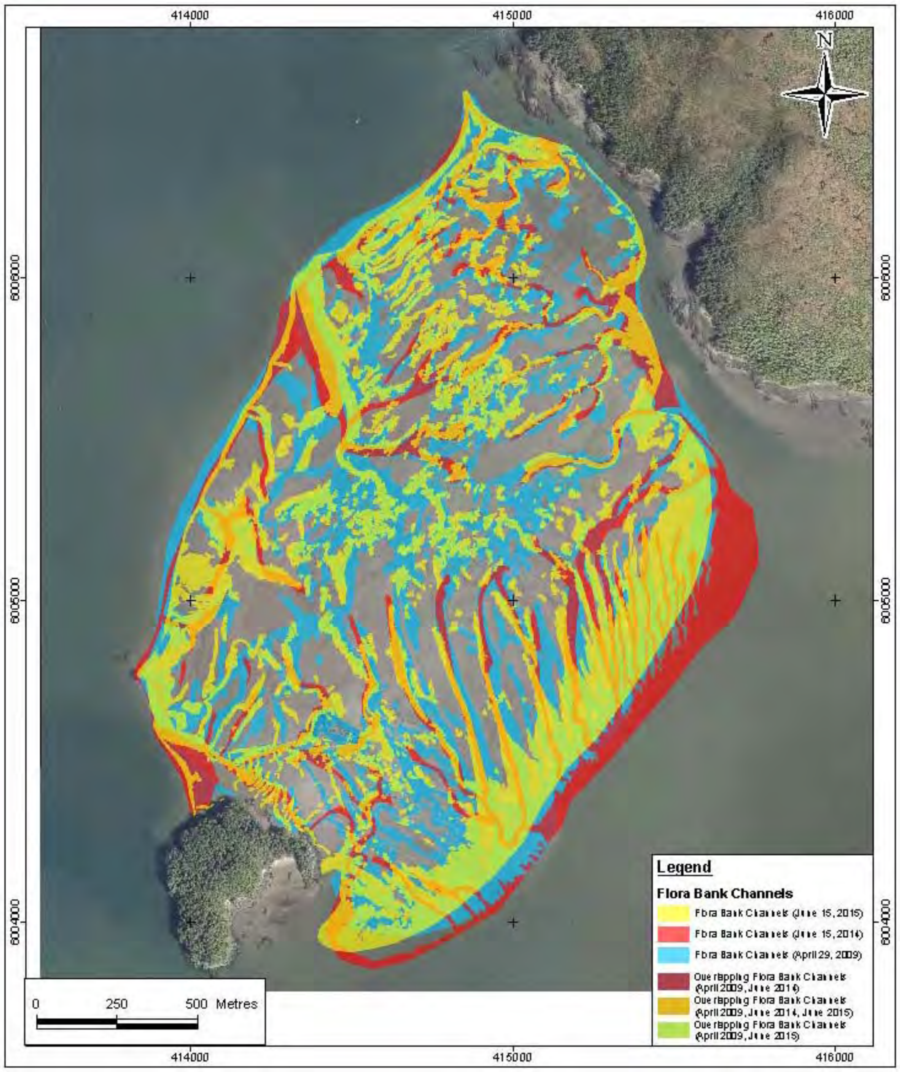


Figure 3-5: Overlay of 2009, 2014, and 2015 Flora Bank Aerials

Figure 3-6 and Figure 3-7 show site photos taken on Flora Bank at low tide. Each figure has a locator map on the left that shows where the photo was taken, and the camera view direction. Figure 3-6 was taken at the very north end of Flora Bank looking southward, and indicates the following:

1. Flora Bank is wide and flat, and likely to have relatively small spatial gradients in hydrodynamic conditions. The flows, waves and resulting sediment transport will be relatively uniform over this consistent seabed feature.
2. Only ripples are present in the sand (no larger sand waves or other types of mobile morphological features). Ripple heights are roughly 2-3 cm and ripple wavelengths are less than 30-40 cm. The ripple wavelengths indicate low flow conditions, as ripple

wavelengths less than 60 cm are indicative of typical flow conditions being “Low” (Boothroyd and Hubbard, 1975).

3. The sand transport directions are from both east to west, and from west to east in the photo, since transport occurs in directions normal to the crests of the ripples.
4. The shapes of the ripples are relatively symmetrical (not leaning one direction or the other), indicating that this is an area of weak net sediment transport, i.e. levels of sediment transport are similar in both directions.

Figure 3-7 was taken in a much different area of Flora Bank, farther south and on the west side, but also looking southward. Photo 2 indicates many similar conclusions as Photo 1, however the sediment transport direction (conclusion 4) differs in that the shapes of the ripples are NOT symmetrical in this location. The ripples are leaning towards the west, indicating that at least at the time the photo was taken, this is an area where the net sediment transport has been directed to the west.

.

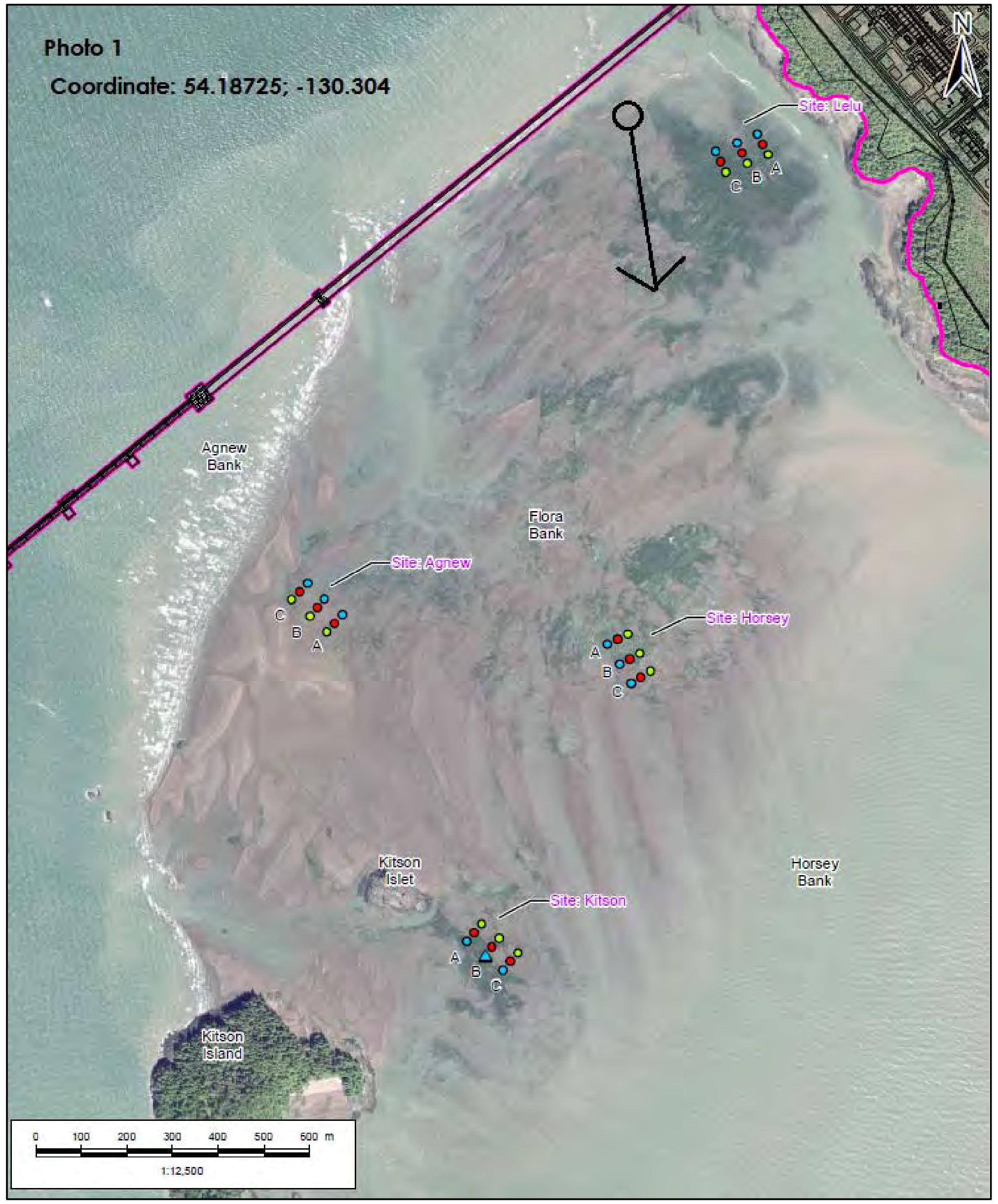


Figure 3-6: Flora Bank Observation Photo #1. At left is aerial photo of Flora Bank with circle showing approximate location where photo (at right) was taken, and arrow showing view direction. (Source: Stantec)

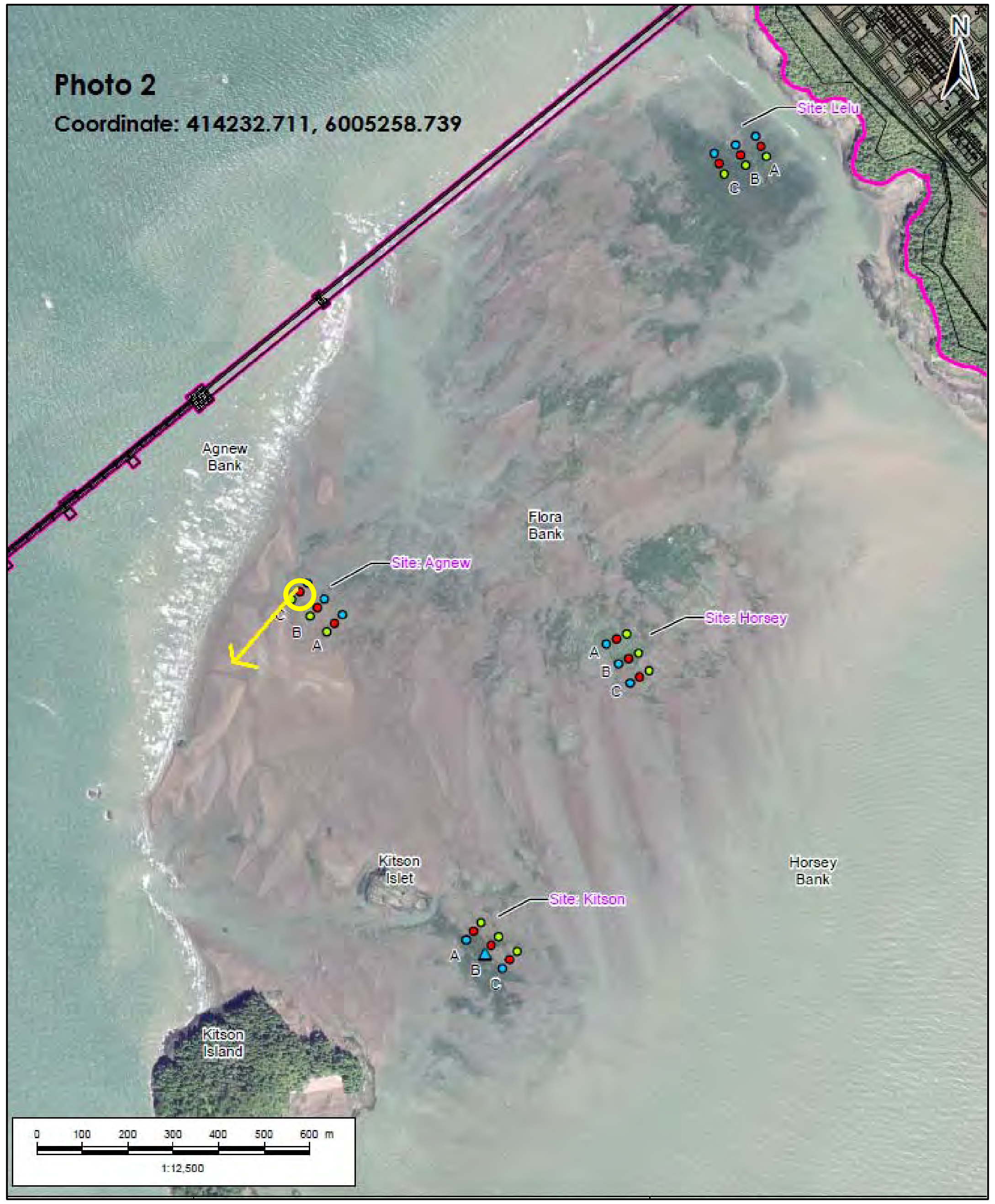


Figure 3-7: Flora Bank Observation Photo #2. At left is aerial photo of Flora Bank with circle showing approximate location where photo (at right) was taken, and arrow showing view direction. (Source: Stantec)

Flora Bank is composed of fine, medium and coarse sand, in contrast with the surrounding sub-tidal bank areas which are composed of a mix of sediments that also includes silts and clays. Figure 3-8 displays the mean sediment grain size over the project area from sediment samples collected by SedTrend Analysis (2015b). Figure 3-8 also includes an inset of the Wentworth grain size classifications used by SedTrend. Sediment grain sizes and the SedTrend Analysis indicate that sediment transport and erosion/deposition patterns are variable in this area of Chatham Sound, which includes many depositional deeper-water areas that likely receive fine sediments from the Skeena River plume. The Skeena River is further described in Section 3.3.4.

Mean grain sizes determined from the SedTrend (2015) data collection effort are roughly between 0.2 and 0.5 mm over the vast majority of Flora Bank. Flora Bank's wide, flat slopes contribute to making it a stable bathymetric feature that gradually dissipates wave energy and resists erosion by wave and current forces.

The combination of coarser sandy material, and wide and flat configuration results in low net transport off of Flora Bank. The low levels of net transport were also corroborated by the results of the SedTrend (2015) analysis, which was unable to discern any transport trends over the vast majority of Flora Bank.

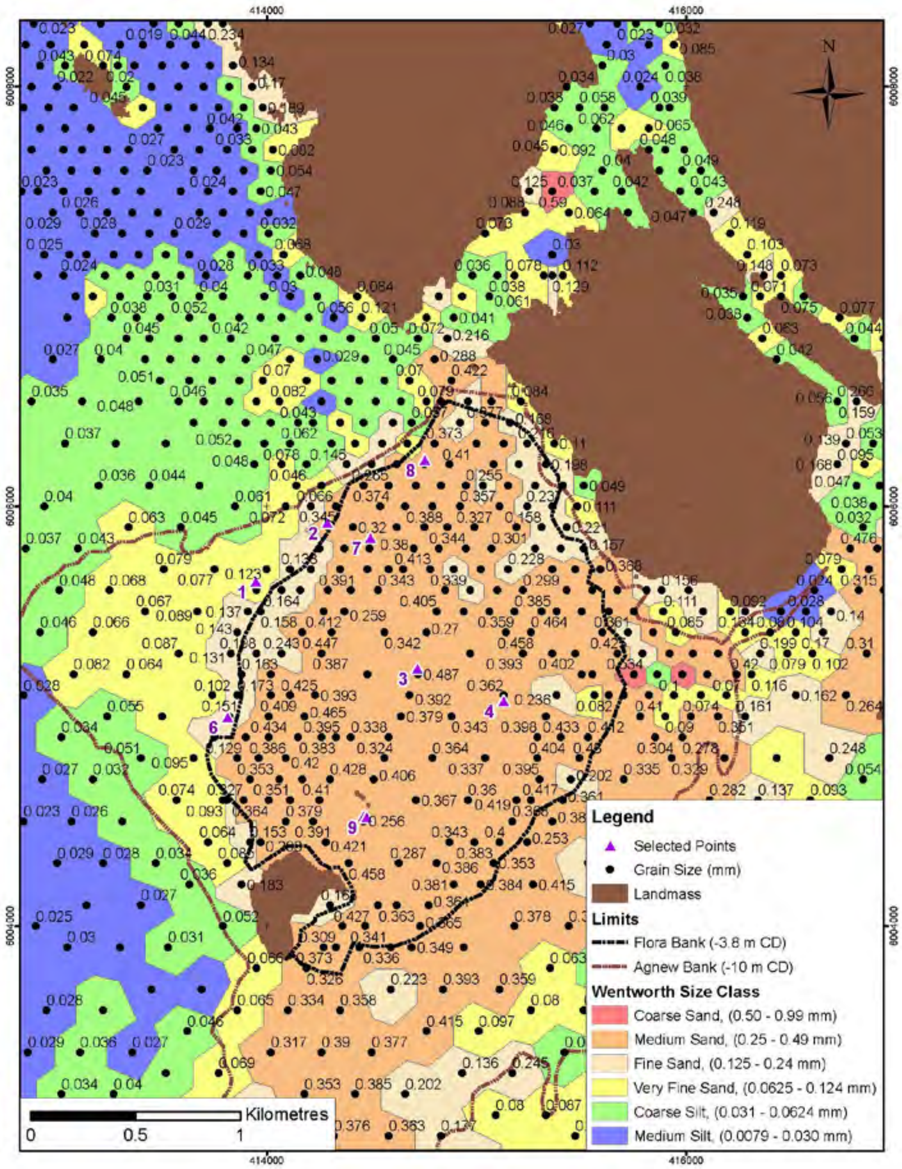


Figure 3-8: Mean Grain Sizes in the Project Area

3.2.2 Description of Agnew Bank

Agnew Bank is a sub tidal flat located on the west side of Flora Bank, with elevations ranging from -5 to 0 m CD (-8.8 to -3.8 m MSL) Agnew Bank differs greatly from Flora Bank in that it is generally deeper and does not become exposed at low tide. It is also different in that it is a depositional environment, with much finer surficial sediments than found on Flora Bank. Most of Agnew Bank is relatively flat and slopes gradually to the offshore, with the exception of the southwest side which slopes more quickly to deeper water near the proposed LNG carrier berths, and along its boundary with Porpoise Channel.

Mean grain sizes determined from the SedTrend (2015) data collection effort vary between approximately 0.05 and 0.3 mm over the majority of Agnew Bank. The SW Tower and SW Anchor Block are located on Agnew Bank in an area with mean grain sizes of 0.3 mm and 0.14 mm, respectively.

3.3 Coastal Environment

Various coastal processes are important in driving the hydrodynamic conditions and the resulting sediment transport and morphology of the project area. The coastal processes evaluated for this site include:

- Tides (water level fluctuations);
- Tidal currents;
- Winds;
- Waves; and,
- River discharge.

The following sections describe each of the above mentioned processes and their influence on the project site.

3.3.1 Tides and Tidal Currents

Tides at the project site are generally semi-diurnal, with two low and two high tides per day. Tidal ranges in the project area are relatively large (as large as 7 m), resulting in the majority of Flora Bank becoming exposed at low tide and submerged during high tides. Figure 3-9 shows tidal datum information from Port Edward which is located at the end of Porpoise Channel, northeast of the project site.

Tidal Datums for Port Edward, BC

	MSL Datum (m)	Chart Datum (m)
Large Higher High Water	3.60	7.40
Mean Higher High Water	2.30	6.10
Mean Sea Level	0.00	3.80
Mean Lower Low Water	-2.50	1.30
Large Lower Low Water & Lowest Normal Tide	-3.80	0.00

Notes:
1. Datums obtained from the Canadian Hydrographic Service
2. Tidal Range = 7.4 m

Figure 3-9: Tidal Information for Port Edward, BC

Note that all following figures in the report refer to elevations according to the Mean Sea Level (MSL) datum. Although tidal ranges are relatively large, the geometrical configuration of Chatham Sound and Flora Bank do not cause these tidal fluctuations to manifest themselves as strong currents, except to some degree within the narrow confines of Porpoise Channel and Inverness Passage. Within these channels, tidal currents are stronger as shown in Acoustic Doppler Current Profiler (ADCP) measurements.

Figure 3-10 (top panel) shows the depth-averaged current velocities in the vicinity of Flora Bank and the marine structures during a typical peak flood current. The currents were calculated as part of a 28 day freshet period simulation using the Delft3D model, which will be discussed further in Section 5.2. Peak current speeds are less than approximately 0.25 m/s on flood tide, and less than approximately 0.3 m/s on ebb tide. Modelling results indicate that current conditions do vary in this area of Chatham Sound, however around the location of the proposed marine structures, the flow field (ebb and flood) is relatively uniform and wide relative to the size of the marine structures. This indicates that the effects of the SW Tower and SW Anchor Block on hydrodynamics, transport and erosion/deposition are likely to be localized.

Figure 3-10 also shows a current rose (bottom left panel) extracted between the SW Anchor Block and SW Tower. The current rose describes the frequency, magnitude and directions of currents (towards directions that currents are going) during the entire 28 day typical freshet simulation. At the location of the larger marine structures, flood currents arrive from the southwest, and ebb currents arrive from the east. Typically, peak ebb currents are stronger than peak flood currents and occur for longer durations.

Figure 3-10 also shows a histogram of current speeds (bottom right panel) which indicates that during the vast majority of the time, current speeds are less than 0.15 to 0.2 m/s. Results of 28 day tides-only simulations indicate that without any winds, waves or Skeena River discharge, peak ebb and flood currents are less than approximately 0.25 m/s at all times.

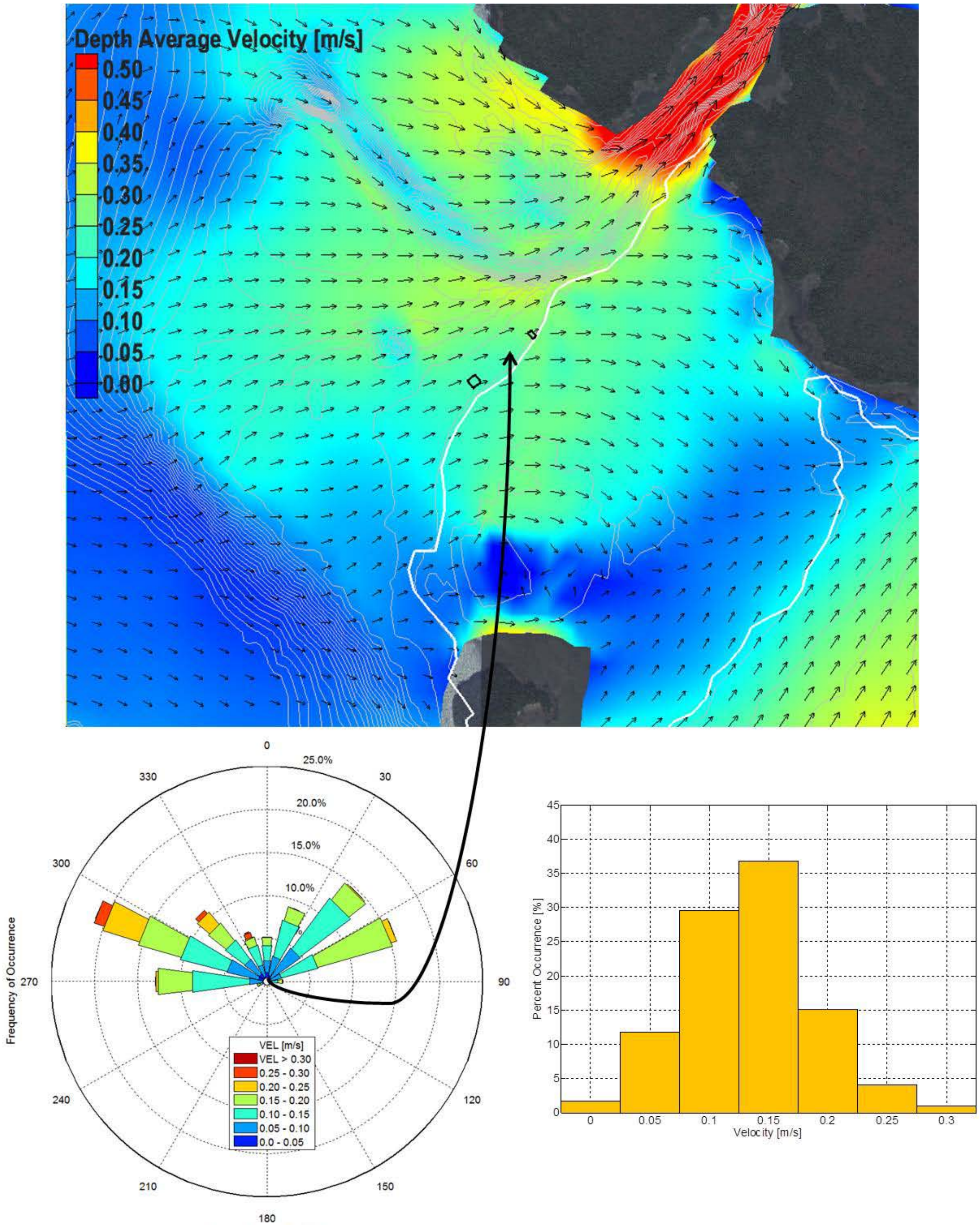


Figure 3-10: Hydrodynamics around anchor block and tower during peak flood current, freshet simulation (top), current rose extracted between the structures (bottom left), and histogram of current speeds extracted at a location between the structures (bottom right). Note: marine structures shown for location only.

3.3.2 Winds

The wind rose shown in Figure 3-11 displays the wind directions and speeds measured at the Holland Rock station, which is located in Chatham Sound near the project site. The location of Holland Rock is shown in Figure 3-12. The wind rose demonstrates that a significant portion of the wind is concentrated from the southeast, however an important northwest component is present, where the waves can develop over a longer fetch (the distance over water which wind can blow). Winds also occur from east and northeast directions but do not generate significant wave energy at the project site due to limited fetch length. Southeast winds are the strongest, however during these storm events the proposed marine structures are located downstream of Flora Bank and will not affect the waves arriving at Flora Bank. Figure 3-12 shows the Chatham Sound area and the primary wind directions that generate waves approaching the project site, including south-southeast, northwest, and to a lesser degree the southwest.

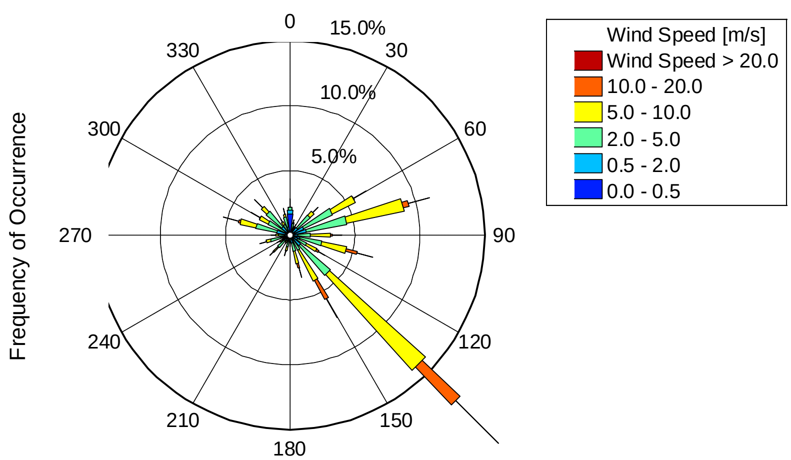


Figure 3-11: Wind speeds and directions measured at Holland Rock station

Further discussion of wind events is mostly limited to westerly and southeast storms as they generate the strongest wave activity at the site, which is the primary driver for morphological change in the area of Flora Bank. A wide variety of wind data sources were analyzed to determine the most appropriate for use in the 3D modelling. Based on comparison with local measurements and wave model validation results it was determined that a combination of regional gridded winds and local wind data sources was appropriate. A more detailed overview of wind data sources and their incorporation into the 3D modelling is included in Appendix C.

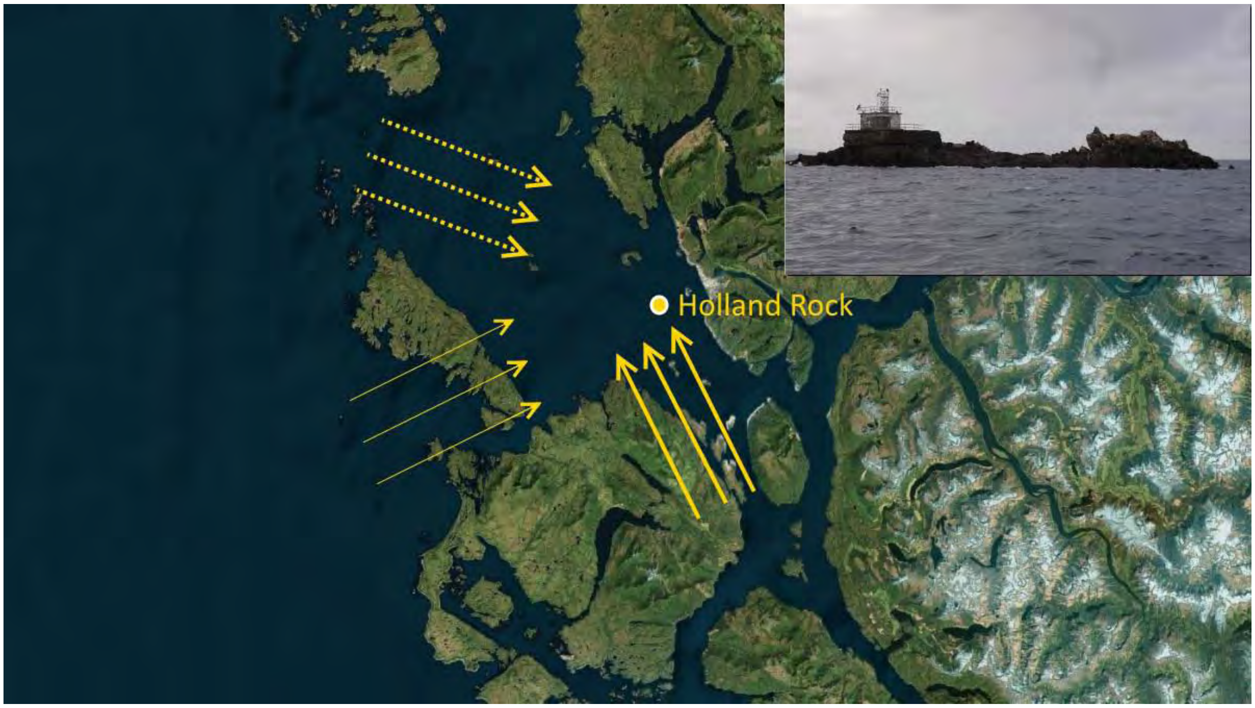


Figure 3-12: Wind directions generating the most wave activity at the site, and inset view of Holland Rock wind station (Source: Bing)

3.3.3 Waves

The wave climate at the project site is composed primarily of wind-waves (seas) generated within Chatham Sound, and with a smaller contribution from offshore Pacific Ocean waves (swells). Pacific Ocean waves travel through Dixon Entrance, and into Chatham Sound and are strongly attenuated along the way. The project site is protected from the offshore waves by Haida Gwaii as shown in Figure 3-13, with offshore waves arriving at the site only from a narrow northwest direction band. Local wave measurements are available from December 2013 to present from the PNW Buoy, located near the project site (Figure 3-14).

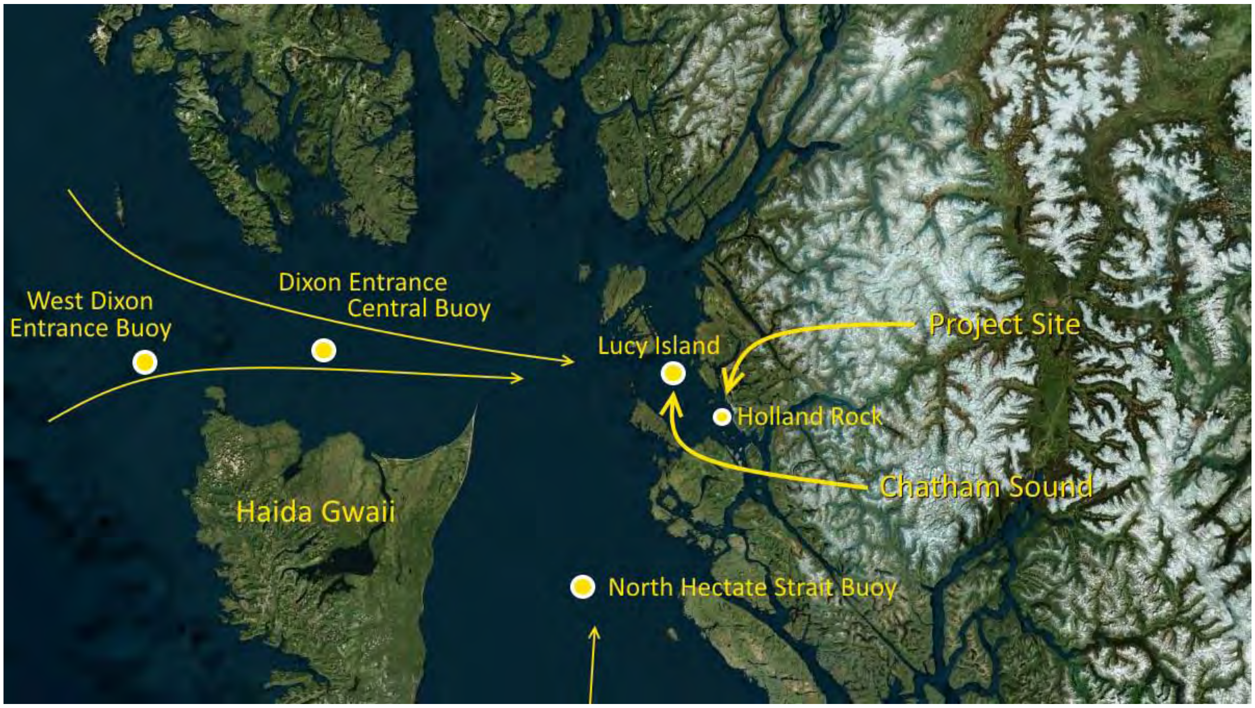


Figure 3-13: Chatham Sound and Transformation of Pacific Ocean Waves to the Site (Source: Bing)

Figure 3-14: PNW Buoy Location Near the Project Site (Source: Bing)

Safety ● Quality ● Sustainability ● Innovation

Figure 3-15 shows an example time history of wave heights measured at the PNW Buoy from January to May 2014. Offshore waves (swells) are shown in red and local wind-waves (seas) are shown in blue. The offshore waves heights are small relative to locally-generated seas due to the attenuation and sheltering of the project site as discussed above.

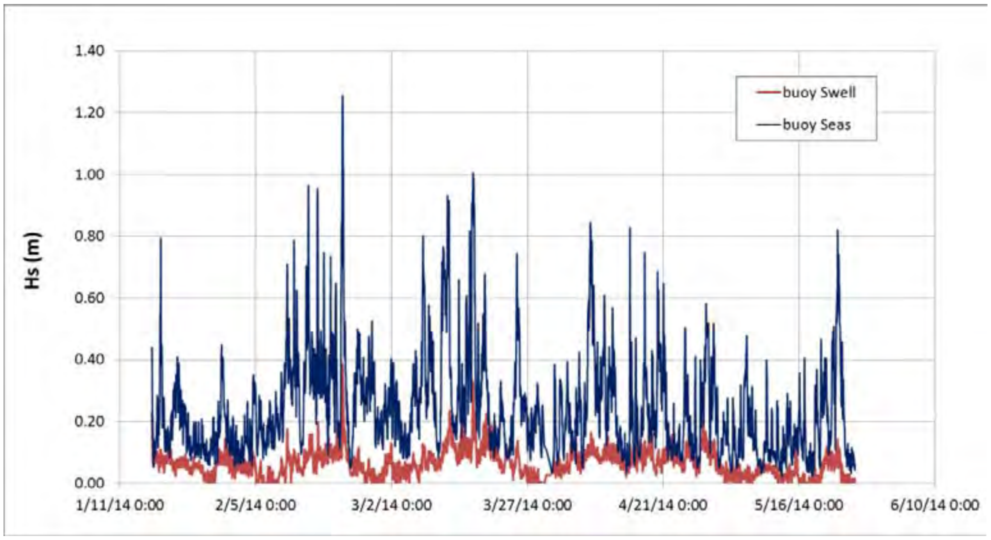


Figure 3-15: Example Time Series of Seas and Swell at the PNW Buoy

Significant wave heights measured at the PNW Buoy were evaluated from January 1, 2014 to December 31, 2014. Within this time period the largest significant wave height measured reached up to 1.48 m and the mean significant wave height was 0.23 m (standard deviation of 0.15 m). The mean significant wave height from westerly directions and southerly directions were 0.18 and 0.24 m, respectively.

Wave conditions vary seasonally at the project site, with the largest waves measured during the winter months due to higher winds and to a lesser degree the larger winter Pacific Ocean waves (swells). Figure 3-16 displays the percent exceedance of various significant wave heights measured during 1 year at the PNW Buoy. Winter months have the strongest wave activity and smaller waves are present during the summer months. The data indicate that overall, wave heights are relatively small. Significant wave heights greater than 0.7 m are exceeded less than 5% of the time in the more energetic Winter period.

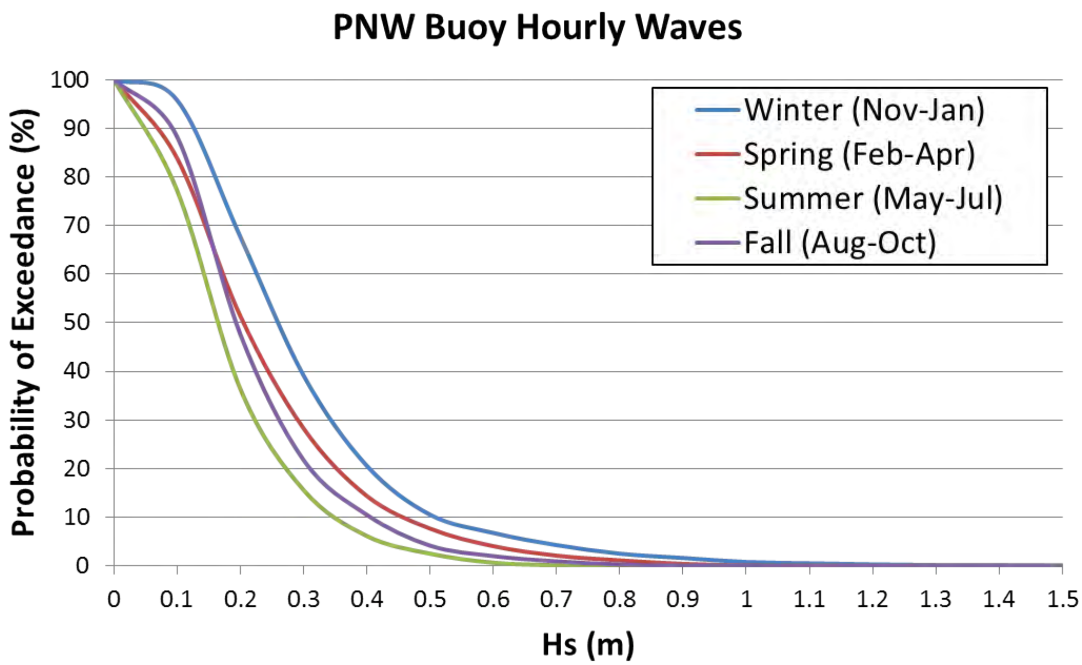


Figure 3-16: Seasonality of Wave Conditions at PNW Buoy (2014)

The bathymetric configurations of Agnew and Flora Banks contribute significantly to shaping the wave conditions over Flora Bank. Strong winds generate significant wave heights in excess of 3 m in deeper water approaching Flora Bank and storm waves generate currents on the west and south sides of Flora Bank, however these waves are significantly attenuated over Agnew and Flora Bank as can be seen in Figure 3-17 and Figure 3-18.

Figure 3-17 depicts a colour map of significant wave heights and vectors showing direction from the 3D model during a southerly 1 year (annual) storm (170^{o} True North) at high tide. The plot shows wave transformation and dissipation over Flora Bank. The wide, shallow areas of Agnew and Flora Banks cause refraction, breaking and wave energy dissipation but these processes occur very gradually over large distances. Significant wave heights are reduced gradually from over 2 m in deeper water to less than 0.5 mover Flora Bank, and even lower in the shallower areas. Figure 3-18 also depicts a colour map of significant wave heights and vectors showing direction from the 3D model however from a westerly 1 year (annual) storm (270^{o} True North) at high tide. Similar to the results for the annual southerly storm, the plot further demonstrates the role of Agnew and Flora Bank which cause refraction, breaking and wave energy dissipation over large distances.

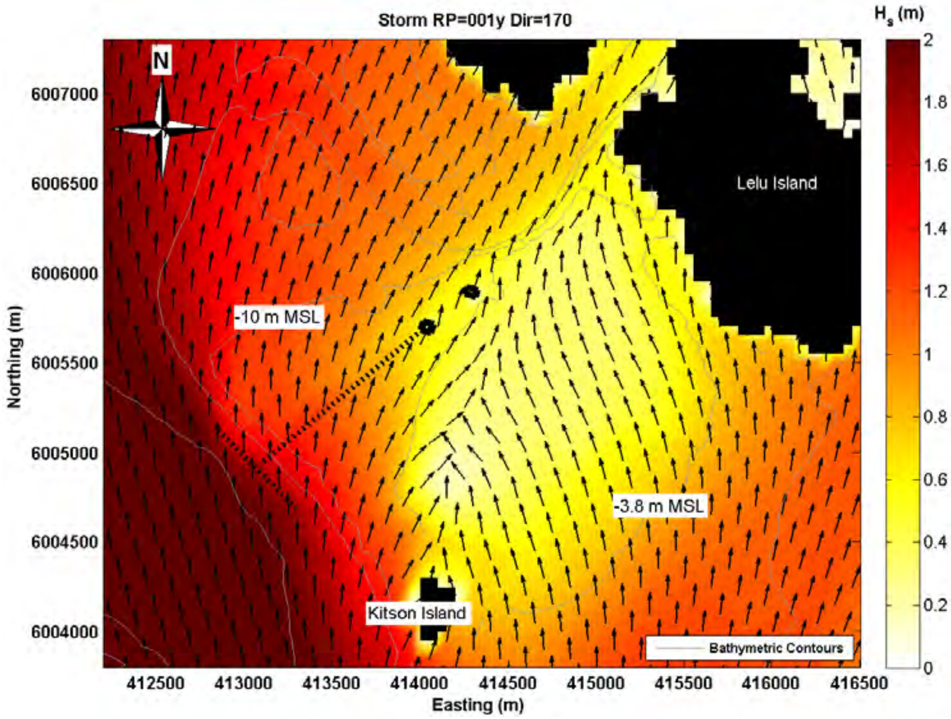


Figure 3-17: Patterns of significant wave heights over Flora and Agnew Bank during annual southerly storm event (170^{o} True North)

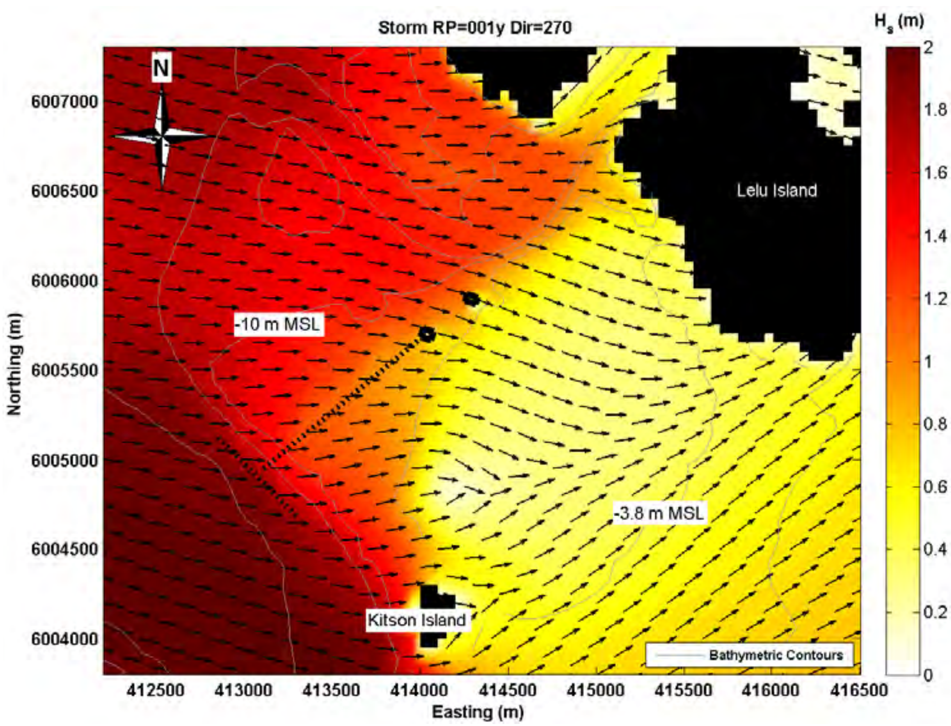
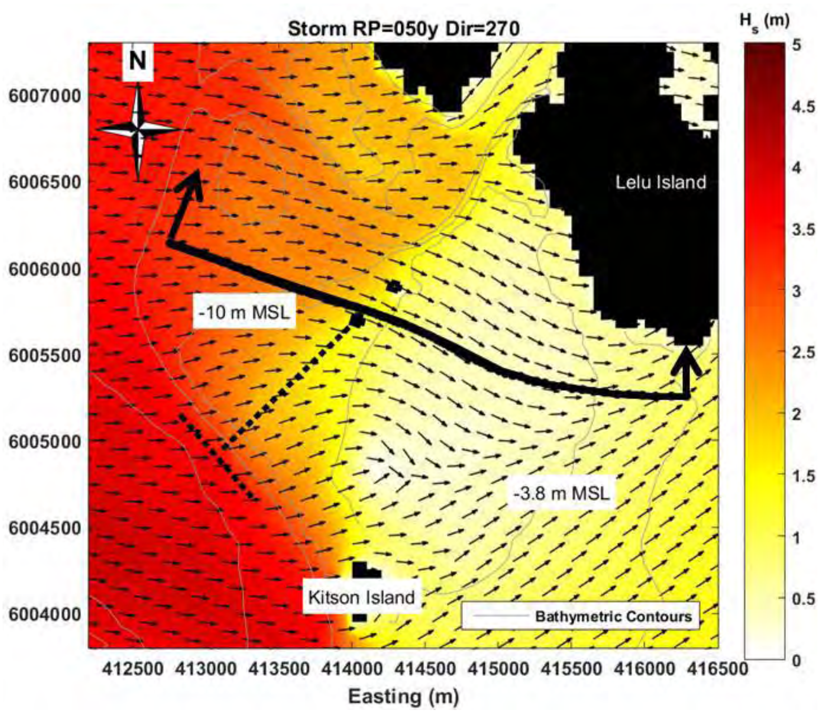


Figure 3-18: Patterns of significant wave heights over Flora and Agnew Bank during an annual westerly storm event (from 270° True North)

Figure 3-19 shows the location of a transect crossing Flora Bank (top), and transect of bottom elevation and significant wave height during the 50-yr storm from 270° True North.
Figure 3-20 displays a close up the transect and significant wave heights in the vicinity of the SW Anchor Block without a vertical exaggeration. The transect was taken through a path of wave travel starting on Agnew Bank in deeper water, up and over Flora Bank. The bottom slopes are also shown, which are very mild and flat (at the steepest roughly 110H:1V on the west side of Flora Bank, and roughly 95H:1V on the east slope). The transect displays that the highest rate of significant wave height reduction (energy dissipation measure) is only 2.7 mm per metre of travel along the transect. The wide, flat slopes of Flora Bank, combined with relatively coarse material, result in a high level of stability.

Figure 3-20 shows a close-up of the transect from Figure 3-19 in the area around the SW Anchor Block without vertical exaggeration (i.e. to real scale). The wave height is nearly constant over this area, and the bed is nearly flat, further demonstrating that very low gradients in transport are likely to be present, hence little bed elevation change.



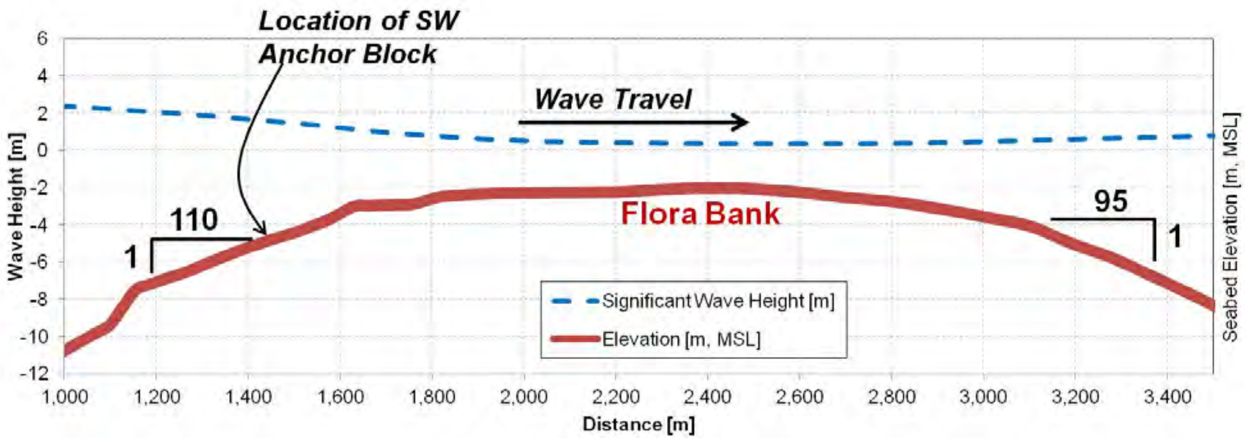


Figure 3-19: Transect location on Flora Bank following path of wave travel (top) and transect of bottom elevation and significant wave heights during 50-yr storm event from 270° True North. *Note: vertical exaggeration approximately 40:1.*

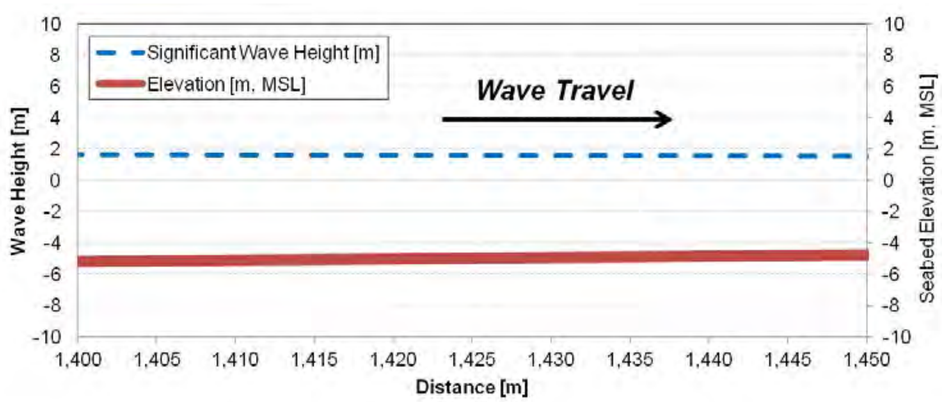


Figure 3-20: Close-up of transect from Figure 3-20 near the SW Anchor Block without vertical exaggeration

3.3.4 Skeena River

The project site is located in the far outer reaches of the Skeena River estuary. The Skeena River discharge is the main contribution of freshwater to the area around Flora and Agnew banks. The freshwater reaches the site primarily through the narrow Inverness Passage and to a lesser extent through Marcus Passage (Figure 3-21), however, only a small portion of the overall Skeena River discharge reaches the project site. The Skeena River has higher discharges occurring during the late spring to mid-summer freshet (spring thaw) period that reach approximately 6,000 m^3/s, with only a small portion of this discharge moving through Inverness Passage.

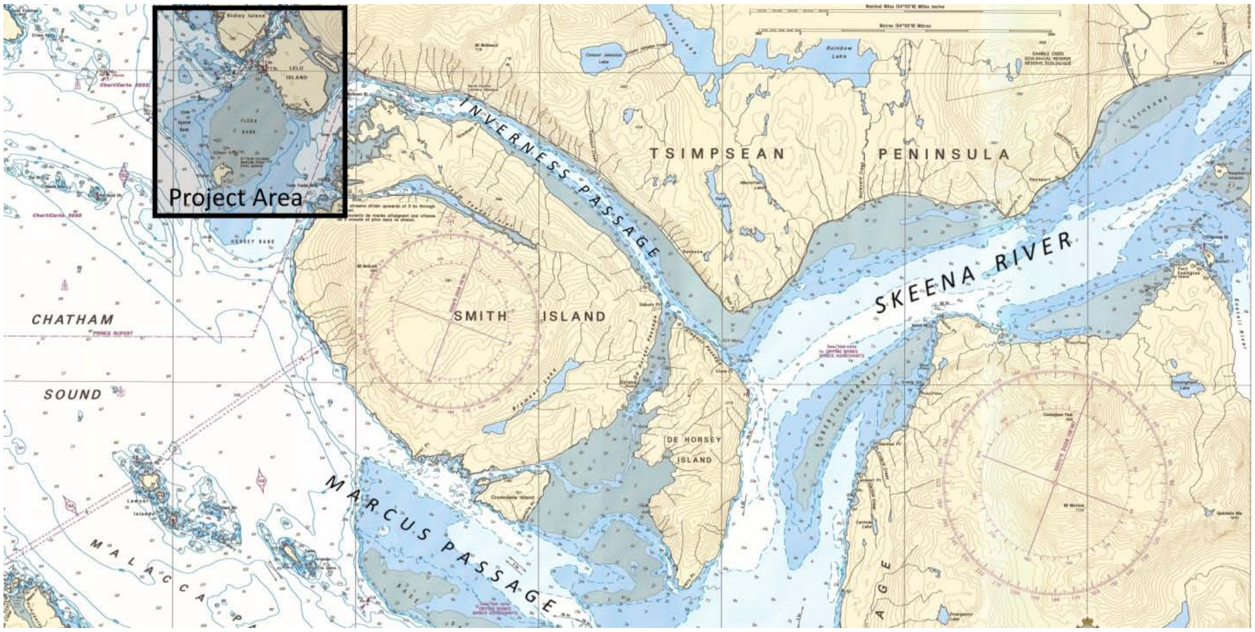


Figure 3-21: Skeena River Estuary and Project Area (Modified from CHS Chart 3947)

Figure 3-22 (top panel) shows discharge measured in 2011 at the Usk station along the Skeena River. The plot indicates that the Skeena River discharge is seasonally variable and episodic. The river flow is low in the spring and winter, mild in the fall, and the peak flows occur late in spring and early in the summer during the freshet period.

Figure 3-22 (bottom four panels) shows snapshots of the surface salinity taken from the Delft3D model that are representative of each season. The plots indicate that the Skeena River delivers fresh water during some periods, but is located far from the project site and its influence is minimal except during the relatively short freshet periods. Seasonal changes in salinity vertical stratification due to the Skeena River discharge are stronger near its mouth and become significantly reduced near the project site due to the distance from the river and the strong influence of saline waters of Chatham Sound. Further discussion of salinity and stratification is included in Appendix E.

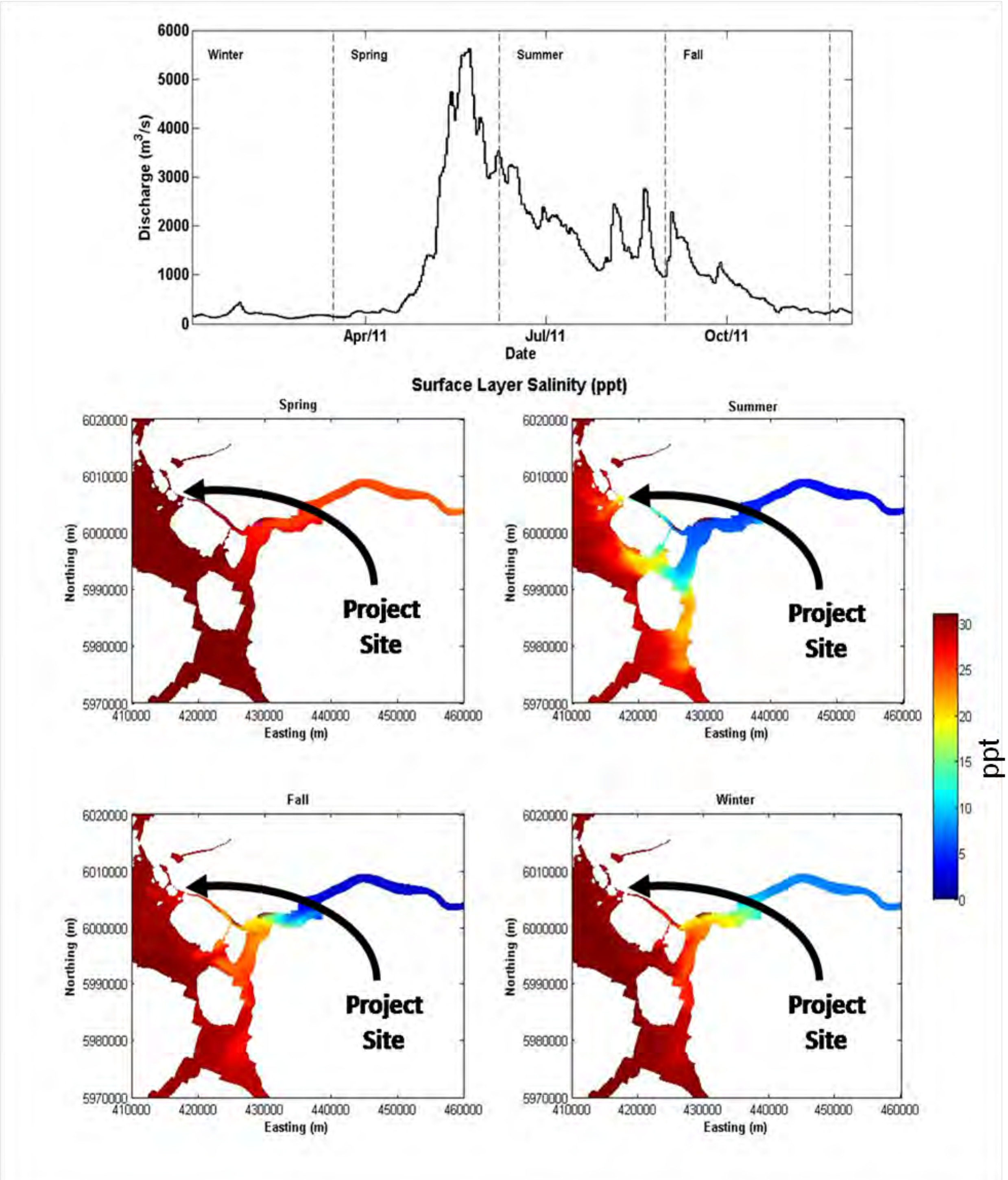


Figure 3-22: Skeena River Discharge (top) and Model Snapshots Showing Surface Salinities indicative of spring, summer, fall and winter

Given the large distance from the Skeena River to the site, only very fine sediment in the Skeena River plume reaches the project area. These suspended materials were observed in measured profiles (see Figure 3-23) but are not found in sediment samples on Flora Bank. These sediments behave similar to a dye in the water, and are easily transported off Flora Bank by waves and currents as the tide goes out.

Figure 3-23 shows a series of salinity and turbidity vertical profiles collected by Stantec at the location of the SW Anchor Block at monthly intervals. Salinity is described in terms of Parts per Thousand (PPT) or Practical Salinity Unit (PSU), and turbidity is described in terms of Formazin Turbidity Units (FTU). The data indicate that overall, the turbidity levels at the project site are less than 5-8 FTU over most of the water column most of the time, but higher in a thin surface layer at times surrounding the freshet period. Turbidity is often described in terms of Total Suspended Solids, or TSS, however no conversion from turbidity to TSS (which requires a sediment-specific conversion effort) was available for the sediments at the project site.

The profiles confirm that for a few weeks per year, during the freshet, a thin surface layer contains reduced levels of salinity and elevated levels of turbidity. The May 19, 2015 vertical profile (bottom left panel) clearly shows the elevated turbidity and reduced salinity in the thin surface layer. The elevated turbidity levels are indicative of the Skeena River plume, which likely delivers very fine sediments (silts and clays) through the PNW LNG project area and Flora Bank. As noted above, these sediments behave like a dye in the water, moving through the area on the surface, and are not found on Flora Bank as demonstrated in the sediment data (SedTrend 2015). These sediments are too fine to remain on Flora Bank during typical conditions. By the time of the June 16, 2015 survey (bottom right panel), the surface salinities are higher, indicating less influence of the Skeena River and the surface turbidity is significantly reduced.

Overall, the salinity and turbidity profiles show very little stratification in the bottom half of the water column where Flora Bank bed sediments are being transported. The profiles indicate that the influence of the Skeena River (either salinity variation or turbidity) does not play a significant role in transport of sand and therefore does not affect the morphology of Flora Bank.

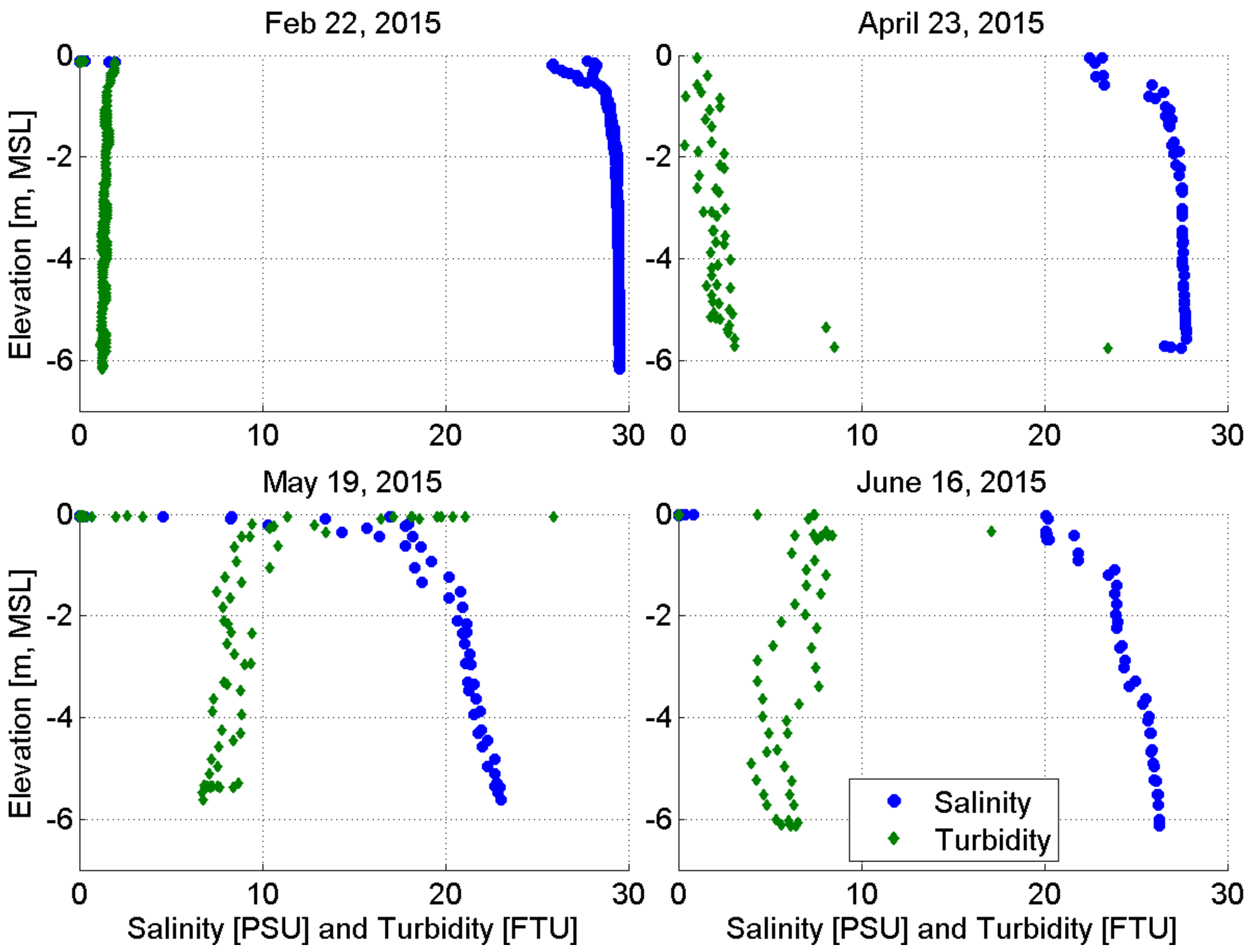


Figure 3-23: Profiles of salinity and turbidity measured at the location of SW Anchor Block in 2015.

3.4 Flora Bank Sediment Transport and Morphology

The following section contains a brief overview of the mobility of sand found on Flora Bank and its observed morphology with the goal of providing a general indication as to how often sediment transport exists on Flora Bank, and at what magnitude, in a further effort to understand the overall stability of Flora Bank relative to the surrounding coastal processes.

3.4.1 Sediment Mobility Evaluation with 1D Model

Sediment mobility analysis was performed to develop a better understanding of how often sediments are mobilized and transported on and around Flora Bank using the Sedtrans05 analysis tool (Neumeier et al, 2008). Sedtrans05 is a single point sediment transport model that incorporates wave-current interaction and computes sediment mobility and transport. Single-point transport and mobility analysis can provide some further insight into how Flora Bank has remained stable for such a long time.

Mean grain size diameters used in the analysis were taken from samples collected and described in the SedTrend report (SedTrend, 2015). Tidal current velocities and water levels were extracted from a 28 day Delft3D regional model freshet simulation (see Section 5.1.2), and wave conditions were assumed to be mild with a significant wave height equal to 0.1 m, and a peak wave period equal to 2 s. The sediment mobility, transport rates and total transport volumes were computed assuming a flat bottom for simplicity as Flora Bank is a relatively flat shoal.

The analysis indicates that sediment transport during mild wave conditions is negligible for a significant portion of the time. Only when shallow water is present over Flora Bank do the currents and waves produce sufficient energy to mobilize its medium and coarse sands. Transport is calculated to be zero (negligible) when either 1) the location of interest on Flora Bank is exposed, or 2) the combined wave-current hydrodynamic forces at the bottom are less than the threshold required for motion of the bottom sediments. Figure 3-24 (top panel) shows the location of the point of interest in the center of Flora Bank, where the mean grain size is approximately 0.35 mm and bed elevation is approximately -2 m MSL. Figure 3-24 (bottom panel) shows separately a time series of the instantaneous total transport for the easterly (shown in blue) and northerly (shown in red) components at this location, for 0.35mm diameter sediments. The instantaneous total transport is indicated on the left axis in terms of volume (m^3) per linear m. The corresponding water level is shown on the right axis. The time series shows that transport occurs only sporadically and only at low tides, and is relatively low in magnitude.

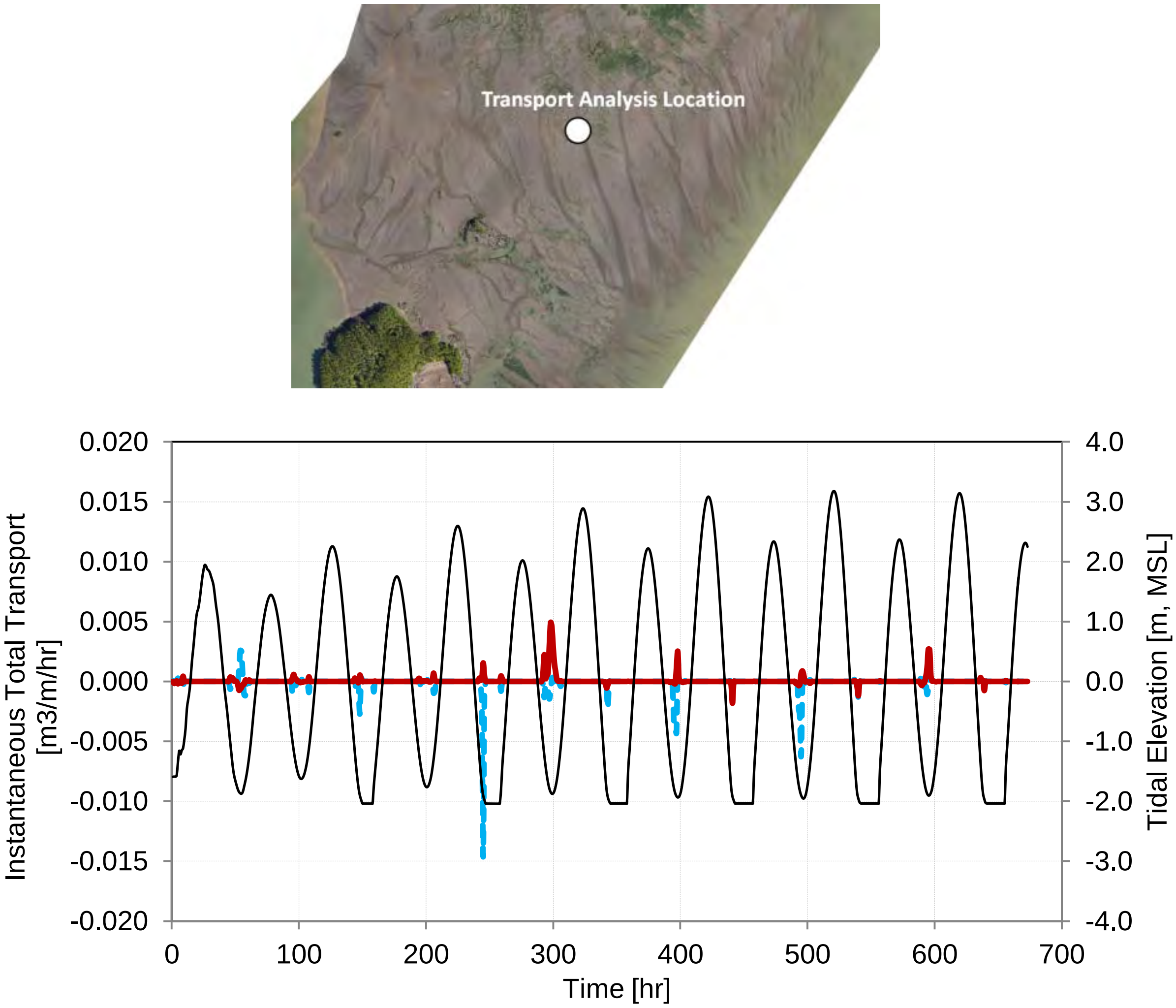


Figure 3-24:Location of analysis (top) and instantaneous total transport (m^3 per m of width) in Easterly and Northerly directions over 28 day freshet simulation at location shown above for 0.35mm diameter sediments (bottom).

Significant fractions of other sediment sizes are also present at the location of Flora Bank shown in the top panel of Figure 3-24. In addition to the mean of 0.35 mm, sediment with diameters 0.125, 0.18, 0.25, 0.5, and 0.71 mm are also present. Analysis results indicate that the periods of mobility are relatively similar for all six (6) grain sizes found here, but slightly higher for the smaller sediments. Table 3-1 shows the percentage of time during a 28 day freshet simulation during which there is zero predicted sediment transport. Even for the smallest sand grain sizes found on the majority of Flora Bank, transport is negligible more than 76% of the time. While these mobility analysis results do not include storm wave events, tides-only simulation results, which have weaker current speeds than the freshet simulation used in the present analysis (the freshet simulation included winds and waves), show current speeds below the mobility threshold for most of the sand sizes all of the time. This indicates that the results here are reasonably representative of longer time periods.

Table 3-1: Frequency of Negligible Sediment Transport on Flora Bank for Various Sand Grain Sizes

Grain Size (mm)	Frequency of Negligible Transport (% of Time in 28 day Simulation)
0.125	76.8%
0.18	78.0%
0.25	78.8%
0.35	79.3%
0.50	80.8%
0.71	81.7%

Appendix K provides additional analysis of sediment mobility, outlining predictions of sediment movement threshold for nine locations on Flora Bank, with points in the vicinity of the SW Anchor Block and SW Tower. Although tidal currents were obtained from Delft3D and include waves, the method for sediment movement threshold is for currents only. The results are consistent with Sedtrans05 predictions, i.e., sediment movement occurs during small intervals when the tidal currents are above the critical values for sediment transport.

3.4.2 Sediment Mobility/Transport Evaluation from SedTrend Analysis (2015)

Sediment mobility and transport analysis was also performed independently by SedTrend (2015a,b) using a vast array of field sediment samples. Samples were analyzed and gradations were developed, including relevant gradation parameters that provide an understanding of the nature of a given location in terms of direction of net sediment transport, and likely bed elevation trends (erosion or deposition). The analysis also provides information about Flora Bank and its relative stability. Figure 3-25 shows the net transport figure from SedTrend (2015a) discerned from analysis of the sediment gradations. The analysis resulted in predictions of net transport directions, determination of which areas are erosional or depositional, and display of areas where no discernable trends could be obtained from the data. The analysis could discern no transport or erosion/deposition trends on Flora Bank as shown in Figure 3-25, indicating that Flora Bank is remarkably stable.

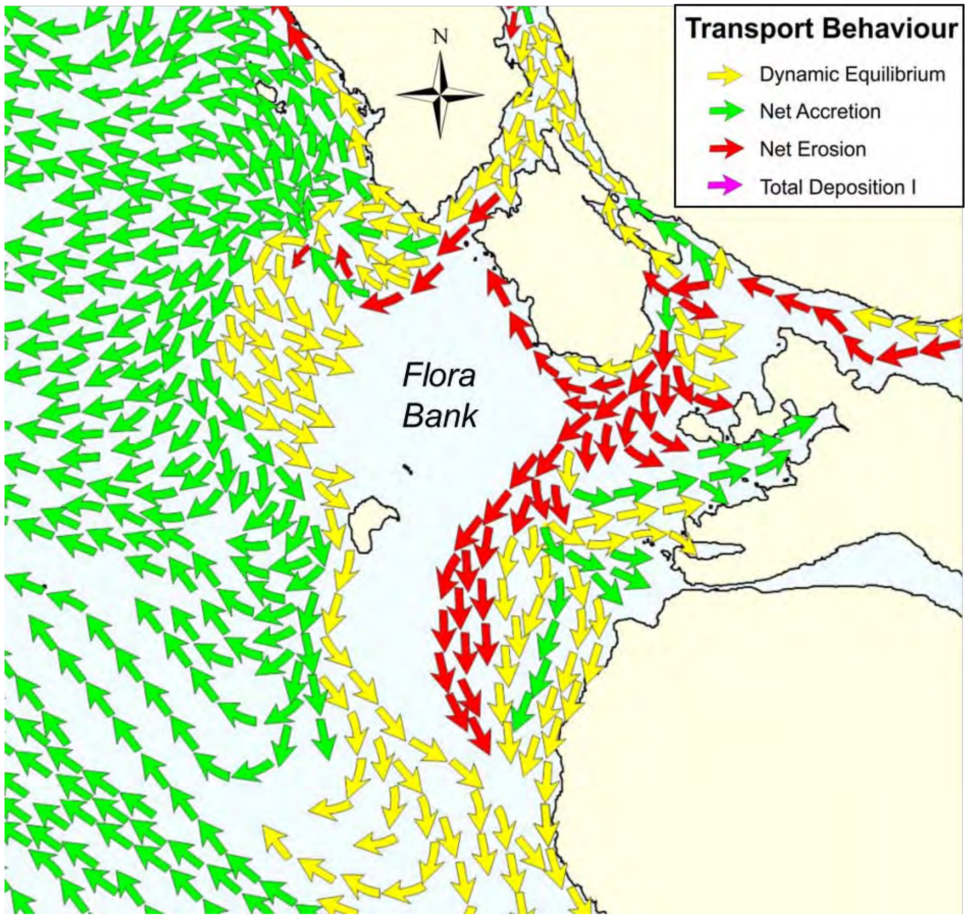


Figure 3-25: Pathways of net sediment transport, from SedTrend (2015a)

3.4.3 Morphology of Flora Bank

Flora Bank is a stable morphological feature that has been observed to undergo relatively little elevation change. It appears that the stability of Flora Bank is largely based on the site's combination of coarser and more stable sandy material, flat and wide configuration, and the relatively mild coastal conditions.

The coastal processes at the site do generate transport, but it appears these conditions generate a low net transport of material off of Flora Bank. The presence of eelgrass and rock outcrops which can also trap sediment movement also likely contribute to the low net transport of material off Flora Bank.

The relatively low net transport of material off Flora Bank and its corresponding stability are indicated by the following:

- SedTrend (2015b) analysis results indicate no discernable transport trends over Flora Bank), and much coarser material than the surrounding areas;
- Flora Bank has relatively low levels of sediment mobility and low transport rates under typical (non-storm) conditions (Section 3.4.1); and,
- Small surface channels (likely drainage features) appear very similar over time as observed in aerial photos (Figure 3-4).

Flora Bank's relatively small observed level of morphological change is further shown through comparison of historical and recent nautical charts (see Figure 3-26) from the SedTrend 2015a report). The comparison of two charts plotted approximately 80 years apart demonstrates that the boundaries of Flora Bank are fairly consistent and the similar bathymetry configuration indicates stability of Flora Bank over long time periods.

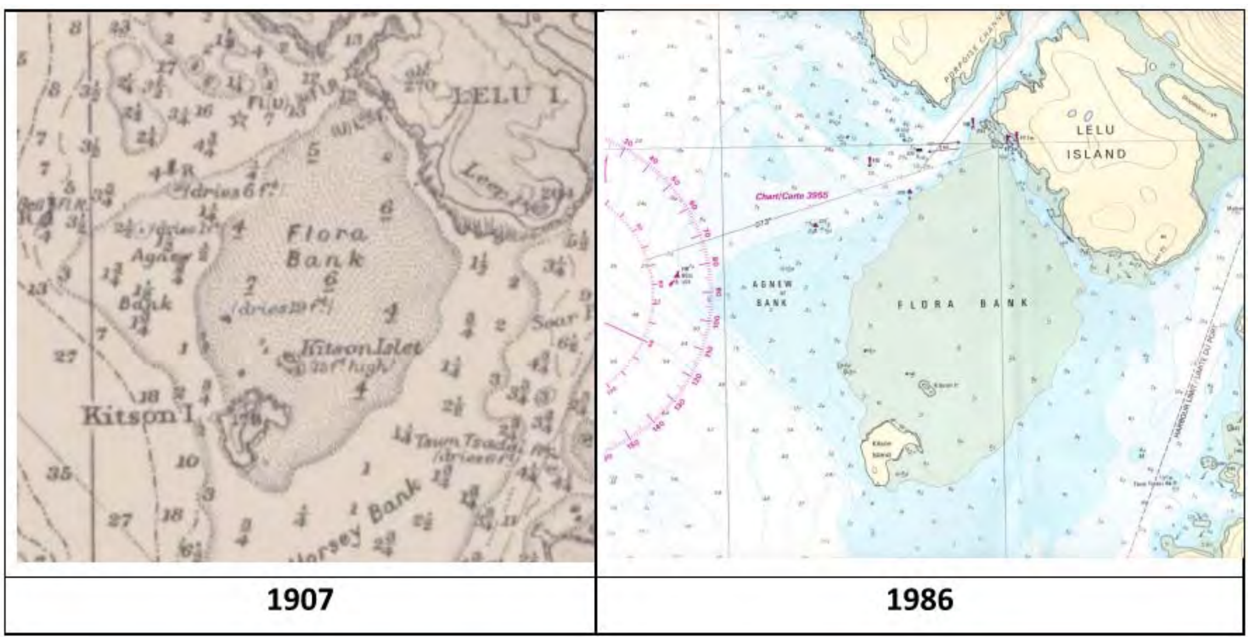


Figure 3-26: Flora Bank configuration in 1907 and 1986, from SedTrend (2015a)

4. Modelling Approach

Analysis of the potential impacts of the marine structures on Flora Bank has been conducted using a combination of state-of-the-art modelling tools. Several tools have been utilized in a range of broadly parallel efforts, in order to fully explore the various processes relevant to understanding both Flora Bank and the potential effect of the proposed structures on hydrodynamics and morphology.

The "3D Modelling" numerical efforts using Delft3D are broadly described in the Terms of Reference jointly developed by CEAA and PNW LNG, and as approved by CEAA in March 2015. Further discussion of refinements to this modelling effort are discussed in the following sections and the accompanying appendices.

Recent efforts have included application of a high-resolution model (nicknamed "MORPHO") to study hydrodynamic and transport processes surrounding the SW Tower and SW Anchor Block, also described further herein. Using this combination of modelling tools, recent analytical efforts may be broadly summarised into the following streams, illustrated in Figure 4-1 :

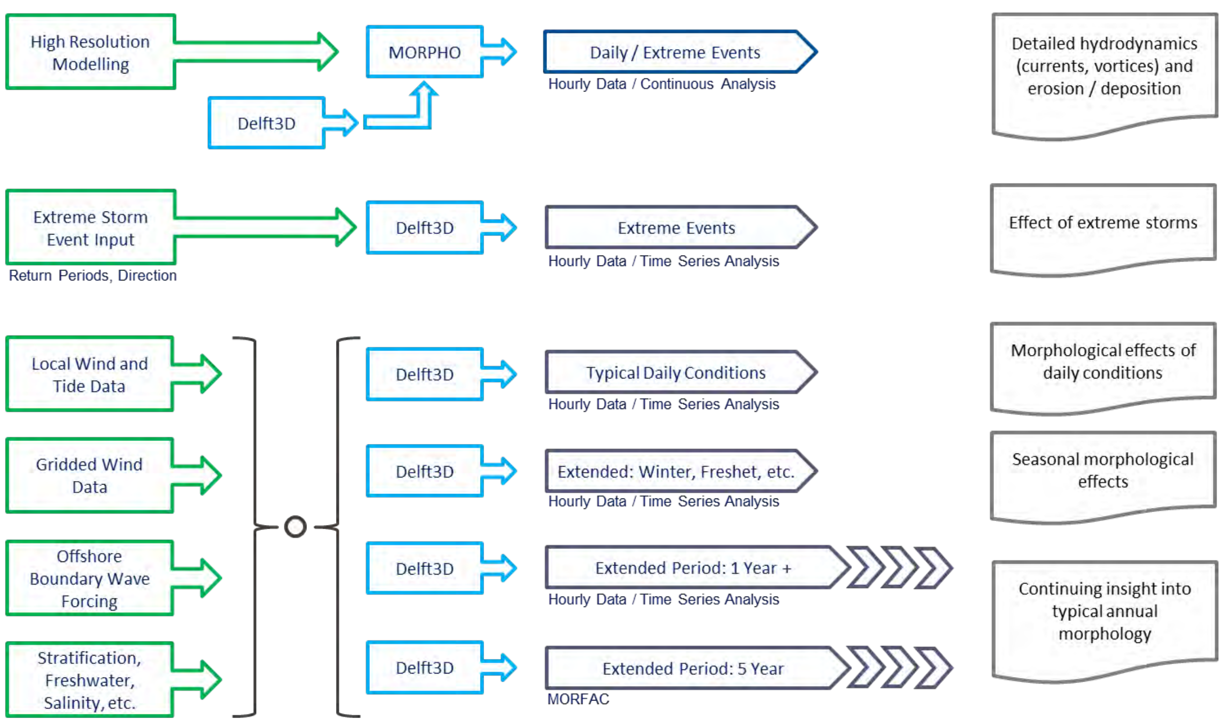


Figure 4-1: Schematic diagram showing the combination of modelling tools and subsequent analytical efforts.

Numerical modelling was performed to simulate coastal processes on both a large/regional scale (hundreds of kilometres down to tens of meters) and a highly localized scale (meters) to ensure accurate simulation of all physical processes that are potentially relevant to the morphology of Flora Bank and potential impacts of the marine structures.

4.1 Regional-Scale Modelling

A regional-scale modelling effort was undertaken for the purposes of developing further insight into the coastal processes, developing accurate site-specific coastal conditions data for driving near-field high-resolution models, and evaluating potential impacts of the marine structures. This modelling study builds on the 3D modelling effort which was presented in the May 5, 2015 Hatch report (Hatch, 2015).

The coastal processes simulated in the regional modelling include the following:

- Offshore wave transformation to the project site;
- Local (Chatham Sound) wind-wave generation and transformation;
- Currents generated by tides, winds and waves;
- Skeena River discharge and sediment influx;
- Salinity transport; and,
- Multi-fraction sediment transport and morphology.

The results of the Delft3D large-scale model were further utilized to evaluate the potential impacts of the marine structures on larger-scale flow and transport processes, and evaluate potential changes to the morphology of Flora Bank.

This section provides an overview of the model selection and setup. Appendix B provides more detailed information on the setup of the Delft3D model.

4.1.1 Model Selection

The Delft3D (Deltares 2014a, b) coastal processes modelling system was selected due to its capability to simulate all coastal processes mentioned above, and pre-eminence in the coastal engineering industry for accurate simulation of morphological change under complex coastal conditions. Delft3D simulates wave growth and transformation, and 3D hydrodynamics, salinity transport, sediment transport, and morphological change.

The scale of the coastal processes simulated in the Delft3D model spanned from hundreds of kilometres down to tens of meters, which is an appropriate scale of application for Delft3D based on its underlying assumptions and computation methods.

4.1.2 Delft3D Model Simulations

The Delft3D regional-scale model was applied to simulate coastal conditions and the potential impacts of the marine structures within the following sets of simulations using a continuous time series of all inputs with no morphological acceleration (MORFAC=1):

- 11 day extreme event (storm) simulations (40 total), 1-hour wave coupling:
- Directions 300^{o}, 270^{o}, 240^{o}, 170^{o} True North
- Wind return periods 1, 5, 20, 50, 100 years
- With and without marine structures
- 28 day Skeena River freshet period simulations between May 11 and June 8 2014 (high flow event), with and without marine structures, 1-hour wave coupling
- 28 day Tides Only simulations (no winds, waves and river discharge), with and without marine structures, 1-hour wave coupling
- Longer-term simulations with a complete range of conditions ("time series runs"), with and without marine structures. The simulations included a simulation covering an 12-month period, two simulations with 1 year period and also, other sensitivity testing simulations were performed to evaluate the importance of waves and other modeling parameters and their effects on the modelling results.

Description of the model setups for the various simulations are described further in Appendix B. Development of the storm simulation inputs are described in Appendix G.

4.1.3 Delft3D Modelling Domains

The Delft3D model utilizes two modules; Delft3D-WAVE and Delft3D-FLOW. Delft3D WAVE uses the Simulating Waves Nearshore (SWAN) model developed by Delft University of Technology to simulate the wave conditions. Delft3D-WAVE is coupled with Delft3D-FLOW which simulates the hydrodynamics, salinity, sediment transport, and resulting morphology.

Figure 4-2 (top panel) shows the regional modelling domain which is used for the Delft3D WAVE to simulate wave growth and transformation from offshore. The localized, nested domain, shown in Figure 4-2 (bottom panel), is used for the nested wave growth and transformation for the Delft3D WAVE module. The modelling domain shown in Figure 4-2 (bottom panel) is also used for hydrodynamics, salinity, transport and morphological change in the FLOW module. The WAVE model has resolution ranging from 2.1 km in the offshore areas (regional domain), to approximately 60 m for the short term simulations and 100 m for the long-term simulation in the vicinity of the marine structures (nested domain). The nested WAVE and FLOW models cover approximately the same area.

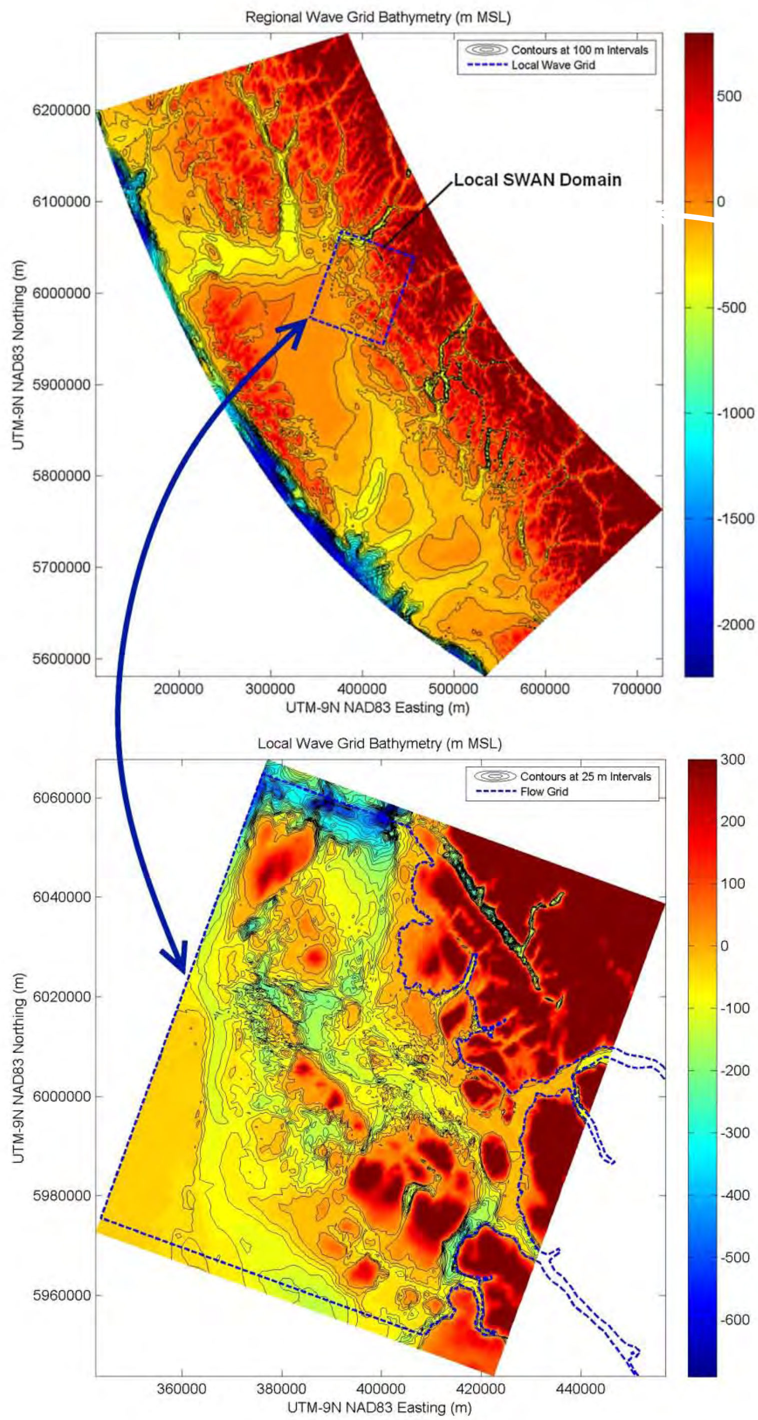


Figure 4-2: Delft3D large-scale wave modelling domain (top), and Delft3D nested wave modelling domain (bottom)

4.1.4 Delft3D Input Sediment Conditions

Sediment fractions were incorporated into the model for transport and morphology modelling, as described in the May 5, 2015 3D modelling report and Appendix B. The initial regional modelling simulations included a wide range of sediments sizes to evaluate not only transport of sand and coarse material, but potential deposition of silts and clays around Flora Bank. In the areas of the marine structures and on Flora Bank, sediments consist of fine, medium and coarse sand (and gravel) with no appreciable silts or clays.

The initial Delft3D regional modelling simulations and longer-term simulations utilized this 4-class sediment grain size distribution in the modelling domain that was intended to evaluate the transport and fate of clay, silt, sand and coarse materials. Those four grain sizes (cohesive, 0.1, 0.14, 2 mm) were mapped to the modelling domain in an approximate manner using the mean sediment size data from SedTrend (2015a). In August 2015, SedTrend notified the project team that the previously supplied sediment grain size data were in error, and that in fact the sediments were slightly finer overall. In order to evaluate the impact of this previous erroneous data on the results of the modelling, additional short-term simulations were performed in August 2015 to evaluate the relative importance of the assumed grain size distribution on the predicted morphology of Flora Bank (as described in Section 5), and on the potential impacts of the marine structures.

The new sediment grain size distribution was developed using the revised SedTrend (2015b) data with a closer focus on the material found on Flora Bank, typically ranging from 0.1 mm to 0.5 mm. Six (6) classes of sediments were created in the Delft3D model (0.1, 0.125, 0.177, 0.25, 0.35, and 0.5 mm). Any finer sediments were lumped into the 0.1mm fraction, and coarser material was lumped into the 0.5 mm fraction.

The results of the sediment grain size sensitivity testing simulations with the regional model are presented in Section 5.1.2 and Section 6.1.2.

4.1.5 Delft3D Model Boundary Conditions

The Delft3D large-scale wave model was driven on the Pacific Ocean boundary using spatially variable gridded wave model results (see Appendix D). The Delft3D nested wave model was driven by results from the large-scale model, and within both models spatially variable gridded winds were used for local wind-wave generation and transformation (Appendix C). The Delft3D FLOW model was driven using tidal constituents (Egbert & Erofeeva, 2010) and salinity (DFO, 2015) at the deep-water boundary, and Skeena River inputs at its upstream boundary which included fresh water (zero salinity assumed), daily discharge (Skeena River at Usk Station, Wateroffice, 2015) and total suspended solids (Skeena River at Usk Station, Wateroffice, 2015). Appendix F also provides an overview of the Delft3D model calibration/validation with measured waves at the PNW Buoy and measured currents in Porpoise Channel and Inverness Channel.

4.1.6 *Delft3D Representation of Marine Structures*

The following two marine structure types were incorporated into the Delft3D model:

1. Trestle. This structure tends to reduce wave and current energy that passes through its field of sparse vertical pipe piles (1-2% in-water coverage). Therefore this structure was incorporated in the wave model as an obstacle with omnidirectional 90% wave height transmission. This transmission is under-stated in reality, resulting in more effects of the marine structures than should be expected in real life. The trestle was incorporated in the flow model as a porous plate with appropriate flow energy reduction. See the May 5 report (Hatch, 2015) for a full description of the marine structure incorporation in the regional model.

2. SW Anchor Block and SW Tower. In the short-term simulations (storms, freshet period), these two larger marine structures were represented in the regional model as dry islands with size equal to the grid resolution of approximately 60 m (i.e. larger than the actual structures). In the long-term simulations the grid spacing near the structures is approximately 100 m which is significantly larger than the proposed structures, therefore a porous-plate was used to represent the flow obstruction imposed by the two larger marine structures.

It is understood that the scale of the regional modelling does not allow a practical simulation of the near-field, fine-scale coastal processes that occur around the larger marine structures, in particular local flow acceleration and scour. For this reason, near-field effects are evaluated separately using high-resolution modelling which is described in Section 4.2.

4.1.7 *Delft3D Model Initial Conditions*

The regional Delft3D model initial conditions consisted of the following:

- Bathymetry. Bathymetry data collected in the field were used as the initial condition. It is expected that some initial morphological adjustment will occur in the modelling that is related to the assumed initial bathymetry, and would not occur to the same degree had the model been already run for a long period of time. However, the initial adjustments are assumed to be similar for simulations both without and with the marine structures.
- Hydrodynamics. All hydrodynamics were initialized with a cold start (zero water level and velocities in the domain), but were spun-up prior to performing any morphological calculation. Spin-up periods were 3 days for shorter storm simulations, and 7 days for longer-term simulations.
- Salinity. Multiple hydrodynamic simulations were performed to provide a reasonable initial condition for modelling salinity, including a 10-layer simulation lasting one full year. In the longer-term simulations that begin on September 1, 2012, salinity conditions at the end of the January 1 to August 31 period were utilized as the initial condition. The final salinity field from the 28 day freshet simulation period was also used as an initial condition, and

no measurable effect on morphological predictions were found. Further information regarding salinity and stratification is provided in Appendix C. The full model setup and input parameters are further described in Appendix B.

4.2 High-Resolution Modelling of the SW Tower and SW Anchor Block

The scale and resolution of the regional Delft3D model allowed evaluation of all relevant physical processes with the exception of the very fine-scale hydrodynamic and transport processes surrounding the SW Tower and SW Anchor Block. The fine-scale physical processes surrounding the proposed SW Tower and SW Anchor Block occur on the scale of meters, and required the use of an independent, high resolution numerical modelling system. The high-resolution modelling system was used to simulate local hydrodynamics around the SW Tower and SW Anchor Block (including vortex shedding effects), sediment transport and morphological change induced by these structures.

4.2.1 High-Resolution Model Selection

The MORPHO modelling system (Kolomiets et al 2014) was selected to simulate fine-scale physical processes around the proposed SW Tower and SW Anchor Block. MORPHO is a proprietary implementation of the COASTOX-UN numerical simulation code, which was developed in cooperation with UCEWP in Ukraine (http://www.ucewp.kiev.ua/about.php). MORPHO is an unstructured, finite volume coastal processes modelling system that simulates fully nonlinear depth-averaged hydrodynamics, sediment transport and morphological change. The scale of the processes simulated in the MORPHO model spanned from hundreds of meters at the far outer boundary of the larger domain, down to meter-scale resolution around the structures.

4.2.2 MORPHO Model Simulations

The high-resolution MORPHO model was applied to simulate hydrodynamics, sediment transport and morphology, and the potential impacts of the marine structures within the following sets of simulations. All simulations were performed using a continuous time series of all inputs, with no morphological acceleration (MORFAC=1), and for conditions both with and without the SW Tower and SW Anchor Block. The following model simulations were conducted using MORPHO:

- 28 day simulations of hydrodynamics during freshet conditions, which include typical daily tidal current forces, minimal wave influence, and the Skeena River freshet (high river flow period).
- 28 day simulations of currents generated by tides alone, without any winds, waves or Skeena River discharge being included.
- 11 day extreme event (storm) simulation from 270^{o} True North with 50-year return period. This storm direction generates strong hydrodynamics at the locations of the SW Tower and SW Anchor Block due to a combination of wave-induced currents and tidal currents, in particular during flood tide when wave and tidal forces are aligned.

The results obtained with the high-resolution model are presented in Section 6.2.

4.2.3 MORPHO Modelling Domains

Three domains were setup using MORPHO; a larger domain which includes the extent of Flora Bank (Figure 4-3), a smaller domain around the SW Anchor Block (Figure 4-4, left inset), and a smaller domain around the SW Tower (Figure 4-4, right inset). The different domains were setup for the purpose of simulating different time periods with different conditions.

The larger MORPHO modelling domain (Figure 4-3) was utilized for the 28 day freshet simulation which includes typical conditions dominated by tidal currents, but also the freshet period (limited time with high river flows). The larger MORPHO modelling domain was also used to perform a 28 day tides-only simulation (no winds, waves or Skeena River discharge). The larger MORPHO modelling domain has resolution ranging from 200 m at the boundary, to 1.5 m along the structures. Resolution in the model was tailored to capture vortex shedding effects as observed in initial testing simulations.

Figure 4-4 shows the local idealized MORPHO modelling domains (one for the SW Tower, one for the SW Anchor Block) which have a circular outer boundary. These modelling domains were utilized for 11 day extreme event simulations, which are dominated by a complex combination of wave-induced currents and tidal currents. The smaller MORPHO modelling domain has resolution ranging from 10 m along the outer boundary, to 1.5 m along the structures. The SW Tower and SW Anchor Block were incorporated into the unstructured MORPHO model in both domains as island features.

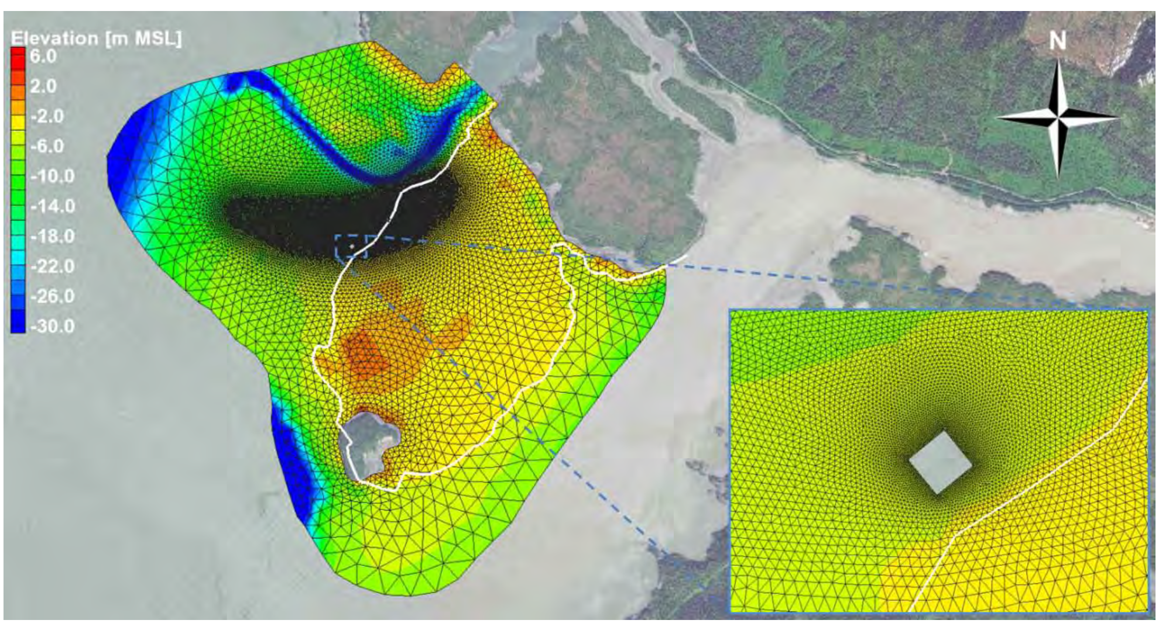


Figure 4-3: MORPHO larger-area modelling domain for 28 day freshet period and 28 day tides-only simulations

Safety • Quality • Sustainability • Innovation

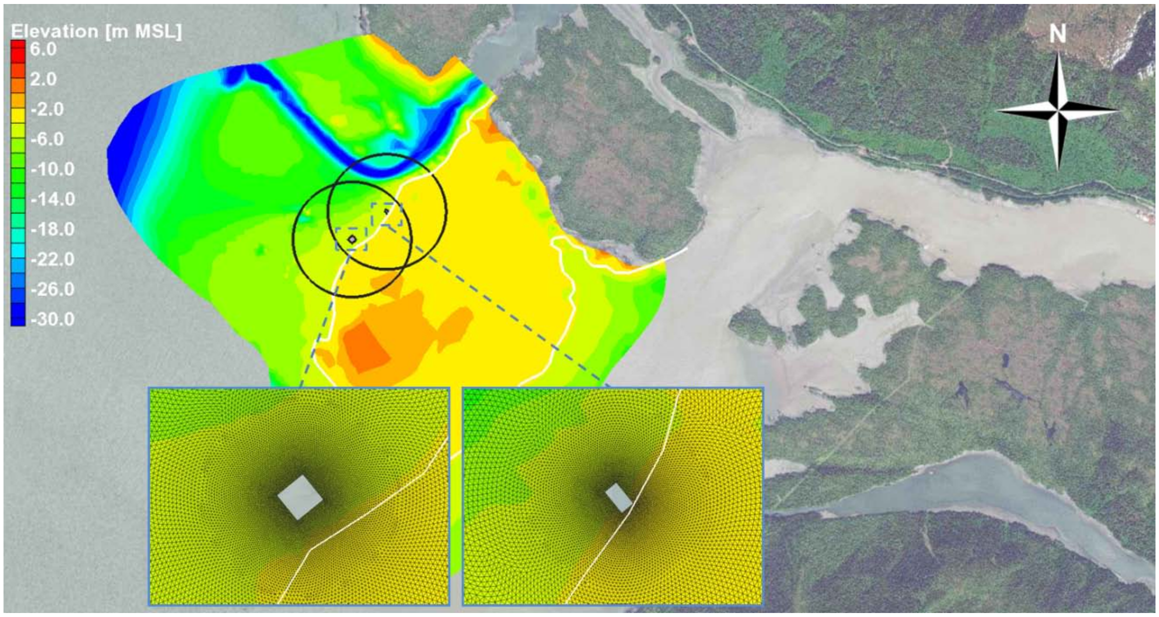


Figure 4-4:MORPHO local storm modelling domain extents for SW Anchor Block and SW Tower (circles) and close-up views of the model grid resolution around the marine structures

4.2.4 MORPHO Model Boundary Conditions

The MORPHO larger-area model was driven along its outer boundary using spatially and temporally variable velocity components and water levels extracted from the Delft3D model results. During the 28 day freshet period and tides-only MORPHO simulations, spatially variable velocity components and water levels from the corresponding Delft3D simulation were used as boundary conditions. During the 50-year storm simulation, a time history of velocity and water level at the location of each structure from Delft3D were used to drive each local idealized model. The MORPHO models were driven using Delft3D results but do not feed information back to Delft3D (results remain independent). Appendix J provides details regarding the coupling between the models.

4.2.5 MORPHO Model Representation of Marine Structures

The MORPHO model incorporated only the SW Tower and SW Anchor Block. Design drawings were incorporated into the model and the layouts of the rectangular blocks were incorporated as dry islands in the MORPHO model. As part of sensitivity analysis, the SW Tower structure was also evaluated using a circular structure, and tested in separate hydrodynamics and sediment transport simulations.

5. Modelling of Existing Conditions

Modelling of the existing conditions, with no proposed structures in place, was conducted to further develop the understanding of the hydrodynamic conditions and the coastal processes at the project area which drive sediment transport and morphology. These coastal processes include:

- Tides (water level fluctuations);
- Tidal currents;
- Winds;
- Waves; and,
- River discharge.

Numerical modelling was performed using Delft3D to simulate coastal processes on a large/regional scale (hundreds of kilometres down to tens of meters) to ensure accurate simulation of all relevant coastal processes and determine which are potentially relevant to the morphology of Flora Bank. Results of wave and flow model calibration and validation are provided in Appendix F.

The results of the Delft3D regional model were utilized to develop insight into larger-scale flow and transport processes surrounding Flora Bank and its morphology over time. The following sections are a summary of the existing conditions modelling results and describe the coastal processes and morphological change around Flora Bank during the following simulations:

- Storm simulations (extreme events);
- Freshet simulations; and,
- Longer-term simulations (long-term time series runs) with a complete range of coastal conditions.

Additional simulation results are provided in Appendix H and Appendix J. The modelling of the proposed conditions (with the marine structures in place) is described in section 6.

5.1 Storm Conditions

Delft3D simulations were performed for extreme storms to evaluate morphological changes on Flora Bank caused by episodic events. A total of 20 different 11 day storm simulations were performed, which included winds, waves, tidal currents, sediment transport and morphology for the existing conditions. Simulations included four different wind directions (300°, 270°, 240° and 170° True North) and five different return periods (1, 5, 20, 50, 100 years). The development of the storm conditions are detailed in Appendix G.

Generally speaking, a storm return period of 50 years indicates that this particular storm is likely to occur once in 50 years. For a marine structure lifetime of 25 years, the likelihood that a 50-year storm will occur during the life of the structure is 40%.

Storm simulations were conducted using winds blowing from the same direction for 11 days. Analysis of the measured winds at Holland Rock indicated that the maximum duration of winds blowing from a same direction was significantly lower (Figure 5-1), therefore the conditions represented in the modelled storms are conservative in terms of significant wave heights, sediment transport and morphology changes.

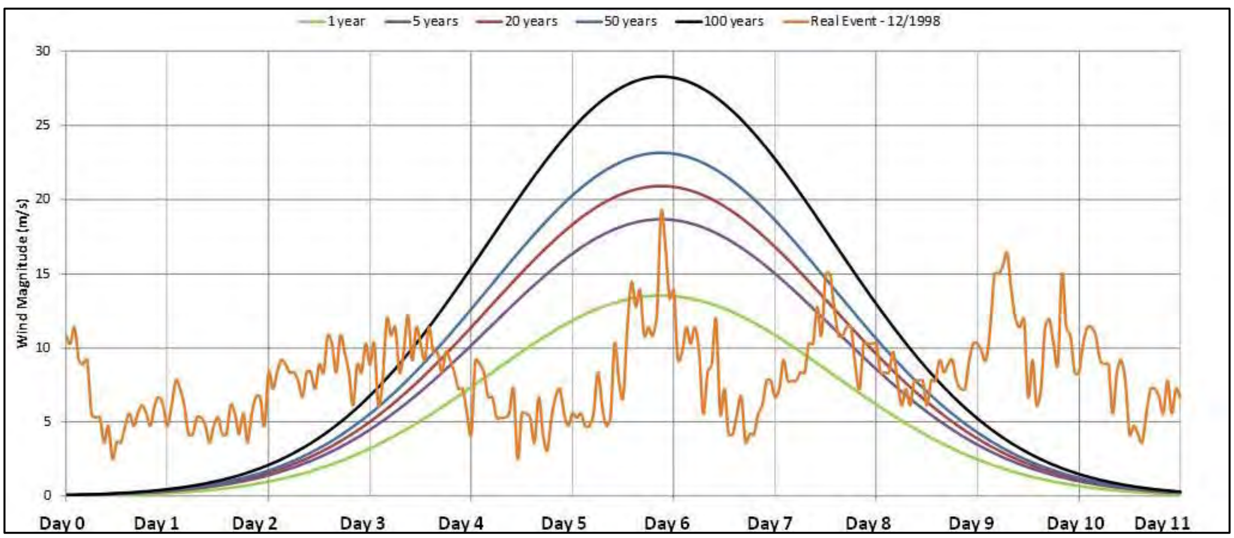


Figure 5-1: Time histories of storm input wind conditions based on Gaussian curves and example of real wind speeds measured at Holland Rock during a storm

5.1.1 Storm Simulation Results

This section provides an overview of the storm simulation results using as an example the 50-year storm from the west (270° True North). This storm was selected as an example to display in the main body of the report because waves from 270° True North will interact with the structure prior to reaching Flora Bank, and therefore the maximum potential impacts of the proposed marine structures can be observed. The results for the storms from other directions and different return periods are presented in Appendix H. This storm is synthetic and as discussed in the previous section has a longer duration than is likely to be found in reality for most storms, however it provides a good understanding of how coastal processes affect Flora Bank and the surrounding areas.

Figure 5-2 shows significant wave heights around Flora Bank at the peak of the 50-year storm from 270° True North. The deep water significant wave height is approximately 4 m approaching the project area. Results indicate that waves are attenuated as they pass over the shallow southwest edge of Agnew Bank (approximately the -10 m contour) and become reduced in height to approximately 1.5 to 2.5 m. Further reduction in significant wave height occurs along the western slope of Flora Bank (inside the -3.8 m contour) with the significant wave height reducing from approximately 1.5 m to 0.5 m. The wave height over Flora Bank is approximately 0.5 m along the western side and lower on the eastern side and in the shallower areas.

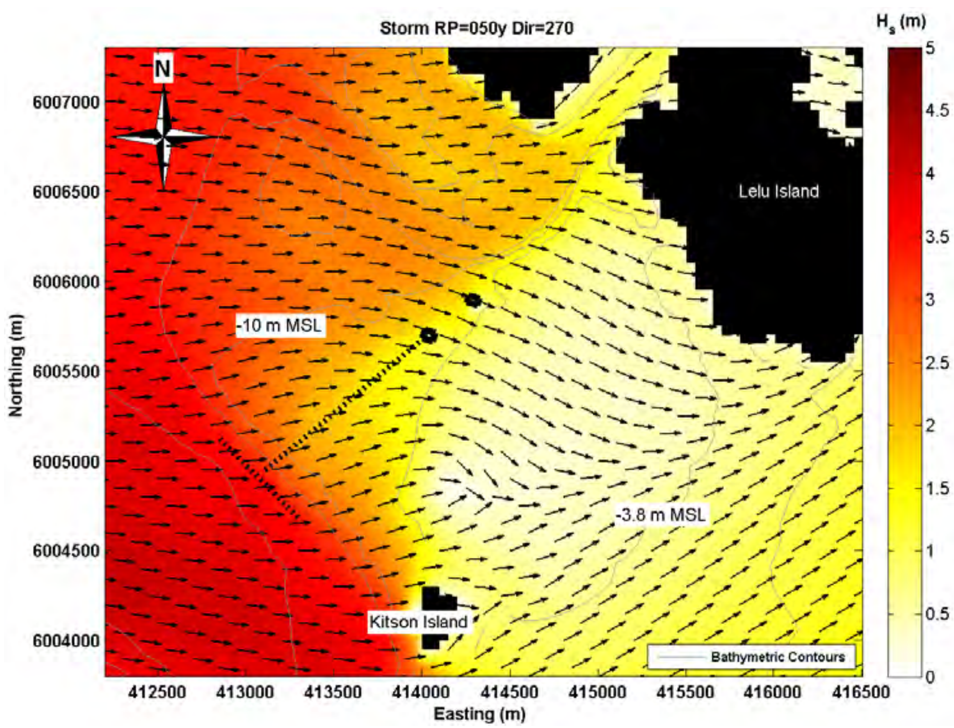


Figure 5-2: Significant wave heights during the peak of the 50-year storm from 270° True North

Figure 5-3 shows a snapshot of depth-averaged currents at the peak of the storm winds which happened to occur during the middle of the flood tidal stage. The inset figure in the top right corner demonstrates the tidal stage when the snapshot was taken. The peak currents over Flora Bank at this stage reach approximately 0.7 m/s moving towards the east. The currents over Agnew Bank are smaller (less than approximately 0.3 m/s) except at the western edge where strong wave-induced currents are directed to the south. The currents over Flora Bank are higher than Agnew Bank due to the shallower water.

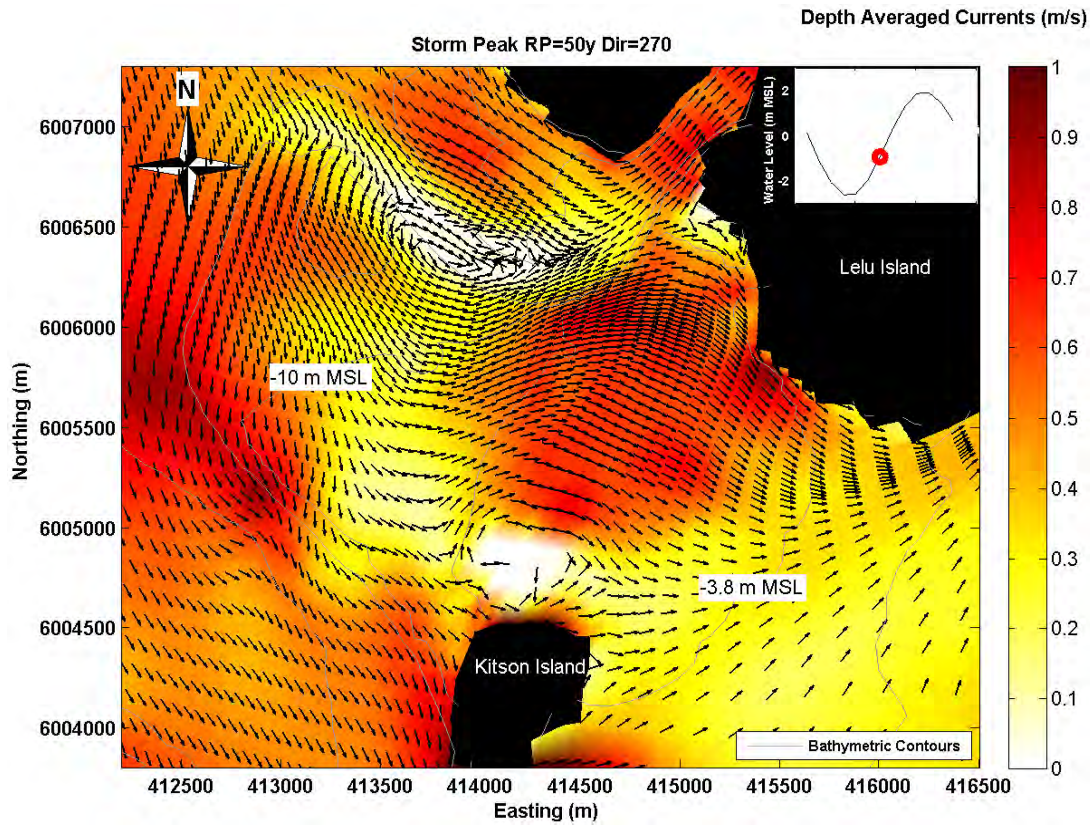


Figure 5-3: Depth averaged current patterns during the peak of the 50-year storm from 270^o True North, with inset displaying tidal stage

As an example of sediment transport generated by these conditions, Figure 5-4 shows snapshots of the total (suspended plus bedload) transport flux taken at three distinct times during the 50-year storm from 270^o. The inset figures in the top right corner of each plot demonstrate the significant wave heights at the PNW Buoy at the times when the snapshots were taken, including before (top), during (middle) and after (bottom) the peak of the storm. The significant wave heights at the times of these three snapshots were 1.7 m, 4.0 m and 1.9 m, respectively. All three snapshots of instantaneous transport flux are presented at the beginning of ebb tide. The total transport fluxes that are generated before and after the peak of the storm are considerably smaller than during the peak of the storm, demonstrating the importance of wave heights on currents and sediment transport in the area.

Figure 5-5 shows analogous total sediment transport flux snapshots for times with similar significant wave heights, but for conditions at the beginning of flood tide. The patterns are consistent between beginning of ebb and flood tide, indicating further the dominance of wave conditions on the transport of sediment around Flora Bank.

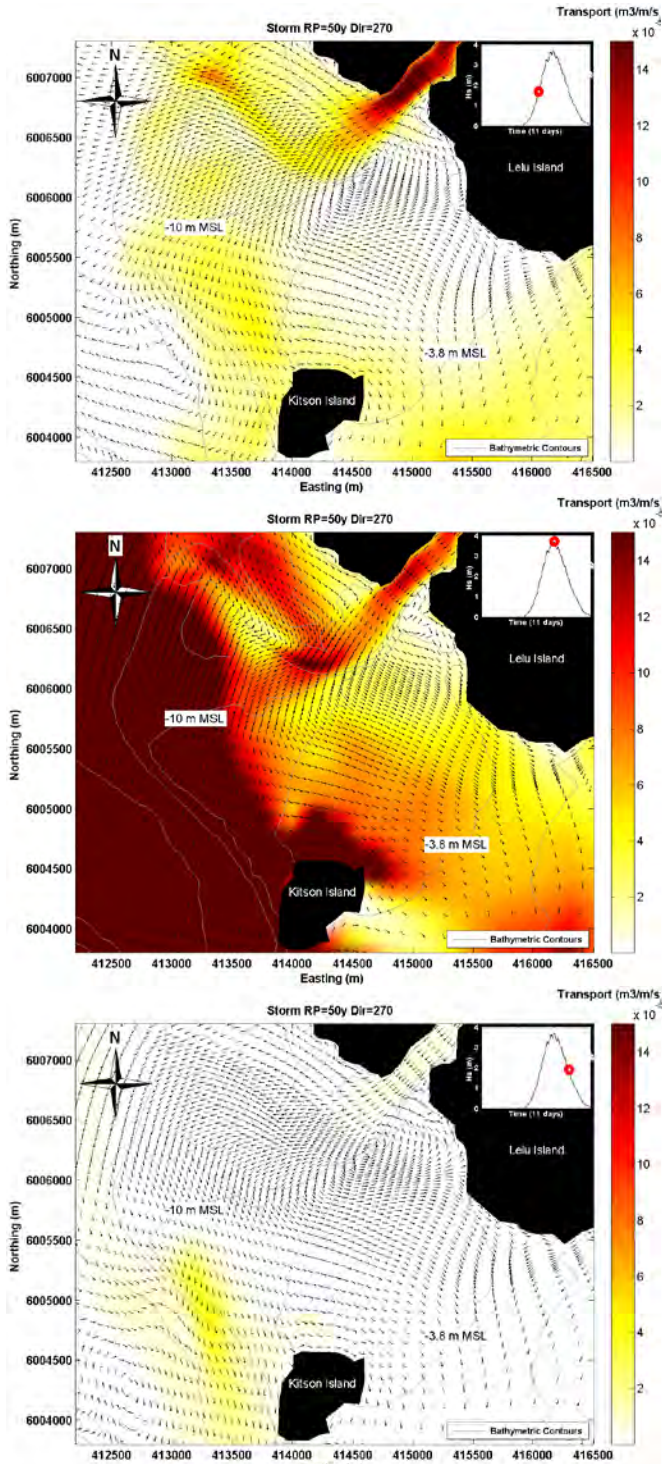


Figure 5-4: Total transport flux snapshots during an early portion (top), at peak (middle), and after the storm (bottom) at the beginning of the ebb tide. Inset figures show the significant wave height at the PNW Buoy when the snapshots were taken.

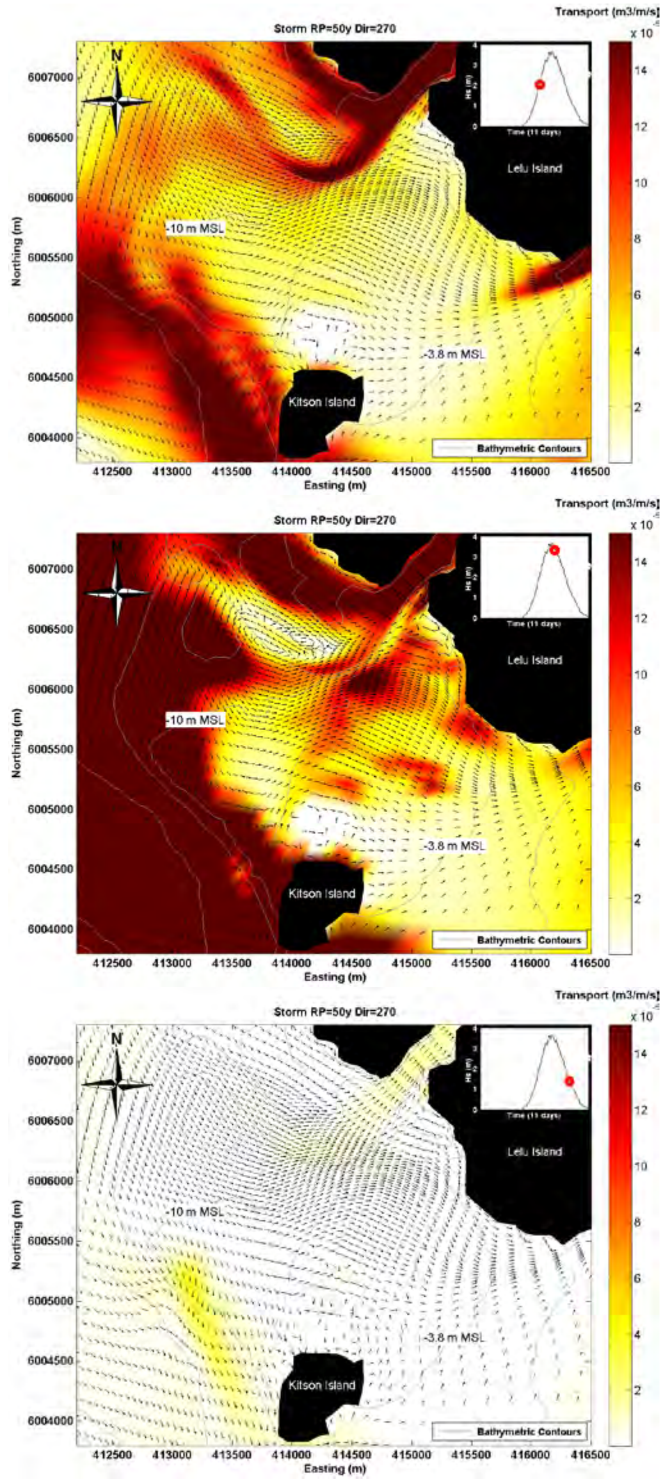
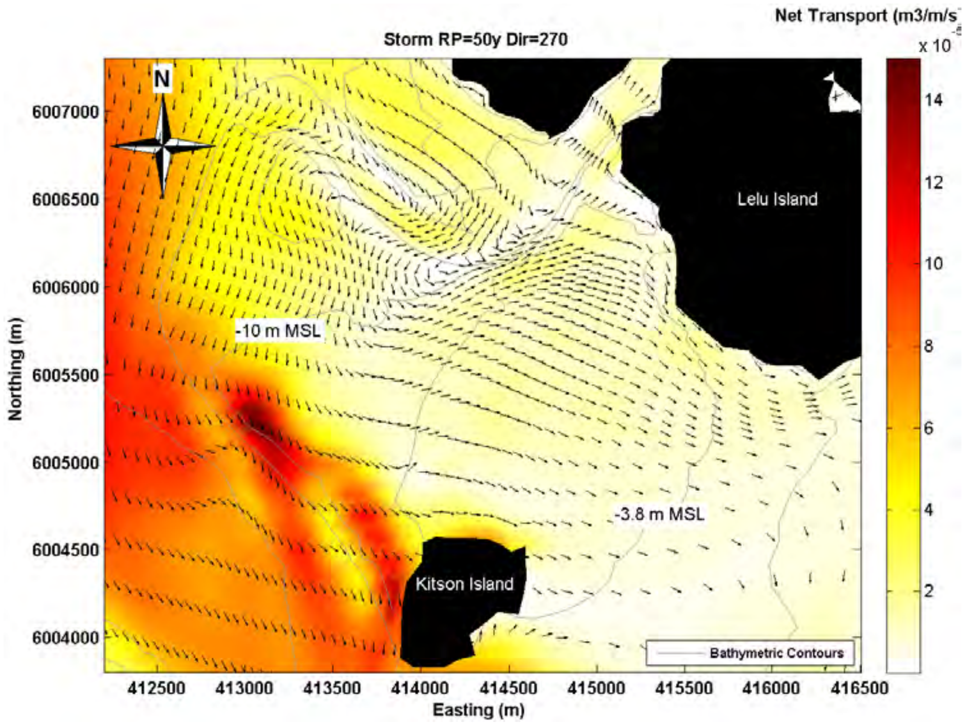


Figure 5-5: Total transport flux snapshots during an early portion (top), at peak (middle), and after the storm (bottom) at the beginning of the flood tide. Inset figures show the significant wave height at the PNW Buoy when the snapshots were taken.

Figure 5-6 shows the net total transport computed throughout the 11 day simulation, with the computation starting and ending at high tides. The net total transport is stronger on the west end of Agnew Bank where heavy wave breaking occurs. The net total transport is lower over Flora Bank and very consistent over a large area due to the flat slopes and low spatial gradients in waves and currents. The consistency of the net transport over wide areas on Flora Bank indicates that material is being transported around, but net elevation changes are not likely to be significant in most areas. Figure 5-6 (bottom) shows an approximately 1700 m long transect (dashed line) across which the total net sediment transport flux was computed. Analysis indicates that a total flux of approximately 91 m^3 of sediment per hour flows eastward across Flora Bank normal to the transect during this large storm event. Net transport flux near Kitson Island was the highest, at roughly 4-5 times larger than the flux across most of the transect which is spatially consistent with approximately 0.043 m^3/m/hr.



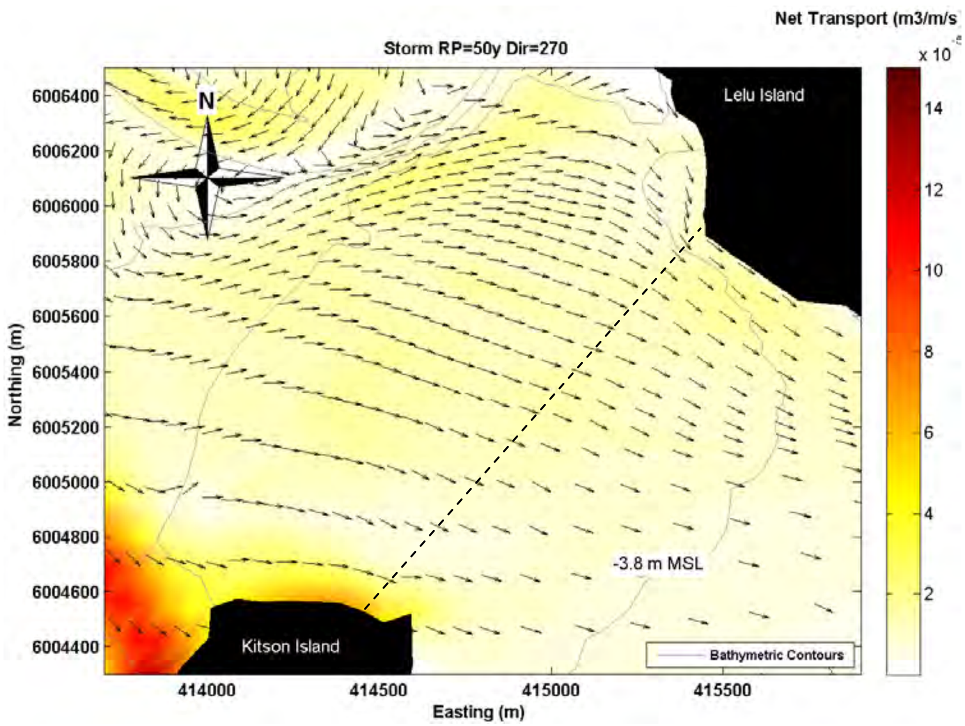


Figure 5-6: Net total transport flux during 11 day simulation (top), and close-up around Flora Bank (bottom), with transect location.

Figure 5-7 shows the net total transport computed throughout the 11 day simulation separately for each of the four grain sizes used in the modelling, including clay (top left), silt (modelled as sand with diameter 0.1 mm, top right), sand (diameter 0.14 mm, bottom left) and coarse (diameter 2 mm, bottom right). Analysis by grain size shows that a large portion of the sediment moving across Flora Bank is clay arriving from Agnew Bank to the west, as well as the fine sand fraction which is also present on Flora Bank. The silt fraction (top right) is not found in significant amounts on Flora Bank and does not become mobilized towards Flora Bank from the west in great amounts. The coarse fraction is too large to be significantly mobilized. The net transport figures also indicate that the total transport fields for both fines and sandy material are relatively homogeneous over large distances, and hence likely to result in small bed elevation changes on Flora Bank.

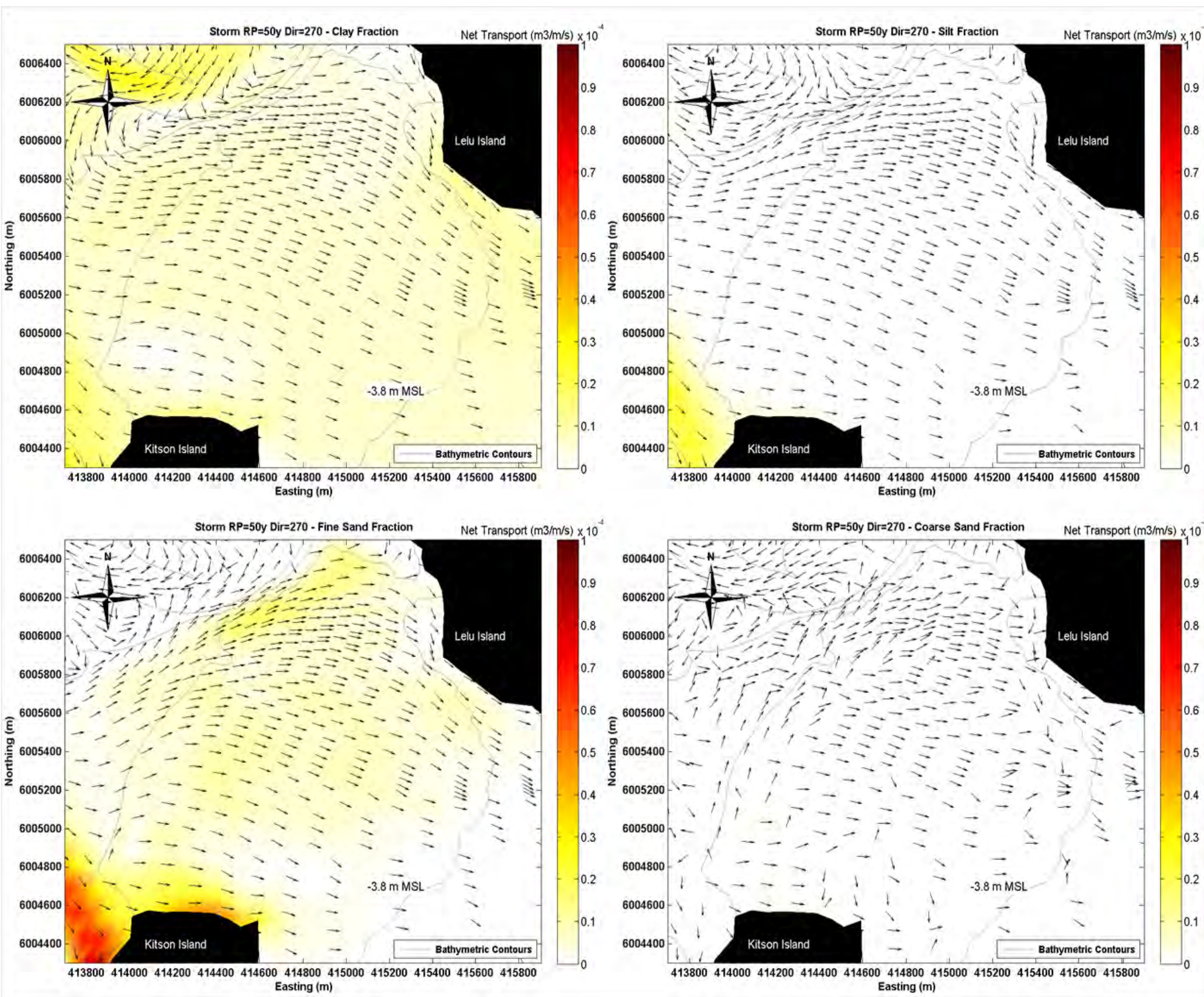


Figure 5-7: Net total transport flux during 11 day simulation for clay (top left), silt (top right), fine sand (bottom left) and coarse sand (bottom right).

Figure 5-8 shows the morphological changes predicted around Flora Bank following the 50-year storm from 270° True North. Bed changes where deposition occurs are shown in blue and areas where erosion occurs are shown in red. Morphological changes greater than 0.25 m were only predicted at the western edge of Agnew Bank, where the larger incident waves are breaking, dissipating energy and transporting sediments.

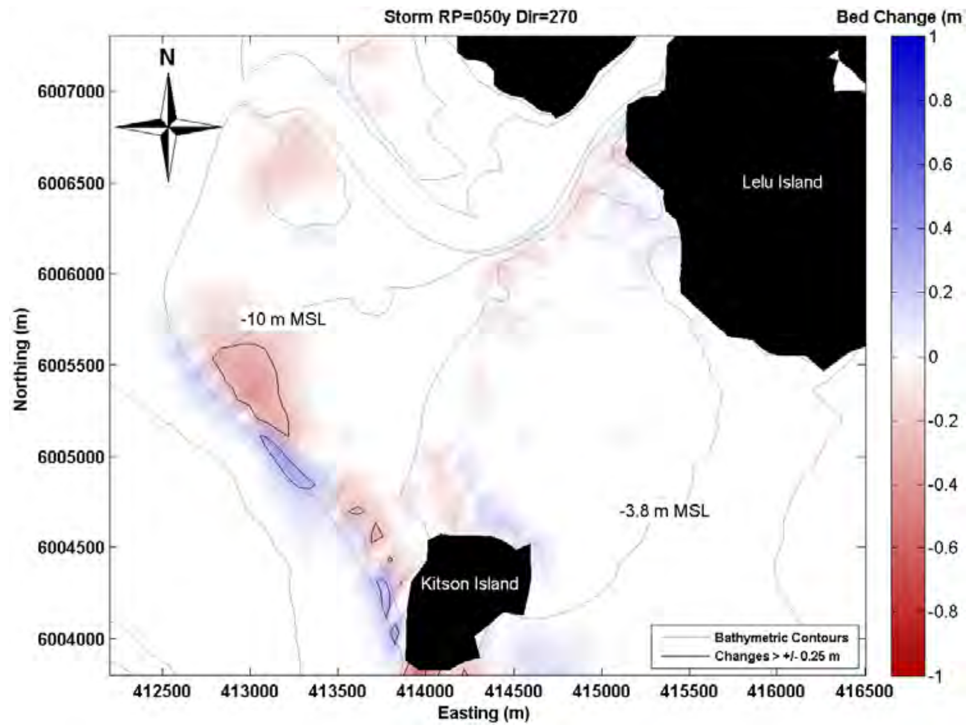


Figure 5-8: Morphological changes during 50-year storm from 270° True North.

Modelling results for a more common (5-year return period) storm from the same direction are also shown for comparison (see Figure 5-9). The probability of occurrence of a 5-year storm during the lifetime of the marine structures is 100%, thus the 5-year storm is an event of importance for the analyses of morphology changes. The results for the 5-year storm indicate that bed elevation changes during this event are negligible in most areas of Flora Bank, and in all areas less than 5-10 cm, and concentrated at the far north and south ends of Flora Bank where bathymetry gradients are larger (steeper slopes). Patterns of bed elevation change during the 5-year storm are similar to, but smaller in magnitude than, those predicted following the 50-year storm.

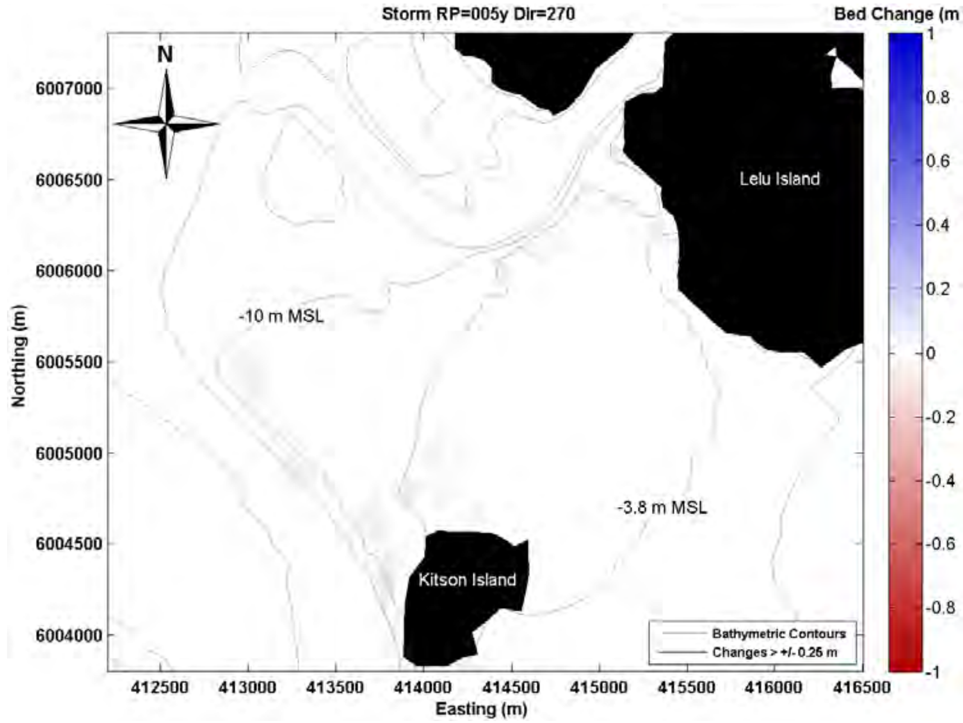


Figure 5-9: Morphological changes during 5-year storm from 270° True North

In order to better demonstrate how changes occur during a storm and why, Figure 5-10 further evaluates the magnitude of the bed elevation changes on Flora Bank during the 50-year storm from 270° True North. Figure 5-10 (bottom) shows the bathymetry of the project area in MSL and the locations of interest. The location of these points were selected because change in morphology was observed at these locations and they are near the proposed positions of the SW Anchor Block and SW Tower. Figure 5-10 (top) shows time histories for water level, significant wave height, and bed elevation. The significant wave height shown was extracted at the location of the PNW Buoy just offshore of Agnew Bank. The changes in bed elevation are shown for the four locations of interest, two of which experience erosion (A and C) and the other two of which experience deposition (B and D).

The changes occur at all locations of interest only during periods where the significant wave height exceeds approximately 2-3 m at the PNW Buoy. No significant erosion or deposition occurs before those wave conditions are exceeded, i.e. no changes occur during time periods dominated by tidal currents. After the peak of the storm when the significant wave height drops, no further bed elevation changes are predicted.

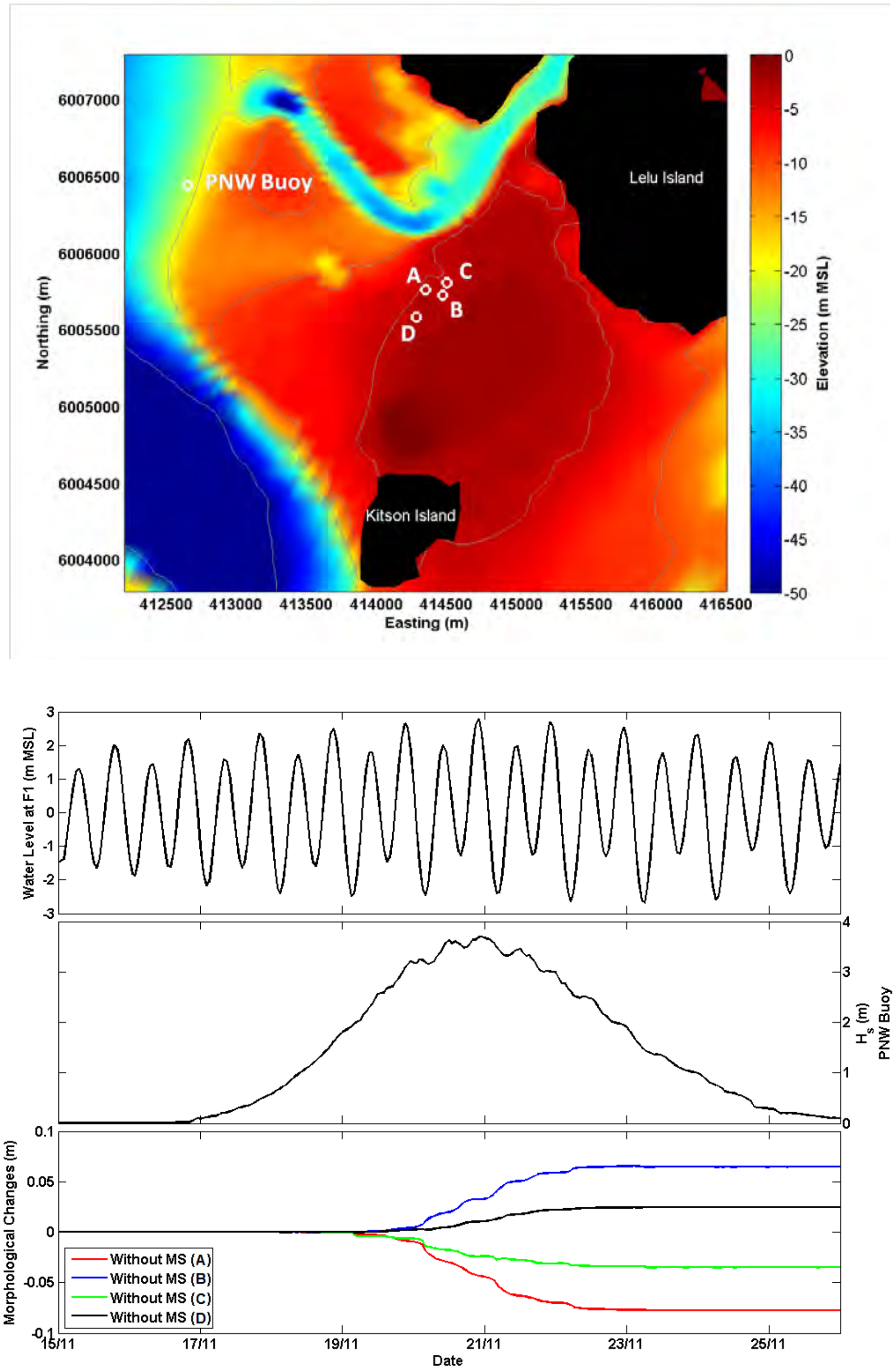


Figure 5-10: Time history of bed changes during 270° 50-year storm simulation at two locations in Flora Bank experiencing erosion (A and C) and deposition (B and D), and area map showing selected locations where the time histories were extracted (top).

5.1.2 Sediment Size Sensitivity Testing

Results presented in Sections 5.1.1, 5.2, and 5.3 incorporated the four original grain sizes as described in the May 5 report (Hatch 2015), Section 4.1.4 and Appendix B. As noted in Section 4.1.4, the original Delft3D regional modelling simulations and longer-term simulations utilized a 4-class sediment grain size distribution in the modelling domain that was intended to evaluate the transport and fate of clay, silt, sand and coarse materials. Those four grain sizes (cohesive, 0.1, 0.14, 2 mm) were mapped to the modelling domain in an approximate manner using the mean sizes from SedTrend Analysis data (SedTrend, 2015a). In August 2015, SedTrend notified the project team that the previously supplied sediment grain size data were in error, and that in fact the sediments were slightly finer overall (SedTrend, 2015b). In order to evaluate the impact of this previous erroneous data on the results of the modelling, additional short-term simulations were performed in August 2015 to evaluate the relative importance of the assumed grain size distribution on the predicted morphology of Flora Bank (as described in Section 5), and on the potential impacts of the marine structures.

The new sediment grain size distribution was developed with a closer focus on the material found on Flora Bank, typically ranging from 0.1 mm to 0.5 mm. Six (6) classes of sediments were created in the Delft3D model (0.1, 0.125, 0.177, 0.25, 0.35, and 0.5 mm). Any finer sediments were lumped into the 0.1 mm fraction, and coarser material was lumped into the 0.5 mm fraction.

Figure 5-11 shows bed elevation changes following the 50-year storm from 270^{o} True North for original sediments (top) and for the new 6-fraction sediment size distribution (all sands, bottom). The bed elevation changes predicted for each of the simulations with different grain size distributions are similar. The changes are similar because the majority of the changes on Flora Bank in the original sediments simulation were for the fine sand (0.14 mm) fraction, and typically a significant portion of the new 6-fraction simulation is also made up of similar size sands. Results indicate that the bed changes predicted on Flora Bank during these types of storm events are not very sensitive (within a range of sand sizes) to the detailed distribution of grain sizes used in the modelling. Sediment grain size sensitivity testing is continued further during evaluation of the potential impacts of the marine structures in Section 6.

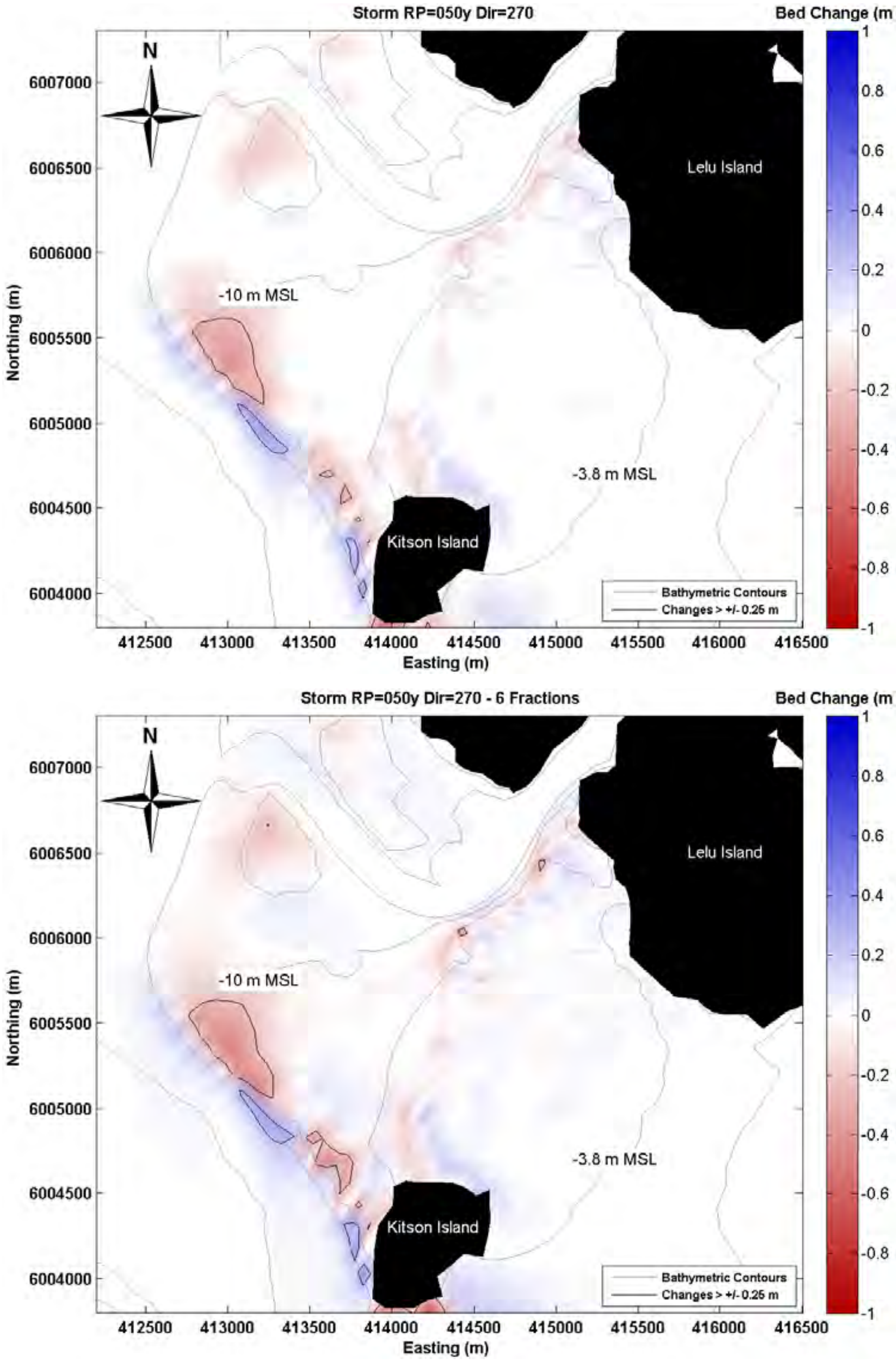


Figure 5-11: Morphological changes predicted during 50-year storm from 270^{o} True North for original sediment distribution (top) and new 6-fraction sediment distribution (bottom)

5.1.3 Storm Conditions Summary

In addition to the 270^{o} storm results shown above, analysis was completed for a complete range of storm directions and return periods (total of 20 storms). The results of these storms are provided in Appendix H. These storm simulations demonstrate that changes in morphology are episodic. For change to occur the sediment transport thresholds for the sands on Flora Bank must be reached. The simulations also demonstrate that the changes in morphology stabilize once the peak of the storm has passed and the hydrodynamic conditions are below the sediment transport thresholds for the material found on Flora Bank.

5.2 Freshet Simulations

Delft3D simulations during a 28 day period with mild winds and waves and high Skeena River flows (freshet) were also performed to evaluate changes during more typical conditions, and during periods with high river flows.

5.2.1 28 day Freshet Simulation

The freshet simulation is based on data representing the time period between May 11, 2014 to June 8, 2014, with peak Skeena River discharge of 5150 m^3/s. Figure 5-12, Figure 5-13, and Figure 5-14 show the significant wave heights, currents, and total transport flux snapshots, respectively, at the time of peak flood current (top) and peak ebb current (bottom), near the peak of the freshet. The insets depict the tidal stage and water level for each snapshot. The wave conditions are mild, less than 0.5 m and approaching the project area from the northwest during both the flood and the ebb tides. The currents are typically up to 0.3 m/s in the vicinity of the marine structures, and slightly larger during short periods of higher wind and wave activity. The highest levels of total sediment transport in the project area occurs in the Porpoise and Inverness channels (driven by high currents) and not on Flora Bank, where total transport is low.

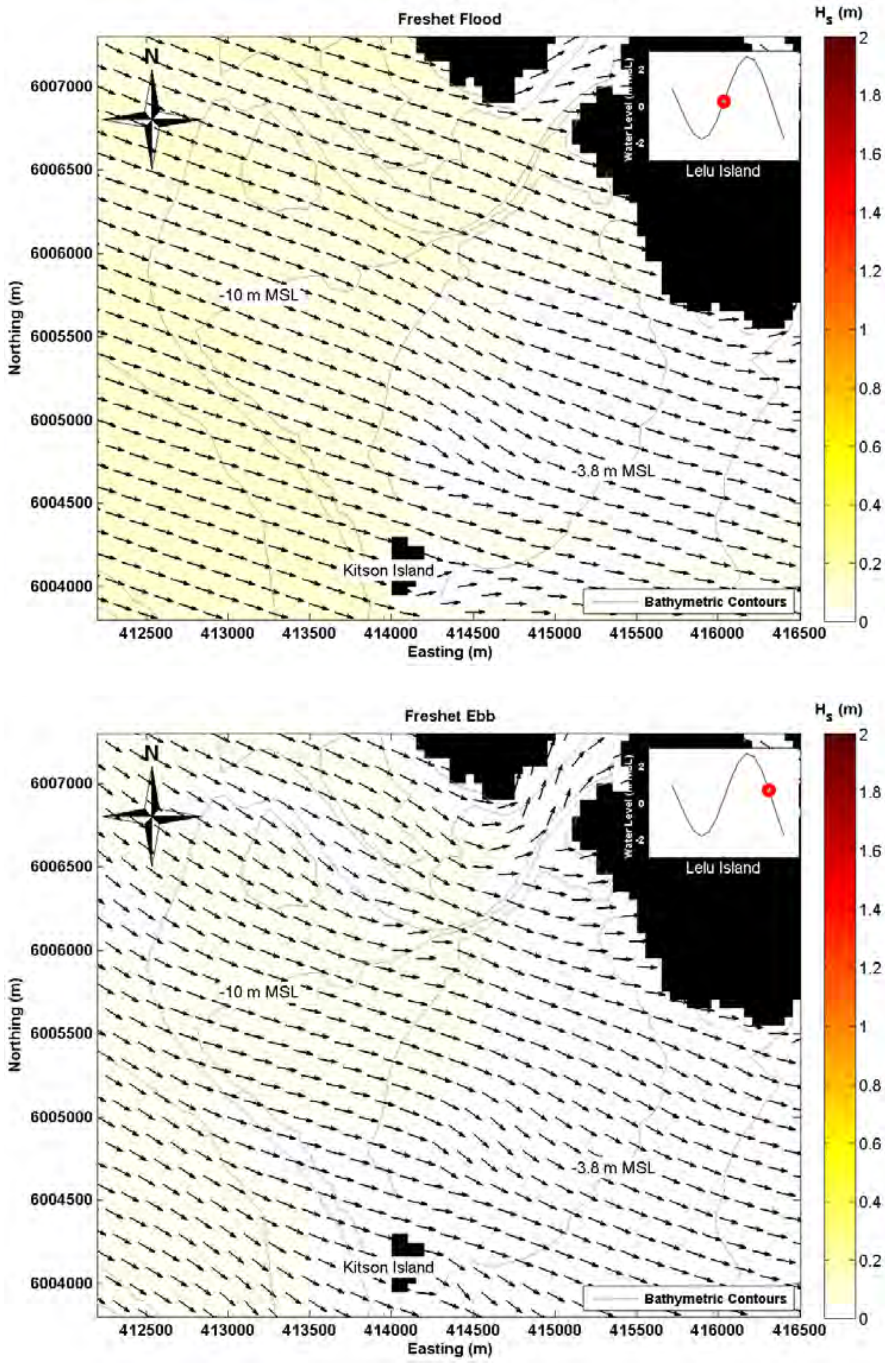


Figure 5-12: Significant wave heights at the peak flood (top) and peak ebb current (bottom), near the peak of the freshet (maximum Skeena River discharge). Inset shows the water levels when the snapshots were taken. *Note: vectors indicate mean wave direction.*

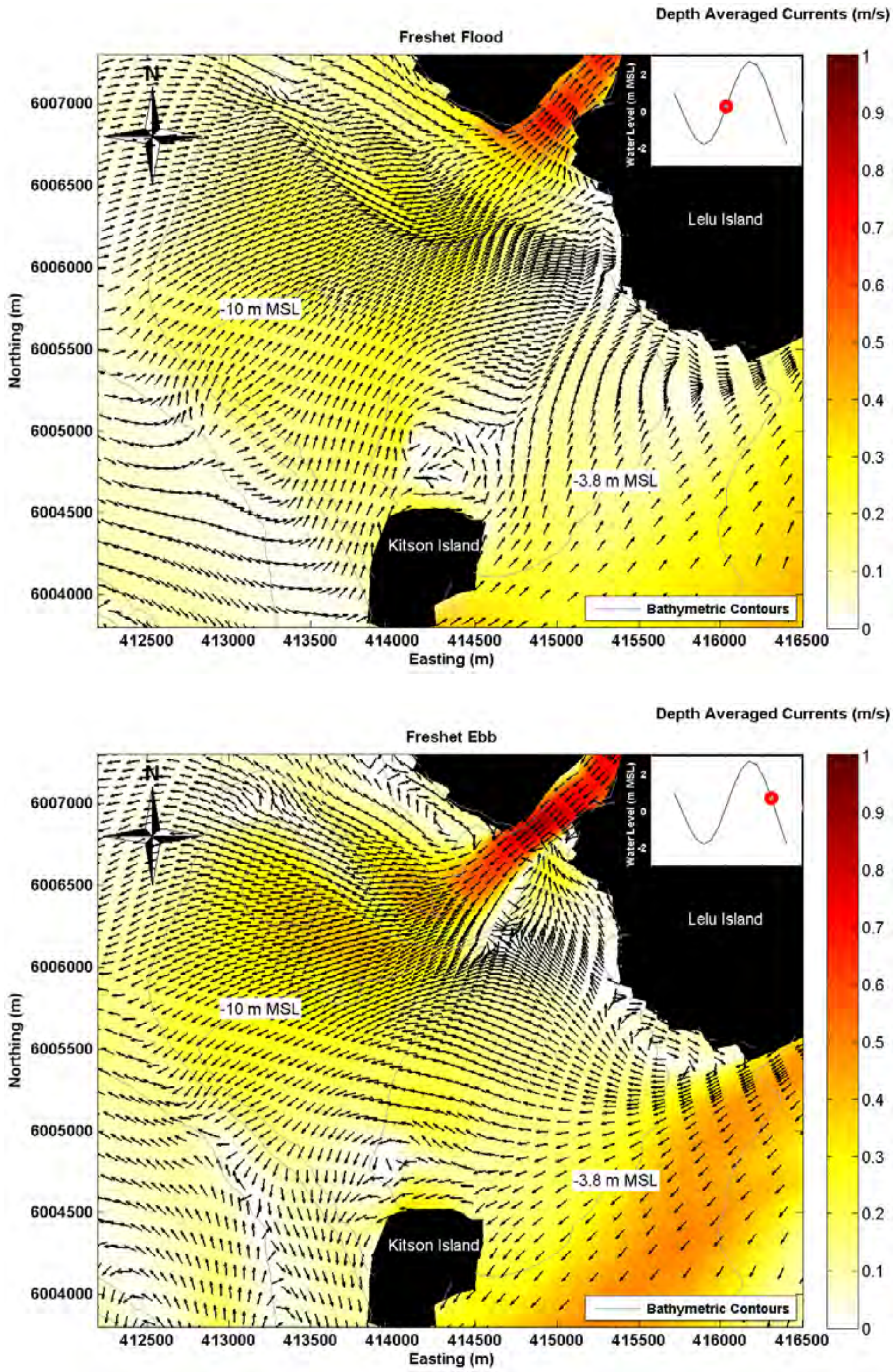


Figure 5-13: Current snapshots at time of peak flood current (top) and peak ebb current (bottom), near the peak of the freshet (maximum Skeena River discharge). Inset shows the water levels when the snapshots were taken. Note: vectors indicate current direction.

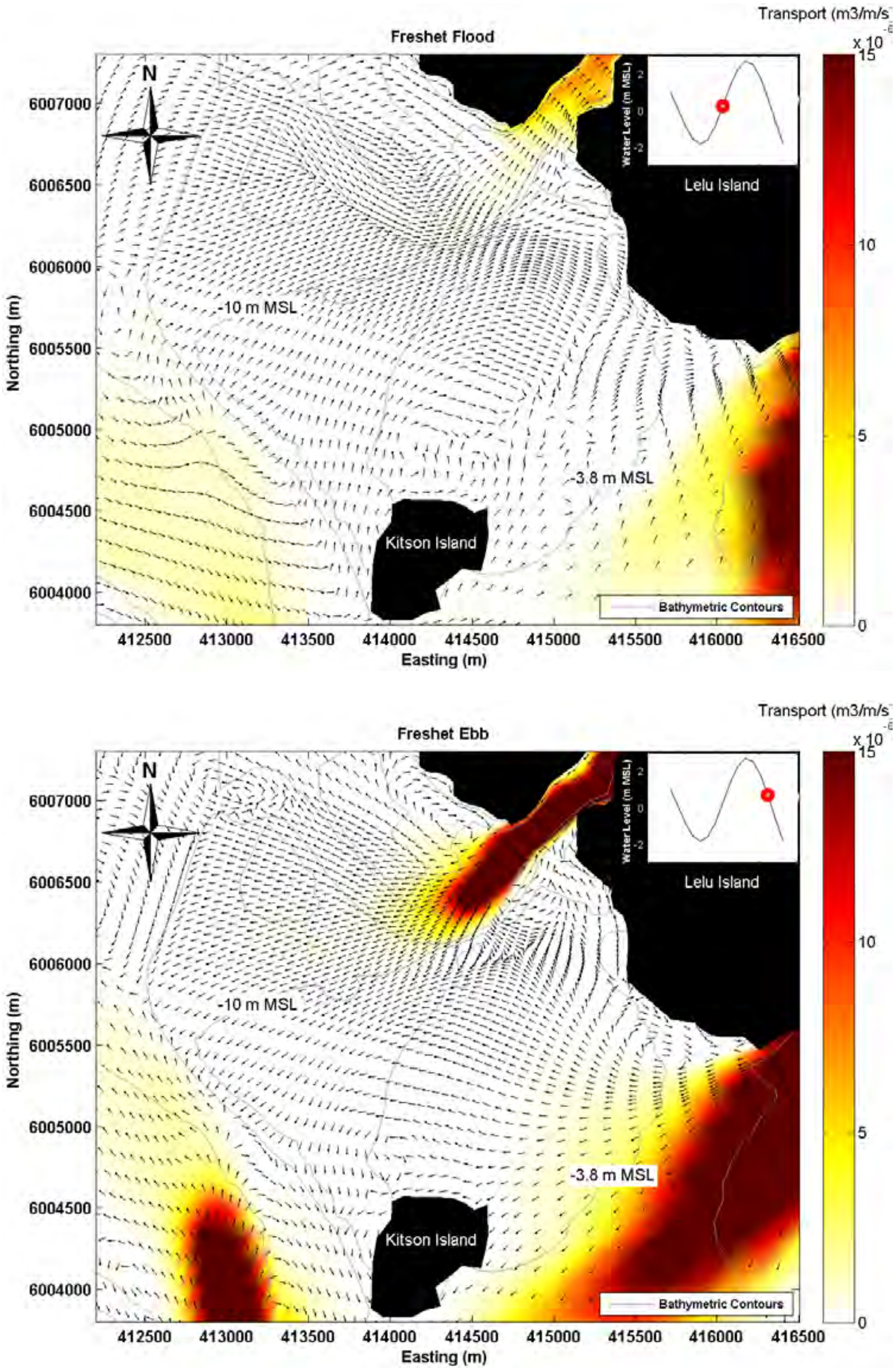


Figure 5-14: Total transport flux snapshots at time of peak flood current (top) and peak ebb current (bottom), near the peak of the freshet (maximum Skeena River discharge). Inset shows the water levels when the snapshots were taken. Note: vectors indicate sediment transport direction.

Figure 5-15 shows the net total transport flux computed during the 28 day freshet simulation. The transport during ebb tides is slightly higher than during flood tides, resulting in a small net transport towards the west of Flora Bank which follows the ebb currents. These patterns of net transport are consistent with the site photo displayed in Figure 3-7, which is taken on the west side of Flora Bank, and also indicate net westerly transport in this area over Flora Bank. In general the net transport is fairly uniform over Flora Bank.

Figure 5-15 also shows an approximately 1700 m long transect (dashed line) across which total net total transport flux was computed. Analysis indicates that during the 28 day freshet simulation, a total flux of approximately 3 m^3 of sediment per hour flowed normal to the transect, westward across Flora Bank.

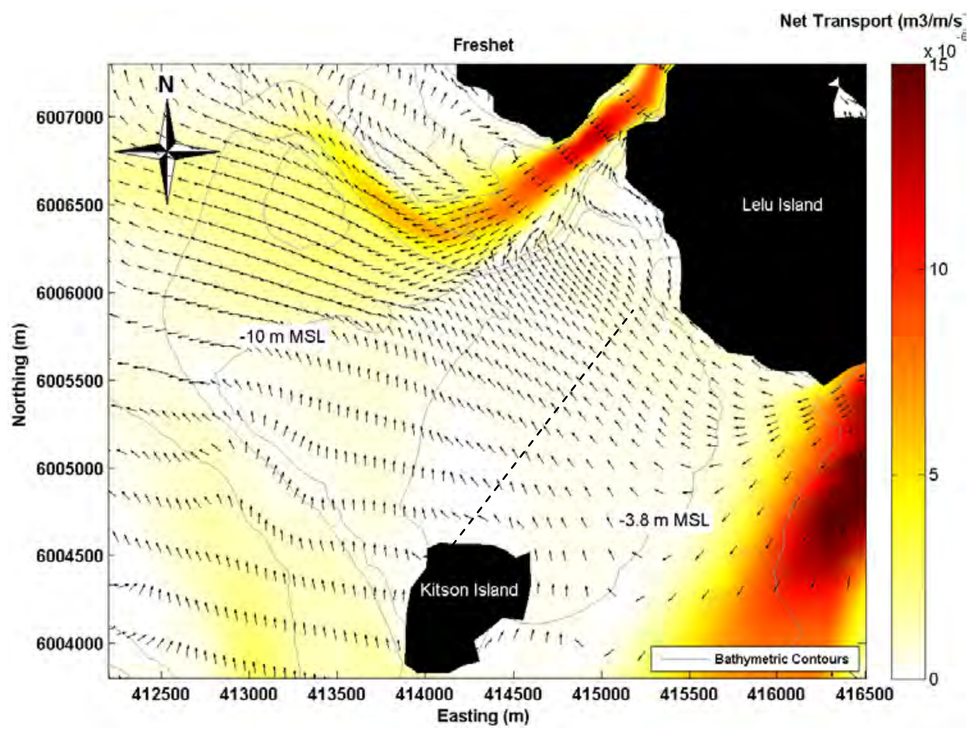


Figure 5-15: Net total transport flux from 28 day freshet simulation

Figure 5-15 shows the same net transport results but with a tighter colour scale which better demonstrates variations in transport flux surrounding and over Flora Bank. Transport fluxes are stronger on the northern half of Flora Bank during the freshet simulation period, and smaller in the area north of Kitson Island which is shallower and has slightly larger sediment sizes in general.

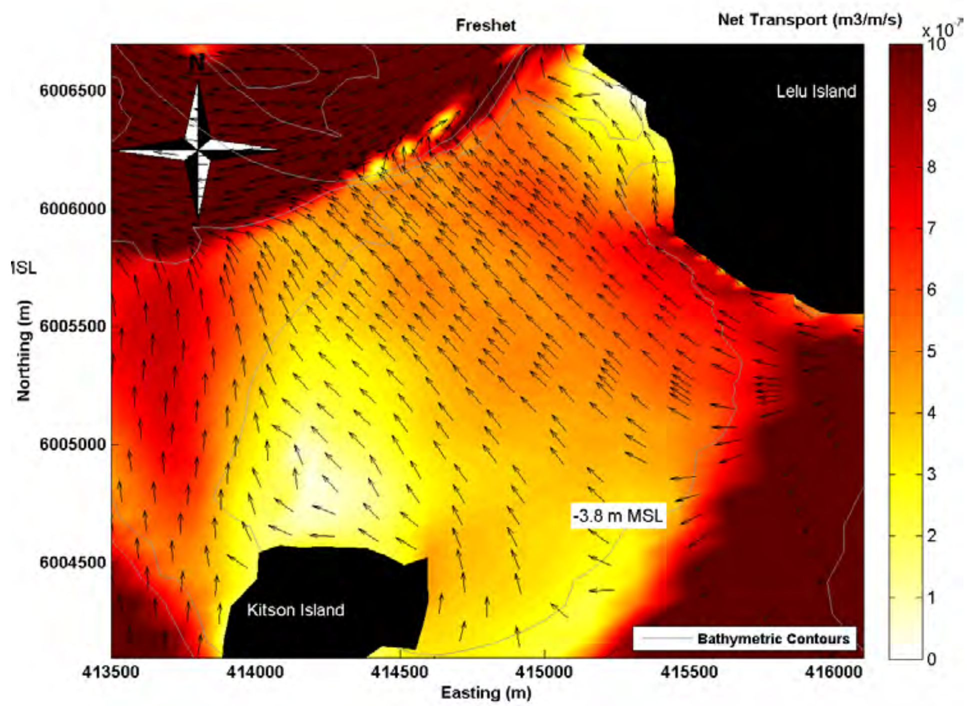


Figure 5-16: Net total transport flux from 28 day freshet simulation. Close up view from Figure 5-15. Note that the colour scale has been changed to 10^{-7}

Figure 5-17 displays a side by side comparison of the net sediment transport predicted by the Delft3D model during the 28 day freshet simulation with typical current and wave conditions and the transport behaviour predicted by the SedTrend Analysis (SedTrend, 2015). The comparison shows that both analyses depict similar trends in sediment transport around Flora Bank. SedTrend Analysis could establish no sediment transport trends over the majority of Flora Bank, generally indicating low levels of transport and static bed elevations. The Delft3D modelling results agree, and indicate very low transport overall and very little net transport.

Stronger net transport exiting Inverness and Porpoise channels predicted by Delft3D is consistent with the net erosion and transport directions determined by the SedTrend Analysis. Both tools also show net erosion behaviour in the deepwater channel connected to Porpoise Channel and offshore of Ridley island. Also, in areas where the SedTrend Analysis predicts dynamic equilibrium (Agnew Bank), the Delft3D model predicts relative low net transport using results from the freshet simulation. Net transport during storm events shows westerly transport on Agnew Bank (see Figure 5-6), and storms likely influence the trends in SedTrend results in this deeper area. Although the Delft3D simulation was relatively short and did not include storm conditions, the net transport patterns from SedTrend Analysis and Delft3D are generally consistent.

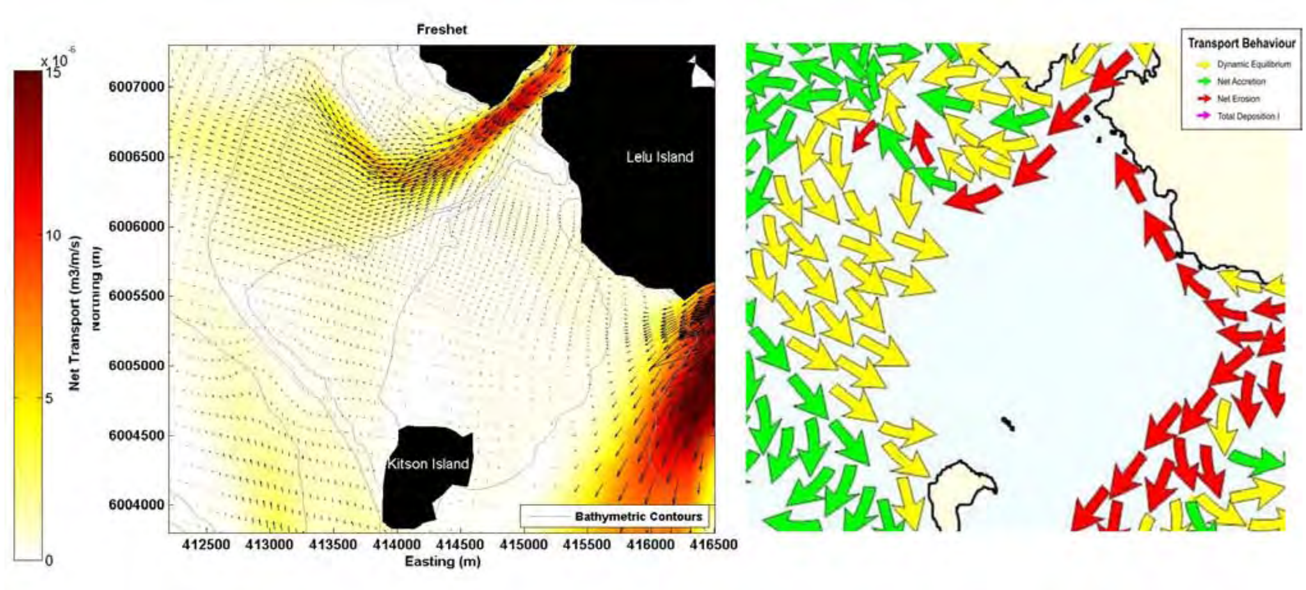


Figure 5-17: Net Sediment Transport Predicted by Delft3D Model (left) and by SedTrend Analysis (right, taken from SedTrend, 2015)

Figure 5-18 shows the bed elevation changes around Flora Bank during the 28 day freshet simulation. Results indicate that during the 28 day freshet simulation, transport and bed changes are extremely low due to relatively mild winds and waves. The net transport maps previously shown indicate low levels of transport during this period and relatively uniform patterns, resulting in small morphological changes on Flora Bank.

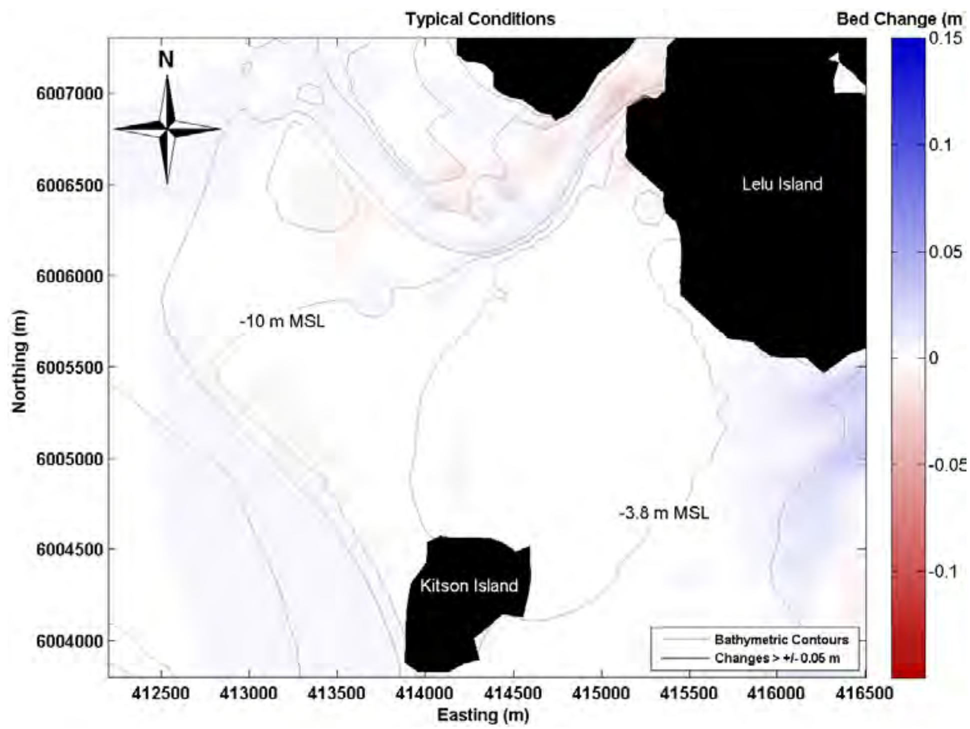


Figure 5-18: Morphological changes predicted during the 28 day freshet simulation

Total Suspended Solids (TSS) concentrations were also evaluated during the 28 day freshet simulation at two locations (points C and D) near the northwest edge of Flora Bank, at the SW Tower and SW Anchor Block. The location are shown in Figure 5-19 (top). Figure 5-19 (bottom) shows the time series of the water levels, depth averaged currents and the TSS concentrations at the two locations over the course of the simulation.

During the vast majority of the simulation, TSS levels are less than 5-10 mg/l. TSS levels are highly episodic, and rise and fall quickly in response to changing hydrodynamic conditions. The spikes generally occur as the water level drops near low tide, resulting in a stronger influence of waves in stirring up sediment in the water column. The largest spike shown roughly on May 22-23 time period was generated by higher winds, which resulted in larger waves, wave-induced currents and suspension of more sediment.

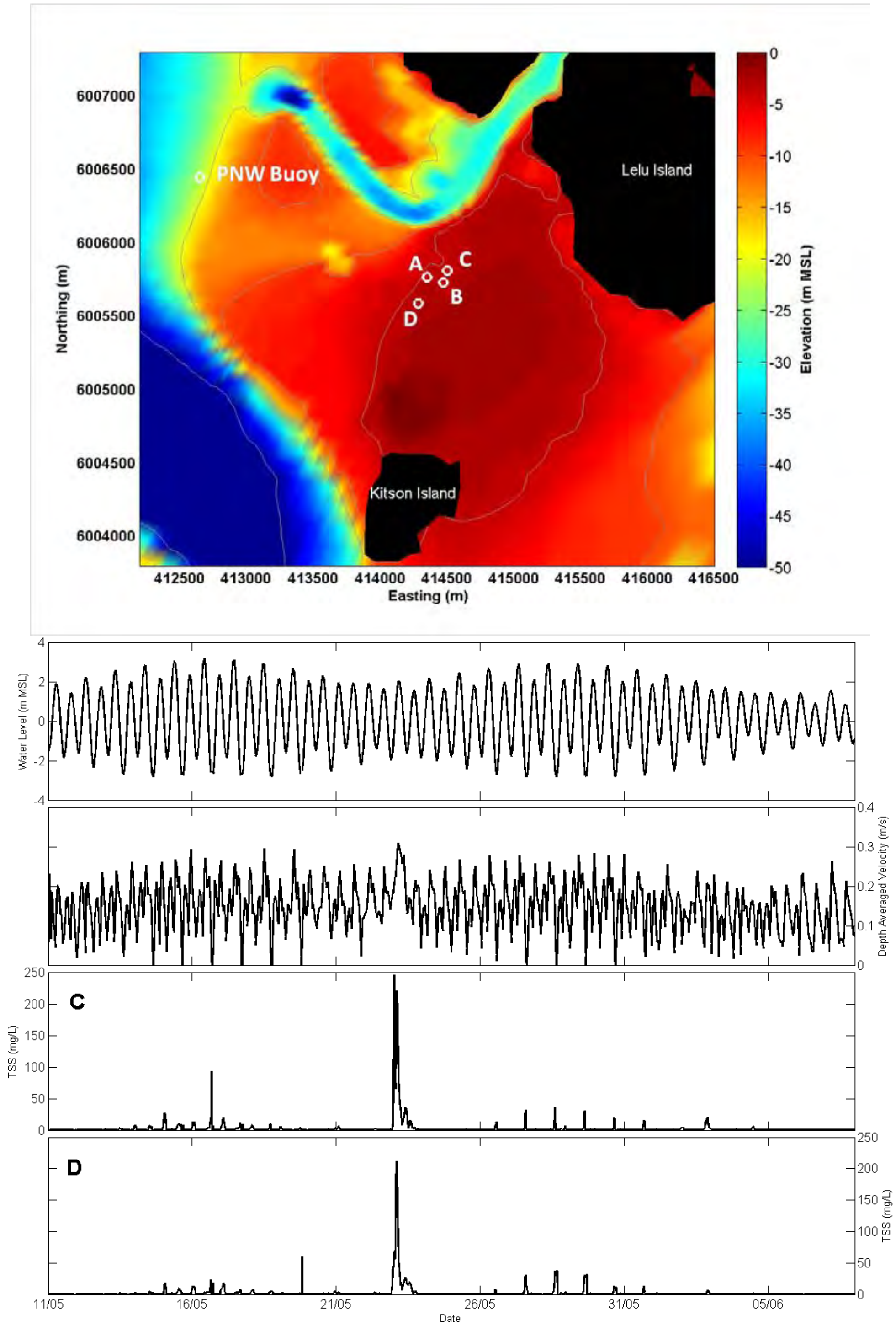


Figure 5-19: Time Series of TSS concentrations during the 28 day freshet simulation at two locations near the SW Anchor Block and SW Tower

5.2.2 *Skeena River Influence on Hydrodynamics at the Site*

Sensitivity testing simulations were performed to determine the level of influence that river discharge has on current speeds in the project area. The freshet simulation (May 11, 2014 to June 8, 2014) was repeated exactly in all respects except that all input flows in the Skeena River were removed. Figure 5-20 shows a time history of depth-averaged current velocity with and without Skeena River discharge at the location of the SW Tower, and the Skeena River discharge at Usk station. Results indicate that the river flows have a very small to negligible effect on depth-averaged current velocities at the project site.

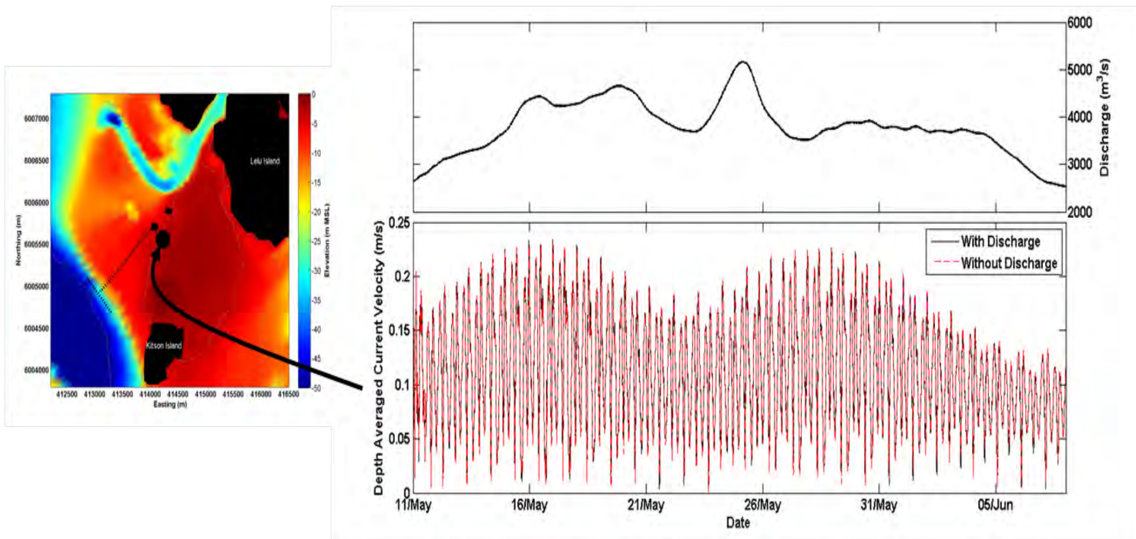


Figure 5-20: Time Series of depth average current velocities with and without Skeena River Discharge during the 28 day freshet simulation

A comparison between depth-averaged velocity with and without the Skeena discharge during the freshet peak (between May 21 and May 31) is presented in Figure 5-21 with a closer focus on the time of peak flows. The results were extracted from the same location presented in Figure 5-20. Results clearly indicate that the Skeena River flows do not significantly affect depth-averaged flows at the project site.

Safety • Quality • Sustainability • Innovation

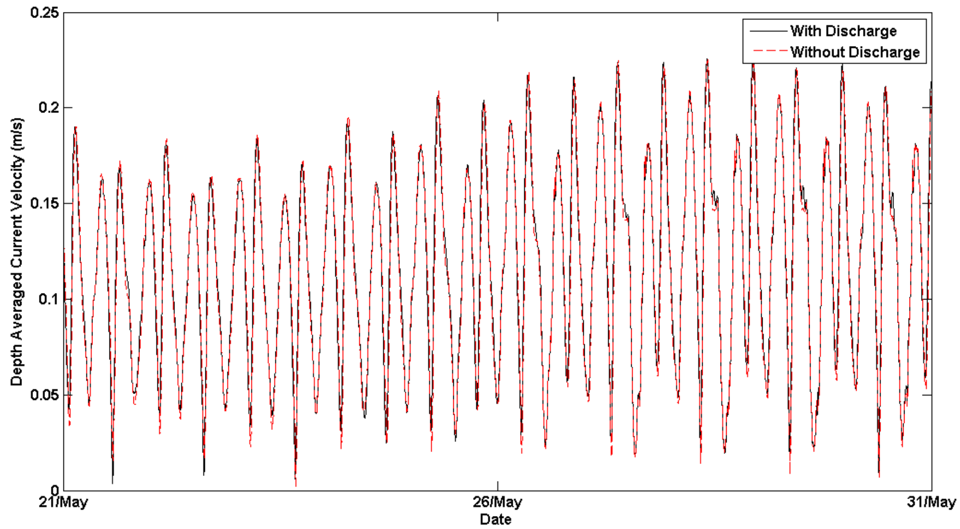


Figure 5-21: Time series of depth-averaged current velocities with and without Skeena River Discharge during the freshet peak (May 21st to May 31st)

Further discussion of the impact of the Skeena River on current velocity, salinity, vertical stratification, and setup within the Delft3D model is provided in Appendix E.

5.2.3 Freshet Summary

Evaluation of morphological changes occurring in the freshet simulations with those predicted during storm simulations confirms that the Skeena River does not appreciably influence transport patterns and has little to no influence on the morphology of Flora Bank. The freshet simulations also demonstrate that very little transport or morphological change occurs to Flora Bank during low-wave and typical current conditions. Comparison with the storm simulation results indicates that morphological changes on Flora Bank are driven during episodic periods of high wave conditions.

5.3 Longer-Term (Time Series) Simulations

5.3.1 Overview of Longer-Term Time Series Simulations

Longer-term “time series” simulations are regional Delft3D model runs that include input of continuous, historically-based conditions to simulate coastal processes. The purpose of performing time series simulations, as opposed to shorter-term storm simulations or seasonal effect (i.e. freshet) simulations, is to provide insight into coastal processes and potential effects of the marine structures that could result only as a consequence of the specific character and sequencing of continuous coastal forces that historically occurred. Conditions in the time series simulations consist of a complete range of tides and tidal currents, a complete range of wind and wave conditions (from calm periods up to annual-type storm events), and the complete range of Skeena River discharges, salinity and sediment loads.

Time series simulations were all performed without any morphological acceleration (MORFAC=1). The following longer-term time series simulations were performed:

- 3 month Time Series of Stormy Period with 1-hour Wave-Flow Coupling
- 4 month Time Series of Calmer Period with 3-hour Wave-Flow Coupling
- 1 year Time Series with 1-hour Wave-Flow Coupling
- 1 year Time Series with 3-hour Wave-Flow Coupling (September 2012 to September 2013)
- 1 year Time Series with 3-hour Wave-Flow Coupling (May 2013 to May 2014)
- 8 month Sensitivity Testing Time Series with No Waves

Figure 5-22 shows the time periods covered by each simulation.

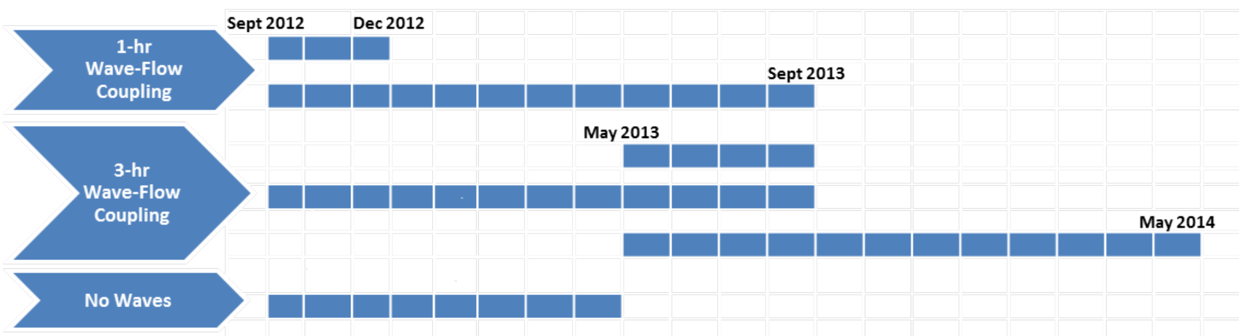


Figure 5-22: Overview of Longer-Term Time Series Simulations

The 3 month time series of the stormy period and the 4 month time series of the calmer period examine seasonal effects over a longer period of several months. The 1 year time series with 1-hour wave-flow coupling provides comprehensive modelling results over a long duration, modelling the most critical and active conditions throughout an annual period. These simulations are presented in the following sections.

The two 1 year time series simulations using 3-hour wave-flow coupling are presented in Appendix H and further demonstrate the coastal processes demonstrated in the 1 year time series modelling simulation. Finally, an 8-month time series simulation with no waves was also conducted as a sensitivity test to further understand the impact of tidal currents and river flows on the coastal processes around the project site.

5.3.2 *Input Data for Time Series Simulations*

Input data for the time series simulations are summarized below.

- Gridded winds, consisting of CFSR gridded winds with assimilation of 90-minute averaged local winds
- Offshore gridded waves from WW3 model simulations
- Tidal constituents
- Original 4-class sediment size distribution (cohesive, 0.1 mm, 0.14 mm, 2 mm)
- Skeena River freshwater discharge and sediment load

Model inputs are described in Appendix B, Appendix C, and Appendix D.

5.3.3 *Coastal Conditions in the Time Series Simulations*

As an example of the complete range of background hydrodynamic conditions that are simulated within these longer-term simulations, Figure 5-24 shows a time history of water depth and velocity at the west side of Flora Bank (location shown in Figure 5-23). Figure 5-25 shows an example time history of waves at the same location, taken from multiple longer-term simulations.

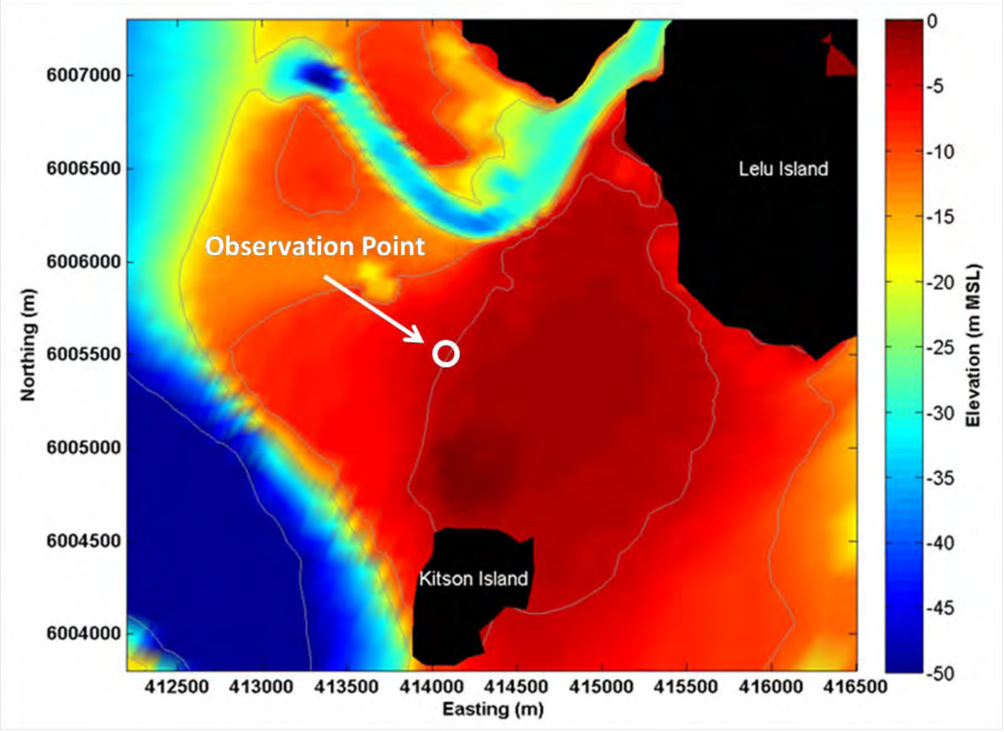


Figure 5-23: Location of water level, current, and wave time histories

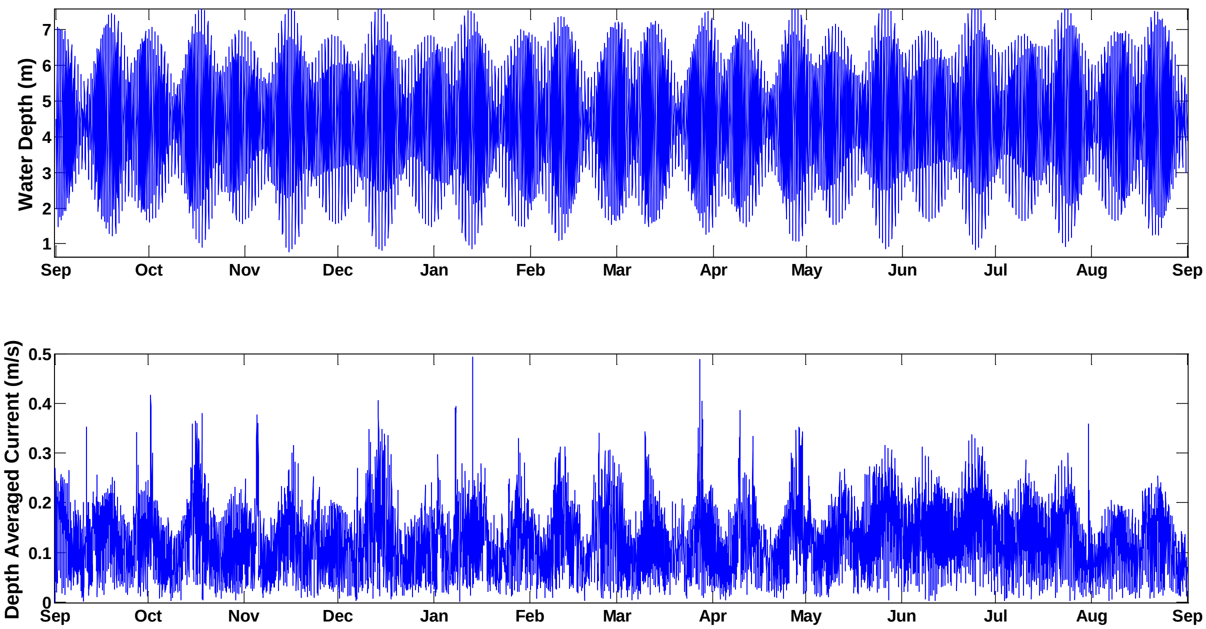


Figure 5-24: Time histories of water level and velocity at the location shown above (see Figure 5-23) during the 1 year time series simulation (September 2012 to September 2013)

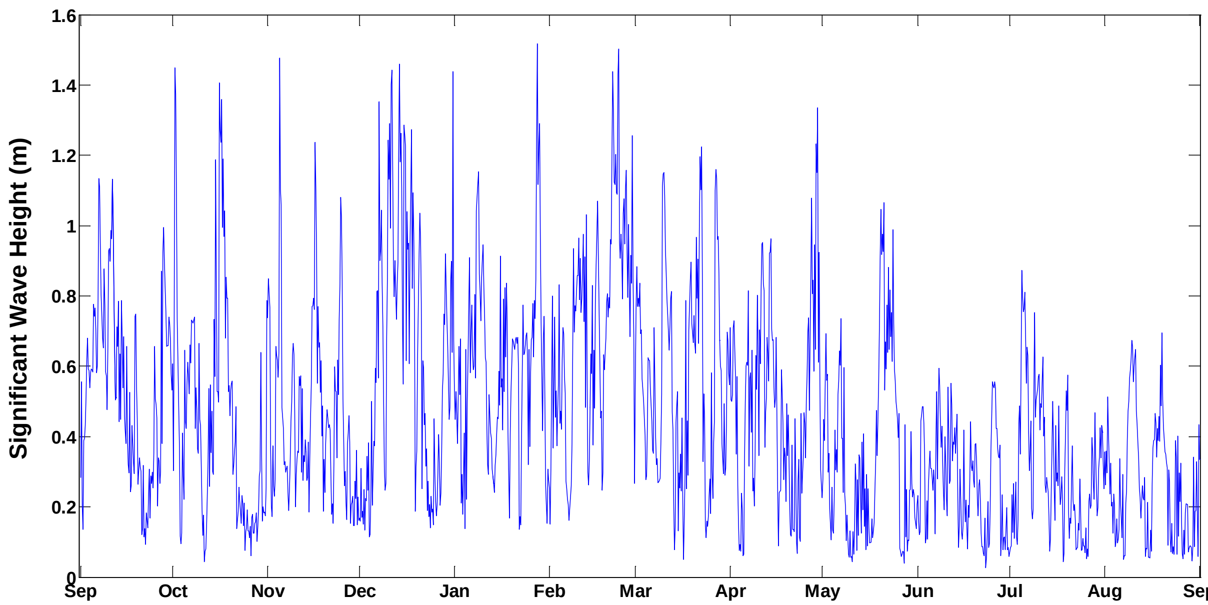


Figure 5-25: Time history of significant wave height at the location shown above (see Figure 5-23) during 1 year time series simulation (September 2012 to September 2013)

5.3.4 *Time Series Simulation Results*

5.3.4.1 *3 month Time Series of Stormy Period with 1-hour Wave-Flow Coupling*

This simulation consisted of a 3 month period beginning September 1, 2012, and included a complete range of coastal processes and stormy periods with high winds and waves, but naturally lower river flows since it did not include the freshet period. This simulation also included highly detailed (frequent) coupling between the wave and flow models (1-hour coupling).

Water depths and velocities were shown in Figure 5-24 for a location on the west side of Flora Bank, which is shown in Figure 5-23. Figure 5-25 shows the record of significant wave height predicted by the model for the same location during the entire simulation period and into 2013. Clearly the period modelled in the fall of 2012 is significantly more energetic than the summer-fall period of 2013.

Figure 5-26 shows that bed elevation changes over Flora Bank are small during the 3 month stormy period beginning September 1, 2012 which includes all coastal conditions and relatively strong wave activity as shown in Figure 5-25. Maximum bed elevation changes are approximately 25-30 cm, and are found near Kitson Island which is a relatively energetic location with stronger waves and currents, when compared with surrounding areas on Flora Bank and Agnew Bank.

The time series results make sense given the relatively low changes observed in the storm simulations, and lack of changes during periods with low wave activity. Results indicate that if enough of the smaller storms occur over long periods of time, some bed elevation changes should be expected.

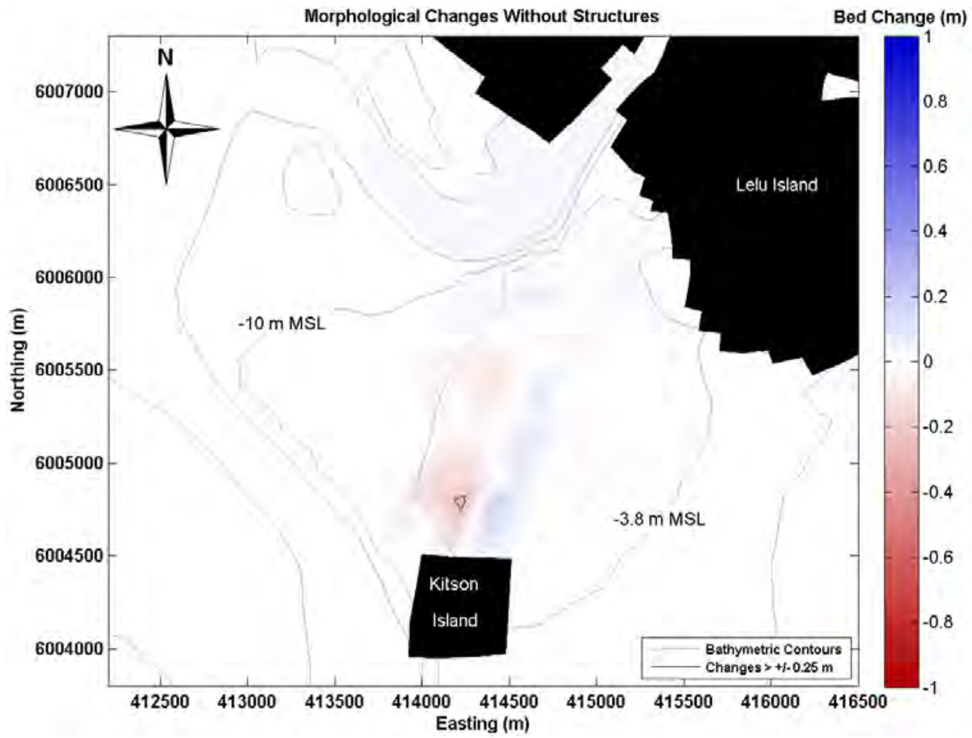


Figure 5-26 : Morphological changes predicted during 3 month time series simulation covering stormy period beginning September 1, 2012.

Bed change results were analyzed to determine the trends in erosion and deposition patterns, volumes, and net changes on Flora Bank over the 3 month period starting from September 1, 2012 and are presented in Table 5-1.

The values listed in Table 5-1 are based on the morphology results from the Delft3D model and computed using AutoCAD Civil3D 2014 (Civil3D). The Civil3D computation method is summarized in the following and explained in more detail in Appendix H.

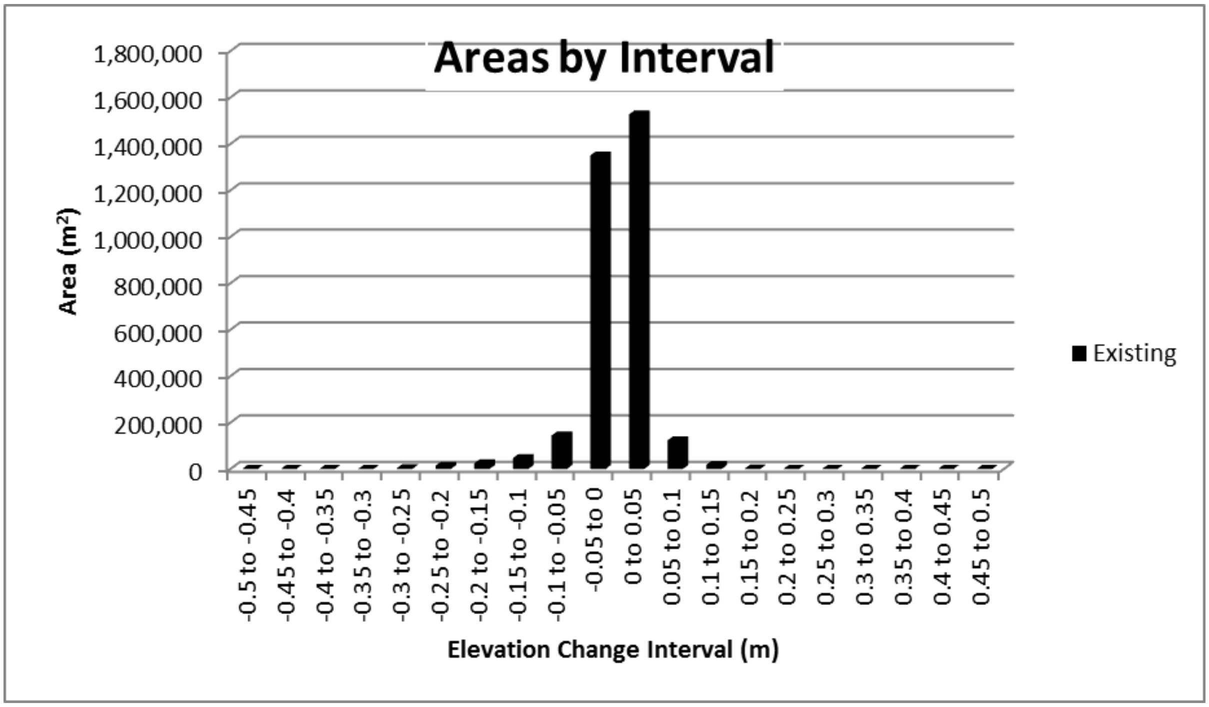
- The bathymetry data points at the start and end of the simulation period were extracted from the Delft3D model and used to create two 3D surfaces (initial and final bed elevations) in Civil3D.
- Each surface is a network of irregular triangular planes created between three adjacent data points (TIN surface). A volume was created between these two surfaces within the -3.8 m MSL contour line around Flora Bank. The volume was negative when the final surface was below the initial surface due to erosion while the volume was positive when the final surface was above the initial surface due to deposition. The areas over which these erosion and deposition volumes occurred were calculated as the footprint area (2D area), not the surface area (3D area) of this volume surface.

- The average elevation change was in turn calculated by dividing both the erosion and deposition volumes by the total footprint area of Flora Bank, 3,247,120 m^2. The net average elevation change is the sum of the average erosion-based elevation change, and average deposition-based elevation change.

Table 5-1: Morphologic Changes During 3 month Stormy Period

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
Sept	**Without**	-41,050	31,780	-9,270	230,430	141,710	-0.01	0.01	0.00

Figure 5-27 displays the seabed elevation change, for intervals of 5 cm, and the corresponding area (top) and volume (bottom). This figure demonstrate that the majority of the changes on Flora Bank have thicknesses between -0.05 m and 0.05 m. Changes greater than 0.2 m (erosion or deposition) are minimal. Additional quantitative results of the morphologic changes are included in Appendix H.



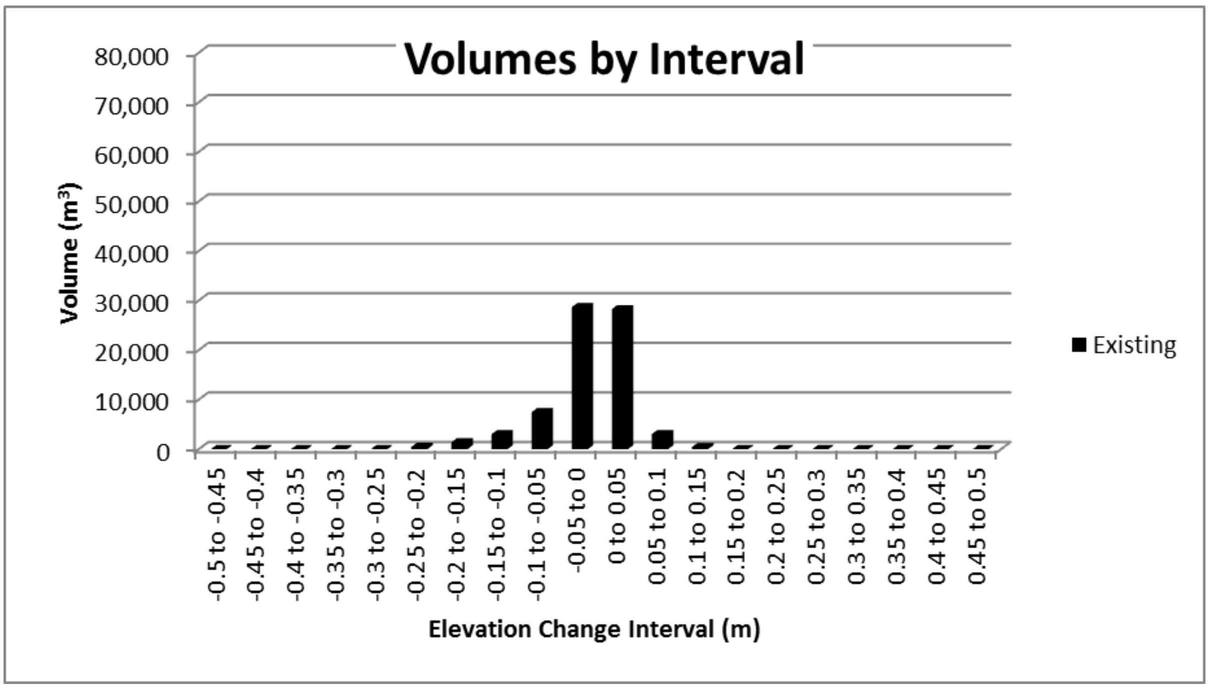


Figure 5-27: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 3 month stormy period simulation.

TSS concentrations during stormy periods are expected to be higher than during calm periods, since larger waves tend to increase the amount of suspended solids in the water column.

Four locations on Flora Bank near the proposed marine structures (Figure 5-28) were analyzed to determine when the existing TSS concentrations on Flora Bank are above 25 mg/l. Figure 5-29 shows water levels during a 3-month period and red dots indicating the moments when the TSS concentrations were above 25 mg/l at these four locations. Observation Point 1 is located in the deepest water (depth 3.8 m MSL) and has the fewest occurrences of TSS above 25 mg/L; Observation Point 4 is located in the shallowest water (1.1 m MSL) experiencing TSS levels above 25 mg/L more often.

TSS concentrations generally increase during low tides, when water is shallower over Flora Bank and the waves and tidal currents have the capability to generate higher suspended sediment concentrations. Analysis indicates that most times when 25 mg/L concentration was exceeded occur during low tide. The histograms in Figure 5-30 show how often the TSS concentrations are above 25 mg/l as a function of depth.

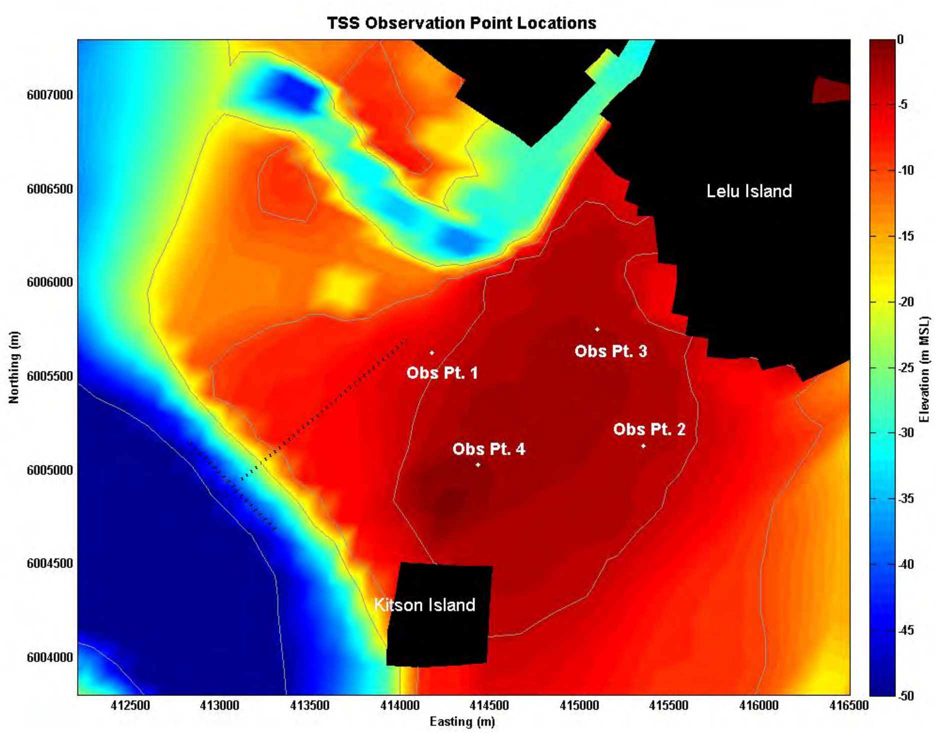


Figure 5-28: Locations of TSS observation points

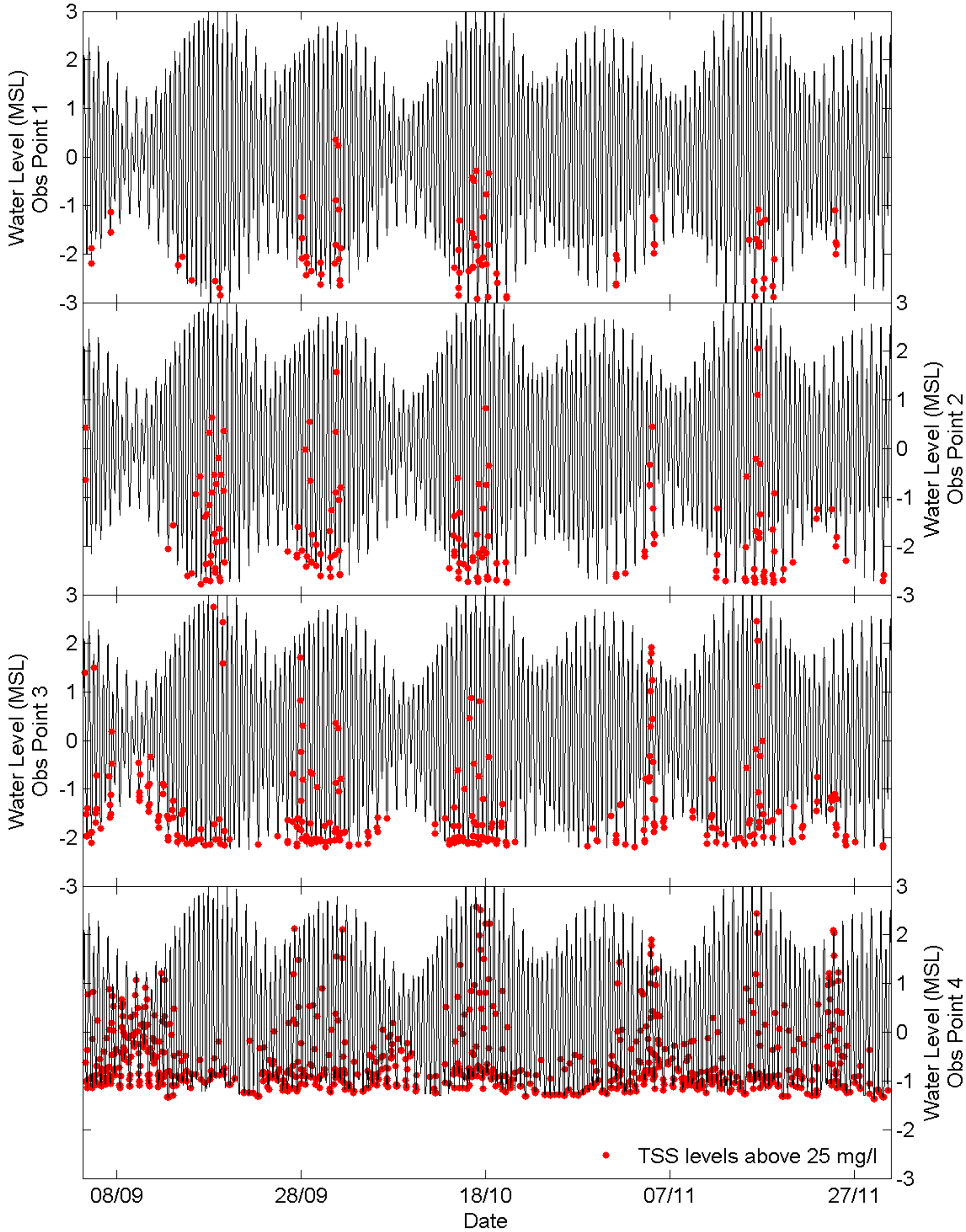


Figure 5-29: TSS concentrations above 25 mg/l at four locations on the project area.

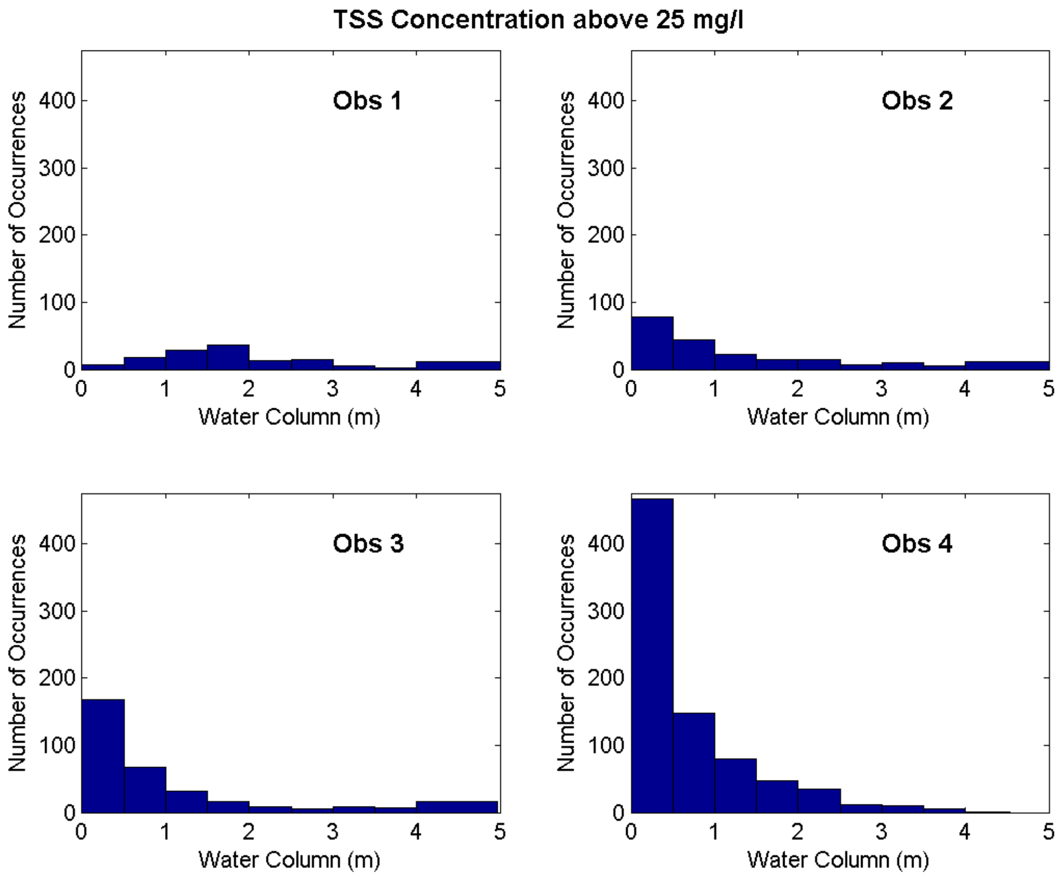


Figure 5-30: Comparison between the water column and number of occurrences of TSS concentrations above 25 mg/l.

5.3.4.2 4 month Time Series of Calmer Period with 3-hour Wave-Flow Coupling

This simulation was performed beginning May 1, 2013 and ending August 31, 2013 (4 months). This simulation included a complete range of coastal processes, with naturally less stormy periods and higher river flows, with less frequent coupling between the wave and flow models (3-hour coupling) for higher efficiency. Given the lower level of wave activity (see Figure 5-25), 3-hour coupling was assumed to have a limited effect on the modelling results. Water depths and velocities during this period are also shown for a location on the western edge of Flora Bank in Figure 5-23. As can be seen in the time histories, a complete range of tides and currents are included in the simulation, however lower wind and wave activity is naturally included since winds and offshore swell are lower in the summer months.

It should be noted that the bed elevation changes resulting from the 4 month summer simulation, while generally occurring in similar locations to those in the 4 month winter simulation that used the preferable 1-hour coupling, and having similar magnitudes, contain higher levels of numerical “noise” which occurs due to less frequent coupling of the wave and flow models during the wetting and drying process. This process is exacerbated by wave activity, and results in velocity spikes in very shallow water that tend to exaggerate the movement of sediment over short durations. Appendix H describes this process in greater detail. Due to the lower level of wave activity in the calmer period, the 3-hour coupling was assumed to have a limited effect on the modelling results and no filtering of numerical artifacts was applied.

Figure 5-31 shows bed elevation changes predicted by the end of the 4 month simulation from May 1, 2013 to August 31, 2013, using 3-hour coupling. The bed changes predicted are similar in nature to the 3-month stormy period results, with slight erosion on the southwest side of Flora Bank, and associated deposition of the eroded material just to the east, however to a lesser extent due to the lower level of wave activity. The bed changes shown here are less than approximately 5 cm over the majority of Flora Bank following this 4 month period. In the absence of storm events, the bed elevation changes over the vast majority of Flora Bank are not likely to be measurable.

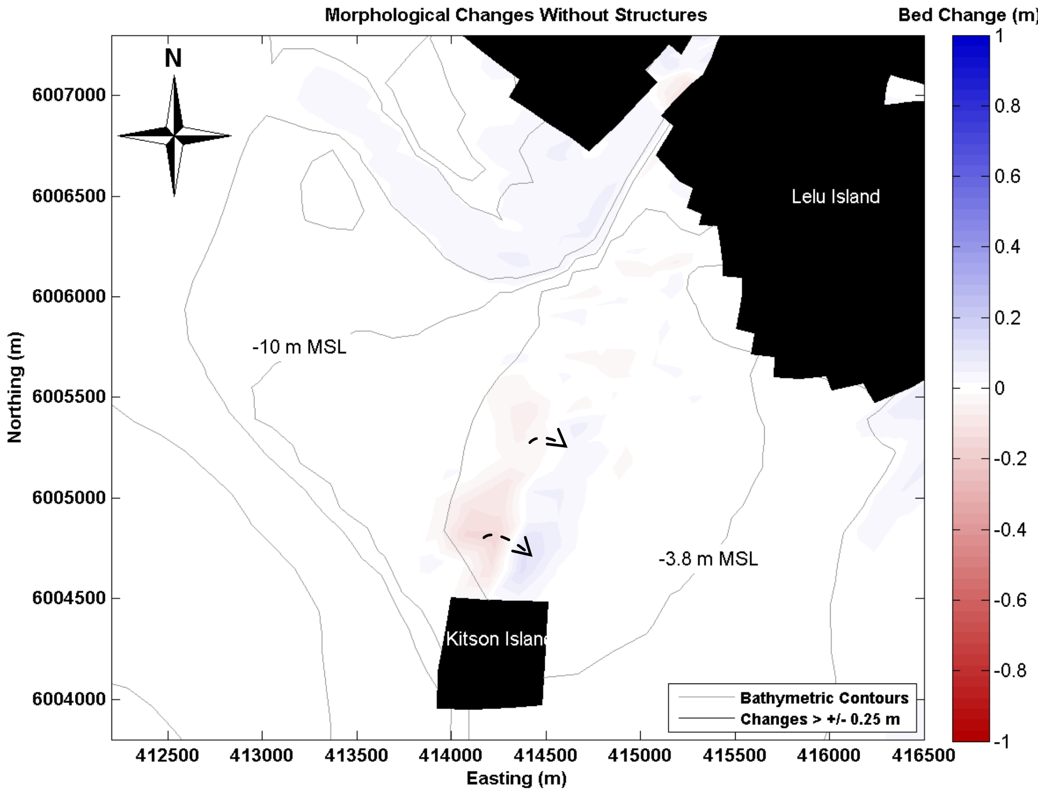


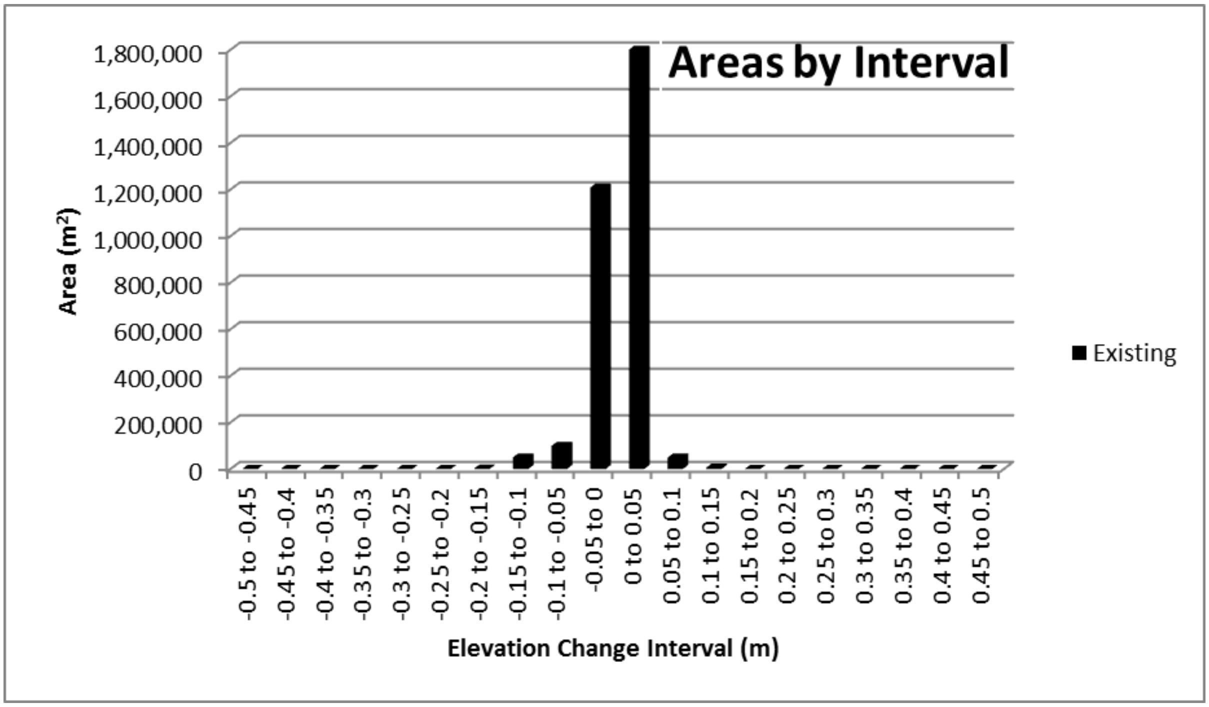
Figure 5-31: Morphological changes predicted during 4 month time series simulation beginning May 1, 2013, with 3-hour coupling. Note, dashed arrows are conceptual in nature to indicate the localized transport pathways.

Bed change results were analyzed to determine the trends in erosion and deposition patterns, volumes, and net changes on Flora Bank over the 4-month period starting from May 1, 2013 and are presented in Table 5-2.

Table 5-2: Morphologic Changes During 4 month Calmer Period

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
May	**Without**	-24,140	19,800	-4,340	149,850	53,710	-0.01	0.01	0.00

Figure 5-32 displays the seabed elevation changes at bed change intervals of 5 cm, and the corresponding area (top) and volume (bottom). This figure demonstrate that the majority of the changes on Flora Bank are between -0.05 m and 0.05 m. Additional quantitative results of the morphological change analysis are included in Appendix H.



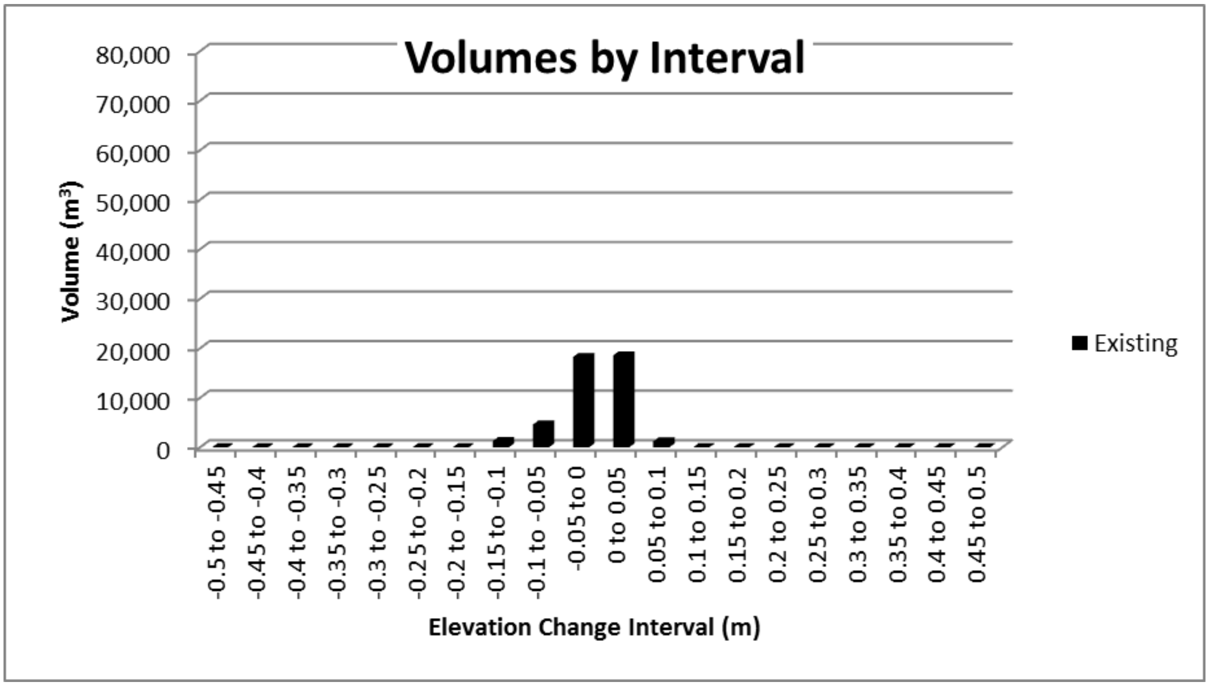


Figure 5-32: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 4 month calmer period simulation.

5.3.4.3 *1 year Time Series with 1-hour Wave-Flow Coupling*

This simulation was performed beginning September 1, 2012 for 1 year and included a complete range of coastal processes and stormy periods with high winds and waves, as well as the freshet period. This simulation also included highly detailed (frequent) coupling between the wave and flow models (1-hour coupling). Water depths and velocities were shown in Figure 5-24 for a location on the western edge of Flora Bank, which is shown in Figure 5-23. Figure 5-25 shows the record of significant wave height predicted by the model for the same location.

Figure 5-33 shows bed elevation changes over Flora Bank during the 1 year period beginning September 1, 2012 which includes all coastal conditions and relatively strong wave activity as shown in Figure 5-25. Maximum bed elevation changes of up to 55-60 cm are predicted near Kitson Island which is a relatively energetic location with stronger waves and currents. These results demonstrate that bed changes occurring over longer periods that include a complete range of coastal processes are consistent with the shorter-term simulations in terms of location of the erosion and deposition patterns over Flora Bank.

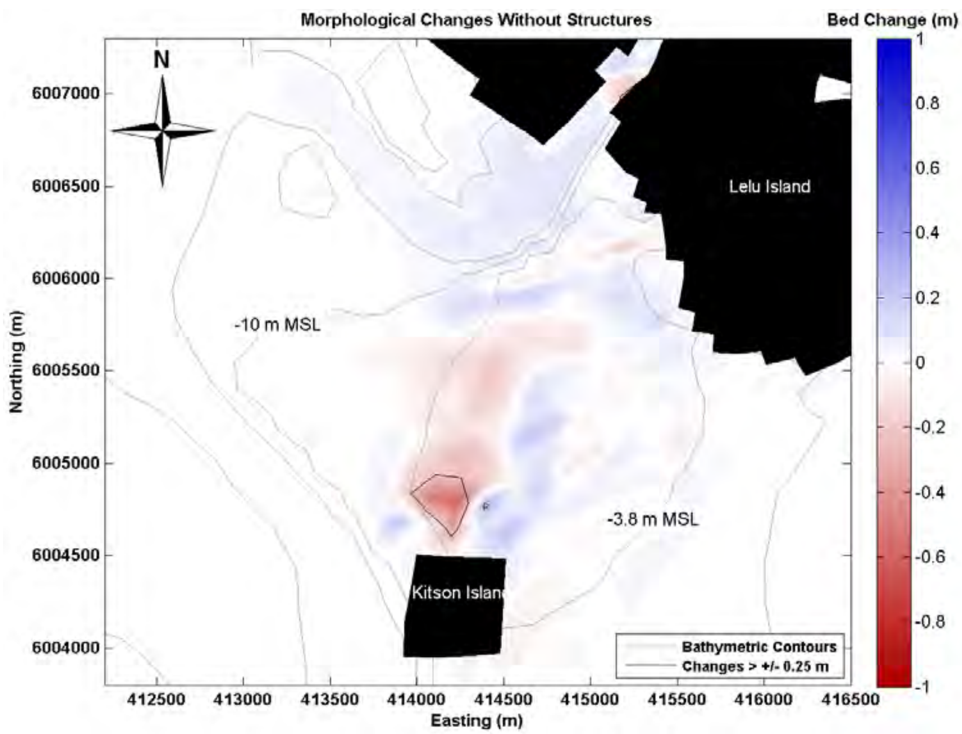


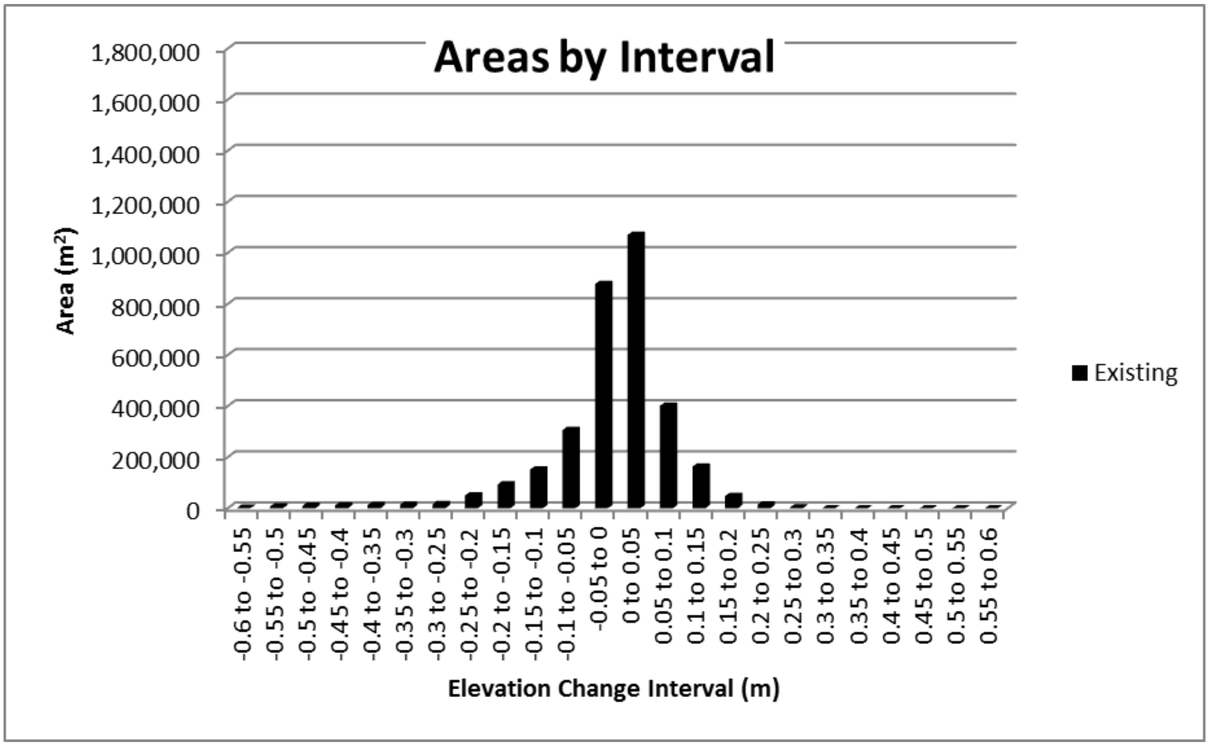
Figure 5-33 : Morphological changes predicted during 1 year time series simulation covering stormy period beginning September 1, 2012.

Bed change results were analyzed to determine the trends in erosion and deposition patterns, volumes, and net changes on Flora Bank over the 1 year period starting from September 1, 2012 and are presented in Table 5-3.

Table 5-3: Morphologic Changes During 1 year Period

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
Sept	**Without**	-112,590	83,840	-28,750	670,930	628,570	-0.03	0.03	0.00

Figure 5-34 shows the area (top) and volume (bottom) where changes occur, organized by bed change intervals of 0.05 m. The results demonstrate that the majority of the changes on Flora Bank are between -0.15 m and 0.15 m, with minimal changes greater than 0.25-0.35 m.



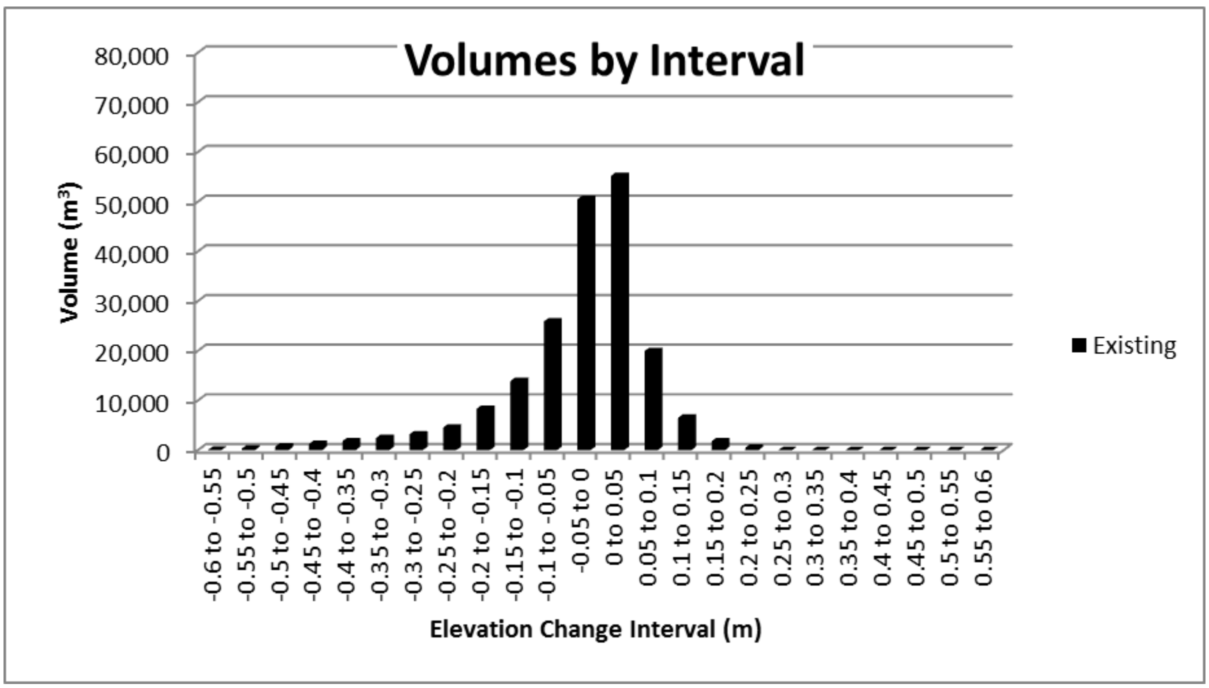


Figure 5-34: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 1 year simulation.

5.3.4.4 8-month Sensitivity Testing Time Series with No Waves

This simulation was performed beginning September 1, 2012 and ending April 30, 2013 (8 full months). This simulation included a complete range of tides, tidal currents and river flows and winds, but no waves in an effort to single out the effects of only flows on sediment transport and morphology. Figure 5-35 shows bed elevation changes predicted by the end of the 8-month simulation beginning September 1, 2012 that does NOT include waves. Overall, even over the entire 8-month period of time, erosion and deposition only occurs in measurable amounts within Porpoise Channel and Inverness Channel, where tidal currents are stronger. In the absence of waves, no measurable bed elevation changes are predicted over Flora Bank, even over this continuous 8-month period which includes complete tidal and river hydrodynamic effects. Note as well that Figure 5-26 uses a very fine color scale (±0.1m).

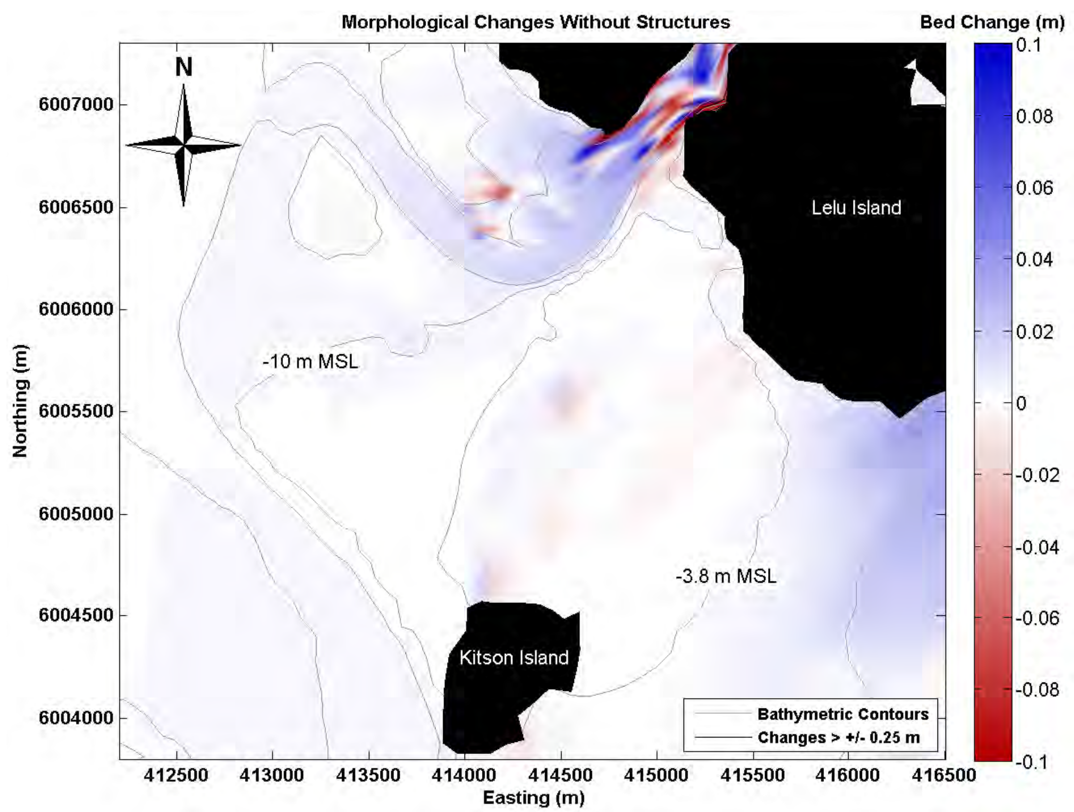


Figure 5-35: Morphological changes predicted during 8-month time series simulation beginning September 1, 2012 with NO waves. NOTE: ±0.1m color scale.

5.3.5 *Summary of Time Series Simulations*

A set of time series simulations covering a complete range of conditions from September 2012 to May 2014 were simulated. Simulations included a 1 year period using 1-hour wave-flow coupling, a closer look at the seasonal impacts over periods of several months, as well as two full-year simulations using 3-hour wave-flow coupling which are included in Appendix H.

Safety ● Quality ● Sustainability ● Innovation

The modeling results were all consistent in terms of the locations of predicted erosion and deposition, with slight erosion occurring on the southwest edge of Flora Bank in an area with steeper slopes, and deposition of that eroded material in areas just to the west, as waves dissipate energy moving eastward. The locations of erosion make sense in that they are steeper, and in reality have slightly larger sediment sizes than most of Flora Bank (>0.4 mm mean diameter), as well as rocky outcroppings visible in aerial and site photos but absent from the sediment data. The deposition locations also make sense, as waves and currents lose energy while moving over Flora Bank the material is deposited on the tidal flats.

The time series simulations confirm that in general, heavy wave activity is required for most of the erosion and deposition on Flora Bank to occur. Only very small changes occur over long time periods in the absence of waves. Even over entire winter periods, erosion and deposition on Flora Bank is expected within or near the accuracy of survey measurements, which is further evidence of the reported long-term stability of Flora Bank. Time series simulations were repeated for conditions with the marine structures, which generally introduce a slight attenuation of waves currents, and subsequent morphological changes. Time series simulations with the marine structures are presented in Section 6.1.4.

5.4 Summary of Existing Conditions Modelling Results

The Delft3D model provides a reasonable representation of tidal currents around the project area, and over Flora Bank, and wave conditions at the project site. The model slightly over-predicts current speeds, as described in Appendix F, which likely results in higher sediment mobility than in real life. Analysis results indicate that currents are relatively small for an area which has 6-7 m tidal ranges, therefore most of the time the sediment on Flora Bank is not mobile. Waves at the project site are significantly but gradually dissipated over the wide, shallow and flat area of Flora Bank. Even during extreme events, storm waves are gradually reduced to less than 0.5 m over the top of Flora Bank, which due to its flat slopes causes low spatial gradients in waves and currents, and hence small bed elevation changes. While field data and modelling results indicate that the Skeena River influences surface salinity and surface turbidity during short periods of the year, the river discharge itself does not significantly affect current velocities on Flora Bank the vast majority of the time.

Model results indicate that measurable erosion and deposition only occurs on Flora Bank in the presence of larger waves. Morphological changes during the freshet condition simulations, for example, are much smaller than those during storms or longer-term simulations that include many smaller wind events. Results also indicate that the patterns of net total transport during the 50-year storm from 270^{o} True North are spatially homogeneous, indicating that material moves over Flora Bank but without strong spatial gradients in transport, little erosion or deposition occurs.

Analysis of existing conditions modelling results confirms the reasons why Flora Bank has been reported to be remarkably stable over very long periods of time. Flora Bank is an effective energy dissipation feature that is generally resistant to significant net elevation changes.

6. Modelling of Marine Structures

Numerical modelling was performed to simulate coastal processes on both a large/regional scale (hundreds of kilometres down to tens of meters) and a highly localized scale (meters). The regional scale analysis, using Delft3D, is described in Section 6.1 and the local scale analysis, using MORPHO, is described in Section 6.2. The use of these two modelling tools ensures comprehensive simulation of physical processes that are potentially relevant to the morphology of Flora Bank and potential impacts of the marine structures.

6.1 Regional-Scale Modelling

The results of the Delft3D large-scale model were utilized to evaluate the potential impacts of the marine structures on larger-scale flow and transport processes, and potential changes to the morphology of Flora Bank. The following is a summary of modelling results for a range of extreme events, freshet conditions, and a complete range of conditions as they occur during longer-term time periods. For each of these conditions, analysis is focused on the influence of the marine structures on the hydrodynamics, sediment transport and the resulting potential changes in Flora Bank morphology.

6.1.1 Storm Conditions

Similar to the modelling of the existing conditions, Delft3D simulations were performed for extreme storm events to evaluate morphological changes on Flora Bank and the potential impacts of the marine structures. A total of 40 different 11 day storm simulations were performed, which included winds, waves, tidal currents, sediment transport and morphology. The 40 simulations included four different wind directions (300^o, 270^o, 240^o and 170^o True North), five different return periods (1, 5, 20, 50, 100 years), and existing (presented in Section 5.1) and proposed conditions. This section further describes storms from 270^o True North. This storm event was selected as an example since this storm direction will interact with the marine structures prior to Flora Bank and therefore provide the most relevant information regarding the impacts of proposed structures on Flora Bank. Results of additional storm simulations are provided in Appendix H.

The significant wave height patterns at the peak of the 50-year storm from 270^o without the marine structures (top) and with the marine structures (middle) are shown in Figure 6-1. The instantaneous difference between the two patterns is displayed at bottom. The strongest wave attenuation naturally occurs due to the local bathymetry over Agnew Bank however some localized attenuation occurs along the trestle and at the SW Tower and SW Anchor Block.

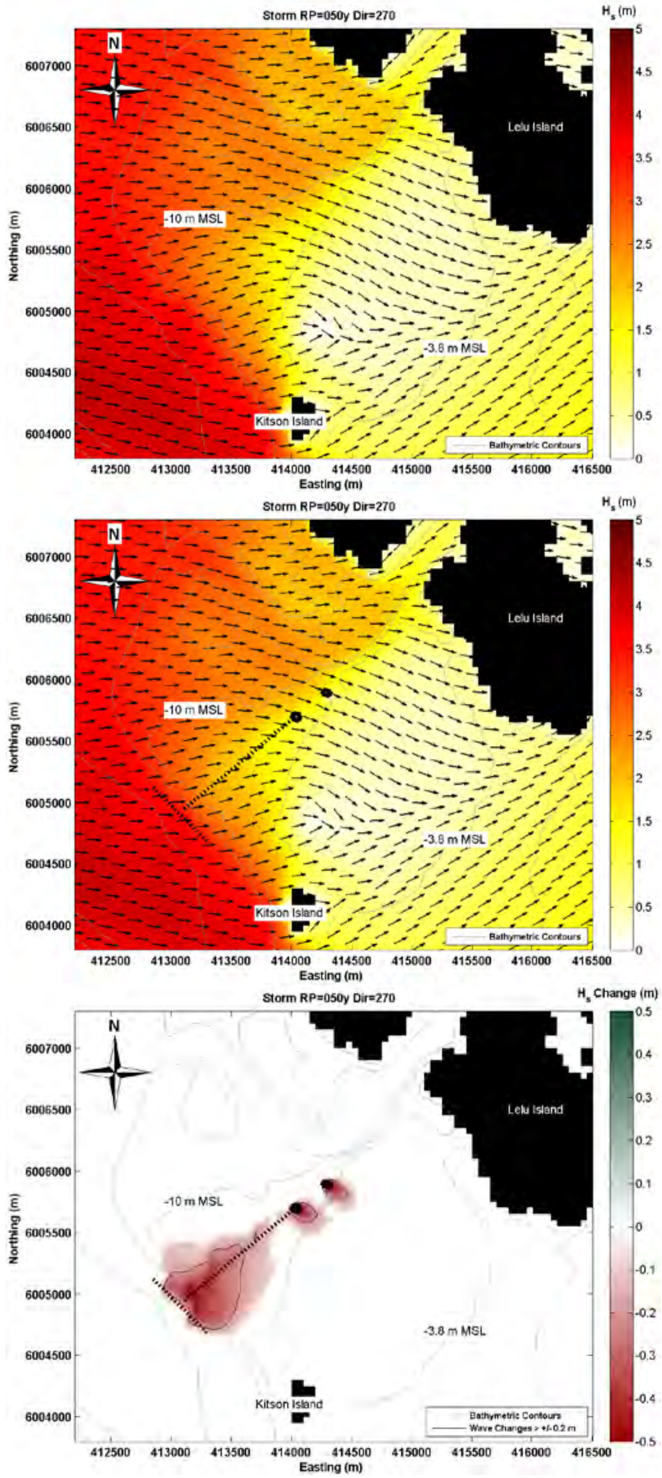


Figure 6-1: Significant wave height at the peak of the 50-year storm from 270° True North for existing (top) and proposed (middle) conditions, and the instantaneous difference (bottom)

Safety ● Quality ● Sustainability ● Innovation

The depth-averaged current velocity patterns at the peak of the 50-year storm from 270^o without the marine structures (top) and with the marine structures (middle) are shown in Figure 6-2. Peak currents reach 0.7 m/s in the area near the marine structures in both simulations. The depth-averaged current patterns with and without the marine structures are similar. The difference in peak flood current speed at one instant during the peak of the storm is shown in Figure 6-2 (bottom panel). Results indicate that the changes in instantaneous current speed are relatively small and located close to the marine structures. It should be noted that the changes in Figure 6-2 represent a subtraction of two instantaneous modelling results, and that slight changes in location of the velocities can indicate relatively large changes when subtracted in this manner. However, the currents are changed so little that the differences computed are relatively small.

During the ebb tide (Figure 6-3), the depth averaged currents at Porpoise and Inverness channels reverse direction, flowing offshore. The depth-averaged currents over Flora Bank are still dominated by the currents induced by winds and waves and are still moving towards the east (similar to during flood tide, but smaller in magnitude).

Figure 6-4 shows total transport flux snapshots during an early portion (top), at peak (middle), and after the storm (bottom) at the beginning of the ebb tide. Inset figures show the significant wave height at the PNW Buoy when the snapshots were taken. Results indicate that transport flux is dominated by wave activity, with much higher transport occurring in all areas during the peak of the storm as compared to the earlier or later portion of the storm when wave heights are lower. Figure 6-5 shows total transport flux snapshots during an early portion (top), at peak (middle), and after the storm (bottom), but this time at the beginning of the flood tide. Compared to the ebb tide transport conditions, more transport is occurring during the earlier portion of the storm, but most of the transport still occurs at the time of peak wave conditions.

These transport flux snapshots were summed over the duration of the storm simulations to determine net transport that occurred in 11 days, and facilitate comparison of the existing and proposed conditions.

Figure 6-6 compares the total net transport for existing (top) and proposed (middle) condition. The bottom panel shows the difference between both simulation during the 50-year storm from 270^o, where the difference indicates that the marine structures decreases the sediment transport around the berth.

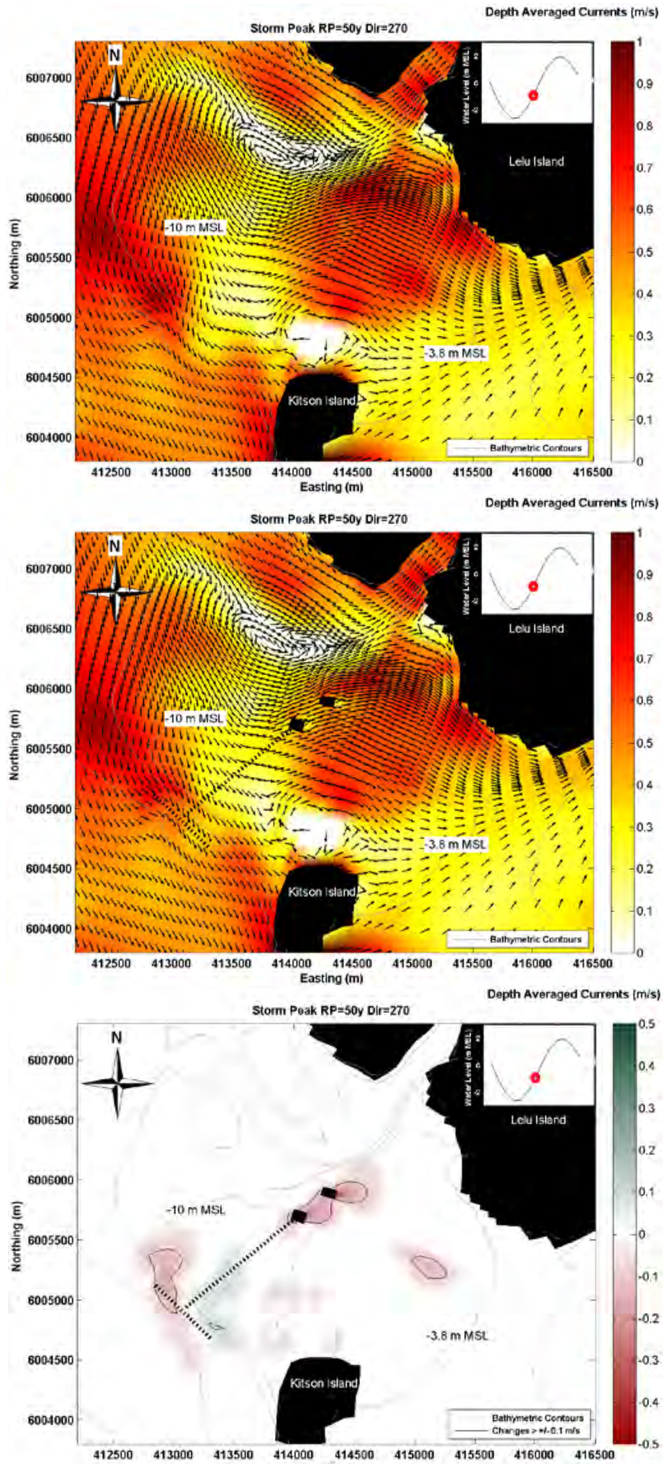


Figure 6-2: Depth-averaged instantaneous flood current patterns during the peak of the 50-year storm from 270^{o} True North for existing (top) and proposed (middle) conditions, and the instantaneous difference (bottom)

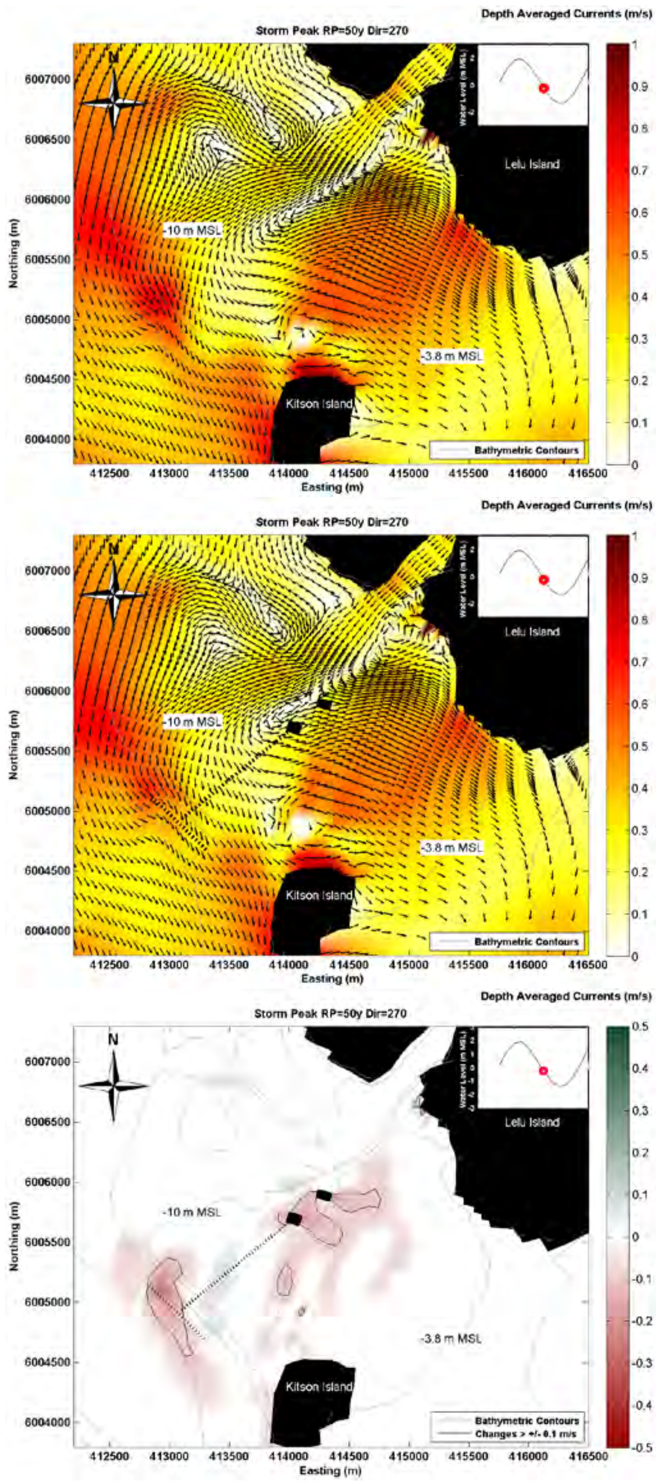


Figure 6-3: Depth-averaged instantaneous ebb current patterns during the peak of the 50-year storm from 270^{o} True North for existing (top) and proposed (middle) conditions and the instantaneous difference (bottom)

Safety ● Quality ● Sustainability ● Innovation

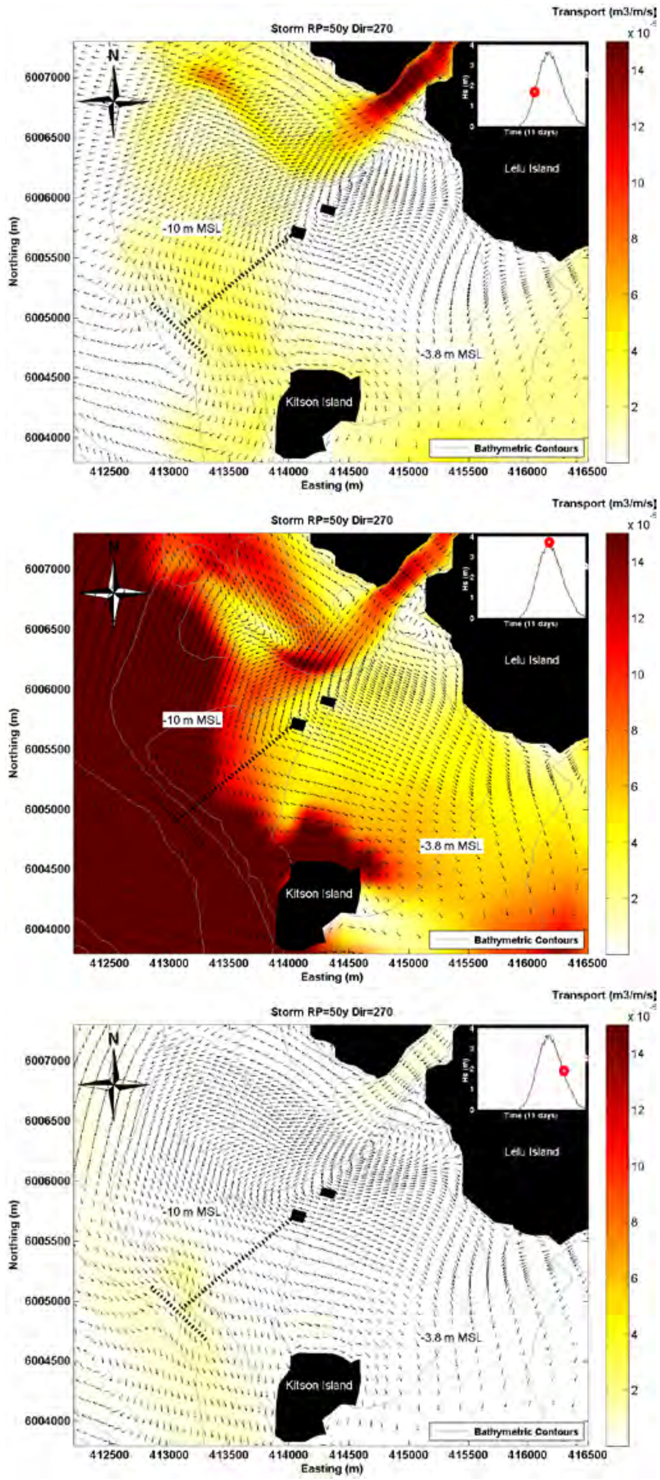


Figure 6-4: Total transport flux snapshots during an early portion (top), at peak (middle), and after the storm (bottom) at the beginning of the ebb tide. Inset figures show the significant wave height at the PNW Buoy when the snapshots were taken.

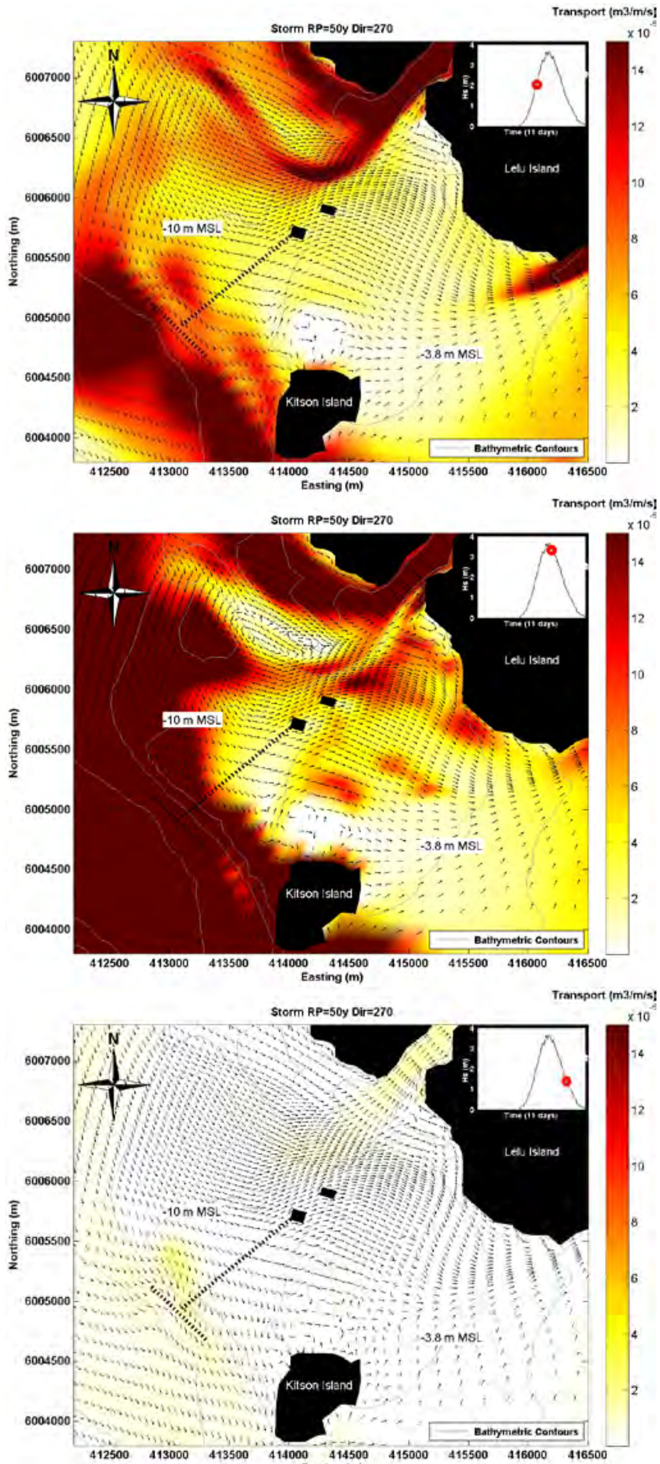


Figure 6-5: Total transport flux snapshots during an early portion (top), at peak (middle), and after the storm (bottom) at the beginning of the flood tide. Inset figures show the significant wave height at the PNW Buoy when the snapshots were taken.

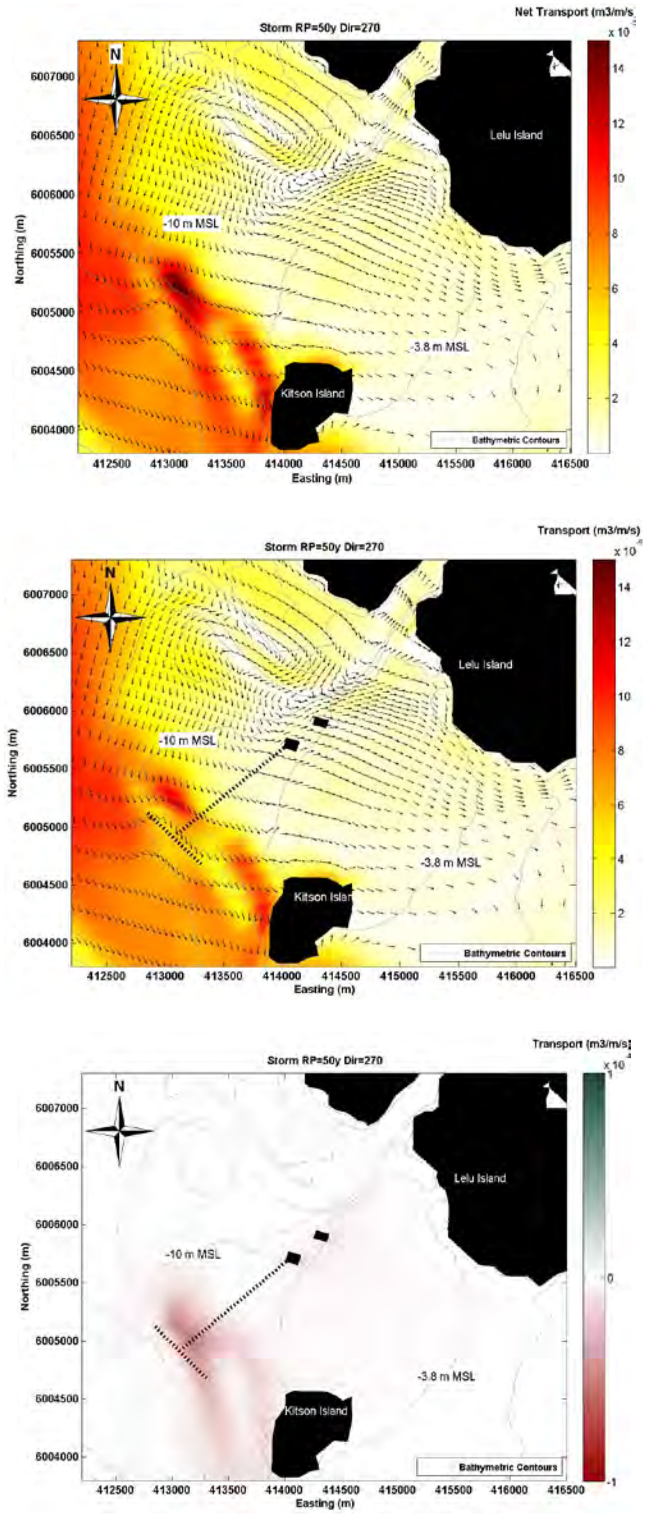


Figure 6-6: Net total transport flux during entire 11 day simulation for existing (top) and proposed (middle) conditions and the net difference (bottom)

Safety • Quality • Sustainability • Innovation

Figure 6-7 shows the morphological change around Flora Bank for existing (top) and proposed conditions (bottom) during the 50-year storm from 270^{o} True North. Changes in the seabed elevation are concentrated at the far north and south ends of Flora Bank. Modelling results indicate that at the south end of Flora Bank, the slight reduction in wave energy from the trestle structure causes a reduction in erosion and the associated deposition, and further enhances bed stability during the event. The results indicate that changes during this event are not likely to be measurable regardless of the presence of the marine structures. Difference plots are not shown as they tend to indicate erosion due to the marine structures when in fact they are causing less deposition, and indicate deposition in areas where the marine structures are causing less erosion.

Figure 6-8 shows the morphological change around Flora Bank for existing (top) and proposed (bottom) conditions, following the 5-year storm from 270^{o} True North. Patterns of change during this smaller 5-year storm are similar but lower in magnitude than the 50-year storm. Similar conclusions can be made regarding the effects of the marine structures; the marine structures cause a reduction in erosion, and reduction in the associated nearby deposition, as they modestly reduce the level of wave energy reaching Flora Bank.

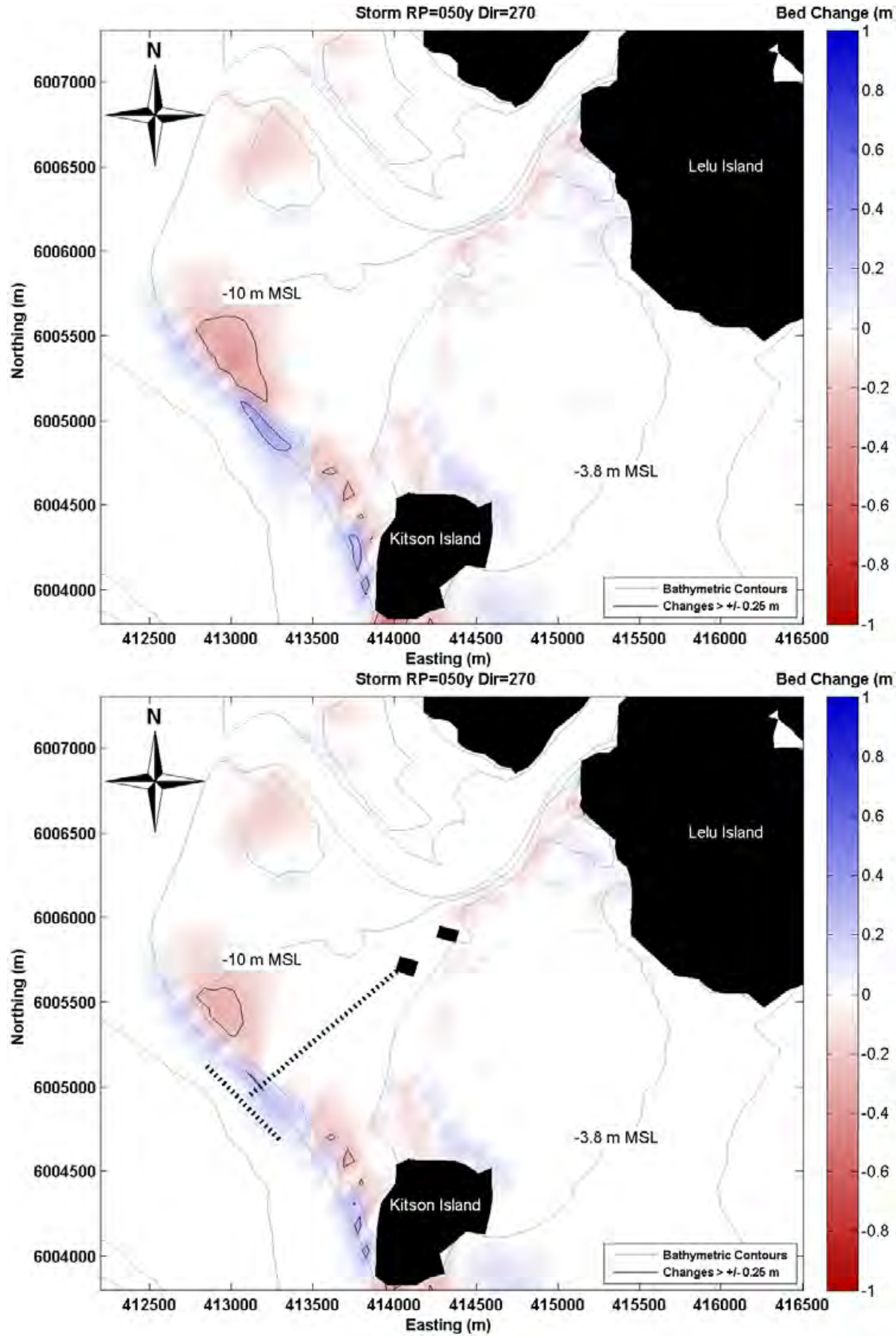
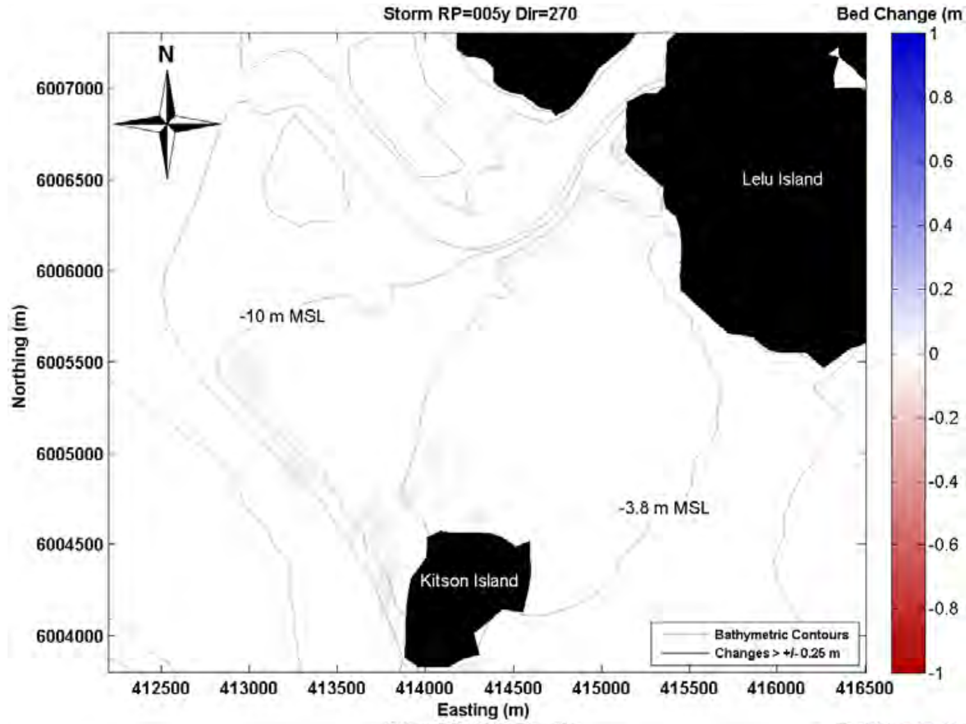


Figure 6-7:Morphological changes during 50-year storm from 270° True North without (top) and with (bottom) the marine structures.



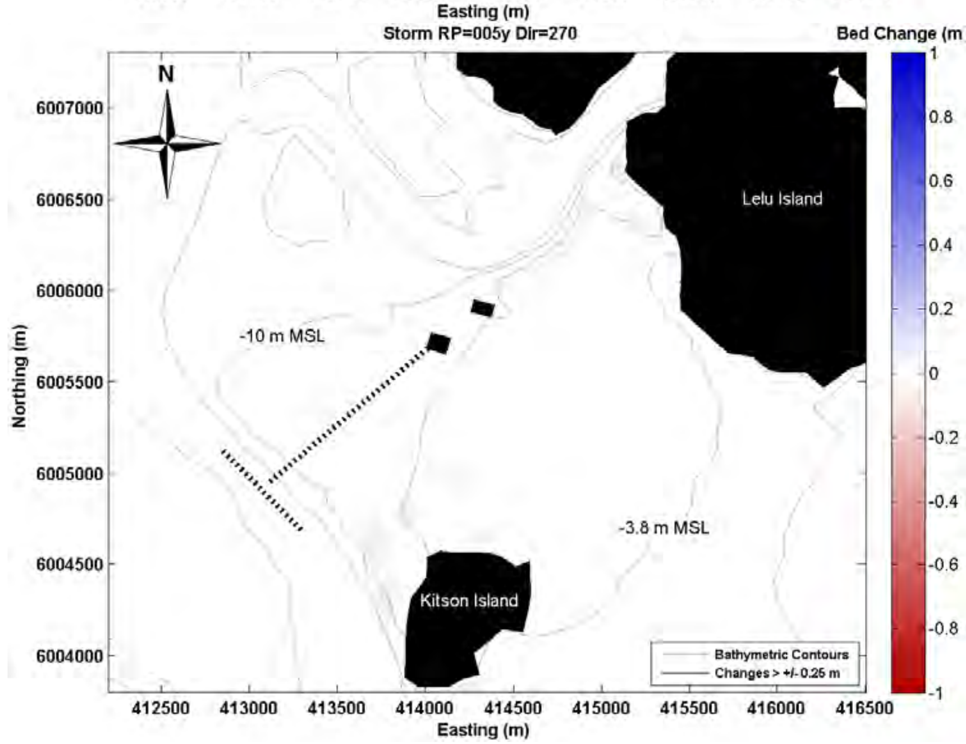


Figure 6-8: Morphological changes during 5-year storm from 270^{o} True North without marine structures (top) and with marine structures (bottom)

To further evaluate when and why bed changes occur, time histories of water level, significant wave height and bed elevation change were extracted at four locations on Flora Bank near the marine structures. Figure 6-9 (top) shows these four locations. Two locations experience erosion (A and C) and the other two experience deposition (B and D). The colour plot shows the initial seabed elevation. Figure 6-9 (bottom) shows time histories of the water level, wave height at the PNW Buoy, and the change in seabed elevation at all four points. The PNW Buoy is located north of the proposed berth location, in the steeper slope off Agnew Bank. Bed elevation changes occur at both locations only during periods where significant wave height exceeds approximately 2 to 3 m at the PNW Buoy, with no erosion or deposition occurring otherwise. Time periods dominated by tidal currents without strong waves result in negligible bed elevation changes. The trends of elevation and deposition for the existing conditions and with the proposed marine structures in place are consistent. However, erosion (at C and D) and associated nearby deposition (B and D) are both slightly dampened with the marine structures in place.

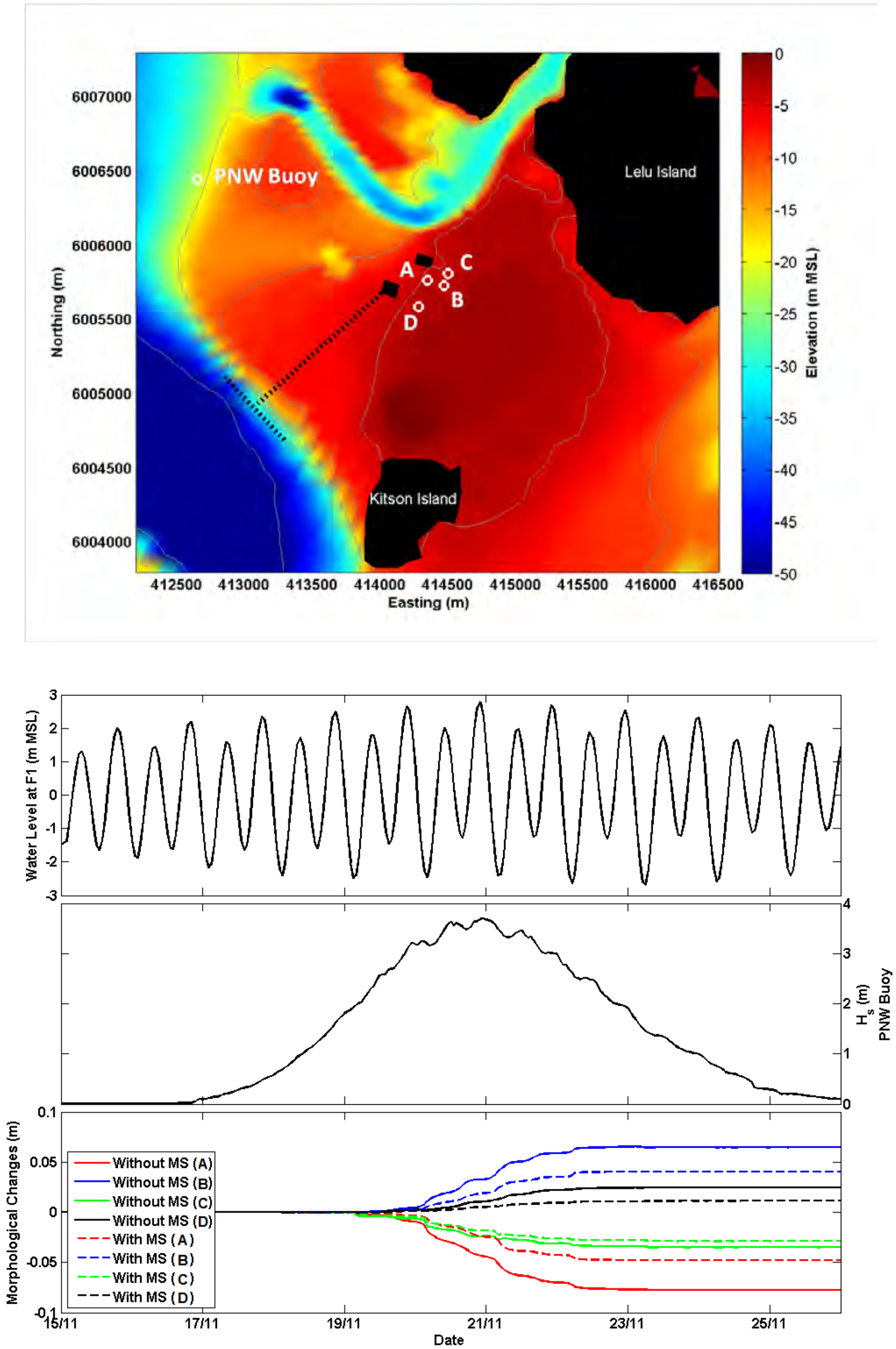


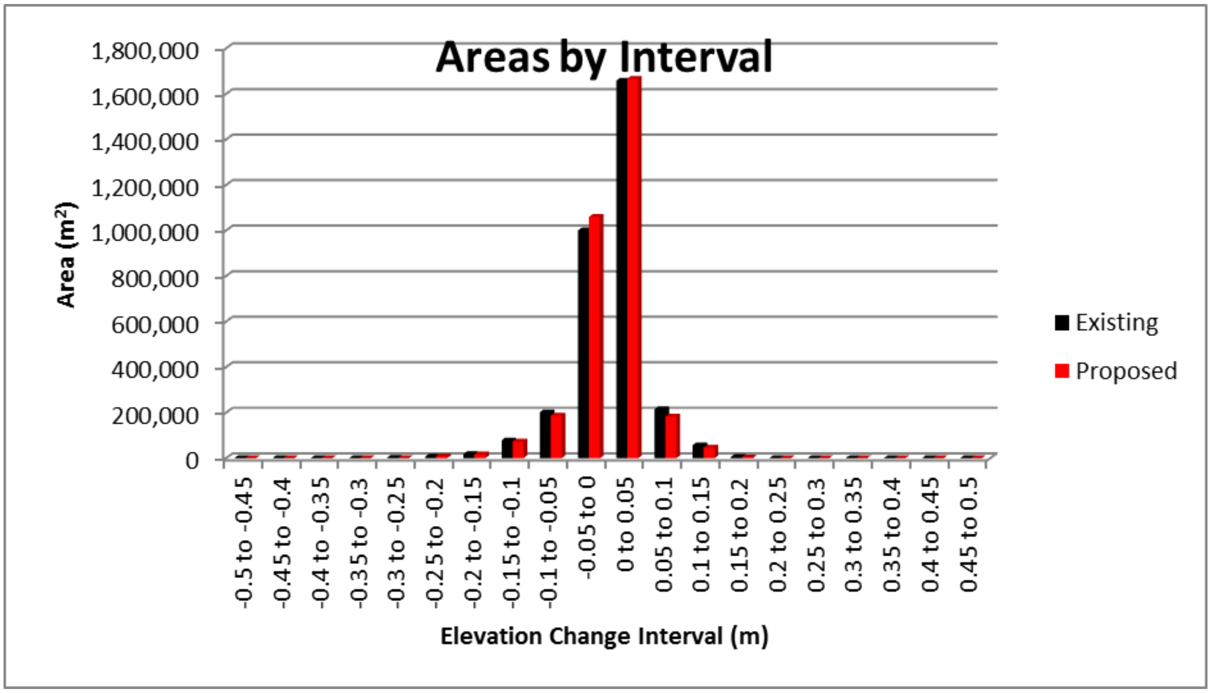
Figure 6-9: Area map showing selected locations where the time histories of bed changes were extracted (top), and time histories of water level, wave height and bed changes during 50-year storm simulation.

Table 6-1 shows the calculated volumes of change for the 50-year storm with and without the marine structures. Results indicate that the presence of the marine structures, in particular the trestle, reduced the volumes of local erosion and reduced the volumes of local deposition. The slight reduction in wave energy due to the trestle structure results in less sediment being moved around locally on Flora Bank during the storm. Appendix H includes morphological change and Flora Bank volumetric change results from all storm events simulated on the project (40 storms). Volumetric changes on Flora Bank were computed using a digital elevation model as described previously in Section 5.

Table 6-1: Volumetric and Area Changes on Flora Bank During a 50-year Storm (270° True North)

Extreme Event Incoming Direction [°N]	Presence of Marine Structures	Erosion Volume [m³]	Deposition Volume [m³]	Net Volume [m³]	Erosion Area [m²]	Deposition Area [m²]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
270	**Without**	-47,340	50,140	2,800	308,920	278,860	-0.01	0.02	0.00
	With	-45,460	43,860	-1,600	287,910	233,160	-0.01	0.01	0.00

Figure 6-10 shows the areas (top) and volumes (bottom) of change on Flora Bank organized by bed change intervals, at 0.05 m increments. The results demonstrate that the majority of the changes on Flora Bank are between -0.05 m and 0.05 m, with minimal changes greater than 0.15 m. The area where change occurs is relatively similar between existing and proposed conditions, comparable to the erosion and deposition patterns observed in the morphological change plots. The volumes of change are modestly reduced for the proposed conditions due to the slight attenuation effect of the trestle structure.



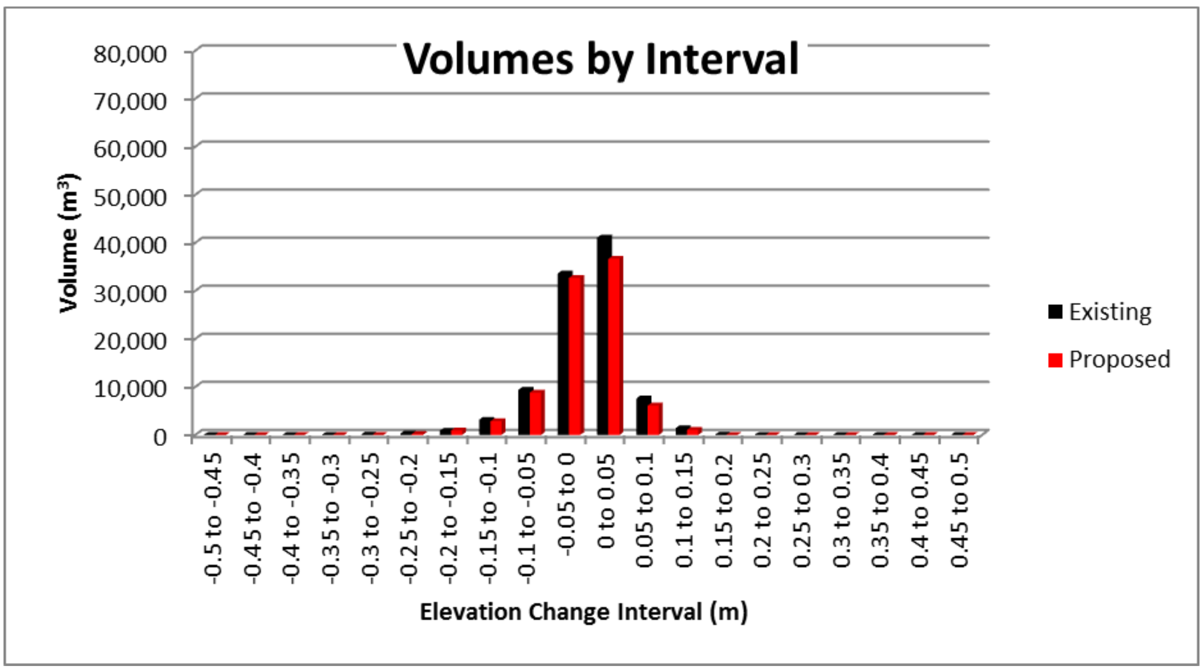


Figure 6-10: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 50-year 270° storm simulation for existing and proposed conditions.

Similar to the results shown here for the 270° storm, results for storms originating from 170°, 240°, and 300° True North also indicate that the presence of the marine structures, in particular the trestle, reduces the volumes of local erosion and reduces the volumes of local deposition. The slight reduction in wave energy due to the trestle structure results in less sediment being moved around locally on Flora Bank during the storm. Appendix H provides further analysis of the storm simulations.

6.1.2 Sediment Size Sensitivity Testing

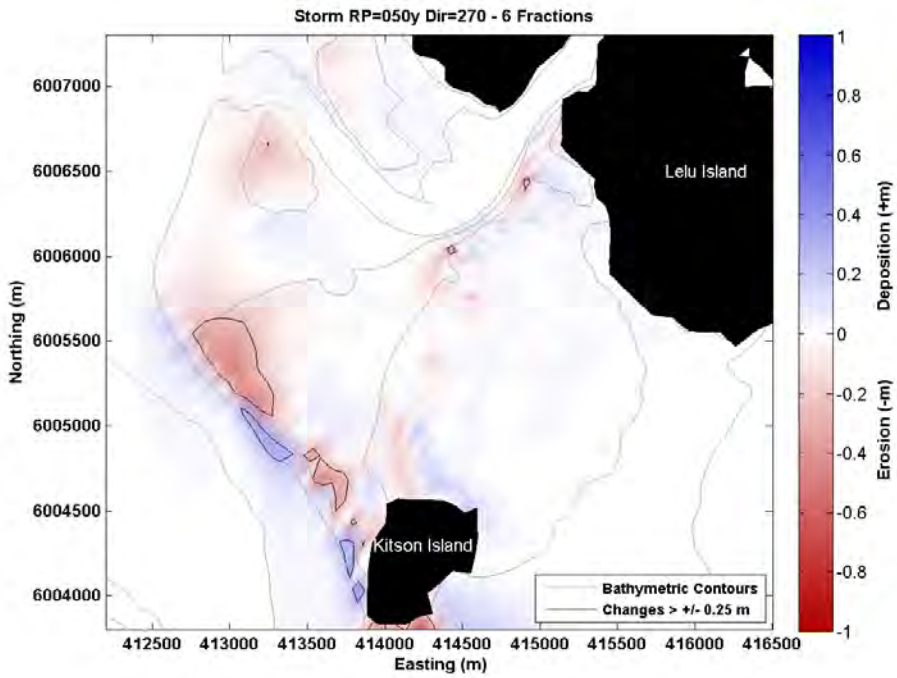
As described in Section 5.1.2, the original Delft3D regional modelling simulations and longer-term simulations utilized a 4-class sediment grain size distribution in the modelling domain that was intended to evaluate the transport and fate of a very wide range of sediments including clay, silt, sand and coarse materials. In order to evaluate the impact of using the previous SedTrend erroneous data on the results of the modelling, additional short-term simulations were performed in August 2015 to evaluate the relative importance of the assumed grain size distribution on the predicted morphology of Flora Bank (as described in Section 5.1.2), and on the potential impacts of the marine structures.

Also as described in Section 5.1.2, the new sediment grain size distribution was developed with a closer focus on the material found on Flora Bank in the corrected SedTrend data, typically ranging from 0.1 mm to 0.5 mm. Six (6) classes of sediments were created in the Delft3D model (0.1, 0.125, 0.177, 0.25, 0.35, and 0.5 mm). Any finer sediments (found elsewhere off Flora Bank) were lumped into the 0.1 mm fraction, and coarser material was lumped into the 0.5 mm fraction.

Figure 6-11 shows bed elevation changes following the 50-year storm from 270° True North for the new 6-fraction sediment size distribution without the marine structures (top) and with the marine structures (bottom). Results indicate that the effects of the marine structures on morphology with either the original or new 6-fraction grain size distribution are very similar, and mostly limited to the berth area. Changes induced by the marine structures on Flora Bank during the 50-year storm from 270° True North are also not likely to be measurable for the new 6-fraction sand simulations.

Results of the sediment grain size sensitivity testing indicates that predictions regarding the potential morphological impacts of the marine structures are not very sensitive to the assumed sand grain sizes on Flora Bank using either the 4-fraction of 6-fraction grain size distribution. Bed elevation changes predicted for simulations with different grain size distributions were similar because the majority of the changes on Flora Bank in the original sediments simulation were for the 0.14 mm fraction, and typically a significant portion of the new 6-fraction simulation are also fine sands.

Results from the new 6-class simulations with refined (more detailed) sand sizes over Flora Bank also indicate that the marine structures tend to reduce both the erosion and deposition that occurs over Flora Bank during storm events, which is consistent with the trends shown in the 4-fraction simulations.



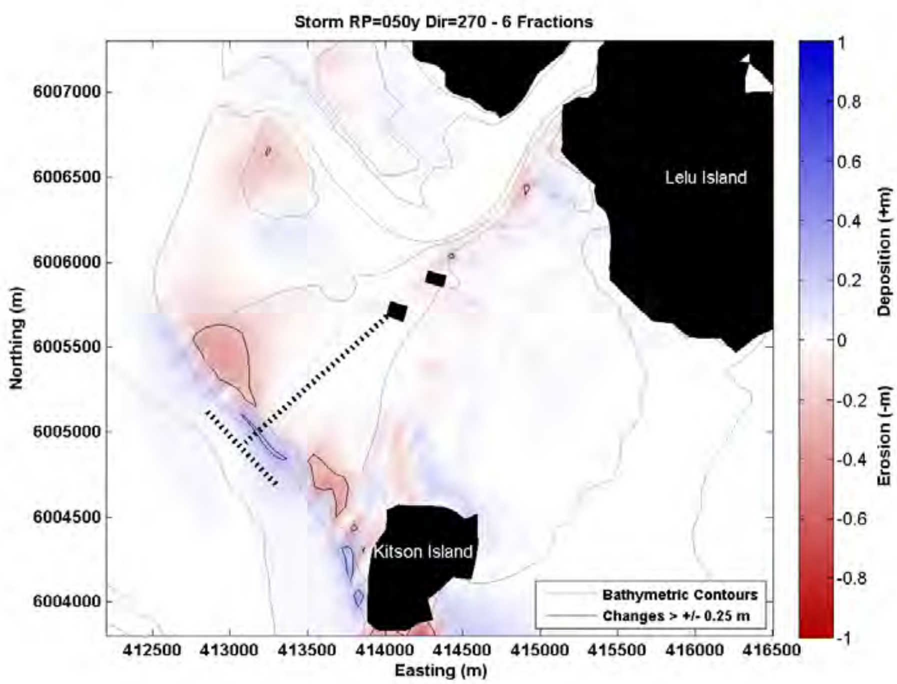


Figure 6-11: Morphological changes predicted during 50-year storm from 270^{o} True North for new 6-fraction sediment distribution without marine structures (top) and with marine structures (bottom)

6.1.3 Freshet Simulations

Similar to the freshet simulations described in Section 5.2, Delft3D simulations during a 28 day freshet period were performed with the marine structures in place to evaluate potential marine structure impacts during periods with typical tidal current conditions, mild waves and high Skeena River flows. The simulation covered the time period May 11, 2014 to June 8, 2014, with peak Skeena River discharge of 5150 m^3/s.

Figure 6-12 shows the net total transport flux around Flora Bank for existing (top) and proposed conditions (bottom) during the 28 day freshet simulation. Results indicate that net total transport is small during this period regardless of the presence of the marine structures, and concentrated in Porpoise Channel and Inverness Passage outflows. The net transport over Flora and Agnew Bank is low and is largely unaffected by the presence of the marine structures.

Figure 6-13 shows the morphological change around Flora Bank without (top panel) and with (bottom) the marine structures following the 28 day freshet simulation. Results indicate that changes on Flora Bank during this period are small (on the order of millimetres) regardless of the presence of the marine structures.

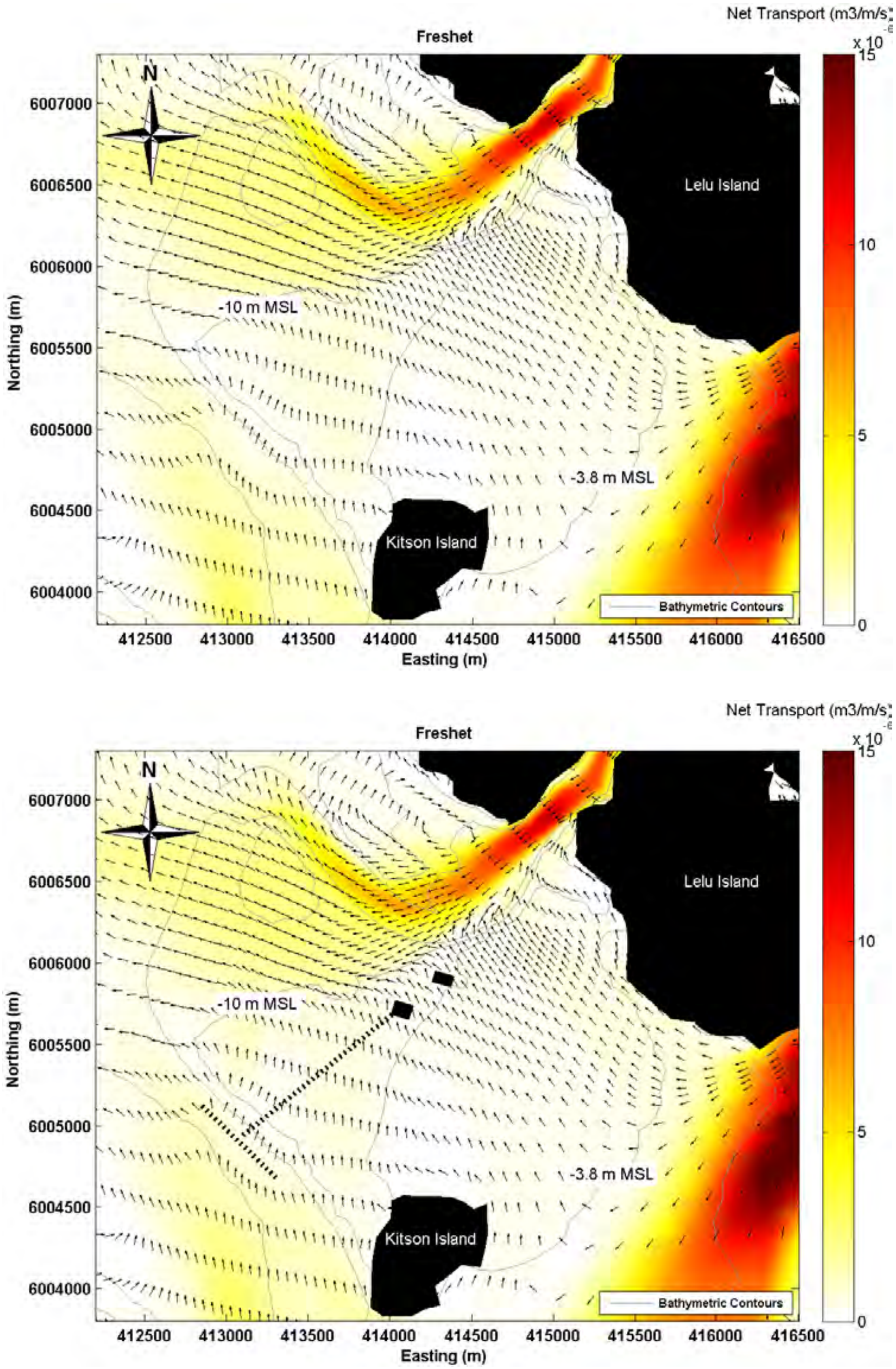
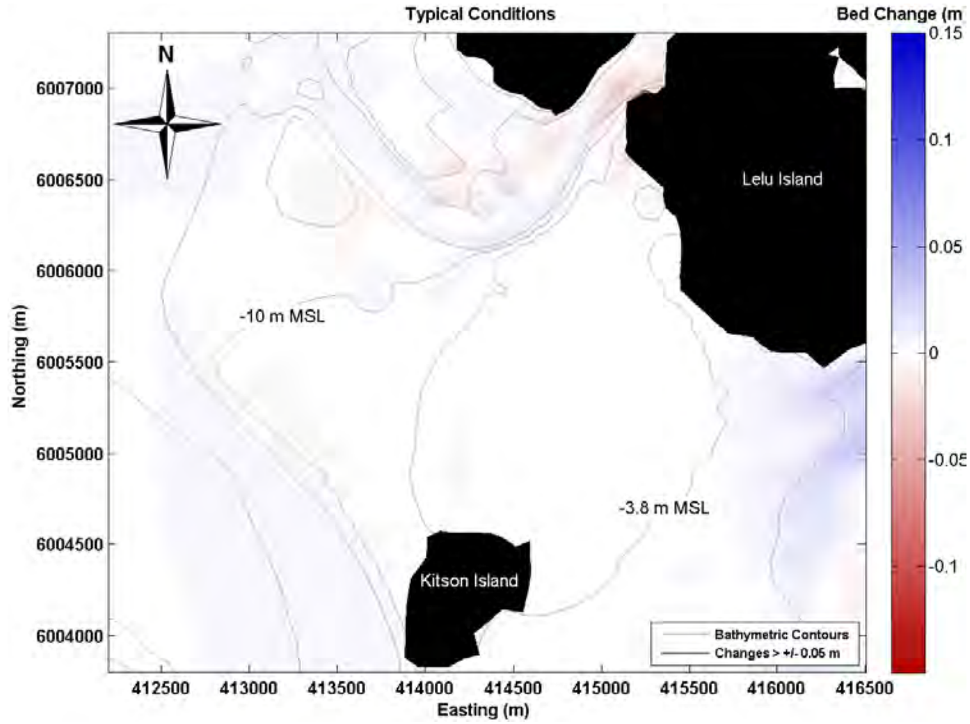


Figure 6-12: Net transport flux from 28 day freshet simulation without (top) and with (bottom) marine structures



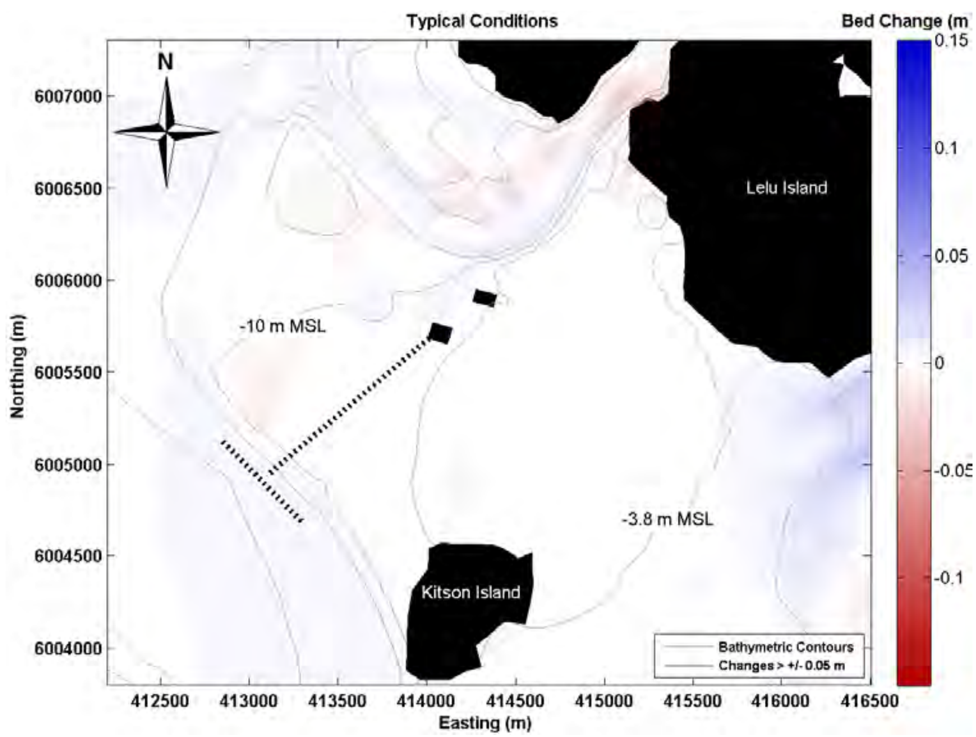


Figure 6-13: Morphological changes predicted during the 28 day freshet simulation without (top) and with (bottom) the marine structures. NOTE: ± 0.15 m color scale.

Total Suspended Solids (TSS) concentrations were compared at two locations with and without marine structures during the 28 day freshet simulation. Figure 6-14 shows extraction point locations (top) and time histories of tides, current velocities, and TSS (bottom) at the two locations of interest. These two locations were selected as they are near the SW Anchor Block and the SW Tower. The TSS concentrations in both locations were very similar in the simulations with and without marine structures. The noticeable peak in TSS predicted on May 23 was generated by higher waves in shallow water as Flora Bank was going dry, which tends to result in high TSS values. Overall, there are no significant larger-scale differences in the magnitudes of peak TSS concentrations after the addition of the proposed structures.

Analysis was performed with TSS time histories to determine the percentage of time that TSS concentrations were above 25 mg/l for either the existing or proposed conditions. Point C and Point D have TSS concentrations above 25 mg/L approximately 1.5% and 1.7% of the time, respectively, for both the existing and proposed conditions. The maximum amount of consecutive hours that TSS concentrations are above 25 mg/l is less than 7 hours for both the existing and proposed conditions in these two locations.

Figure 6-13 shows a comparison of TSS predicted at Point C (left) and Point D (right) for both existing and proposed conditions. Except for a few outlier points (1-hour measurements), the TSS concentrations for existing and proposed conditions at Points C and D are very similar.

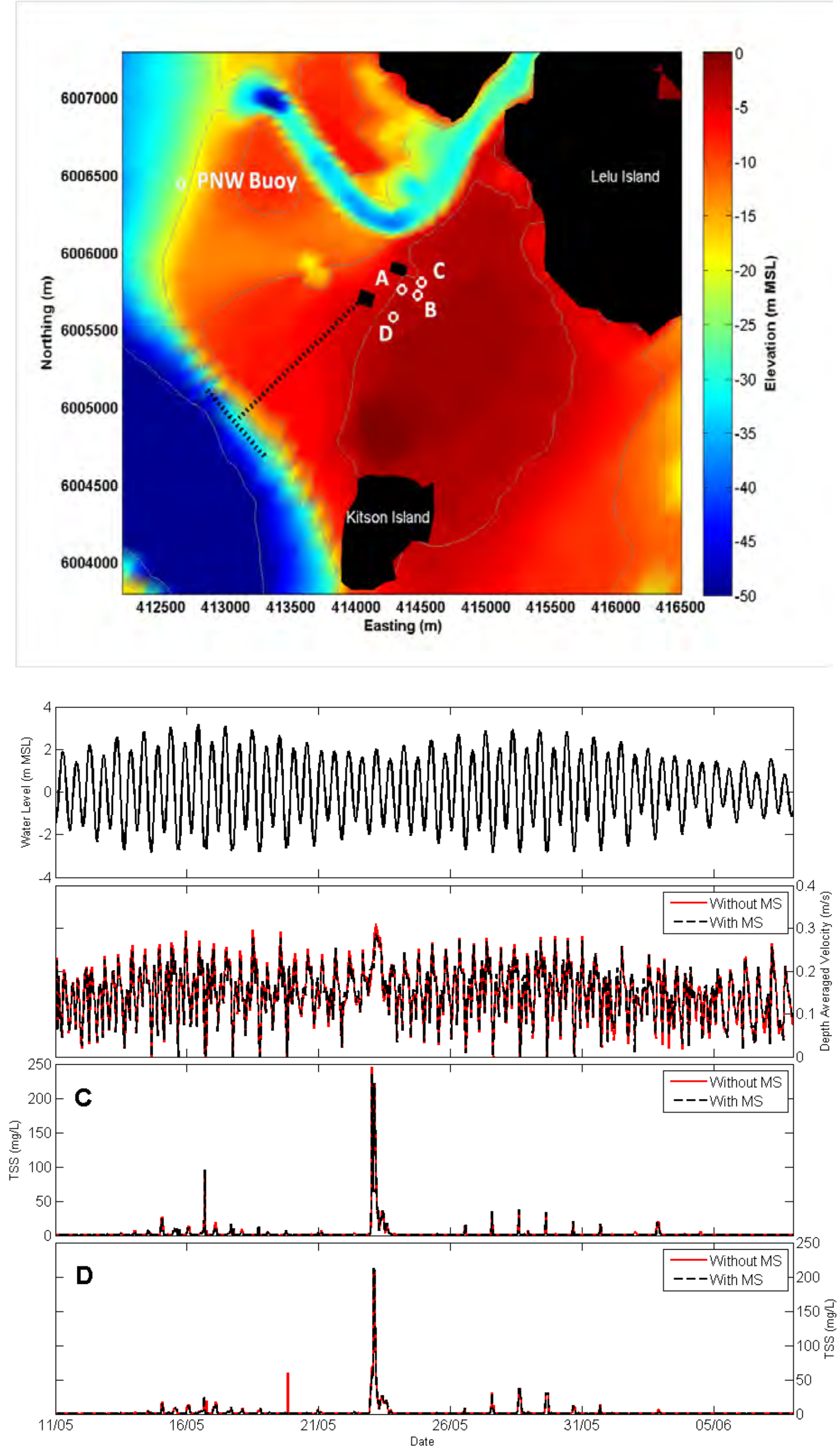


Figure 6-14: Extraction point locations (top) and time series of TSS concentrations during the 28 day simulation for existing and proposed condition (bottom) at two locations near the SW Anchor Block and SW Tower

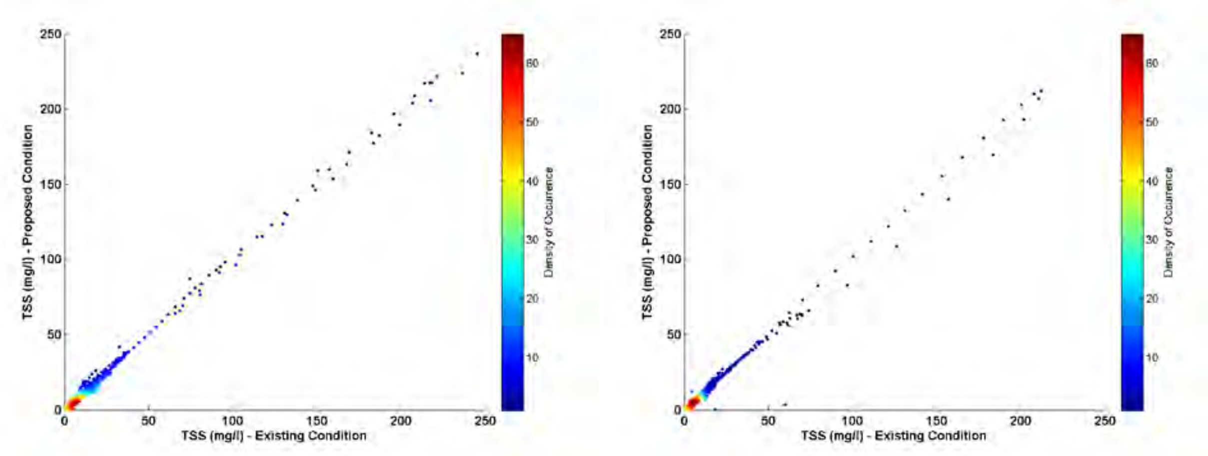


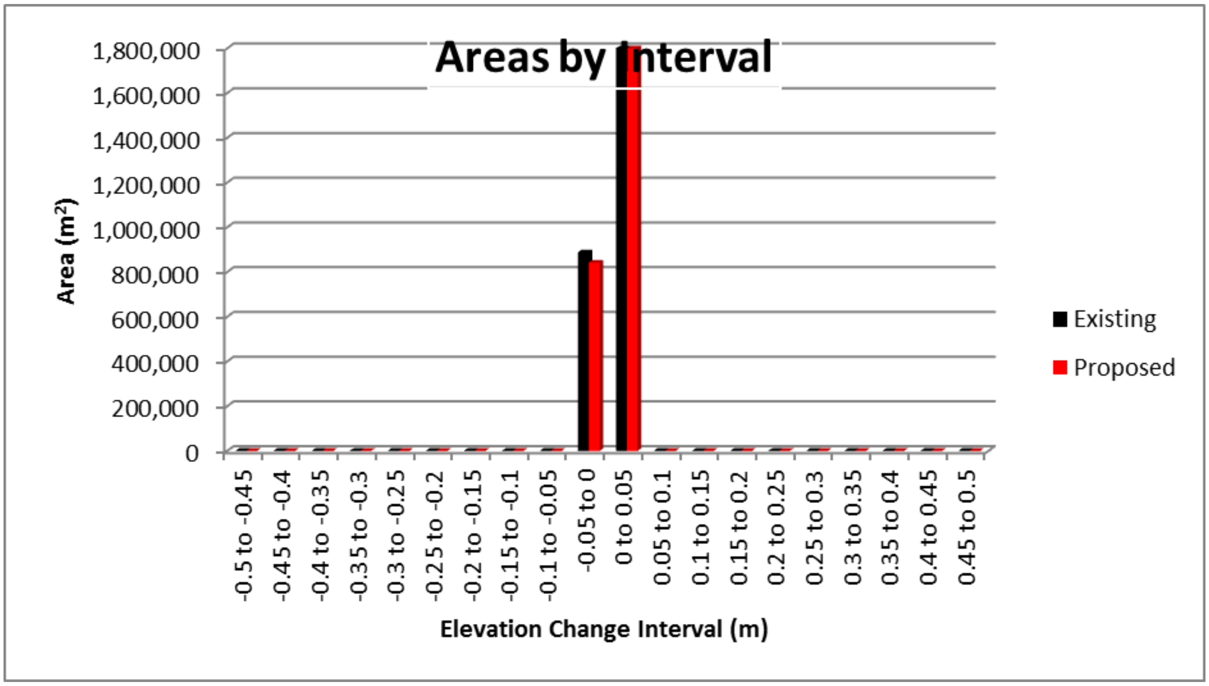
Figure 6-15: TSS concentration comparison between existing and proposed conditions at Point C (left) and Point D (right)

Volumetric changes during the freshet simulation were computed using a digital elevation model as described previously in Section 5. Table 6-2 shows the calculated volumes of change for the 28 day freshet period with and without the marine structures. Results indicate that the net erosion and deposition over Flora Bank during the freshet simulation is negligible and there is no measurable difference between the existing and proposed conditions.

Table 6-2: Volumetric and Area Changes on Flora Bank During 28 day Freshet Simulation

Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
Without	0	-650	1,560	910	0	1,500	0.00	0.00
With	0	-810	1,400	590	0	0	0.00	0.00

Figure 6-16 shows the areas (top) and volumes (bottom) of changes on Flora Bank organized according to bed change intervals of 0.05 m. The results demonstrate that almost all the changes modelled on Flora Bank are between -0.05 m and 0.05 m and the overall volume change is negligible.



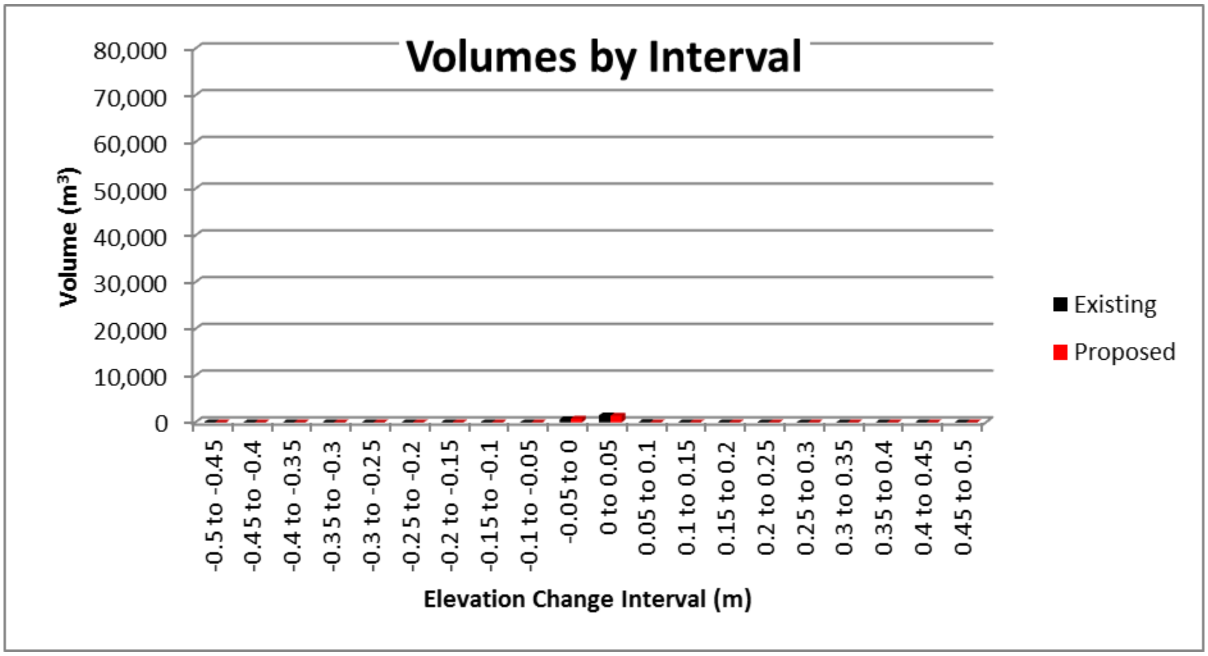


Figure 6-16: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 28 day freshet simulation for existing and proposed conditions.

6.1.4 Longer-Term Time Series Simulation Results with Marine Structures

Longer-term time series simulations for the proposed conditions (with the marine structures) were also conducted. The following sections examine the results for a 3 month simulation during the stormy period, a 4 month simulation during the calmer season, and a 1 year simulation which provides an analysis of the most active periods within the annual cycle.

Two 1 year simulations using 3-hour coupling were also conducted and further support the patterns and conclusions determined in the 3 month simulation with 1-hour coupling. These results are presented in Appendix H.

6.1.4.1 3 month Time Series Simulation of Stormy Period with 1-hour Wave-Flow Coupling

This simulation was performed beginning September 1, 2012 for 3 months, and included a complete range of coastal processes and stormy periods with high winds and waves, but naturally lower river flows since it did not include the freshet period. This simulation also included highly detailed (frequent) coupling between the wave and flow models (1-hour coupling). The simulation presented in Section 5.3.4.1 was repeated with the marine structures in place to evaluate potential impacts on coastal processes and the morphology of Flora Bank.

Figure 6-17 (top) shows that without the marine structures, some bed elevation changes do occur over Flora Bank during the 8-month stormy period beginning September 1, 2012, which includes a complete range of coastal conditions and relatively strong wave activity. Maximum bed elevation changes are approximately 25-30 cm near Kitson Island, which is a relatively energetic location with stronger waves and currents, and bed changes are not likely to be measurable elsewhere on Flora Bank. Figure 6-17 (bottom) shows the bed changes with the marine structures in place. As for all other simulations performed to date (storms, freshet periods), since the marine structures slightly attenuate waves from the northwest and west, the effect of the marine structures is to slightly dampen the process of local erosion and deposition that occurs on Flora Bank. Also as found in all other results, the erosion occurs primarily on the southwest edge of Flora Bank, with material moving with the waves until they are reduced in height and can no longer transport the material, producing deposition directly to the east of the erosive areas.

Safety • Quality • Sustainability • Innovation

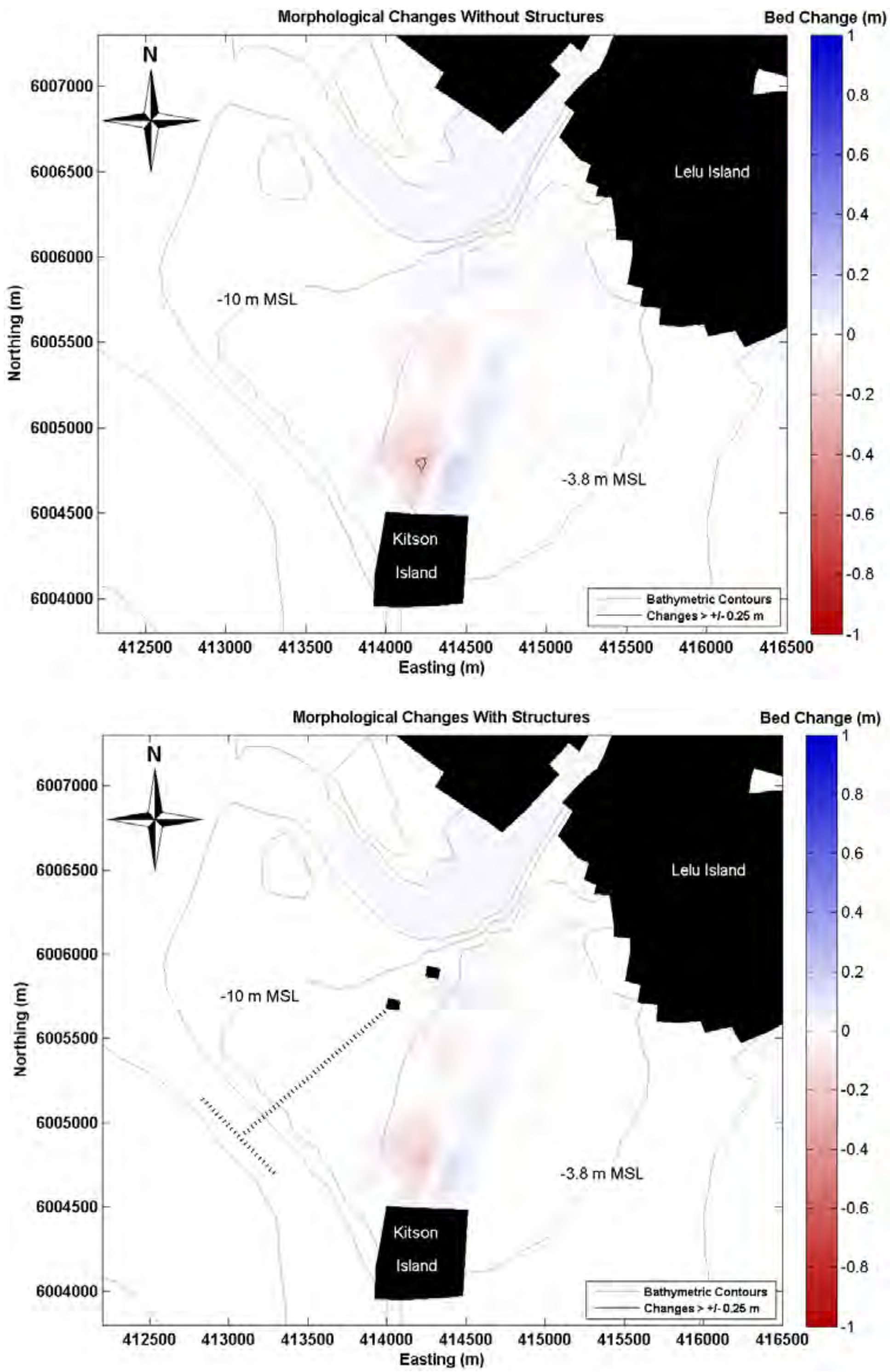


Figure 6-17: Morphological changes predicted during 3 month time series simulation covering stormy period beginning September 1, 2012 without marine structures (top) and with marine structures (bottom).

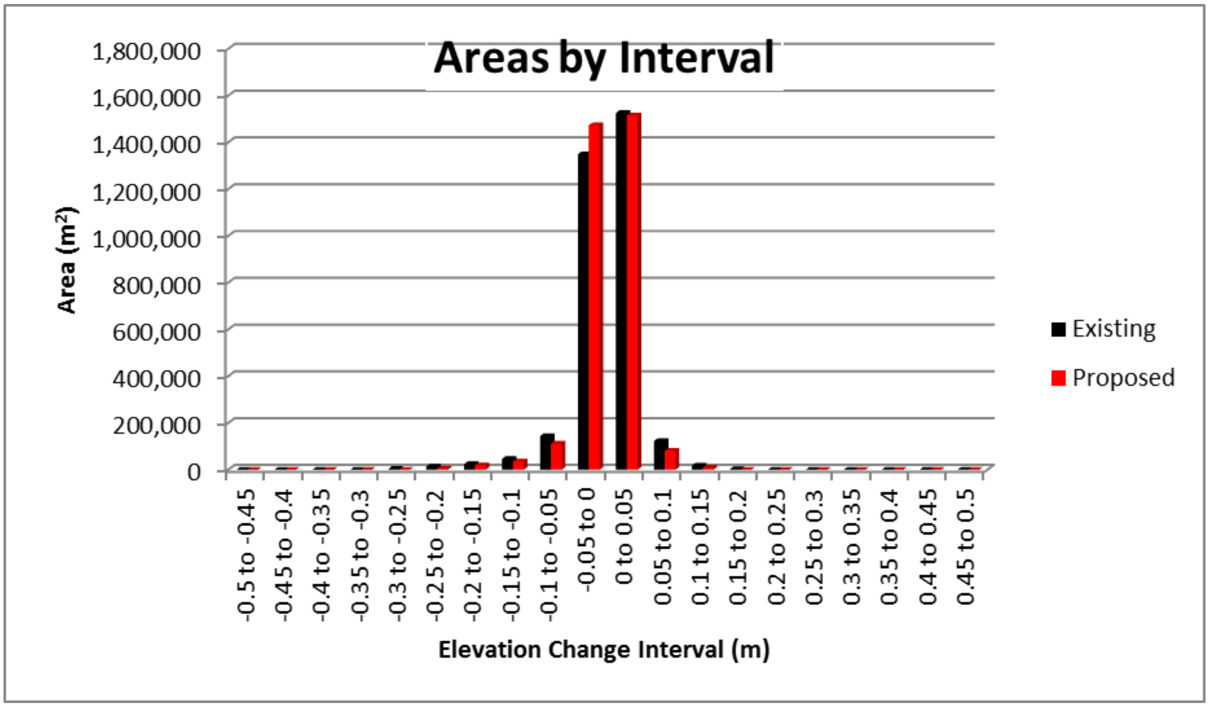
Safety • Quality • Sustainability • Innovation

Bed change results were analyzed to determine the trends in erosion and deposition patterns, volumes, and net changes on Flora Bank over the 3-month period starting from September 1, 2012. These results are presented in Table 6-3. Results indicate that overall, changes on Flora Bank due to the presence of the marine structures are small and include reduction in both the erosion and deposition that occurs.

Table 6-3: Volumes of Change During a 3 month Period

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
Sept	**Without**	-41,050	31,780	-9,270	230,430	141,710	-0.01	0.01	0.00
	With	-32,290	24,820	-7,470	170,350	89,420	-0.01	0.01	0.00

Figure 6-18 shows the areas (top) and volumes (bottom) of changes organized by bed change intervals of 0.05 m. The results demonstrate that the majority of the changes on Flora Bank are between -0.05 m and 0.05 m, with minimal changes greater than 0.15 m.



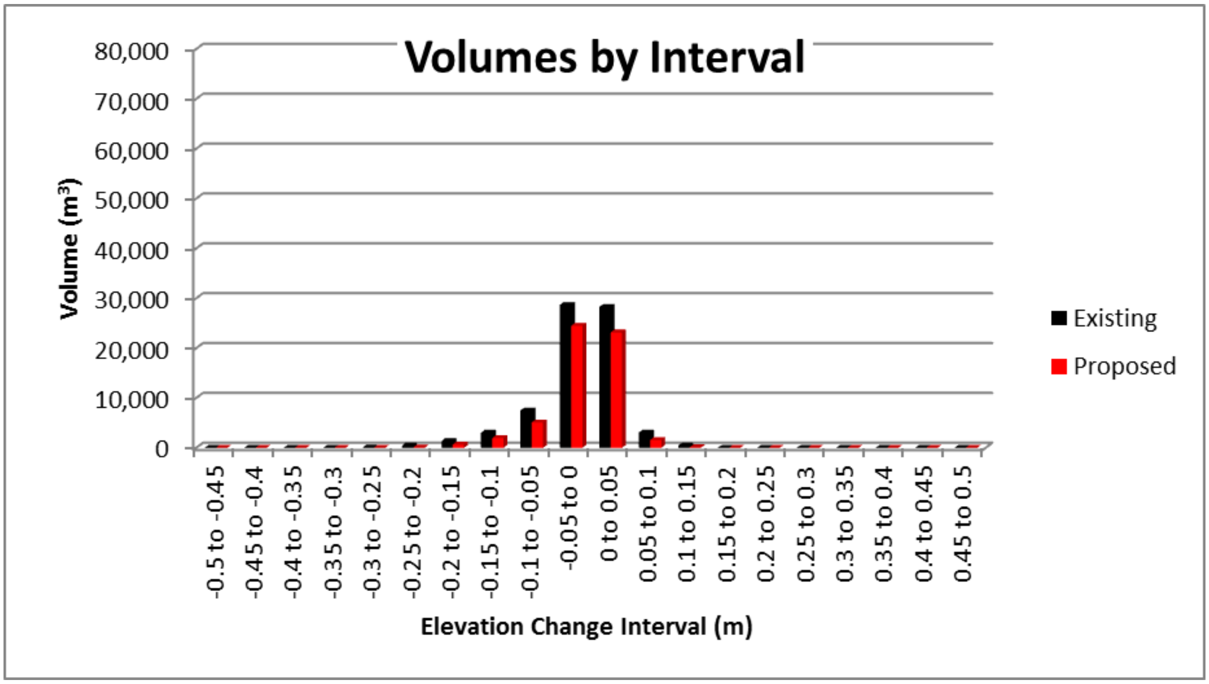


Figure 6-18: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 3 month simulation for existing and proposed conditions.

6.1.4.2 4 month Time Series Simulation of Calmer Period with 3-hour Wave-Flow Coupling

This simulation was performed beginning May 1, 2013 for 4 months, and included a complete range of coastal processes, with naturally less stormy periods and higher river flows, with less frequent coupling between the wave and flow models (3-hour coupling) for higher efficiency. The identical simulation presented in Section 5.3.4.2 was repeated with the marine structures in place to evaluate potential impacts on coastal processes and the morphology of Flora Bank. Figure 6-19 shows bed elevation changes predicted by the end of the 4 month simulation from May 1, 2013 to August 31, 2013, using 3-hour coupling, without the marine structures (top), and with the marine structures (bottom). The predicted bed changes are smaller than were found during the 3 month stormy period, with slight erosion on the southwest side of Flora Bank, and associated deposition of the eroded material just to the east.

The bed changes shown here are less than approximately 5 cm in all areas of Flora Bank for the entire 4-month period. As for all other simulations performed to date (storms, freshet periods), since the marine structures slightly attenuate waves from the northwest and west, the effects of the marine structures is to slightly dampen the erosion and subsequent nearby deposition that occurs on Flora Bank downstream of the erosive area when waves lose energy.

It should be noted that the bed elevation changes resulting from the 4 month summer simulation, while generally occurring in similar locations to those in the 3 month stormy simulation, and while having similar magnitudes, contain higher levels of numerical "noise" which occurs during the wetting and drying process from coupling the wave and flow models at 3-hour intervals. However, the effect of the marine structures is still to slightly dampen the changes due to a slight reduction in northwest/west wave energy.

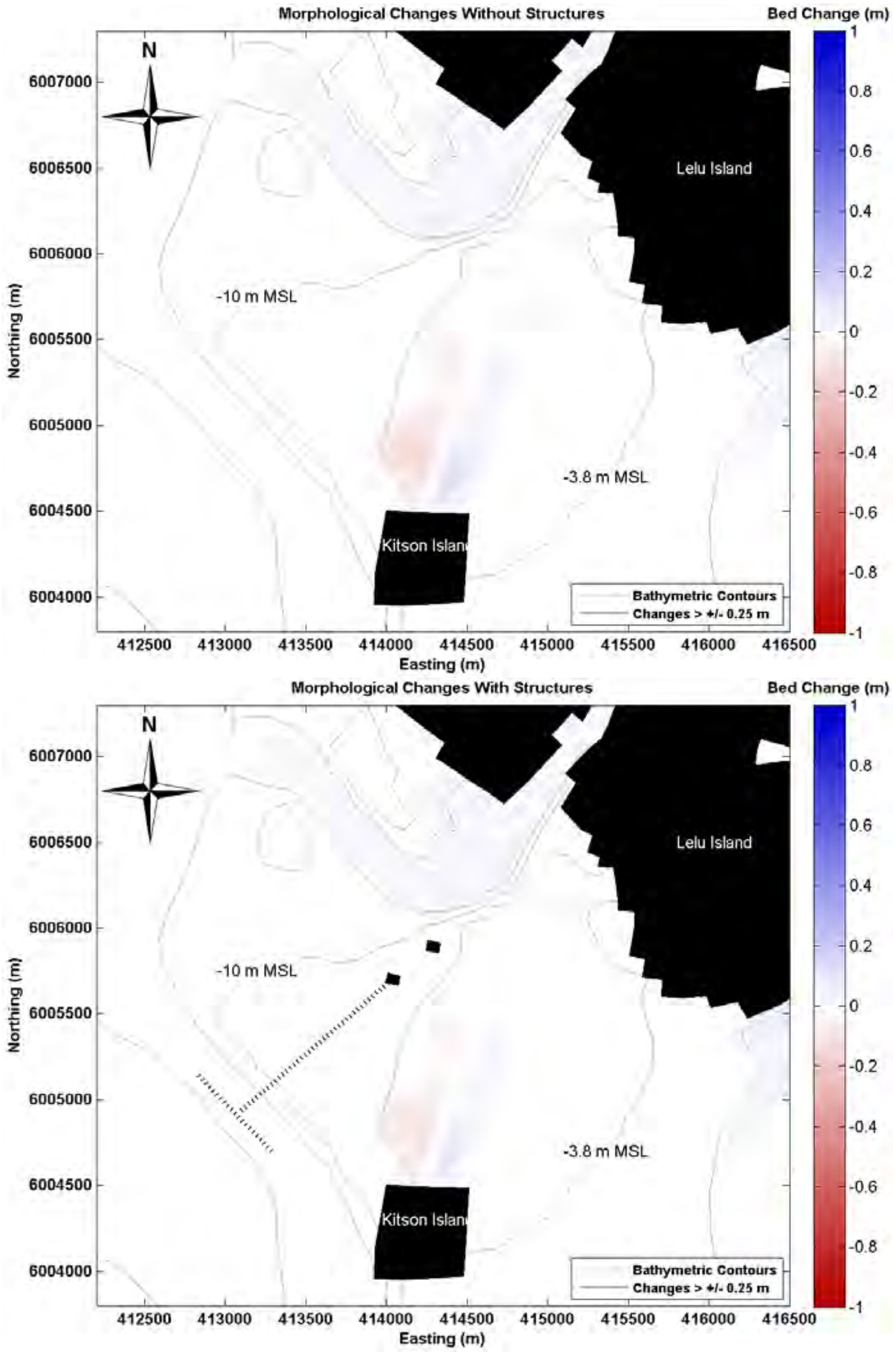
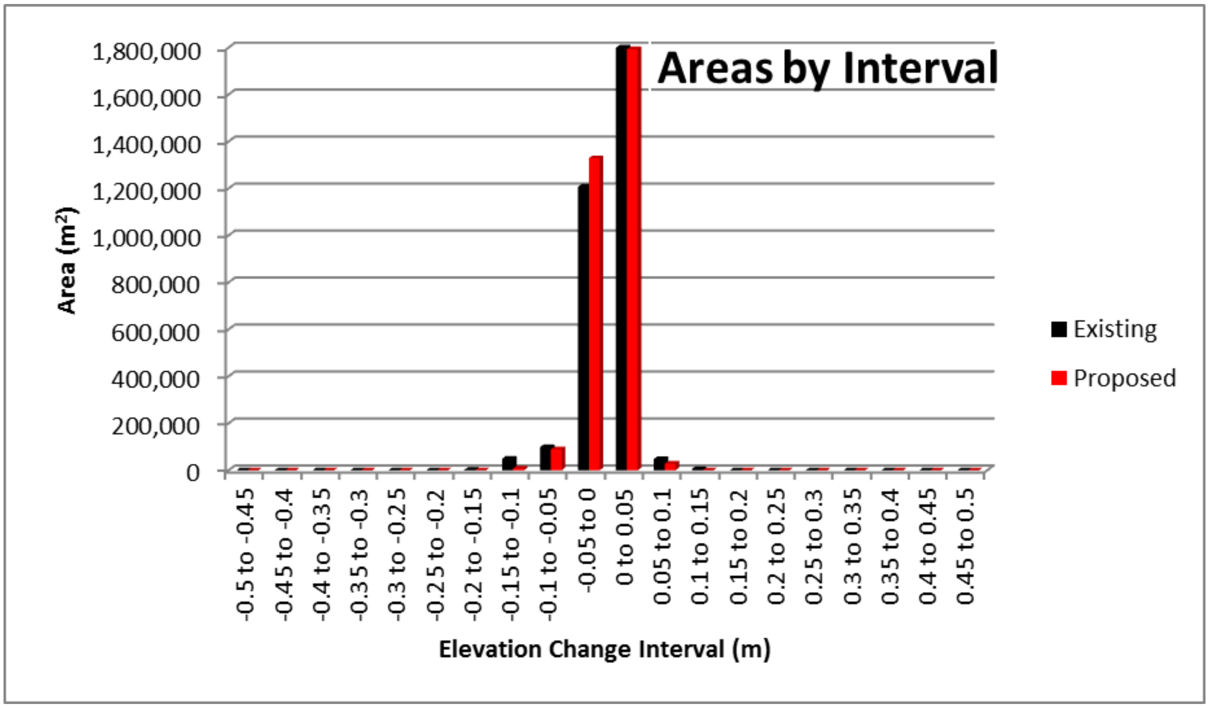


Figure 6-19: Morphological changes predicted during 4 month time series simulation beginning May 1, 2013 with 3-hour coupling, without marine structures (top) and with marine structures (bottom)

Table 6-4: Volumes of Change During 4 month Calmer Period

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m³]	Deposition Volume [m³]	Net Volume [m³]	Erosion Area [m²]	Deposition Area [m²]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
May	**Without**	-24,140	19,800	-4,340	149,850	53,710	-0.01	0.01	0.00
	With	-16,730	14,660	-2,070	97,630	28,180	-0.01	0.00	0.00

Figure 6-20 shows the areas (top) and volumes (bottom) of change organized by bed change intervals of 0.05 m. The results demonstrate that the majority of the changes on Flora Bank are between -0.05 m and 0.05 m, with minimal changes greater than 0.10 m.



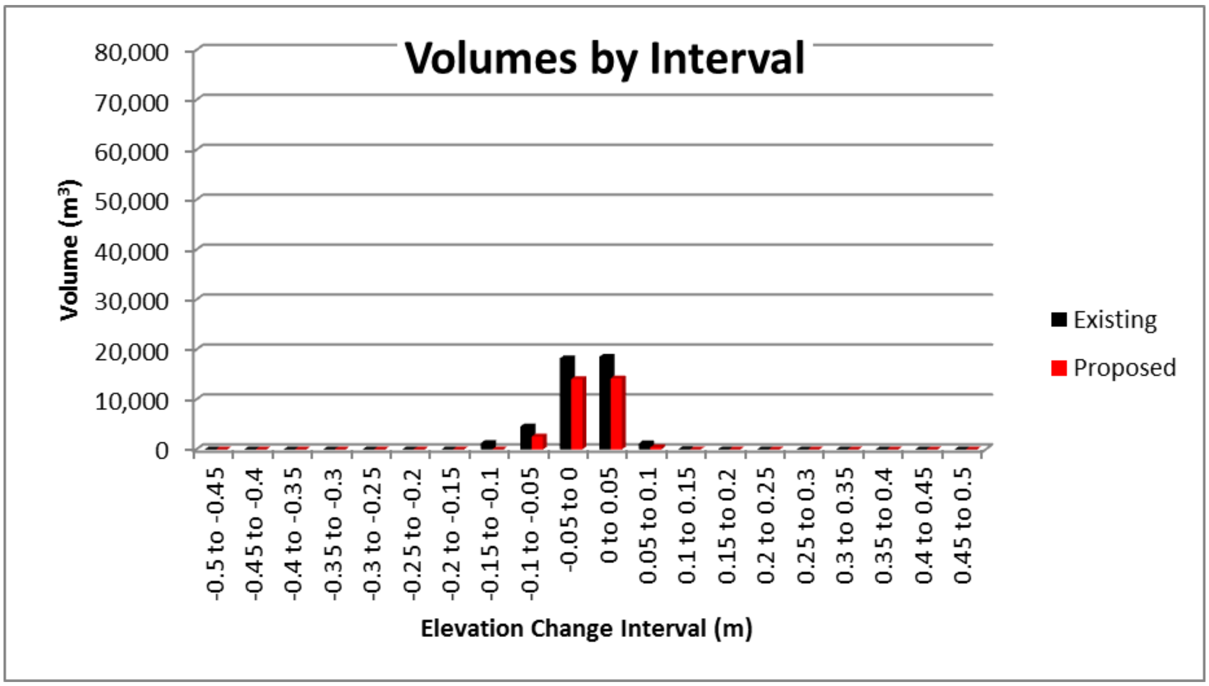


Figure 6-20: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 4 month simulation for existing and proposed conditions.

6.1.4.3 1 year Time Series Simulation with 1-hour Wave-Flow Coupling

This simulation was performed beginning September 1, 2012 for 1 year, and included a complete range of coastal processes and stormy periods with high winds and waves, as well as the freshet period. This simulation also included highly detailed (frequent) coupling between the wave and flow models (1-hour coupling). The identical simulation presented in Section 5.3.4.3 was repeated with the marine structures in place to evaluate potential impacts on coastal processes and the morphology of Flora Bank.

Figure 6-21 (top) shows that without the marine structures, some bed elevation changes do occur over Flora Bank during the 1 year period beginning September 1, 2012, which includes a complete range of coastal conditions and relatively strong wave activity. Maximum bed elevation changes are approximately 55-60 cm near Kitson Island, which is a relatively energetic location with stronger waves and currents, and bed changes are not likely to be measurable elsewhere on Flora Bank. Figure 6-21 (bottom) shows the bed changes with the marine structures in place. As for all other simulations performed to date (storms, freshet periods), since the marine structures slightly attenuate waves from the northwest and west, the effect of the marine structures is to slightly dampen the process of local erosion and deposition that occurs on Flora Bank. Also as found in all other time series results, the erosion occurs primarily on the southwest edge of Flora Bank, with material moving with the waves until they are reduced in height and can no longer transport the material, producing deposition directly to the east of the erosive areas.

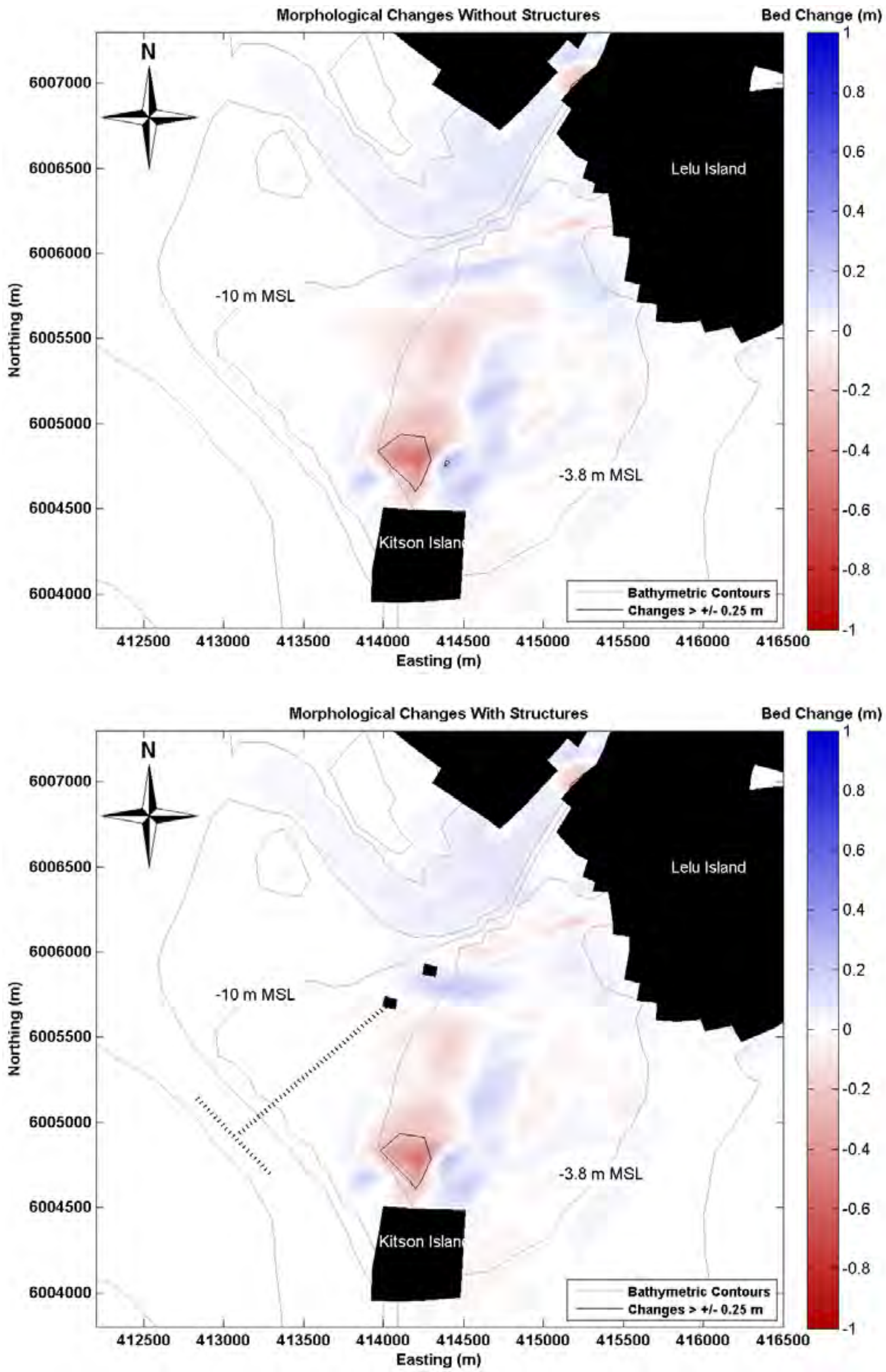


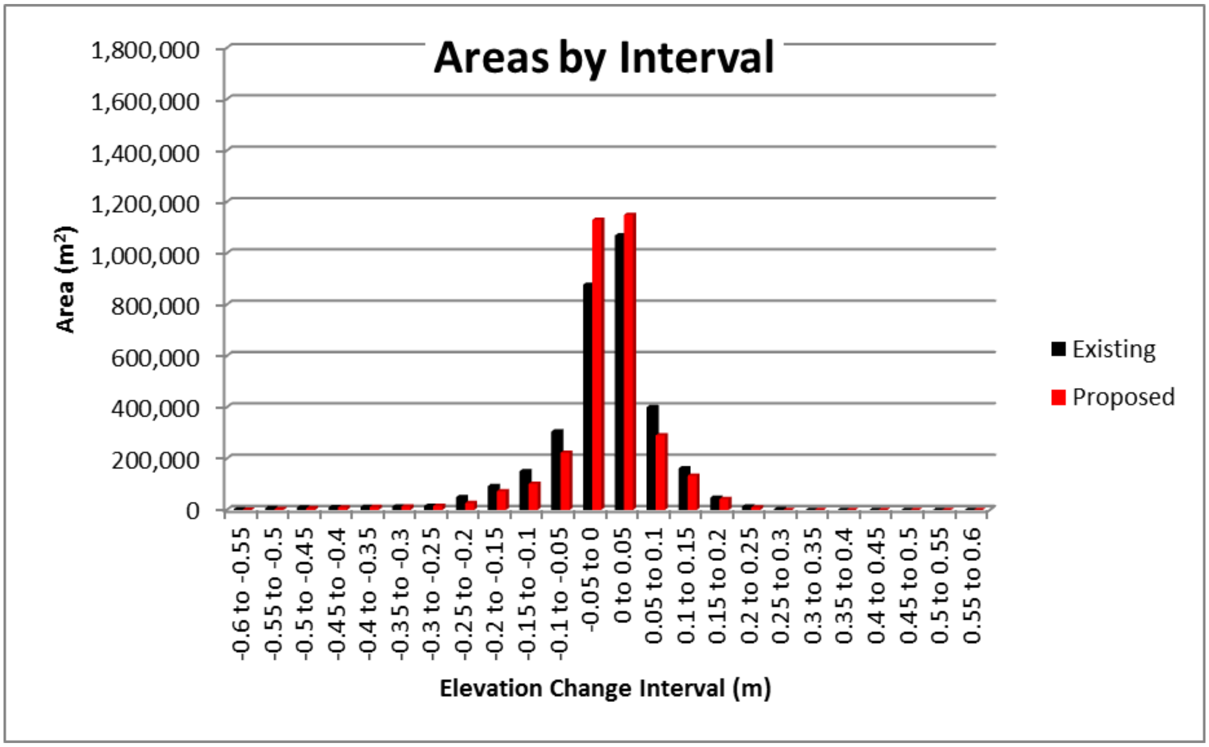
Figure 6-21: Morphological changes predicted during 1 year time series simulation covering stormy period beginning September 1, 2012 without marine structures (top) and with marine structures (bottom).

Bed change results were analyzed to determine the trends in erosion and deposition patterns, volumes, and net changes on Flora Bank over the 1 year period starting from September 1, 2012. These results are presented in Table 6-5. Results indicate that while the changes are larger than during calm periods, the influence of the marine structures is still to reduce the volumes of both erosion and deposition that occur.

Table 6-5: Volumes of Change During 1 year Period

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
Sept	**Without**	-112,590	83,840	-28,750	670,930	628,570	-0.03	0.03	0.00
	With	-94,090	69,350	-24,740	488,350	478,400	-0.03	0.02	-0.01

Figure 6-22 shows the areas (top) and volumes (bottom) of changes organized by bed change intervals of 0.05 m. The results demonstrate that the majority of the changes on Flora Bank are between -0.15 m and 0.15 m, with minimal changes greater than 0.25-0.30 m.



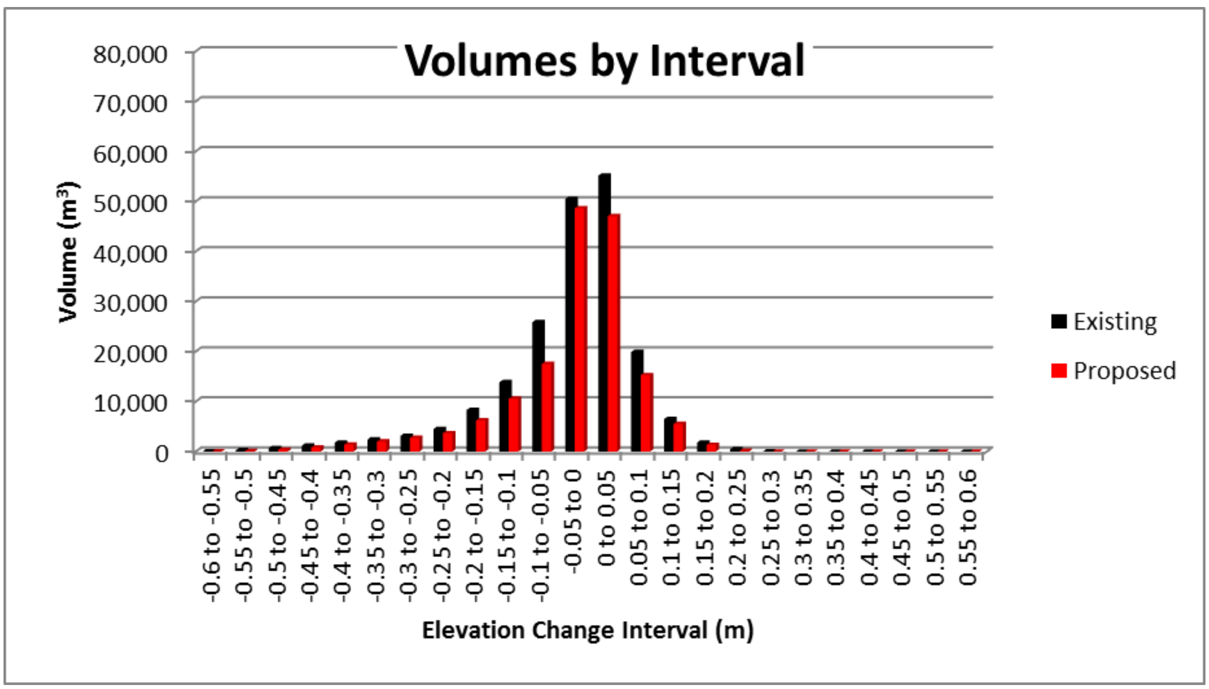


Figure 6-22: Changes in area (top) and volume (bottom) organized by bed change intervals of 0.05 m during the 1 year simulation for existing and proposed conditions.

6.1.4.4 8-month Sensitivity Testing Time Series Simulation with No Waves

This simulation was performed beginning September 1, 2012 and ending April 30, 2013 (8 full months). This simulation included all coastal processes except waves, and had naturally lower river flows since it did not include the freshet period. The identical simulation presented in Section 5.3.4.4 was repeated with the marine structures in place to evaluate potential impacts on coastal process and the morphology of Flora Bank in the absence of wave activity.

Figure 6-23 shows bed elevation changes predicted at the end of the 8-month simulation from September 1, 2012 to April 30, 2013, that does NOT include waves. Overall, even over the entire 8-month period of time, erosion and deposition only occurs in measurable amounts within Porpoise Channel and Inverness Channel, where tidal currents are stronger. In the absence of waves, no measurable bed elevation changes are predicted over Flora Bank, even over this continuous 8-month period which includes complete tidal and river hydrodynamic effects. Note also that Figure 6-23 uses a finer colour scale of ± 0.1 m.

Results from the 8-month continuous simulation without waves indicate that waves control the vast majority of morphological change on Flora Bank. During this simulation period, the marine structures have a negligible effect on sediment transport and morphology on Flora Bank.

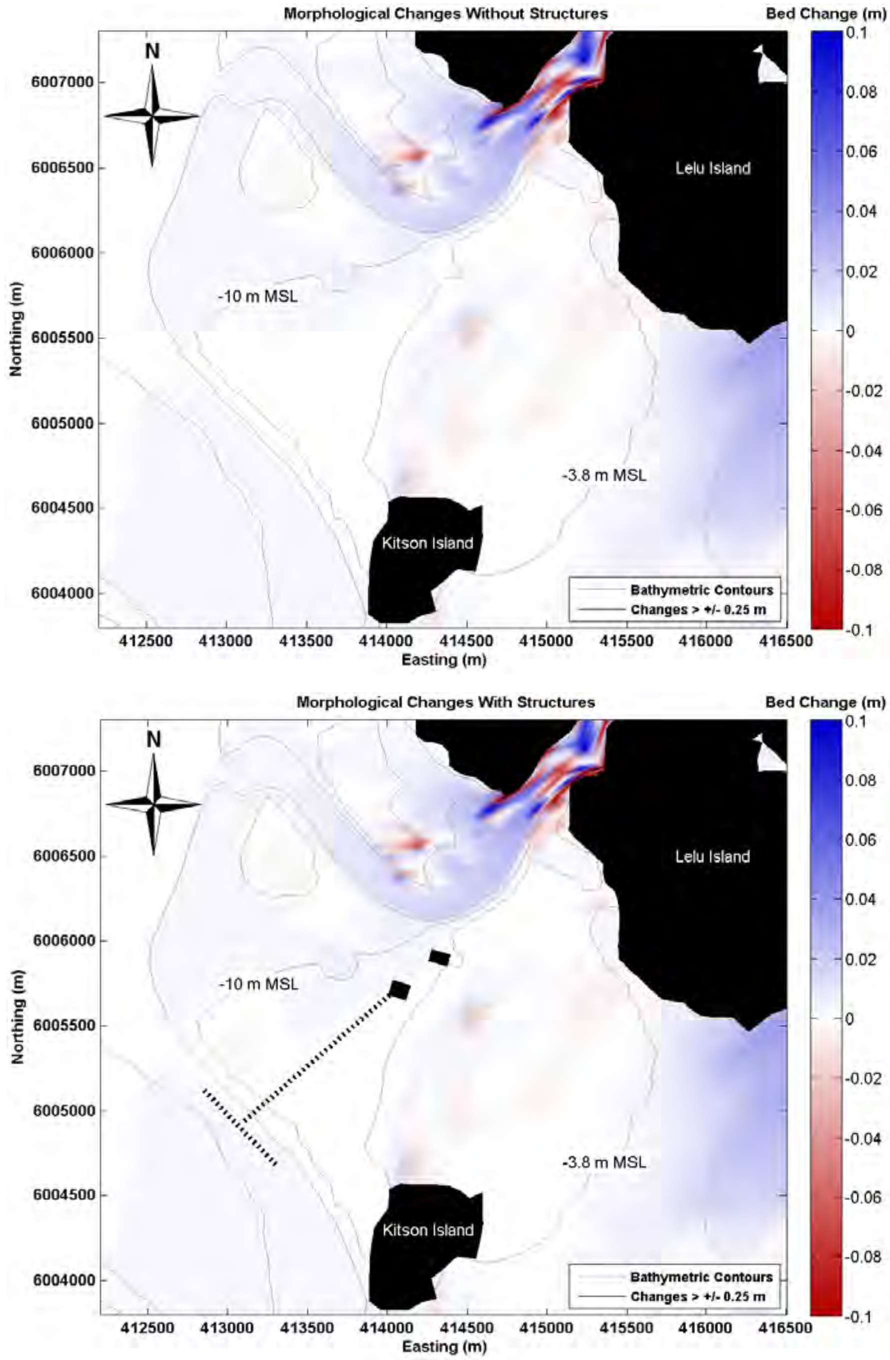


Figure 6-23: Morphological changes predicted during 8-month time series simulation September 1, 2012 to April 30, 2013 with no waves for existing (top) and proposed (bottom) conditions. NOTE: ± 0.1 m color scale.

6.1.5 *Summary of Time Series Simulations with Marine Structures*

A set of time series simulations covering a complete range of coastal processes were performed including one 8-month long simulation during the stormy periods as well as two year-long simulations starting in September 2012, and in May 2013 which are included in Appendix H. Sensitivity testing simulations were also performed to evaluate the relative influence of wave activity on Flora Bank morphological changes, as well as the importance of wave-flow model coupling on the predicted bed elevation changes.

The results of the time series simulations consistently show the following:

- Regardless of the time of year being modelled, or the duration of the time series simulation, the locations of erosion and deposition on Flora Bank are relatively consistent.
- Bed elevation changes on Flora Bank are almost entirely dependent on how much wave activity the time period contains. Therefore, modelling long time periods that do not include significant wave energy (such as the May to August period) provides little further information about the morphology of Flora Bank.
- The marine structures tend to slightly attenuate the levels of erosion and deposition that occur on Flora Bank during periods of heavy wave activity as they slightly reduce the incoming wave energy. There are no areas that showed measurable divergence from trends observed in the existing conditions modelling results.
- No measurable deposition of fines was predicted due to the slight attenuation effects of the marine structures.

In aggregate, the results of the longer-term “time series” simulations provide insight into the potential effects of the marine structures that are entirely consistent with results from storm simulations and freshet simulations.

6.1.6 *Sensitivity Testing Simulations for Understanding Long-Term Implications of Storms and Marine Structure Impacts*

A series of simulations were performed using synthetic input conditions to develop additional information on the likely changes on Flora Bank following a succession of storms, as well as the potential impacts of the marine structures following more occurrences of extreme events with varying severity and from varying directions. The intent of these hypothetical synthetic storm simulations is to speak further to any long-term impacts of the marine structures or impacts that may occur due to a particular sequence of storms, and evaluate whether those impacts compound in some way due to multiple events.

Figure 6-24 shows the time history of wind speeds and directions that are included in the simulation, in addition to a constant Pacific Ocean background swell and typical daily tides and tidal currents. Each of the storm curves developed for single storm simulations (see Appendix G) was truncated and installed back to back in the time series, and directions from the south, southwest, west, and northwest were prescribed. The order of these storms and directions were selected randomly without any prescribed methodology. Simulations were performed with the new 6-class sediment size distribution that consists of all sands ranging from 0.1 to 0.5 mm in diameter, with the distribution taken from the SedTrend (2015) corrected data.

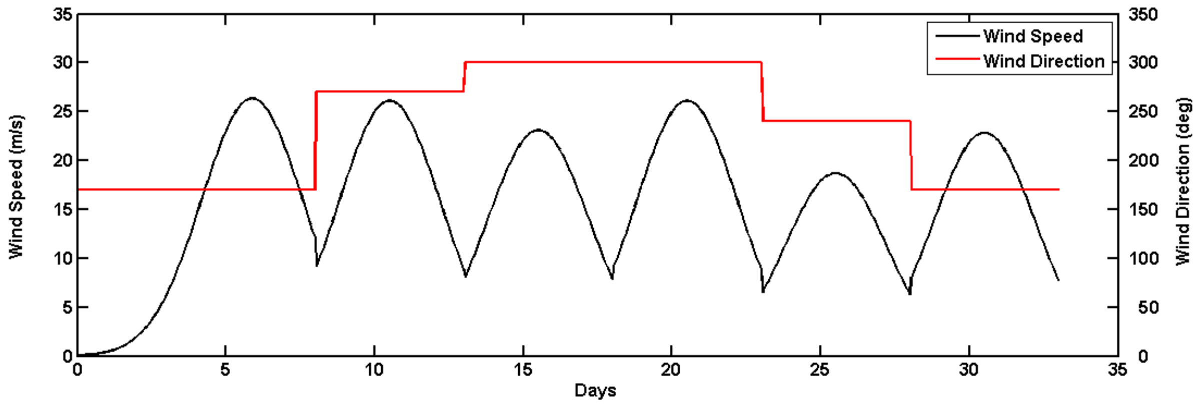


Figure 6-24: Synthetic and hypothetical series of 6 separate extreme events from varying directions occurring back to back during 33 day simulation.

First, sensitivity analysis was performed to determine differences in morphological change on Flora Bank for the 33 day hypothetical synthetic series of storms in comparison to a single 50-year storm from 270^{o} True North. Figure 6-25 shows morphological changes following a single 50-year storm simulation from 270^{o} True North (top) and changes following a synthetic and hypothetical series of 6 separate extreme events from varying directions occurring back to back during a 33 day simulation (bottom).

The 33 day series of storms causes significantly more bed elevation changes, in particular over Agnew Bank. On Flora Bank, a similar pattern of changes is observed (similar areas are erosional and similar areas are depositional), but the changes are larger in magnitude for the series of storms. Given that the same areas are erosional and depositional, it appears that the series of storms generates changes on Flora Bank that are conceptually similar to those generated during a single storm. Relatively small bed changes occur on Flora Bank even for the massive series of over-conservative super storms, speaking volumes to the long-term stability of Flora Bank.

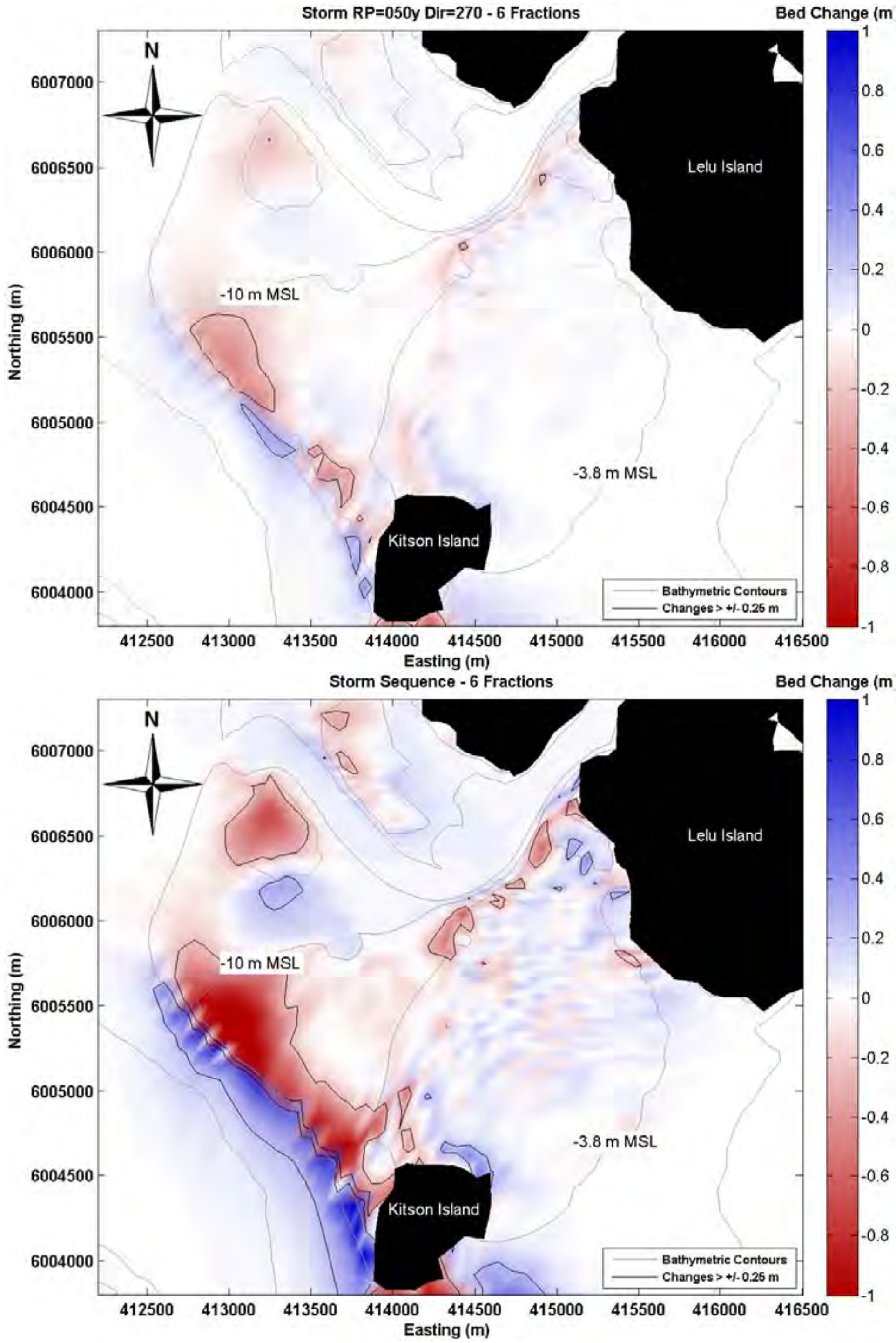
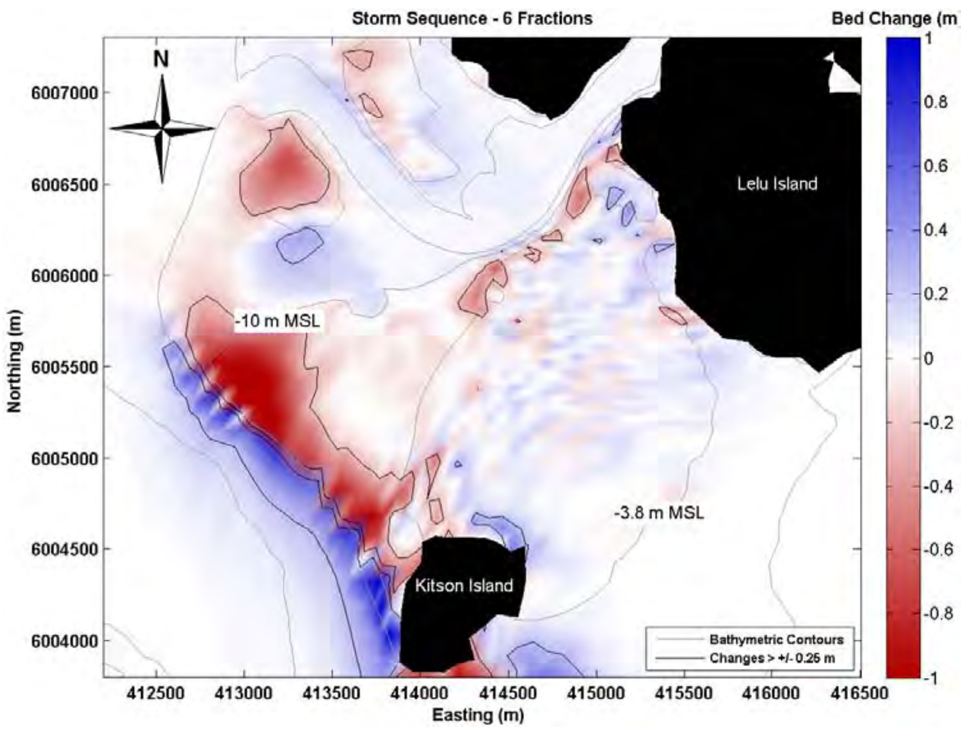


Figure 6-25: Bed elevation changes predicted following the 50-year storm (top panel) and following the hypothetical synthetic 33 day storm series (bottom panel) using the revised 6 sediment fractions.

Figure 6-26 shows morphological changes following a synthetic and hypothetical series of 6 separate extreme events from varying directions occurring back to back during 33 day simulation, without marine structures (top) and with marine structures (bottom). The revised sediment grain size distribution (6 sand fractions) was used. Results from the 6-storm simulation continue to indicate, as in all other simulations performed to date, that the marine structures tend to slightly attenuate the levels of erosion and deposition that occur on Flora Bank. This result is consistent with the results of the many individual storm events that have been simulated.

Comparison of bed changes following single storms and the storm series indicates that changes occur in similar places on Flora Bank, meaning that long-term implications (variability of storm direction and magnitude, and number of storms over time) can be reasonably addressed using the range of single storms that were simulated in the analysis. Also, the impacts of the marine structures, specifically the relative magnitudes of change they cause during energetic storm events, and the slight reduction in those changes they generate, appear to be reasonably addressed through evaluation of the wide array of individual storm events in this analysis.



Safety ● Quality ● Sustainability ● Innovation

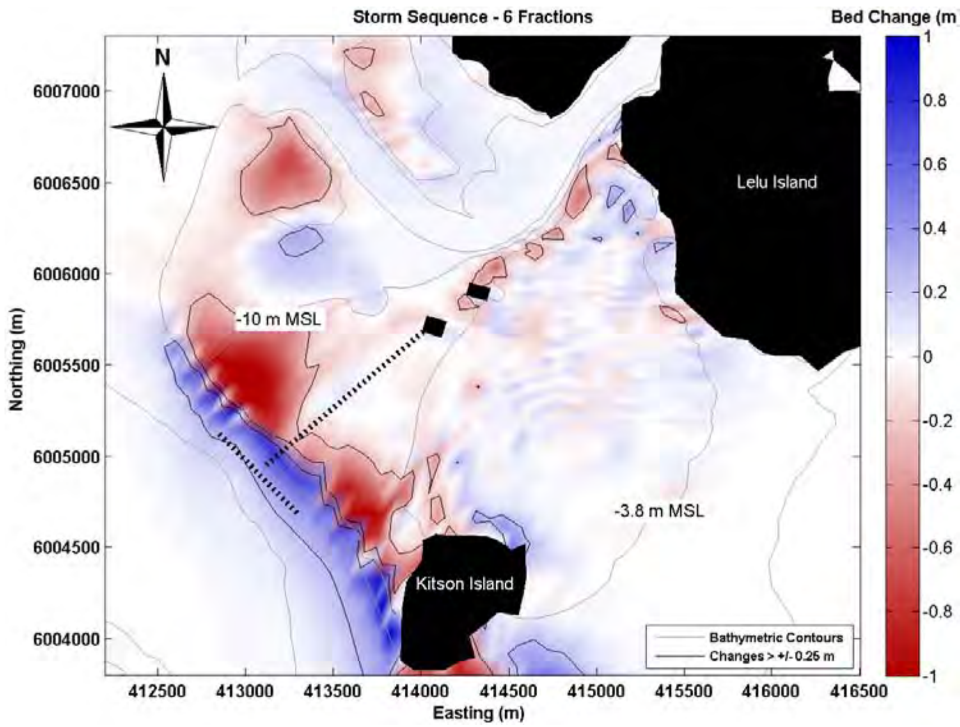


Figure 6-26: Bed elevation changes predicted following the hypothetical synthetic 33 day storm series without marine structures (top panel) and with marine structures (bottom panel) using the revised 6 sediment fractions.

6.1.7 Summary of Regional Modelling

The Delft3D model provides accurate large-scale physical processes for insight into coastal processes and a conservative evaluation of the potential impacts of the marine structures on the morphology of Flora Bank (trestle in particular). Results indicate that measurable erosion and deposition occurs on Flora Bank episodically only under strong wave forcing, and during lower water levels. Since most of the bed elevation changes occur due to the presence of waves, the trestle structure and its mild wave height attenuation reduces the magnitudes of both erosion and deposition on Flora Bank.

Results indicate that longer-term simulations that contain many smaller storms produce small bed elevation changes similar to individual storms, since they have similar resulting wave heights on top of the shallow Flora Bank. Longer-term simulations without any significant wave activity show negligible bed changes on Flora Bank and hence provide no further information as to potential morphological effects of the marine structures. In all of the longer-term time series simulations, as well as freshet and storm event simulations, the marine structures cause a slight reduction in erosion, and a reduction in the associated nearby deposition, on Flora Bank.

The localized effects of the larger marine structures (SW Tower and SW Anchor Block) occur at a scale below the resolution of the regional model. Therefore the larger-scale hydrodynamic conditions from the Delft3D model were used further to drive high-resolution modelling of freshet conditions, 50-year storm conditions and conditions with tides-only forcing to provide detailed evaluation of localized impacts to hydrodynamics, transport and morphology.

6.2 High-Resolution Modelling of the SW Tower and SW Anchor Block

High-resolution modelling of hydrodynamics and transport around the larger marine structures was performed to resolve fine-scale coastal processes and evaluate potential impacts in greater detail. Results from the high-resolution modelling include detailed local hydrodynamics around the SW Tower and SW Anchor Block (including vortex shedding effects), sediment transport and morphological change induced by the presence of the structures. The sediment sizes used for the high-resolution modelling are based on the revised SedTrend Data (Sedtrend, 2015). Background is first provided regarding potential effects of the marine structures, which are similar to bridge piers which are commonly studied in hydraulic engineering.

6.2.1 Laboratory Studies on Influence of Marine Structures

Numerous laboratory and field studies have been performed to evaluate the influence of bridge piers (similar to the larger PNW LNG marine structures), specifically the scour and deposition patterns that form around them when subjected to waves and currents. The relationships between current velocity (relatively low), water depth (very low), sediment size (relatively large) and structure diameter (large) for the SW Tower and SW Anchor Block are somewhat outside the bounds of what has been previously studied in the laboratory. Even the field studies that are available (Whitehouse 2004, Whitehouse et al 2010) have significantly larger water depth-to-structure diameter ratios and other factors that render them less applicable to the present analysis.

In general, both field studies and scour evolution empirical models (Escarameia & May, 1999; Harris et al, 2010) show that when water depths are small relative to the structure diameter, equilibrium scour depths and thus equilibrium scour extents are significantly reduced. Whitehouse et al (2010) supports this same conclusion across a number of offshore structures in distinct seabed sediment types (although the water depth-to-structure diameter ratios were still much higher, ranging from 0.6 to 3.5). Given the much smaller water depth-to-structure diameter ratio (approximately 0.1 at MSL) for the SW Tower and SW Anchor Block, and trends reviewed in the literature, the scour potential can reasonably be assumed to be less than predictions from other studies focused on structures where the water-depth-to-structure diameter is 1 or larger. However, in even the more conservative of these types of studies (studies that show larger scour depths and extents), the extents of measurable scour are limited to a few structure diameters away from the structure itself.

Given the complexities of the combination of parameters involved, numerical modelling was also utilized to evaluate scour and scour extents. Further discussion of the expected scour and time scales over which scour is expected to occur is provided in Section 6.4.

6.2.2 High-Resolution Simulations

The MORPHO model, described in Section 4.2, was used in the following high-resolution simulations to evaluate the hydrodynamics, sediment transport and erosion/deposition surrounding the proposed SW Tower and SW Anchor Block:

- 28 day freshet period;
- 50-year storm condition from the west (270^o); and,
- 28 day period with only tidal forcing included. The tides-only simulations are summarized in Appendix J.

6.2.3 Freshet Conditions Simulations

MORPHO simulations were performed for the 28 day freshet period previously described in the regional modelling to evaluate potential impacts of the marine structures on a finer scale during periods with typical tidal current conditions, mild waves and high Skeena River flows. The MORPHO model was forced by the regional Delft3D model results as described in Appendix J.

6.2.3.1 Hydrodynamics During Freshet Conditions

Fine-scale hydrodynamics around the proposed SW Tower and SW Anchor Block were a focus of the analysis and hence are described in detail here. The structures are located in an area subject to a wide, relatively homogenous flow field, and therefore represent isolated individual structures. Local hydrodynamic effects including vortex shedding are expected and have the potential to influence local sediment transport and morphology around the structures.

During the 28 day freshet simulation, the peak flood-directed current speeds (when Flora Bank is downstream of the marine structures) were approximately 0.25-0.30 m/s. For comparison during the tides-only simulations, the currents speeds were less than approximately 0.2 to 0.25 m/s at all times since no wind or wave activity was included. Analysis indicates that the frequency of vortex shedding from each of the structures is within expected ranges from theory considering the sizes of the structures and hydrodynamic conditions they experience.

Figure 6-27 shows instantaneous snapshots of flow fields around the SW Tower and SW Anchor Block during typical ebb currents (top) and typical flood currents (bottom). The presence of the marine structures generates vortex shedding as expected based on known hydrodynamic principles. The shedding occurs more frequently for the smaller SW Tower structure, and with stronger intensity due to its shape and orientation with the flow. Vortices are dissipated more quickly on flood currents since they move into shallower water. The eddying effects are generally noticeable within 8-10 structure diameters away.

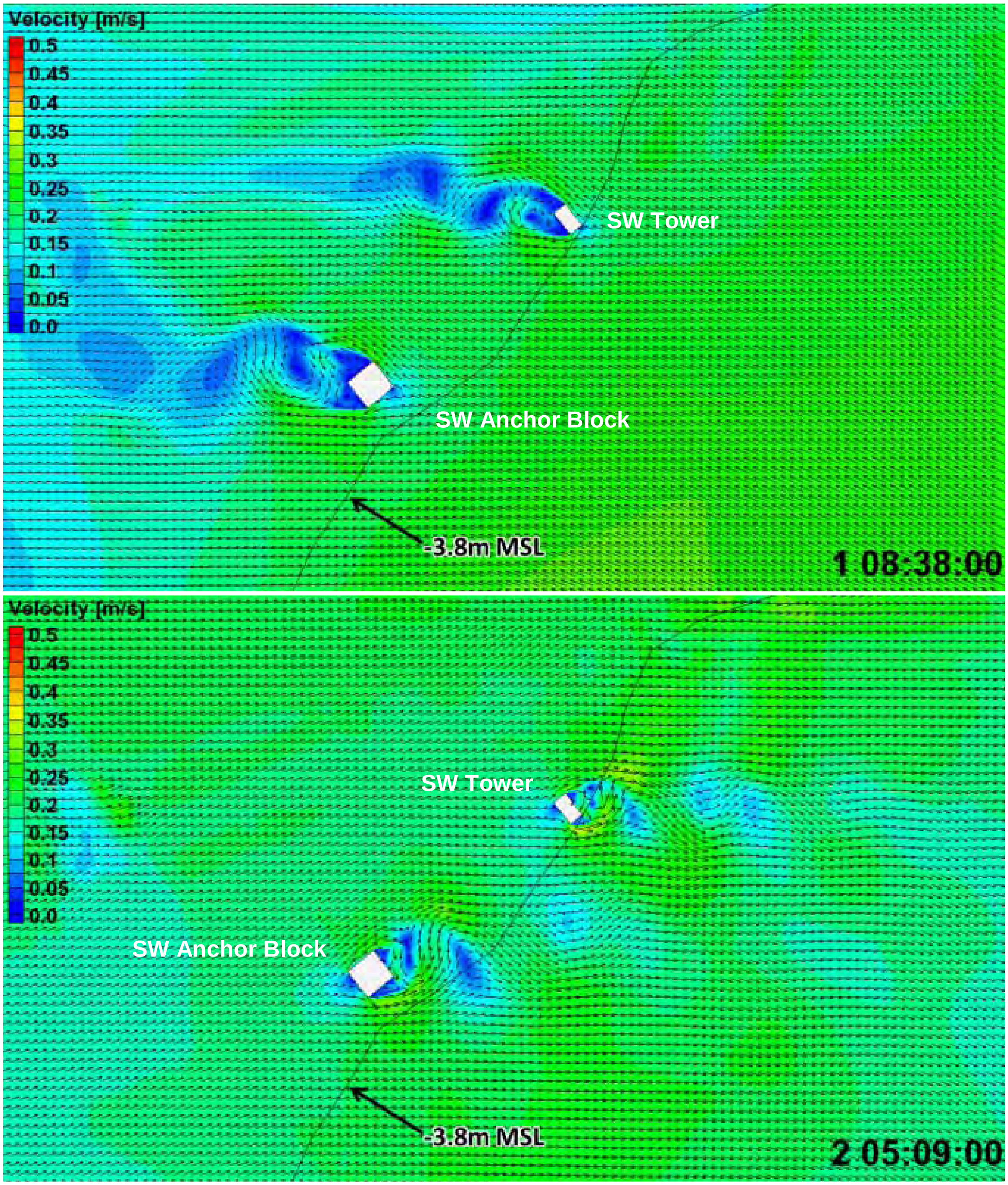


Figure 6-27: Hydrodynamics around marine structures during typical ebb current (top) and typical flood current (bottom)

Figure 6-28 shows the maximum instantaneous current speed at every point within the domain during the 28 day freshet simulation for existing conditions (top panel left, structures only shown for reference), with marine structures (top panel right), and the changes in maximum current speed at each point (bottom panel). This is a stringent way to calculate velocity changes due to the structures (i.e. a method that demonstrates small differences to the maximum extent possible) by computing the maximum speed during the entire simulation at every point in the domain for existing conditions, and with marine structures, and performing a subtraction. Changes in Figure 6-28 (bottom panel) indicate how the highest velocity in the simulation at every point was either increased or decreased by the presence of the marine structures. A time history provided with Figure 6-28 (bottom panel inset) shows that although an increase or decrease may have occurred at one instance in time (or typically at the time of each peak current), overall the general time history of current speed and hence sediment transport is similar.

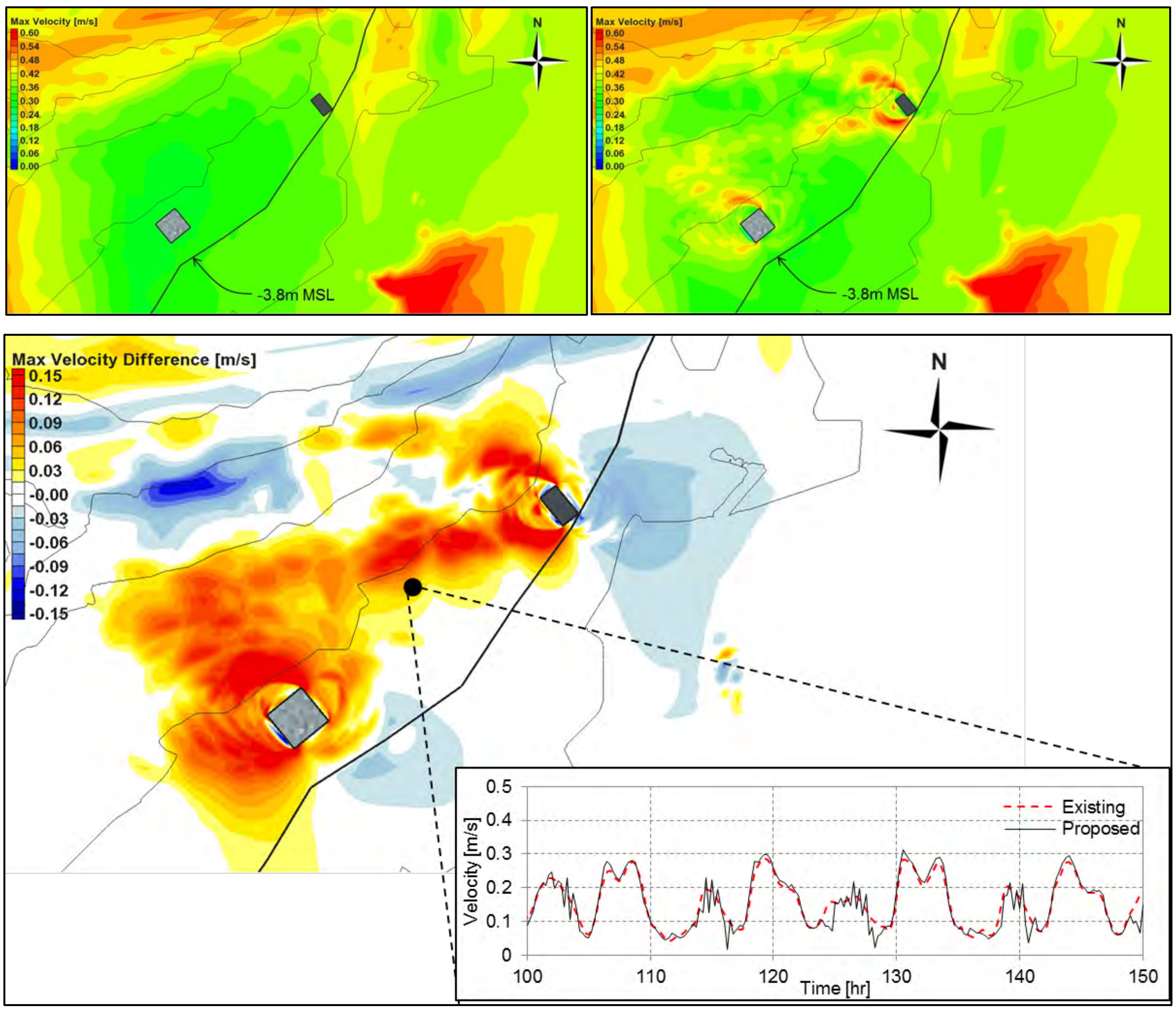


Figure 6-28: Maximum instantaneous current speed at every point in the domain during the 28 day freshet simulation without marine structures (top left) and with marine structures (top right). At bottom is the computed difference in maximum instantaneous current speed and inset showing typical current speed time histories with and without the marine structures in an area of velocity increase.

6.2.3.2 *Sediment Transport and Morphology During Freshet Conditions*

Sediment transport modelling was performed using the MORPHO model for the 28 day freshet conditions simulation. The 28 day tides-only conditions simulation results are presented in Appendix J. For the larger-scale MORPHO model, transport and erosion/deposition were simulated separately for each marine structure with different sediment sizes: mean grain diameter 0.14 mm, representative of the SW Anchor Block area, and mean grain diameter 0.3 mm, representative of the SW Tower area. Simulations included scour protection with a width of 10 m around the SW Tower, and 15 m around the SW Anchor Block. Scour protection was simulated in the modelling as a zone of non-erodible hard bottom flush (inset) with the surrounding bed elevation. The hard bottom used the same relatively low roughness used elsewhere, resulting in higher velocities than are likely to be found over the proposed rip-rap. Further details on the sediment transport modelling are provided in Appendix G and the proposed scour protection are provided in Appendix K.

Figure 6-29 shows the erosion and deposition pattern induced by the SW Anchor Block structure (0.14 mm-diameter sediments, top) and induced by the SW Tower structure (0.3 mm diameter sediments, bottom) after simulation of 28 days of freshet conditions. The existing conditions erosion and deposition patterns have been subtracted from the results to clearly show the changes only due to the marine structures. The lines over Flora Bank with different colours (yellow, green, pink and blue) indicate the mapped locations of eelgrass from recent surveys.

Without the marine structures, the modelling results showed no significant erosion or deposition at the location of the marine structures, indicating that the area is in a state of dynamic equilibrium. For reference, freshet simulations without scour protection were performed and results showed significantly higher levels of scour at all corners of the structures. Without scour protection, scour at individual grid points exceeded 2.6 m and 0.6 m at the worst-case corners of the SW Anchor Block and SW Tower, respectively. Results indicate that the scour protection system significantly limits maximum scour depths, but spreads the scour at 5 cm level over a slightly wider area. This is primarily due to less sediment scoured from the face of the structure being deposited there.

Scour on the outside edge of the scour protection system during this period was approximately 0.05 and 0.13 m at the SW Anchor Block and SW Tower, respectively. Results indicate that the vortex shedding and oscillating current directions tend to cause the material eroded from the vicinity of the structures to be spread thinly over the bed in downstream areas, with the majority of material deposited on the west side since ebb-directed currents are stronger and net currents are directed to the west.

Figure 6-30 shows the erosion and deposition pattern induced by the SW Anchor Block structure with simulation of 0.14 mm-diameter sediments (top) and induced by the SW Tower structure with simulation of 0.3 mm-diameter sediments (bottom), both after one full year, using linear extrapolation from the 28 day freshet simulation results. Scour at the outer edges of the scour protection systems for the SW Anchor Block and SW Tower were approximately 0.6 and 1.6 m, respectively. While the scour will not continue linearly over time, even a linear multiplication of the scour results in erosion rates less than 5 cm per year within a few structure diameters away.

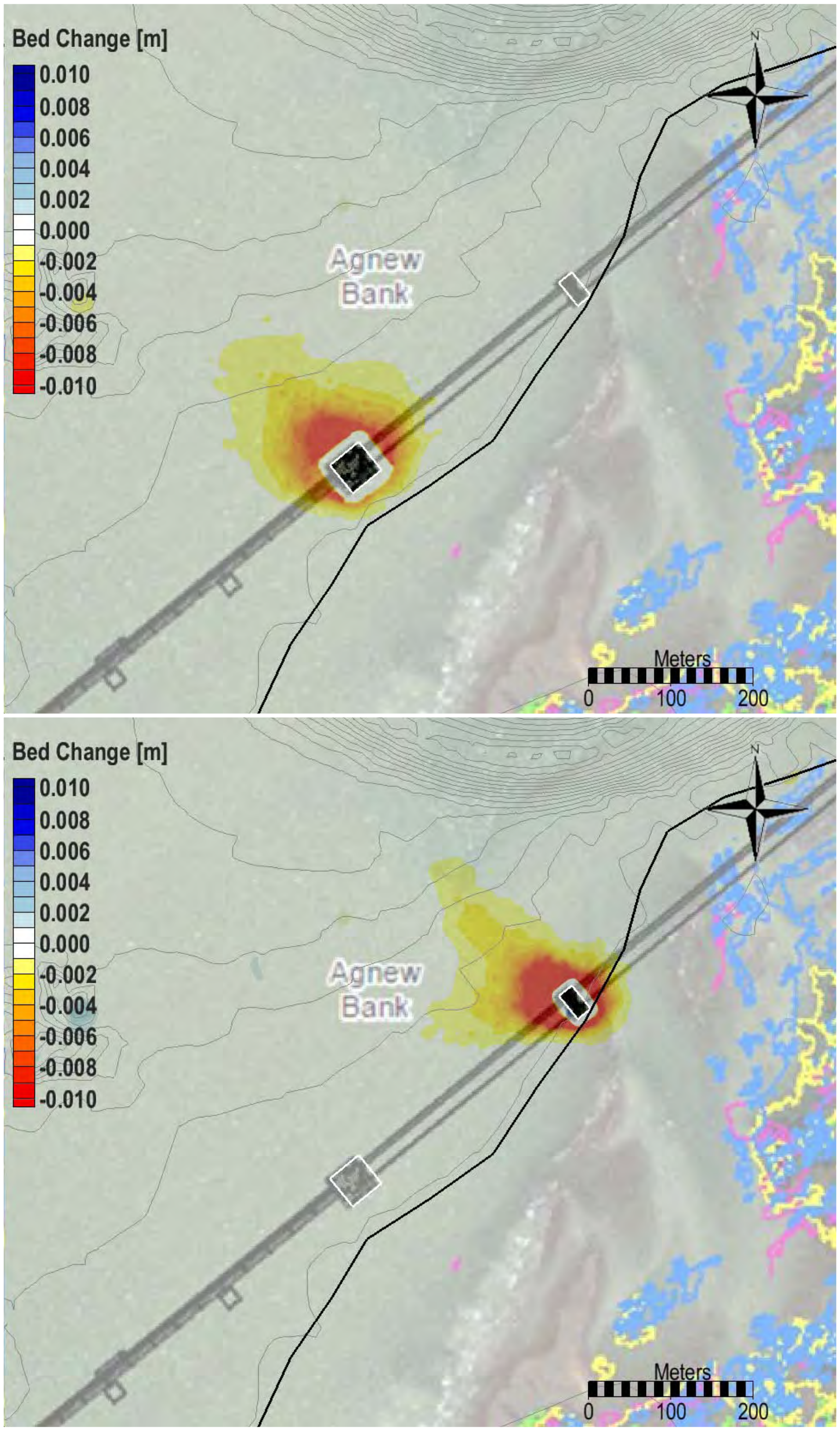


Figure 6-29: Erosion and deposition patterns caused by the marine structures during 28 day freshet simulation for the SW Anchor Block (top) and the SW Tower (bottom). Note that the colour contour scale is ± 1 cm.

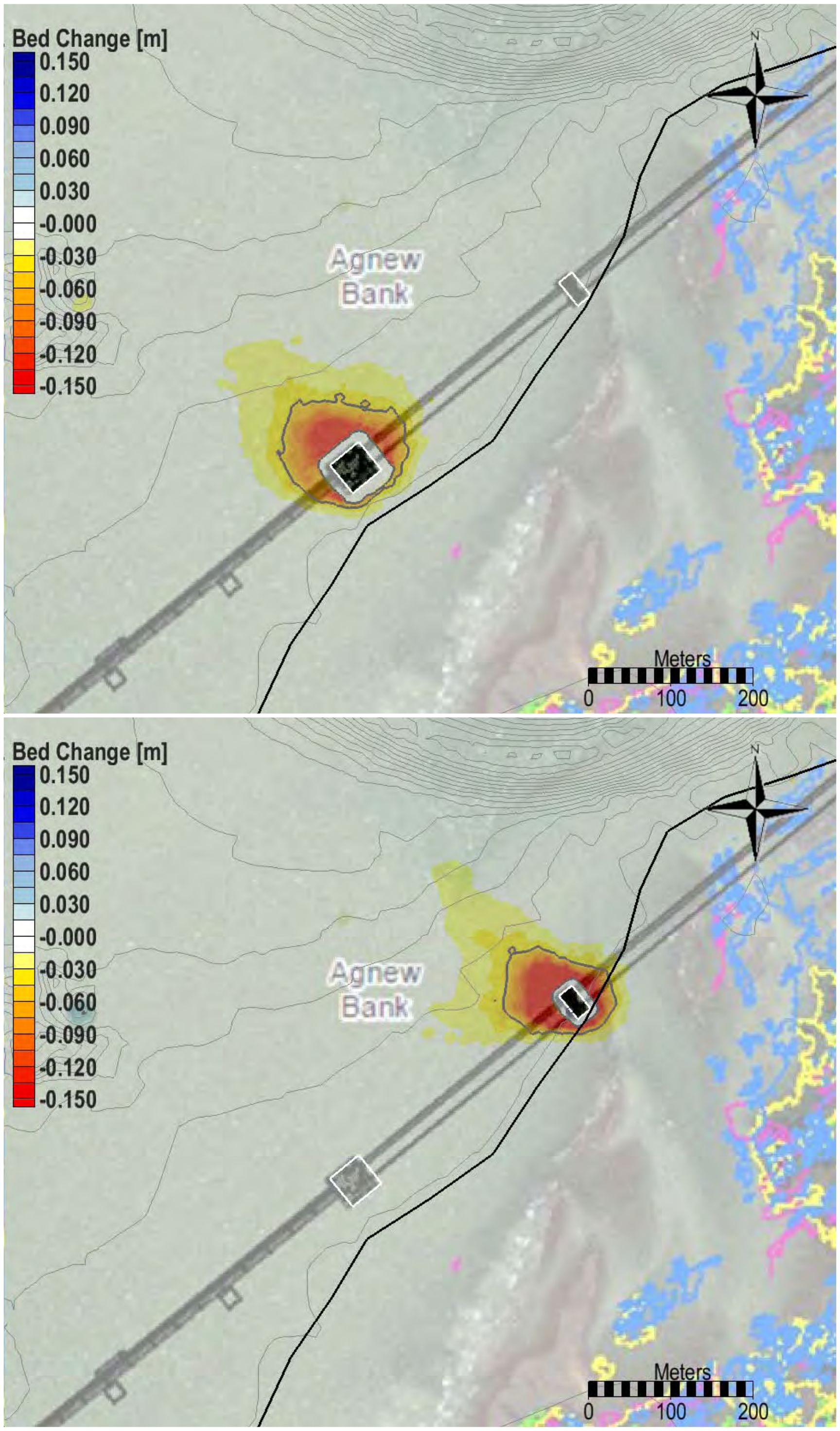


Figure 6-30: Erosion and deposition patterns caused by the marine structures for the SW Anchor Block (top) and the SW Tower (bottom) over a one-year period, extrapolated linearly from results of 28 day freshet simulation. Dark lines indicate changes in excess of 5 cm/year.

The 1 year extrapolated scour results were further processed to provide additional insight into what the erosion and deposition actually looks like from more realistic perspectives, rather than just a red area on a map. Figure 6-31 shows the 1 year extrapolated bed change map with the location of a transect (top right) where original and final bed elevation cross-sections were taken (bottom). Transects taken before and after 1 full year of scour show that slopes are very flat, and changes are hardly noticeable. **Note that this cross-section still has vertical exaggeration of 5:1 so that the changes can be visible.** The maximum 1 year scour on the cross-section of 0.19 m, hardly discernable even with 5:1 vertical exaggeration, occurs on the east side along the edge of the scour protection area.

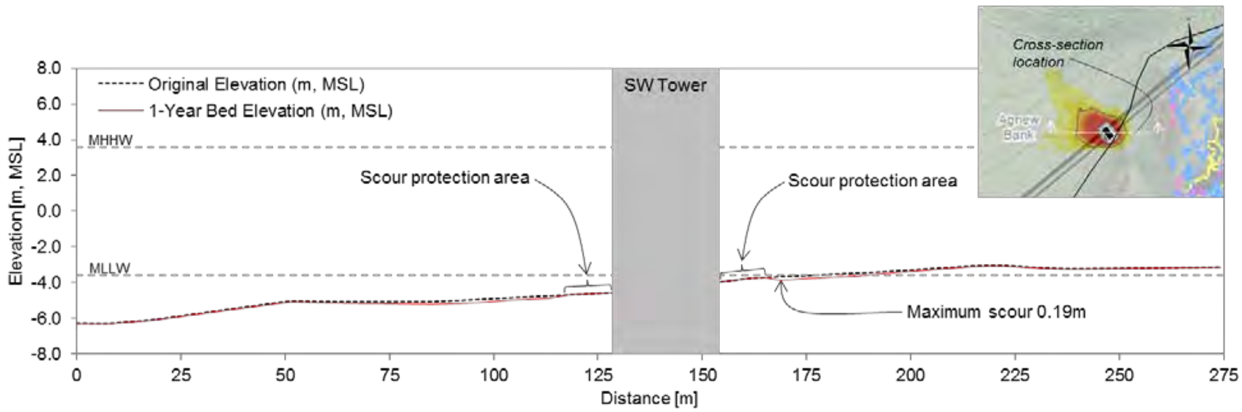


Figure 6-31: Transect showing erosion and deposition around SW Tower after 1 full year (extrapolated from 28 day freshet simulation). *NOTE: transect has vertical exaggeration of 5:1.*

These same 1 year extrapolated scour results were also shown from a 3D perspective in Figure 6-32. The figure first shows the bed condition for existing conditions (top), followed by the bed after 1 year of scour with 5:1 vertical exaggeration (bottom). Vertical exaggeration is included here so that the bed elevation changes will be visible to the reader. The changes shown here are clearly not likely to cause material impacts to habitat and areas of Flora Bank located away from the marine structures since the slopes are very flat, structures are relatively far from eelgrass areas, and erosion and deposition due to the structures are modest and occur relatively slowly.

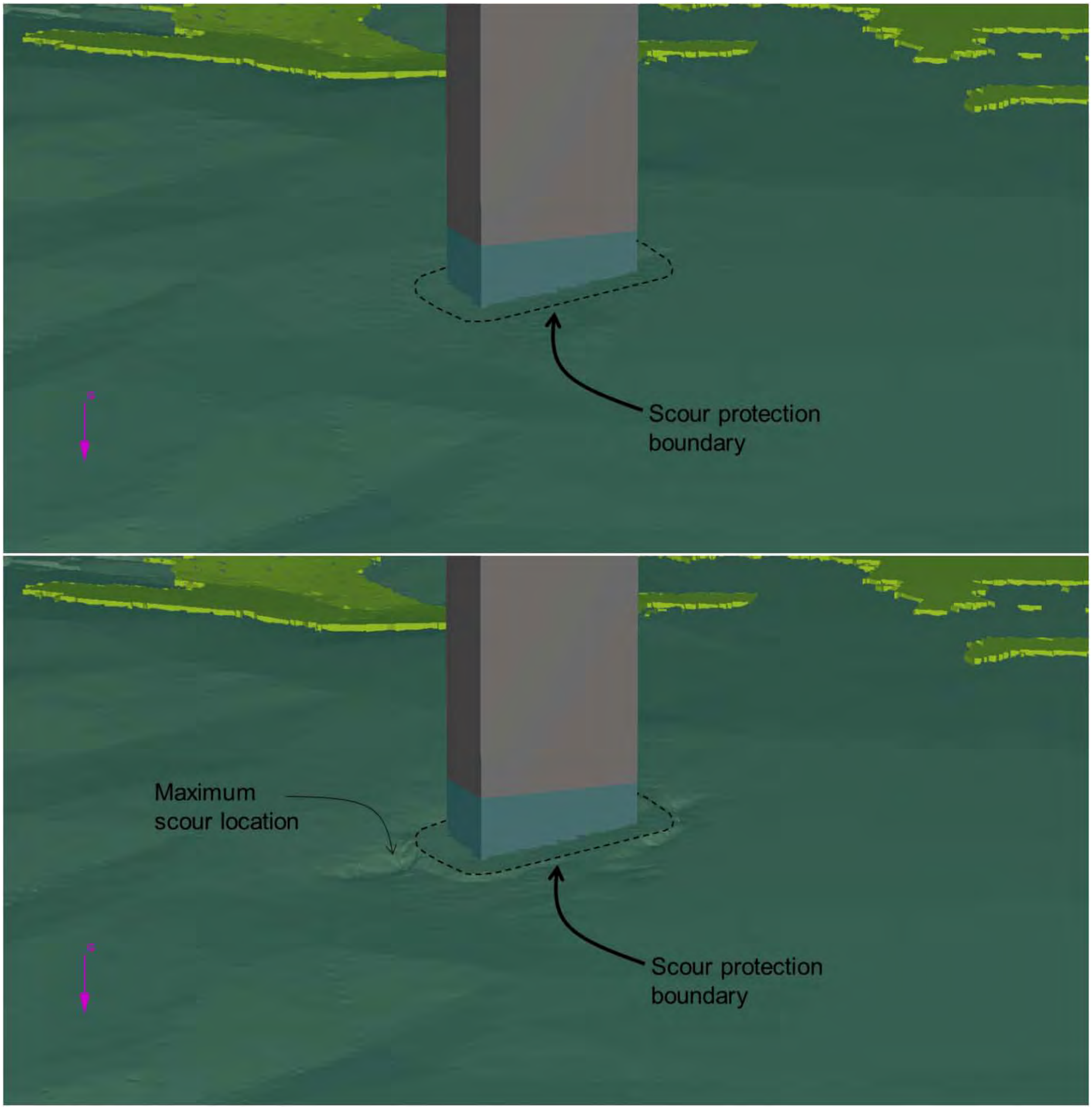


Figure 6-32: 3D view of bed elevation surrounding the SW Tower for existing conditions (SW Tower shown only for reference, top), and bed elevation surrounding the SW Tower after 1 full year with 5:1 vertical exaggeration to allow the changes to be visible to the reader (bottom). Light green areas in the background represent eelgrass locations from all available surveys.

Modelling results were also evaluated to determine if the marine structures cause an increase in TSS in eelgrass habitat areas. TSS increases due to the marine structures can be caused by local scour that occurs after installation, but will reduce over time as scour reaches an equilibrium. Therefore the anticipated increases in TSS are likely temporary until the bottom area outside the scour protection zone reaches an equilibrium.

Figure 6-33 shows the increase in 28 day average TSS due to the presence of the marine structures (SW Anchor Block at top, SW Tower at bottom) during the 28 day freshet simulation. Average suspended sediment concentrations are increased around the structures but reduce to within a few mg/L outside the immediate area. The average TSS increase caused by the marine structures is less than 1 mg/L higher at the locations where eelgrass have been found in all recent surveys.

Figure 6-34 shows colour contours of the maximum instantaneous TSS increases that occurred at any time during the entire 28 day freshet simulation relative to conditions without the marine structures. White contour lines on the figures indicates where increases of 5 mg/L and 25 mg/L occurred at any instant during the simulation. At the SW Tower, increases of 5 mg/L are predicted over the observed eelgrass areas to the east in at least one instance during the simulation, however increases of 25 mg/L do not pass over any eelgrass areas at any time. At the SW Anchor Block, no increases of 5 mg/L pass near eelgrass areas, and no increases of 25 mg/L are predicted anywhere.

These increases occur for a limited duration. TSS fluctuates greatly based on current speeds, either without or with the marine structures. As an example to demonstrate time frames over which TSS concentrations become elevated, Figure 6-35 shows a time history of TSS at a location over Flora Bank directly east of the SW Tower (during flood currents, this location is downstream of the SW Tower). The highest TSS in the simulation is approximately 35 mg/L, which is similar with or without the marine structures. The time histories show that the elevated levels of TSS are episodic and occur around eelgrass areas only over a short period of time and only during peak flood currents. The results show that with the marine structures in place, vortex shedding downstream produces more common short-term increases up to approximately 5-10 mg/L. These elevated levels of TSS are expected to reduce as scour depths around the structure reach an equilibrium.

Additional animations of TSS for both existing and proposed conditions have been generated and provided that demonstrate how TSS levels fluctuate in the area, in particular when the water level drops at low tide.

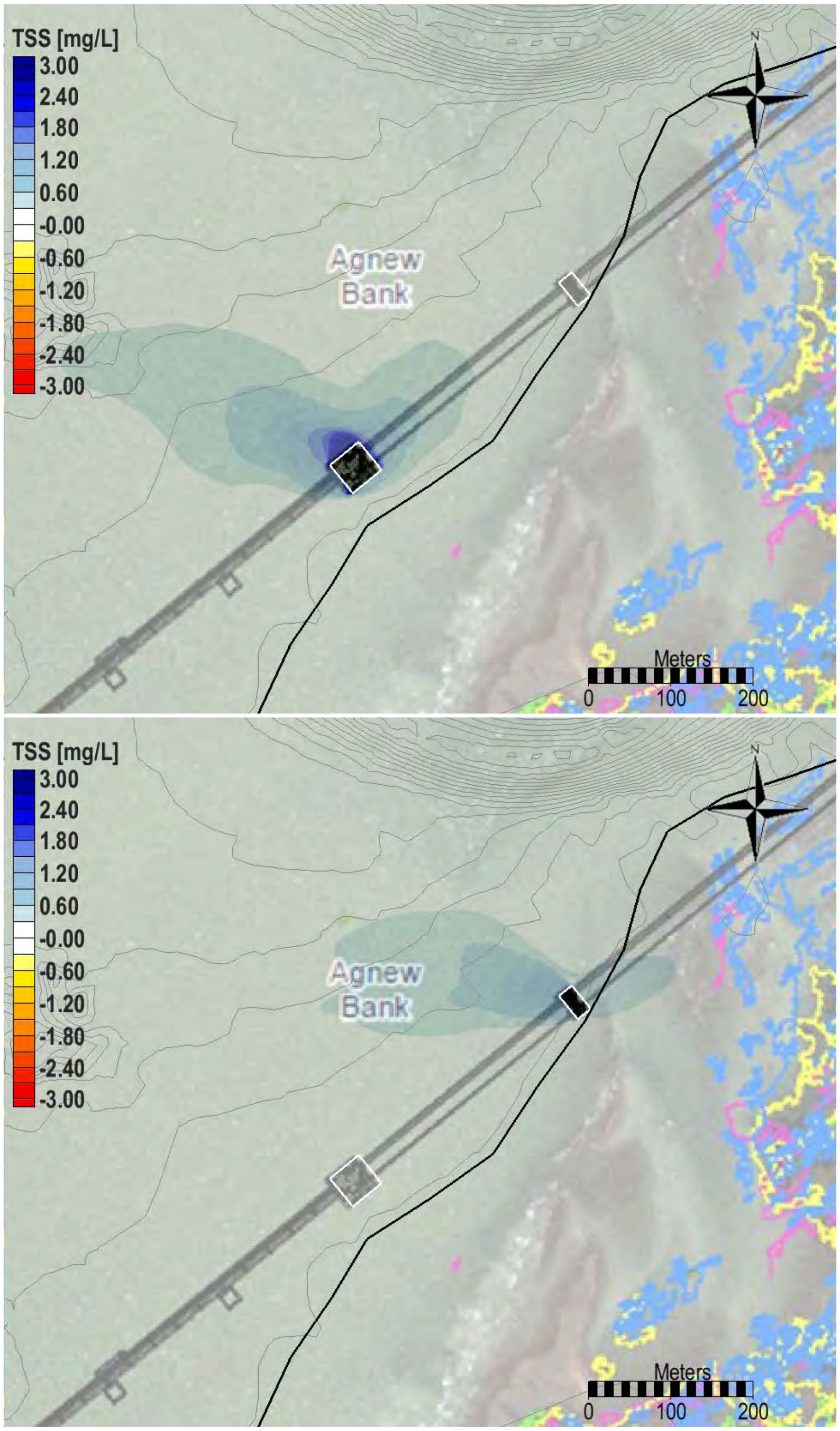


Figure 6-33: Difference in 28 day average suspended sediment concentration (TSS, or Total Suspended Solids) during the freshet simulation due to the presence of the SW Anchor Block (top) and SW Tower (bottom).

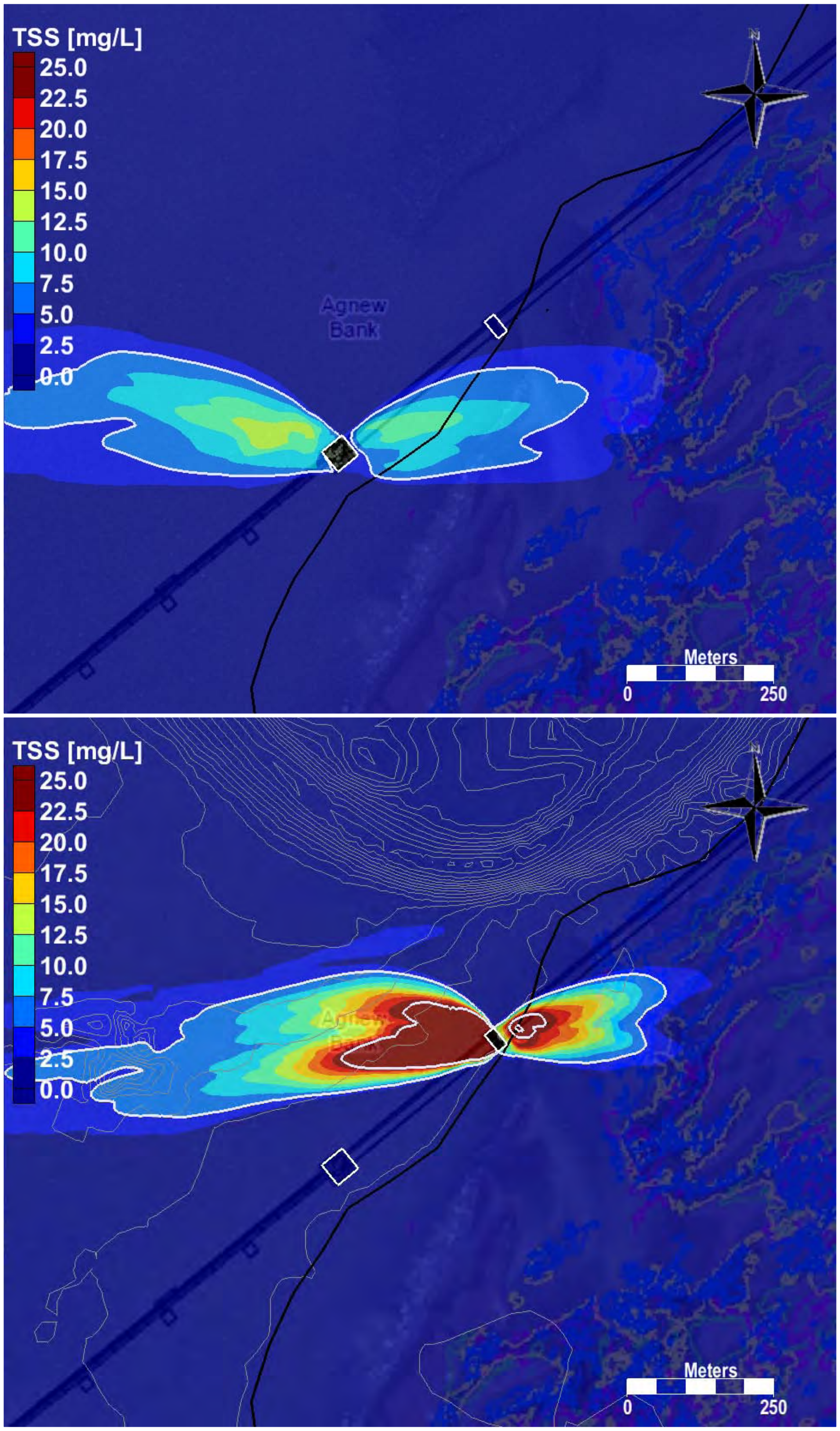


Figure 6-34: Maximum instantaneous increases in TSS during 28 day freshet simulation due to the presence of the SW Anchor Block (top) and SW Tower (bottom). White lines indicate increases of 5 mg/L and 25 mg/L.

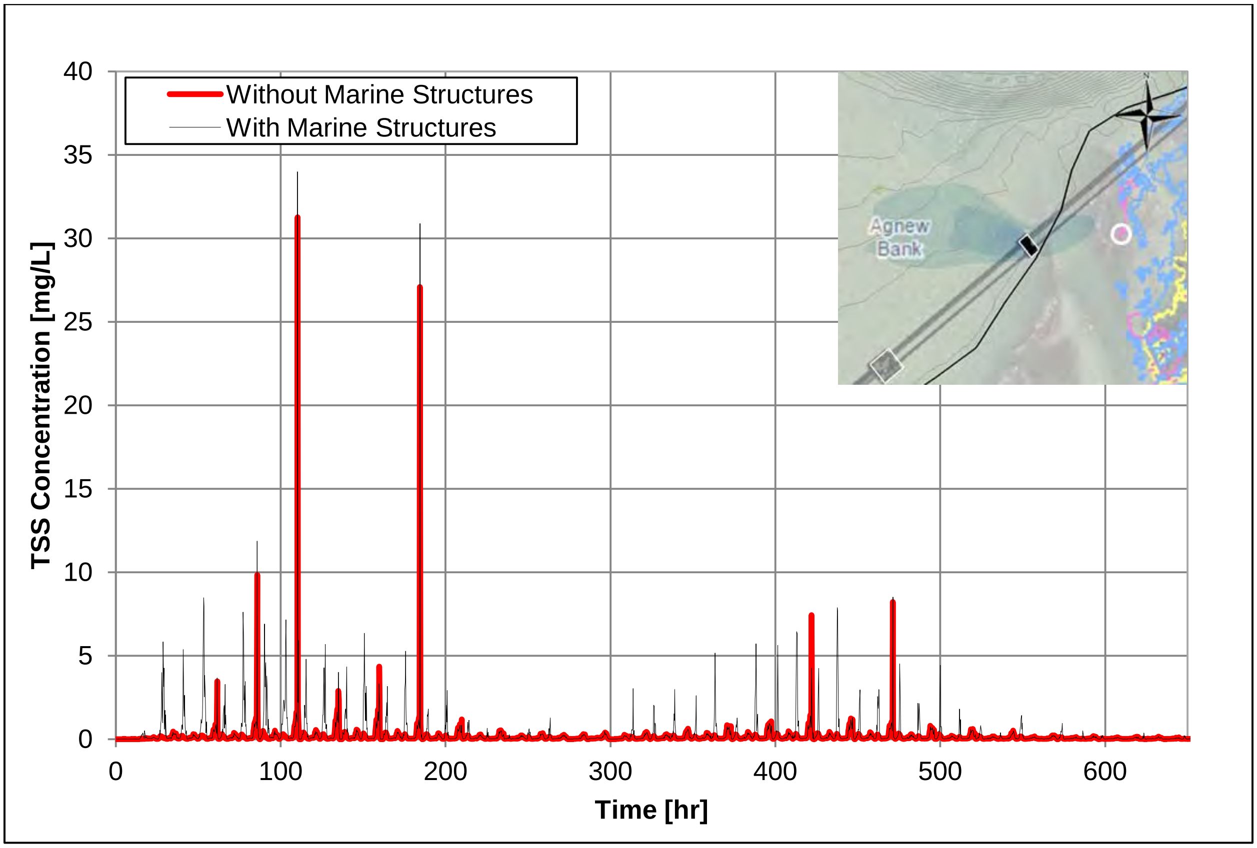


Figure 6-35: Time histories of TSS without and with the marine structures at a location east of the SW Tower during 28 day freshet simulation (location of closest eelgrass observed in all surveys, shown in inset graphic).

6.2.4 Storm Conditions Simulation

MORPHO simulations were also performed for 50-year storm conditions to evaluate potential impacts of the marine structures on a finer scale during extreme events. The MORPHO model was driven by results from the regional Delft3D model. Coupling and setup of the simulations is described in Appendix J.

6.2.4.1 Hydrodynamics During Storm Conditions

A complete range of currents and waves were included in the 50-year storm event from 270°. The peak flood-directed current speeds (when Flora Bank is downstream of the marine structures) during the entire simulation were approximately 0.65-0.70 m/s.

Figure 6-36 shows snapshots of the local hydrodynamics around the SW Anchor Block (top) and SW Tower (bottom) during the peak currents experienced in the 50-year storm event from 270°. The strongest currents during the storm, shown in this snapshot, are directed from southwest to northeast, similar to the direction of typical flood currents. During the storm event, vortex shedding is more intense due to the higher current velocities, and is concentrated towards the northeast which is the direction of strongest currents on flood tide. During westerly storm conditions, flows are slightly stronger at the SW Tower than at the SW Anchor Block due to wave-induced currents, which combines with the shape of the SW Tower in producing stronger vortex shedding effects.

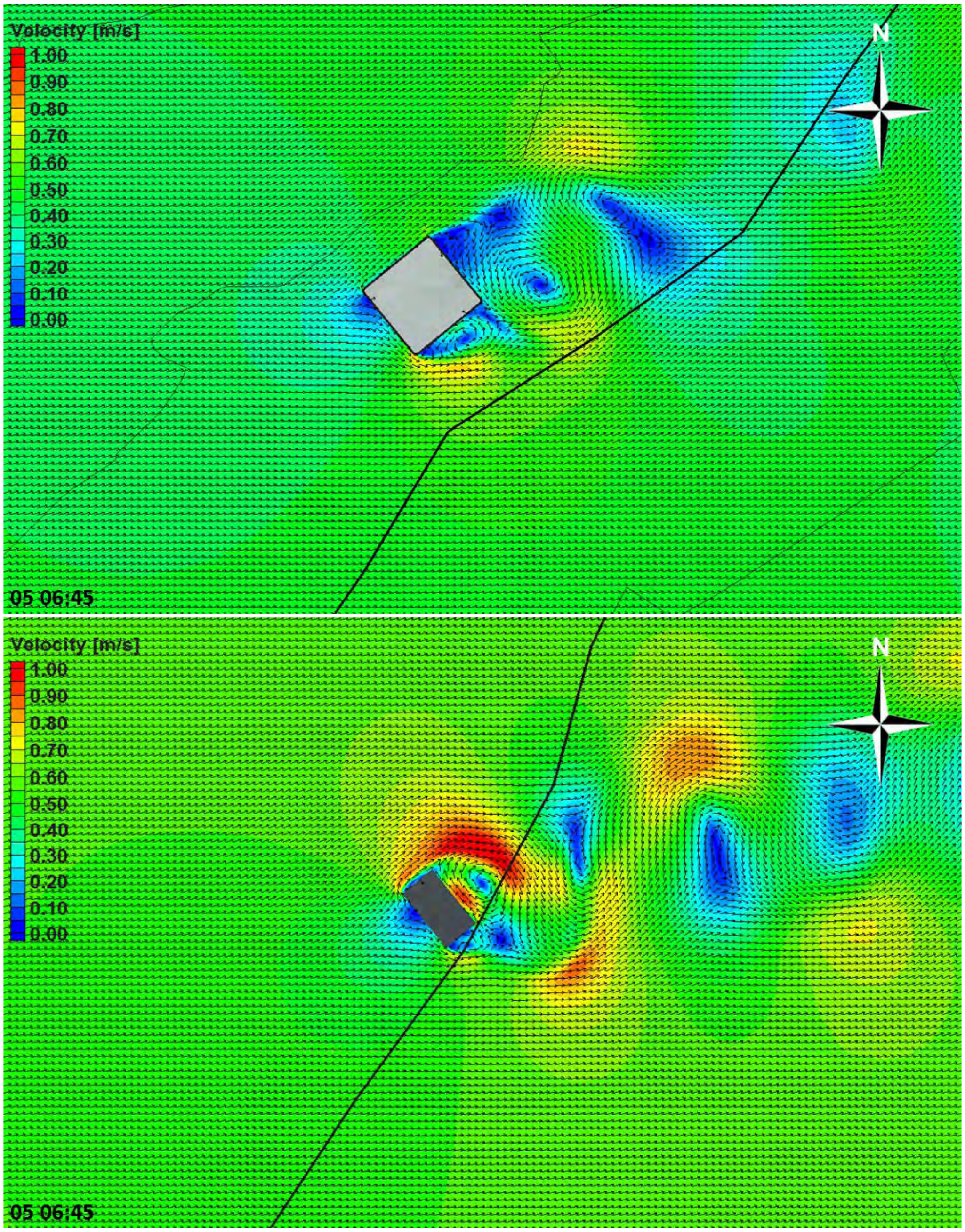


Figure 6-36: Snapshots of local flows around SW Anchor Block (top) and SW Tower (bottom) at the time of peak current velocities in the 50-year storm event from 270° True North

Figure 6-37 shows the maximum instantaneous increase in current speed induced by the SW Anchor Block (top) and SW Tower (bottom) at each point in the domain during the 50-year storm. Changes in Figure 6-37 indicate how the highest instantaneous current speed during the simulation at every point in the domain was either increased or decreased by the presence of the marine structures.

Generally since the storm velocities were greatest moving towards the northeast, the velocities are lower to the southeast of the structure, increased around the sides of the structures due to flow acceleration, and increased in the back of the structure due to vortex shedding effects. The SW Tower causes greater increases in currents than the SW Anchor Block due to higher ambient velocities at its location, and stronger vortex shedding due to its shape. Changing the shape of the SW Tower (and SW Anchor Block as well) has the potential to significantly reduce the influence of the structures. This is further discussed in Section 6.2.5.

To demonstrate the relatively short duration of the instantaneous TSS increases, a time history of current speed was extracted downstream from the SW Tower (towards the East) at the location of the nearest mapped eelgrass (see Figure 6-37). The results indicate that the range of current speeds are similar after construction of the SW Tower, however the short-term peak velocities are slightly higher and tend to oscillate downstream due to vortex shedding.

Since the areas over Flora Bank are relatively flat with medium to coarse sand, increases in current velocity do not necessarily translate to actual bed elevation changes (erosion or accretion). 50-year storm sediment transport and morphology modelling were also performed in tandem with the hydrodynamic modelling (fully coupled simulation) to determine the magnitudes and extents of bed elevation changes that may be induced by the presence of the SW Tower and SW Anchor Block.

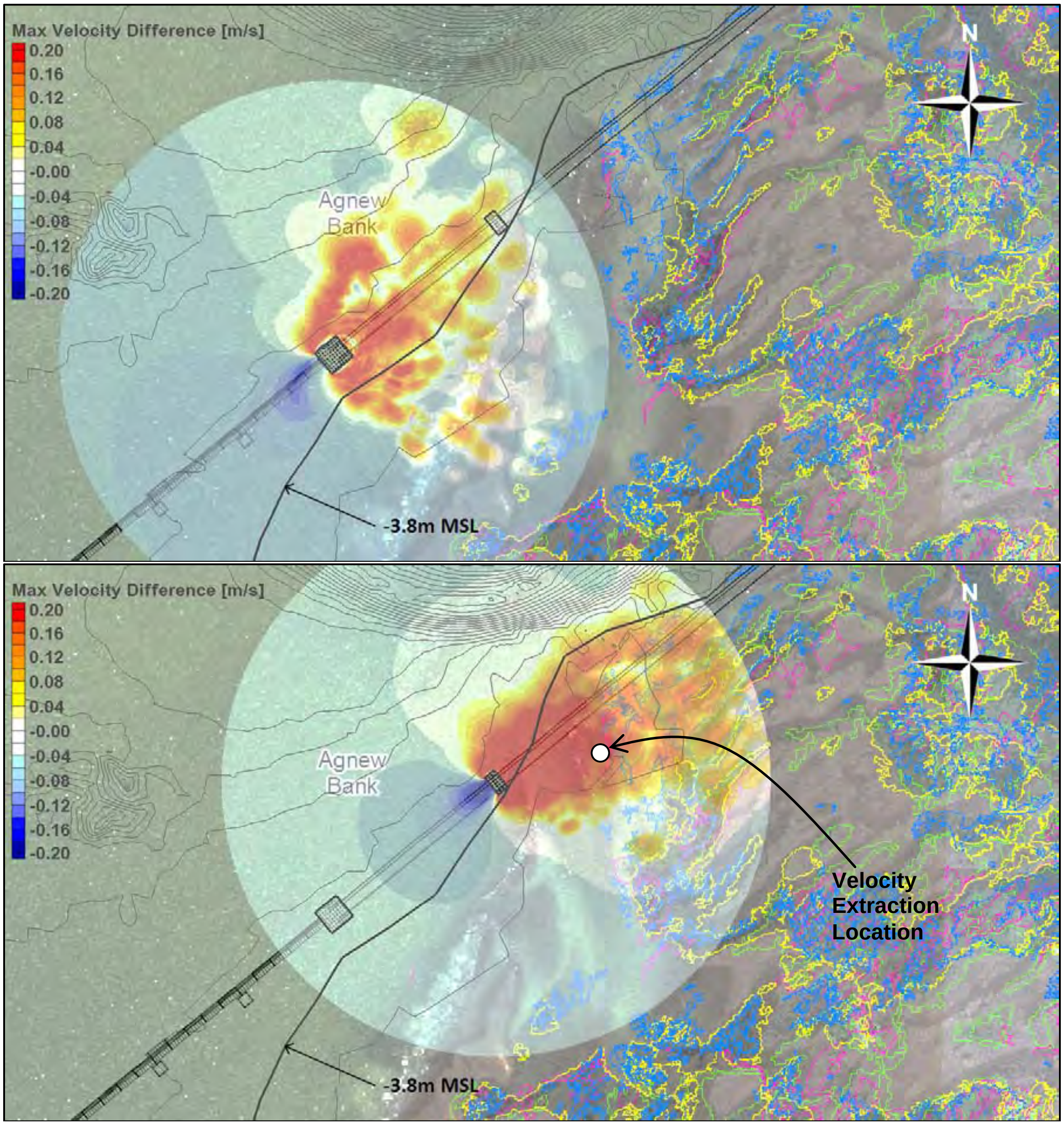


Figure 6-37: Changes in maximum instantaneous current speed at every point in the domain at any time during the 11 day, 50-year storm simulation following installation of the SW Anchor Block (top) and SW Tower (bottom).

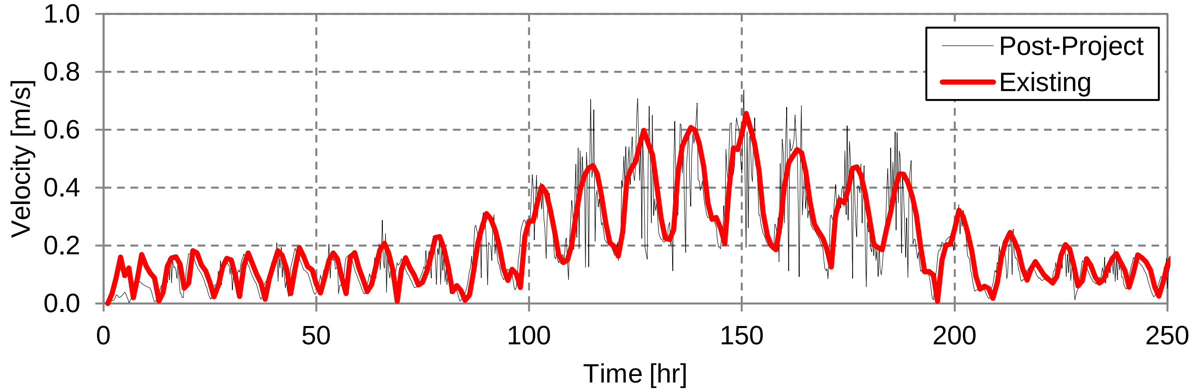


Figure 6-38: Current speed time history extracted downstream of the SW Tower (location shown in Figure 6-37) during the 11 day, 50-year storm simulation.

6.2.4.2 Sediment Transport and Morphology During Storm Conditions

This section evaluates sediment transport and morphology around the larger marine structures driven by the high-resolution hydrodynamics for the purpose of evaluating the relative impact of the marine structures on erosion and deposition in the area.

Sediment transport and morphology modelling were performed in tandem with the hydrodynamic modelling for the 50-year storm from 270^o True North using the smaller-scale idealized modelling domains. Each modelling domain (one for SW Anchor Block, one for SW Tower) used the appropriate grain size found at each structure. Figure 6-39 shows the erosion and deposition pattern induced by the SW Anchor Block (0.14 mm diameter sediment, top) and by the SW Tower (0.3 mm-diameter sediments, bottom) after 11 days of storm simulation.

During the 50-year storm (270^o True North), maximum scour at the SW Anchor Block and SW Tower occurred near the corners of the scour protection blankets, and were approximately 0.2 and 1.6 m, respectively. Scour depths are significantly reduced due to the scour protection system and would be much higher up against the corners of the structures if no protection were installed, as was confirmed in sensitivity testing simulations. Appendix J includes results of simulations both with and without scour protection, as examples.

As with the typical conditions results, during storms the vortex shedding tends to cause the material eroded from the immediate vicinity of the structures to be spread thinly over the bed in downstream areas, however for westerly storms the deposition is concentrated on the northeast side. Neither scour, nor deposition, greater than 5 cm occurs near the eelgrass locations in previous surveys (yellow, pink, blue and green lines in Figure 6-39). It should be noted that by the time a 50-year event occurs, scour under typical tidal current conditions will likely have already progressed, and less scour and less deposition downstream would occur during this extreme event.

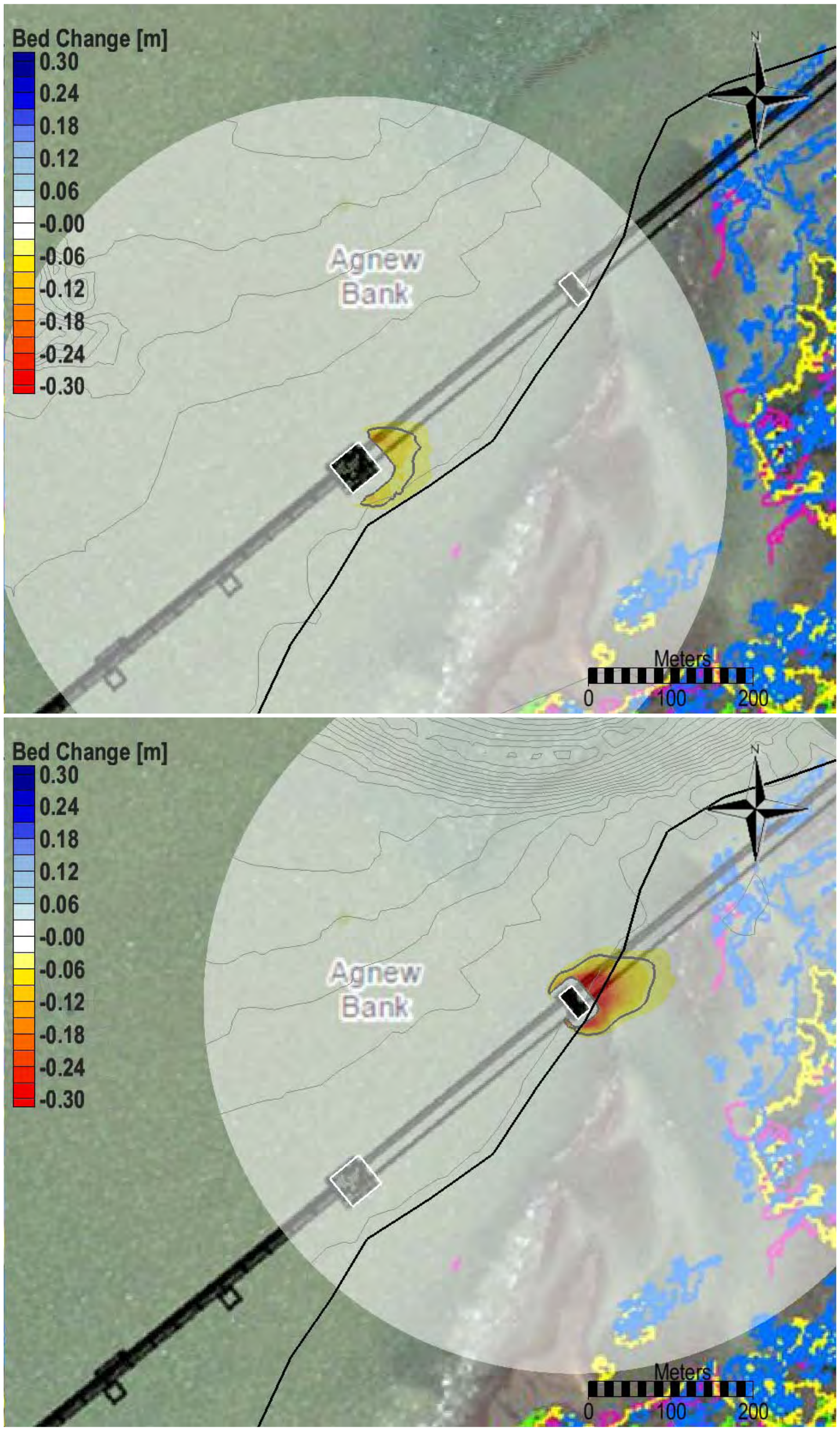


Figure 6-39: Erosion and deposition patterns surrounding the marine structures following the 50-year storm event from 270° True North at the SW Anchor Block (0.14 mm sediment, top) and the SW Tower area (0.3 mm sediment, bottom). Dark lines indicate changes in bed elevation greater than ± 5cm.

6.2.5 *Sensitivity Analysis for SW Tower Shape*

Additional modelling was performed to evaluate the potential changes in hydrodynamics and transport around the SW Tower if another structure shape were used to encapsulate the support piles. A circular shape that covers the entire previous SW Tower shape (i.e. larger overall) was used in the testing simulations. Figure 6-40 below shows a snapshot of current velocities during the peak of the 50-year west storm event. Results indicate that similar vortex shedding still occurs, and periodic short-term increases in current speeds can be noticed around the sides of the structure, and within the vortices that are shed and move downstream.

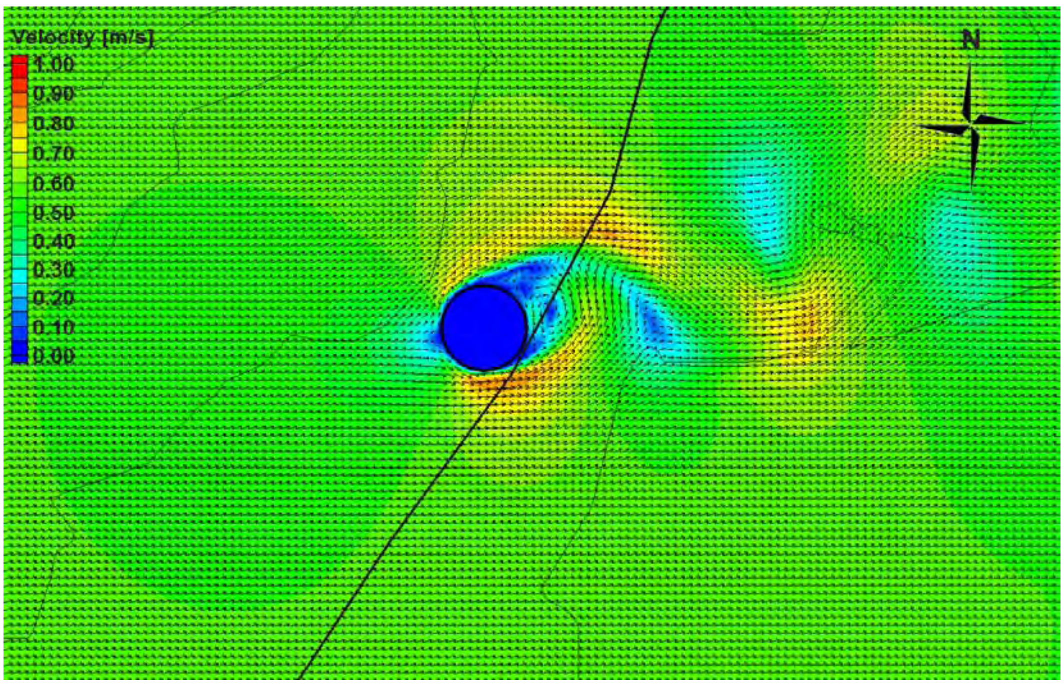


Figure 6-40: Snapshot of local flows around circular SW Tower during peak current velocities in the 50-year storm event from 270° True North

Figure 6-41 shows the differences in instantaneous maximum velocity after installation of the circular SW Tower at each point in the modeling domain during the entire 11 day simulation, relative to the existing conditions (no marine structures). Generally speaking, even though the circular-shaped SW Tower is larger than the original SW Tower, it produces less velocity increases in most locations. Figure 6-42 shows a time history of velocity before and after installation of the circular SW Tower at a point downstream (shown in Figure 6-41), which indicates that the changes in instantaneous current speed occur over only very short periods of time, and the overall character of the flows is very similar.

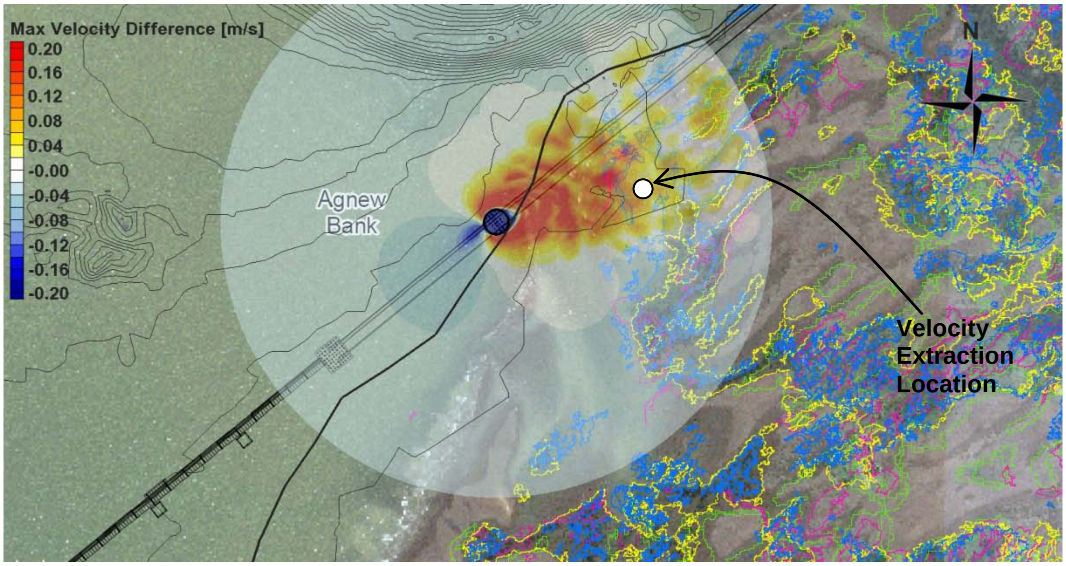


Figure 6-41: Changes in maximum instantaneous current speed calculated at each point in the domain at any time during the 11 day, 50-year storm simulation caused by installation of a circular SW Tower

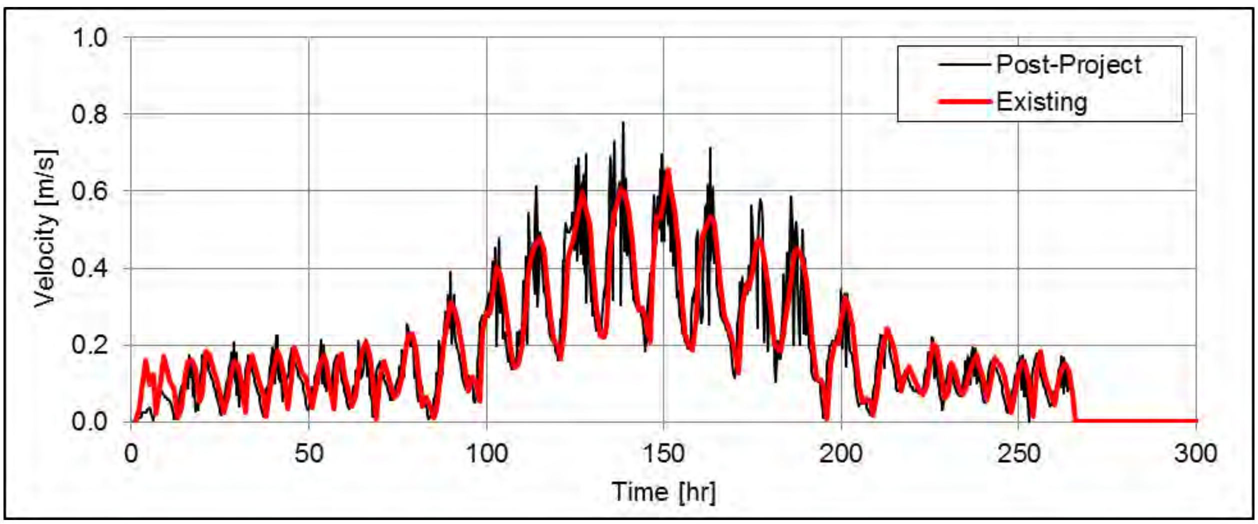


Figure 6-42: Current speed time history extracted downstream of the Circular SW Tower (location shown in Figure 6-37) during the 11 day, 50-year storm simulation.

Safety • Quality • Sustainability • Innovation

Figure 6-43 shows a comparison of erosion and deposition patterns surrounding the SW Tower following the 11 day, 50-year storm event from 270^{o} True North for a circular SW Tower (top) and the original rectangular SW Tower (bottom). Results indicate that the change to a circular shape, even though it increased the overall area of the structure, results in less erosion and deposition than the original SW Tower. The lower increases in current speeds and weaker vortex shedding cause less scouring, lower TSS increases and less downstream deposition.

Figure 6-44 shows erosion and deposition patterns surrounding the SW Tower following a full year of tides-only conditions, extrapolated linearly from a 28 day tides-only simulation, for a circular SW Tower (top) and the original rectangular SW Tower (bottom). Results also indicate for the tides-only conditions that the change to a circular shape, even though it increased the overall area of the structure, results in less erosion and deposition than the original SW Tower, in particular on the east side nearest the areas of observed eelgrass. The lower increases in current speeds and weaker vortex shedding cause less scouring, lower TSS increases and less downstream deposition.

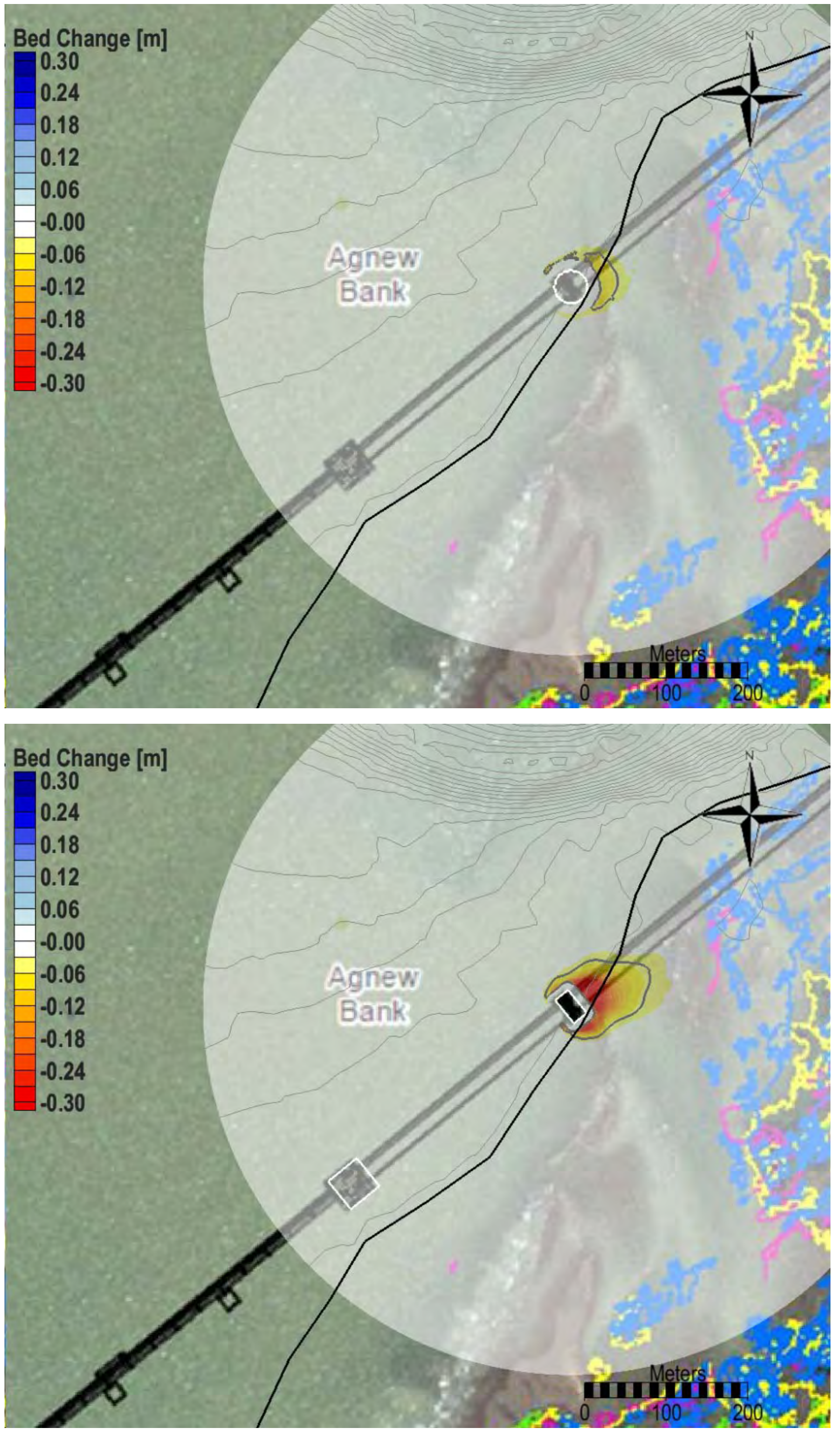


Figure 6-43: Comparison of erosion and deposition patterns surrounding the SW Tower following the 11 day, 50-year storm event from 270° True North for a circular SW Tower (top) and the original rectangular SW Tower (bottom, repeated for comparison). Dark lines indicate changes in excess of 5 cm.

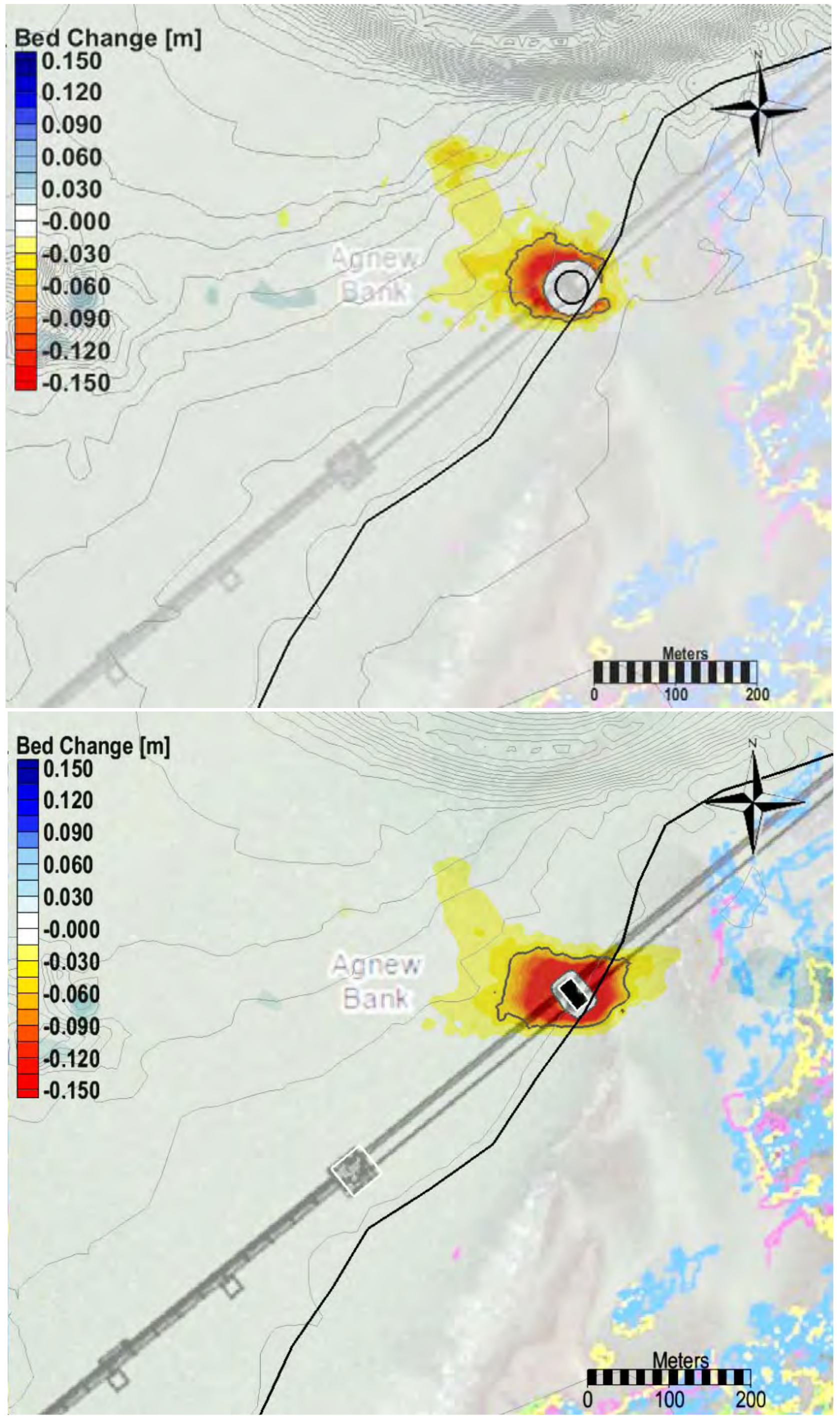


Figure 6-44: Erosion and deposition patterns surrounding the SW Tower after 1 year of tides-only conditions, extrapolated linearly from 28 day tides-only simulation, for a circular SW Tower (top) and the original rectangular SW Tower (bottom, repeated for comparison). Dark lines indicate changes in excess of 5 cm.

6.2.6 *Summary of High-Resolution Modelling*

High-resolution modelling indicates that the SW Anchor Block and SW Tower generate local changes in hydrodynamics and erosion/deposition effects that are typical of isolated marine structures in relatively large and homogeneous flows. Hydrodynamic effects of the structures oscillate with the varying tidal current directions and magnitudes. Results indicate that the structures produce localized increases in current velocity and vortex shedding which affect sediment mobility, transport and morphology in the area surrounding the structures.

Sediment transport modelling results indicate that erosion/deposition patterns are localized, and dependent on the location of the structures, size and shape of the structures, and local sediment sizes. During freshet and tides-only conditions, the localized scour pattern surrounds the structures in all directions since flow directions oscillate, and deposition is spread thinly in all directions with more material found to the west of the structure. Vortex shedding tends to spread the materials over wide areas downstream, resulting in small thicknesses of deposition. During storm events, the peak flows are directed to the northeast, focusing the scour on the sides and northeast (downstream) ends of the structures.

Overall, the results of the high-resolution modelling are consistent with observations of scour and deposition around marine structures such as bridge piers. Changes are localized and are likely to be measurable only in the vicinity of the structures (few structure diameters away).

Sensitivity analysis with a circular SW Tower structure indicates that although velocity increases occur around the structure as expected (relative to existing conditions), significantly less scour and deposition occurs as a result of the structure than was predicted for the original shape. The sensitivity testing results indicate that the hydrodynamic and morphological impacts of the marine structures can be significantly reduced through further design refinements.

6.3 Summary of TSS Increases due to Marine Structures

The SW Anchor Block and SW Tower are likely to cause localized and transient increases in TSS while the process of near-field scour is occurring after construction. The only TSS increases that are predicted in the high-resolution modeling occur as short-duration effects associated with vortex shedding and the process of scour around the structures, not due to larger-scale hydrodynamic changes. As the scour around the structures progresses towards equilibrium, TSS increases can be expected to reduce over time. Section 6.4 below further describes the scour process.

6.4 Summary of Scour due to Marine Structures

As briefly described in Section 6.2.1, the large marine structures are representative of isolated structures such as bridge piers because these structures are small relative to the large, homogeneous flow fields in which they are located, and the bottom slope at the structures is flatter than 100H:1V. Extensive empirical equations for equilibrium scour depth and equilibrium scour extents have been developed for riverine and coastal applications. All research fundamentally shows that equilibrium exists, and will be reached regardless of the coastal conditions or structure shapes.

Many laboratory studies (Escarameia & May, 1999) have been performed to better understand the effect of major factors (e.g. water depth, pier shape, sediment size, reversal of flow direction) upon equilibrium scour depth and evolution of the scour depth over time prior to reaching equilibrium. Many publications demonstrate that individual or groups of structures cause localized bed changes but those bed changes reach an equilibrium state. The equilibrium state is shown in many of the publications, such as Das et al (2014).

The scour patterns vary based on structure shape as has been demonstrated in this report; however they all do reach a state of equilibrium. Numerous entities have published formulations to determine equilibrium scour, for the purposes of design. This means that it is a well-known fact that scour will not continue at the same rate, but will slow to a relative halt when the sediment around the structure is too deep to be mobilized.

In addition, the following references provide formulations which describe “equilibrium” scour depth and extents, which were determined using laboratory studies:

- Sheppard et al (2010)
- Arneson et al (2012)
- Nordila et al (2014)
- Escarameia & May (1999)

Escarameia & May (1999) found that equilibrium scour depths, measured in tidal conditions in the laboratory, were always much less than those found for unidirectional conditions. The combined findings above as well as the characteristics of the project site and marine structures (SW Tower and SW Anchor Block) strongly imply that the rate of scour will be slow, that equilibrium depths around the structures will be reached, and that the equilibrium scour depth will be relatively small in comparison to predictions made using empirical formulations because of the extremely shallow water at the project site.

Figure 6-45 shows scour trends over time for live-bed scour (situations where sediments are mobile approaching the structure) and for clear-water scour (situations where flows approaching the structure are mostly below threshold of movement in the absence of the structure). Most of the time, the SW Tower and SW Anchor Block are located in areas of limited mobility and hence clear-water scour would better apply. The trend of scour progression indicates that scour is nearly linear in the very beginning, which agrees with the scour trends in the 28 day freshet and tides-only simulations, but will taper off and eventually come to a halt.

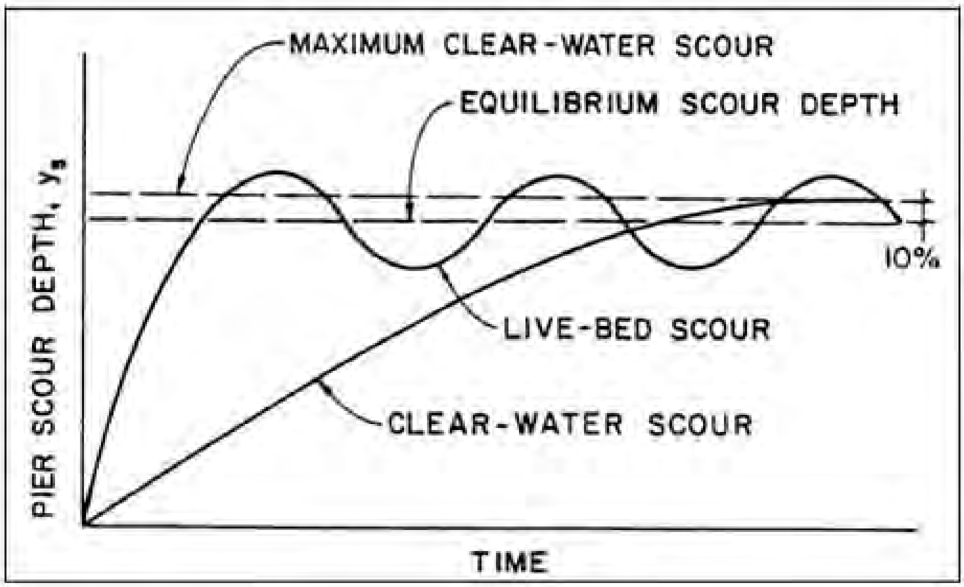


Figure 6-45: Scour depth progression over time (source: Richardson, 2001)

Time scales over which scour reaches equilibrium vary significantly depending on a number of factors. One important factor is the fraction of time where bottom velocities at the structure are above threshold. At the SW Tower and SW Anchor block, in particular in the areas surrounding the scour protection (i.e. some distances away from the actual structures), scouring is likely to occur only during peak currents. Given the relatively low scouring rates observed in the modelling, with scouring only occurring for short durations during peak flows, it is anticipated that equilibrium depths around the edges of the riprap scour protection are likely to be reached in time periods ranging from several months to a few years.

A rip-rap scour blanket is proposed to be installed around the marine structures at the time of construction (Hatch, 2014b). This will effectively eliminate scour directly up against the structures, but some scour is still expected to occur to a much lesser degree in areas farther away from the structure at the edge of the rip-rap. While scour will occur around the outer edges of the scour protection (rip-rap), a state of equilibrium scour will be reached surrounding the scour protection as well.

Modelling results using conservative transport formulations indicate that areas scouring greater than 5 cm/year, even immediately following construction, are located far from areas where eelgrass has been mapped.

6.5 Summary of Marine Structures Modelling Results

The Delft3D and MORPHO models provide accurate representation of the physical processes that affect the project area on both a regional and local scale. The simulations conducted with these models allow for the evaluation of the potential impacts of the marine structures on currents, transport, and morphology.

6.5.1 Summary of the Marine Structures Impact on Hydrodynamics

The regional modelling demonstrated that the strongest wave attenuation occurs due to the local bathymetry over Agnew Bank however some localized attenuation occurs along the trestle and at the SW Tower and SW Anchor Block. The model also showed changes in instantaneous current speed are relatively small and located close to the marine structures.

The high-resolution modelling indicates that the SW Anchor Block and the SW Tower generate local changes in hydrodynamics typical of isolated marine structures in relatively large and homogenous flows. Hydrodynamic effects of the structures oscillate with the varying tidal current directions and magnitudes. Results indicate that the structures produce localized increases in current velocity and vortex shedding. Predicted changes are localized and are likely to be significant only in the immediate vicinity of the structures.

6.5.2 Summary of the Marine Structures Impact on TSS

Results from both the regional and high-resolution modelling efforts indicate that TSS increases occur both for existing and proposed conditions, depending on the hydrodynamics, and with similar magnitudes overall. Changes due to the trestle are primarily a mild reduction in TSS on average since the trestle tends to mildly attenuate wave energy, which is a primary factor in TSS increases observed near Flora Bank.

High-resolution modelling indicates that TSS increases are likely to occur due to scour around the SW Tower and SW Anchor Block, however the TSS increases are short in duration (minutes) and pass over the eelgrass areas as vortex shedding occurs, and do not constitute a longer-term average increase. In addition, TSS increases that are generated from scour and vortex shedding will reduce over time as the scour around the structures reaches equilibrium.

6.5.3 *Summary of the Marine Structures Impact on Morphology*

The regional modelling results indicate that measurable erosion and deposition occurs on Flora Bank episodically only under strong wave forcing, and during lower water levels. Since most of the bed elevation changes occur due to the presence of waves, the trestle structure reduces the magnitudes of both erosion and deposition on Flora Bank. Longer-term simulations that contain many smaller storms produce small bed elevation changes similar to individual storms, since they have similar resulting wave heights on top of the shallow Flora Bank. The longer-term, freshet, and storm simulation results all demonstrate that the marine structures cause a slight reduction in erosion, and a reduction in the associated nearby deposition, on Flora Bank.

The high-resolution sediment transport modelling results indicate that erosion/deposition patters are localized, and dependent on the location of the structures, size and shape of the structures, and local sediment sizes. During freshet and tides-only conditions, the localized scour pattern surrounds the structures in all directions since flow directions oscillate, and deposition is spread thinly in all directions with more material found to the west of the structure. Vortex shedding tends to spread the materials over wide areas downstream, resulting in small thicknesses of deposition. During storm events, the peak flows are directed to the northeast, focusing the scour on the sides and northeast (downstream) ends of the structures.

Analysis with a circular SW Tower structure indicates that significantly less scour and deposition occurs as a result of the structure. This sensitivity testing demonstrates that the hydrodynamic and morphological impacts of the marine structures can be significantly reduced through refinements during the design process.

Overall, the results of the high-resolution modelling are consistent with observations of scour and deposition around marine structures such as bridge piers. Bed changes are localized and are likely to be measurable only in the immediate vicinity of the structures (few structure diameters away).

7. Implications to Fish and Fish Habitat

PNW LNG has worked with Fisheries and Oceans Canada (DFO) and the CEA Agency to achieve alignment on how to update the marine resources effects assessment (with a focus on fish and fish habitats) relative to the potential physical changes on Agnew and Flora Banks resulting from the presence of the Project's marine terminal infrastructure.

7.1 Impact Pathways

The outcome of this engagement was an alignment on the four distinct impact pathways that may be induced, triggered, or activated by the marine infrastructure and lead to adverse effects on fish and fish habitat.

These impact pathways were identified and include:

1. Direct harmful alteration or loss of fish habitat in Porpoise Channel Harbour on Agnew Bank from construction of the infrastructure and placement of scour protection and/or armouring of suspension bridge substructures, trestle pipe pile bents and the berths for erosion control.

2. Potential for indirect harmful alteration or loss of eelgrass due to induced erosion and/or deposition on Flora Bank.

3. Potential for an increase in total suspended solids (TSS) that may directly affect fish or limit a fish's ability to feed (the threshold for TSS concentrations is based on Canadian Council of Ministers of Environment [CCME] guidelines)

4. Potential for a material increase in currents around the SW Tower and SW Anchor Block that affects the ability of CRA species to move through the water and use the habitat.

The results of the modelling efforts have been carefully analysed and the findings, discussed in detail in earlier sections of this report, may be summarized in the context of these pathways.

7.2 Direct Impacts

The direct footprint of the proposed marine infrastructure has been carefully reviewed based on the preliminary design of the elements, including allowance for probable scour protection immediately adjacent to the proposed structures and piles, and the total footprint has been conservatively estimated as an area of 21,300 m^2 (2.13 ha). Refer to Appendix L for details about the total footprint.

7.3 Erosion and/or Deposition Affecting Eelgrass

The results of both the regional scale and local high-resolution modelling inform evaluation of the likely potential impacts of the marine structures on currents, sediment transport and morphological change in the vicinity of Flora Bank.

Results indicate that peak tidal currents and smaller waves during typical conditions are capable of transporting sediments, however little morphological change at Flora Bank is likely to occur as a result of the marine structures due its combination of flat slopes and relatively coarse sediments. The influence of the trestle is generally to reduce wave conditions slightly during extreme events, resulting in less morphological change than would be present without the structures. Changes on Flora Bank are expected to be local, due to small gradients in wave conditions and flows that tend to erode and deposit the eroded sediments nearby.

Visual comparisons of regional modelling results indicate detectable, but marginal, apparent change between the results of time-series modelling runs without, and with, the proposed structures. Detailed volumetric change computations were made for Flora Bank as a whole, the area above -3.8 m MSL (approximate perimeter of Flora Bank) across a wide range of both storm and extended condition simulations (typical and stormy conditions) to validate these observations. It was found that volume changes (total erosion and total deposition within Flora Bank) are consistently smaller with the proposed structures included.

Typically there is little or no general bed elevation changes caused by the marine structures evident in simulations dominated by southerly winds and/or ebb currents large enough to initiate transport. This is logical given the proposed location of the structures northwest of (i.e. downstream of) Flora Bank during these conditions.

Simulations dominated by westerly to northerly winds and currents large enough to initiate transport consistently demonstrate less general changes on Flora Bank due to a modest attenuation of waves and currents by the trestle.

Local high-resolution modelling of the hydrodynamics and transport surrounding the larger individual marine structures (SW Anchor Block and SW Tower) indicates that these isolated structures are likely to cause local changes in flows and morphology within areas typical of bridge piers and other structures studied in the literature. Local scour as predicted by these studies is the only significant erosion that is produced, and is typically found within a few diameters of each structure. This result is consistent with laboratory studies.

Local scour protection is already proposed in the immediate perimeter of the proposed structures, and the effect of this work on habitat is accounted for as “direct impact” discussed above. The local scour protection prevents significant deterioration of the seabed due to increased currents along the face of structural elements.

Results of the high resolution modelling indicate that localized currents and eddies in the vicinity of the proposed SW Tower and SW Anchor Block are likely to cause limited local bedform changes that lie beyond the scour protection, but within tens of metres of the structures, and will occur gradually and in any event do not extend to the limits of eelgrass habitat identified by survey.

This is principally due to the moderate, broad flow fields within which the structures are located. Localized current changes caused by the structures are limited and within the ranges of currents occurring naturally on the higher-elevation, shallow areas of Flora Bank during the wetting and drying process.

In summary, analysis of the modelling results do not indicate the likelihood for significant changes to erosion and deposition patterns and the overall magnitude of morphology change arising from natural processes, and demonstrates that effects local to the structures do not extend near the limits of eelgrass habitat. Significant effort has been taken to validate these conclusions against a fundamental consideration of the relevant flow fields and bathymetric conditions on Flora Bank and the likely effects of the relevant coastal processes.

The conclusion from these analyses is that the proposed structures are not likely to cause morphology changes which will measurably affect eelgrass habitat.

7.4 Currents

Consistent with the discussion above, results of the high resolution modelling indicate that localized current changes and eddies in the local vicinity of the proposed SW Tower and SW Anchor block are evident, but are localized, transient, mobile and of limited magnitude. The velocities of these transient currents are consistent with values found regularly in local areas of Flora Bank during various tidal conditions. This is principally due to the broad, moderate velocity, flow fields within which the structures are located.

In summary, the modelling results do not indicate that the proposed structures are likely to generate material increase in currents which would affect fish.

7.5 Total Suspended Solids Concentrations

In direct connection to the transient current velocities discussed above, high-resolution modelling indicates that total suspended solids (suspended sediment) concentrations are increased on the lee side of the structures when erosion is occurring (limited to a few structure diameters away), and quickly subsides as peak currents subside. Downstream outside of this area, no measurable difference in average suspended sediment concentration (TSS) is expected. As bedform changes around the structures slow down and reach equilibrium, these occasional, transient and localized increases in suspended sediment concentrations downstream of the structure are expected to reduce.

A careful review of regional modelling results has confirmed that occasions of high TSS values, both with and without the proposed structures, are highly episodic and appear closely correlated to low water levels. A careful comparison of both cases confirms that the local TSS concentrations are dominated by natural changes, and these patterns are not meaningfully affected by the proposed structures.

7.6 Opportunity for Further Reduction in Local Effects

All modelling efforts discussed in this report have assumed conservative rectangular geometry for the SW Tower and SW Anchor Block analysis. These shapes represent essentially a “worst case” for prediction of local current and eddy effects.

As discussed in section 6.2.5, during permitting and design, the area of influence of these SW Anchor Block and SW Tower can potentially be further reduced through design refinements to the shapes of these structures and the extents of scour protection, which will tend to further reduce the limited amount of erosion and deposition downstream, as well as transient higher suspended sediment concentrations (TSS) due to the local erosion.

8. Conclusions

This report summarizes results of modelling efforts conducted subsequent to the May 5th, 2015 3D Modelling report, including continued refinement of previous of hydrodynamic and morphology efforts using Delft3D, extensive new high resolution modelling efforts to closely examine behaviour in the immediate vicinity of the proposed SW Tower and SW Anchor Block, and additional supporting analysis. Although this report supplements previously completed work, the analytical and modelling efforts to date, taken in combination with works by others (including SedTrend, 2015), have yielded a strong understanding of the coastal processes acting on Flora Bank and its environs, providing further confidence that the predicted impacts of the marine structures are well understood.

Several tools have been utilized in a range of broadly parallel efforts, in order to fully explore the various processes relevant to understanding both Flora Bank and the potential effect of the proposed structures on hydrodynamics and morphology. Numerical modelling was performed to simulate coastal processes on both a large/regional scale (hundreds of kilometers down to tens of meters) and a highly localized scale (meters) to ensure accurate simulation of relevant physical processes.

Recent efforts have continued to contribute to further understanding of the effect of coastal processes on Flora Bank and to increase both understanding of and confidence in its long-term stability.

A key focus of recent efforts has been to further refine these modelling efforts in order to respond to a set of five key concerns expressed by the CEA Agency and relevant federal agencies. Recent efforts include:

1. Refining wind and wave inputs to account for spatial variability of the wind fields (gridded winds) and offshore waves (gridded offshore waves), to determine whether variability of offshore inputs results in improved predictions of waves at the project site. Analysis of model outputs indicate that predictions of local and offshore waves at the Project site (as compared with on-site measurements) are not appreciably affected by inclusion of the refined inputs.

2. Modifying the representation of extreme storm events to include synthetic longer-duration events, from a broader range of directions. The refined modelling efforts have included development and modelling of extended duration, unidirectional storms with intensities appropriate for the relevant return periods, which will likely amplify modelled hydrodynamics and transport in comparison to “natural” records. Results show that the proposed structures have only a modest, and mildly attenuating, effect on the predicted changes.

Safety ● Quality ● Sustainability ● Innovation

3. Improving representation of the larger marine structures and their local effects. Significant additional modelling of local effects has been conducted in the vicinity of the proposed SW Tower and SW Anchor Block structures. This work has included development of a new high-resolution model driven by results from the regional Delft3D model, and examination of hydrodynamic and transport effects of these structures during typical, seasonal and extreme storm conditions. This additional high-resolution modelling has verified the presence of local, transient current variations in the immediate vicinity of each of the proposed structures, and confirmed that the structures induce only limited local erosion and deposition patterns adjacent to the structures themselves.

4. Performing longer-period simulations with real continuous inputs (no input data averaging). A wide range of time-series simulations have been completed with continuous real inputs and without any morphological acceleration in order to supplement insights gained through previously conducted time series studies and the 5 year extensive MORFAC = 13.5 results presented previously (Hatch, 2015). Continuous time-series simulations have been completed for circumstances including both typical daily and seasonal periods, for the full range of extreme events discussed above, and over a series of extended time periods up to 1 year in duration covering the full annual cycle. This refined modelling approach continues to support the conclusion that Flora Bank is a highly dissipative feature and morphologically stable environment.

5. Improving presentation of results to better convey the coastal processes being simulated. Significant efforts have been undertaken to quantitatively review and present model results, particularly sediment flux and net sediment transport across a wide range of modelled conditions. Modelling results indicate large, wide and extremely homogeneous fields of transport (of primarily the finer materials) over Flora Bank, which provides a clear indication as to why Flora Bank experiences little bed elevation change.

In addition, recent modelling efforts have refined a range of other inputs, including Skeena River freshwater discharge and salinity, to further enhance the detail with which the Skeena River inputs to the site area are represented in the model. Based on extensive modelling efforts it is evident that the Skeena River discharge plays a limited role in physical processes at the project site.

Results of the modelling efforts have been carefully analysed and considered in the context of four distinct “impact pathways’ articulated through engagement between PNW LNG and the federal agencies. This analysis indicates that:

- There will be a direct alteration or loss of approximately 21,300 m^2 of area due to the footprint of the proposed structures.
- The erosion, deposition and morphology changes due to the proposed structures are not predicted to affect the eelgrass habitat on Flora Bank.

- There is no potential for a general increase in total suspended solids (TSS) beyond occasional, local, transient changes within the immediate vicinity of the proposed southwest tower and southwest anchor block structures.
- There is no potential for a general increase in currents beyond occasional, local, transient changes within the immediate vicinity of the proposed southwest tower and southwest anchor block structures.

Recent modelling efforts have involved significant refinement of the Delft3D modelling and the additional development of new high-resolution models to closely examine behaviours in the immediate vicinity of the SW Tower and SW Anchor Block structures. These refinements provide further confidence in previous findings, which indicate little change to the overall morphology patterns with the proposed marine structures in place relative to modelled baseline results. The proposed marine structures are not expected to result in changes to the natural conditions, and while small variations in erosion and deposition occurred over Flora Bank in the model, these changes are consistent in scale with the naturally occurring bedform variations on Flora Bank and generally are modestly attenuated compared to existing conditions. Modelling does not indicate a net change in erosion or deposition patterns, nor does the model suggest long-term loss of sand or increased sedimentation of Flora Bank by fine silt materials.

9. References

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., & Clopper, P. E. (2012).Evaluating scour at bridges (No. FHWA-HIF-12-003).

Boothroyd, J. C., and D. K. Hubbard. 1975. Genesis of bedforms in mesotidal estuaries. In Estuarine Research, L. E.

Das, S., Das, R., & Mazumdar, A. (2014). Variations in clear water scour geometry at piers of different effective widths. Turkish Journal of Engineering and Environmental Sciences, 38(1), 97-111.

Deltares (2014a). Delft3D-FLOW, Simulation of Multi-Dimensional Hydrodynamic Flows and Transport Phenomena, Including Sediments. User Manual Hydro-Morphodynamics, Version: 3.15.34158. Delft, the Netherlands.

Deltares (2014b). Delft3D-WAVE, Simulation of Short-crested Waves with SWAN, User Manual, Hydro-Morphodynamics, Version: 3.05.34160. Delft, the Netherlands.

Department of Fisheries and Oceans (DFO) (2015). http:// www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/range-profiles/index-eng.html

Escarameia, M., & May, R. W. P. (1999). Scour around structures in tidal flows.

Harris, J., Whitehouse, R. J. S., & Benson, T. (2010). The time evolution of scour around offshore structures. ICE-Maritime Engineering, 163(1), 3-17.

Hatch (2014a). “Pacific Northwest LNG Potential Impacts of the Marine Terminal Structures on the Hydrodynamics and sedimentation Patterns”. H345670-0000-12-220-0028, Rev B. December 11, 2015.

Hatch (2014b). “Pacific Northwest LNG Lelu Island LNG Terminal Marine Structures Scour”. H345670-0000-12-124-0008, Rev 1. December 11, 2015.

Hatch (2014c). “Pacific Northwest LNG Jetty Propeller Scour Analysis”. H345670-0000-12-124-0009, Rev 1. December 11, 2015.

Hatch (2015). “3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation”. H345670-0000-12-124-0012, Rev. 0, May 5, 2015.

Kolomiets, P., Sorockin, M., Kivva, S. and M. Zheleznyak (2014). UCEWP-MOR-UN -- A Numerical Simulator for Depth-Averaged Surface Water Flow, Sediment Transport and Morphodynamics in Nearshore Zone on Unstructured Grids.

Neumeier, U., Ferrarin, C., and G. Umgiesser. 2008. SEDTRANS05 User Manual. Revision 1.05, March 2008.

Nordila, A., Ali, T. M., Faisal, A., & Badrunnisa, Y. (2014, January). Local Scour at Wide Bridge Piers. In International Journal of Engineering Research and Technology (Vol. 3, No. 1 (January-2014)). ESRSA Publications.

Sheppard, D. M., Jones, J. S. (2010). Scour at Wide Bridge Piers.

Stantec (2015a). “Pacific NorthWest LNG Project Marine Fish and Fish Habitat Program Interim Data Report”.

Stantec (2015b). “Pacific NorthWest LNG Project Flora Bank Area Analysis”. August 24, 2015.

Stantec (2015c). “Pacific NorthWest LNG Flora Bank Lidar DEM June 18, 2015”.

SedTrend (2015a). “Final Report A Sediment Trent Analysis (STA) of Prince Rupert Harbour and its Surrounding Waters”. January 3, 2015.

SedTrend (2015b) “Final Report A Sediment Trent Analysis (STA) of Prince Rupert Harbour and its Surrounding Waters”. August 11, 2015.

Egbert, G., Erofeeva, L. College of Atmospheric and Oceanic Sciences. 2010. “TPXO 7.2 Global Inverse Tide Model”. http://volkov.oce.orst.edu/tides/TPXO7.2.html [online November 9, 2015].

Wateroffice, Government of Canada (2015). Skeena River at Usk Station (08EF001). http://wateroffice.ec.gc.ca/station_metadata/referenceIndex_e.html?stnNum=08EF001 [online November 9, 2015].

Whitehouse, R. J. (2004). Marine scour at large foundations.

Whitehouse, R. J. S., Harris, J., & Sutherland, J. (2010). Evaluating scour at marine gravity structures.

Appendix A:
Work Plan

Pacific Northwest LNG

Updated 3D Modelling Work Plan

13 July 2015	1	For Use	L. Absalonsen R. Arbuckle	S. Fenical O. Sayao	C. Mealing	David Kyle
3 July 2015	0	For Use	L. Absalonsen R. Arbuckle	S. Fenical O. Sayao	C. Mealing	David Kyle
17 June 2015	C	For Comment	L. Absalonsen R. Arbuckle	S. Fenical O. Sayao	C. Mealing	
Date	**Rev.**	**Status**	**Prepared By**	**Checked By**	**Approved By**	**Approved By**
HATCH						**Client**

Table Of Contents

Safety • Quality • Sustainability • Innovation

1. Introduction

1.1 Background

In early May 2015, Hatch completed a comprehensive 3D modelling effort consistent with the Terms of Reference for 3D Modelling, March 19, 2015. Hatch's report "*Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation*" was provided to CEAA as Appendix B of Stantec's overall Information Request # 3 response, entitled *Predicted Project Effects on Fish and Fish Habitat* on May 4, 2015.

CEAA subsequently provided comprehensive feedback contained in correspondence from CEAA to PNW LNG dated June 2, 2015, which in turn referenced review comments from

- Natural Resources Canada (NRCan letter, May 29)
- Fisheries and Oceans Canada (DFO letter, May 29; and DFO Science Technical Review, May 20)

CEAA provided further feedback to PNW LNG in a slide deck presented June 4, 2015, which summarized CEAA's principal concerns in 5 key points:

- Modelling of Wind and Wave Fields
- Wave, wind and current model inputs (MORFAC)
- Extreme storm values and modelling procedures
- Modelling of flows at Anchor Block and Tower Base
- Model Outputs for TSS and sediment transport

Direct interaction between CEAA, NRCan, DFO, PNW LNG and Hatch was facilitated in a technical meeting held in Vancouver on June 8, 2015. At this meeting Hatch fostered further discussion of CEAA's concerns through a presentation based around the concepts of "model input refinements"; "additional model runs"; and "improved model output presentation".

1.2 Work Plan

This document presents a work plan to guide further modelling and related analysis efforts intended to address the comments raised by CEAA and the federal experts. The 3D modelling and analysis effort described herein are intended to both support the CEAA assessment process as well as to inform subsequent permitting and detailed design efforts.

Although described in a sequential manner as an aid to visualizing the process, many of these efforts will in practice be undertaken in parallel, in order to allow Hatch to efficiently evaluate:

- Whether information currently available will assist in addressing CEAA's principal concerns;
- Whether any significant "driving" effects were underestimated in the previous effort; and
- How best to include – where appropriate – these parameters into the detailed and time-consuming continuous time step model runs.

Through this effort Hatch will be seeking to either confirm or further improve:

- Confidence that the baseline model appropriately represents the hydrodynamic and sediment transport behavior of Flora Bank (i.e. through refinement of the Skeena River discharge parameters) at the level of detail necessary to substantiate valid comparisons;
- Confidence that the potential effects of the new structures on the hydrodynamics and sediment transport are appropriately represented (i.e. through improvements to the modelling of the anchor block, etc.); and
- Confidence that any potential adverse effects of the new infrastructure have been determined, particularly when comparing the relative effects of relevant extreme storm events, and relative long-term erosion/deposition trends.

This work plan explicitly intends to guide efforts to allow PNW LNG to explicitly address CEAA's 5 key concerns while continuing the ongoing modeling that will be required to support permitting and detailed design. In this light, and based on the foregoing comments and discussions, the principal objectives of the work plan are to:

- Evaluate and further refine selected inputs to the modelling analysis, including review and as appropriate refinement of the input of wind and wave fields in the model (CEAA concern #1);
- Review the scaling and directionality of the extreme events and amend the model approach as appropriate (CEAA concern #3);
- Refine the representation of the proposed bridge infrastructure in the model(s) (CEAA concern #4);

- Undertake additional modelling runs using an hourly time series (MORFAC = 1), in order to further refine the understanding of the model response to daily and seasonal effects and the potential impacts of the marine structures, supported by additional long-term modelling runs in order to refine understanding of the long-term morphology and potential impacts of the marine structures (CEAA concern #2);

- Refine the presentation of output data resulting from both of the above efforts and using data already available from previous efforts in order to allow greater insight, validation and quantification of observed trends (CEAA concern #5); and

- Undertake ongoing technical exchange with CEAA and federal experts from DFO and NRCan to foster continued collaboration and to increase confidence in the modelling results.

1.3 Objective of this Work Plan Document

As described in section IV of the Terms of Reference, the modelling system consists of several integrated and coupled modules, and the efforts described in this work plan include supporting input data preparation and analyses; calibration and sensitivity studies; as well as careful review and analysis of output data. Each aspect of this effort requires ongoing professional expertise and judgement.

Since modelling and analysis of this type is an inherently iterative process, as the study progresses, interim results will lead to ongoing refinement of the general efforts outlined in this work plan.

This work plan should therefore be understood as intended to provide guidance to the overall modelling effort, and to facilitate ongoing discussion with CEAA and its federal experts.

The evolving data, methods and results of these efforts will be clearly documented as they become available with a view to increasing the confidence of federal experts in providing advice to CEAA, as well as at the completion of this effort.

2. Review of Spatially Variable Input Winds / Waves

2.1 Wind Data

Objective:

Determine which spatially variable input wind datasets provide an improvement to 3D model predictions of waves, and thereby refining predictions of marine structure impacts on the morphology of Flora Bank.

Approach:

Perform a comprehensive evaluation of both measured and model data sets available for the project area, and determine through comparison with local measurements and wave model calibration results (comparison with wave measurements) which datasets are likely to provide the most accurate morphology predictions. If necessary, a combination of datasets may be used, or calibration of gridded datasets may be performed.

Methodology:

The following methodology is proposed to develop the input wind data set:

- Analysis of local measured wind data will be conducted taking into consideration the following data sources:
    - Environment Canada Stations: Holland Rock, Lucy Island Light Station
    - Fisheries and Oceans Canada (DFO) Buoys: North Hecate Strait (C46183), Dixon Entrance Central (C46145), West Dixon Entrance (C46205)
- Spatially variable gridded wind datasets will also be evaluated to determine if they provide enhancements in model performance. Table 1 provides a listing of available gridded wind datasets and their relevant characteristics such as spatial and temporal resolution. The datasets include those from the European Center for Medium Range Weather Forecasting (ECMWF), North American Regional Reanalysis (NARR), NOAA Wave Watch III, and the National Center for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFSRv2).
- The potential influence of coastal topography on wind fields and storm fields will be carefully considered to determine if possible channeling effects will alter predicted wave fields sufficiently to alter predictions of sediment transport and morphology impacts of the proposed structures.
- The predicted wave fields will be reviewed for evidence of bias resulting from the spatial resolution utilized.

Table 1. Gridded Wind Data Sources to be Evaluated

Dataset*	Spatial Resolution***	Temporal Resolution
ECMWF – ERA 40yr Interim	50 km East-West, 80 km North-South	6 hrs
NARR 8x Daily	32 km	3 hrs
WWIII**	28 km East-West, 16 km North-South	3 hrs
CFSRv2 Winds	15 km East-West, 20 km North-South	6 hrs
CFSRv2 Pressure @ MSL	55 M	6 hrs

* Other data sources were evaluated but eliminated from consideration based on relatively sparse data around the project site (low spatial resolution), or infrequent output (low temporal resolution, such as NARR 4x Daily). Also, many of the available gridded wind datasets are not yet available for the 2012-2014 time period used in the modelling.

** Surface winds. All others 10m elevation. The spatial variability of the winds from these datasets will be evaluated and potential changes in wind-wave growth and transformation within the 3D model will be determined using sensitivity testing simulations. If wind-wave growth and transformation predictions can be improved using the spatially variable data, these data will be incorporated into the 3D model.

*** Resolution of datasets will be confirmed.

2.2 Wave Forcing

Objective:

Determine whether additional input from offshore wave datasets are likely to provide an improvement to 3D model predictions of marine structure impacts on the morphology of Flora Bank.

Approach:

Perform a comprehensive evaluation of both measured and model wave data sets available for the project area, and determine through comparison with local measurements and wave model calibration results (comparison with wave measurements) which datasets are likely to provide the most accurate morphology predictions. If necessary, a combination of wave datasets may be used, or calibration of gridded datasets may be performed.

Methodology:

The following methodology is proposed to select the input wave data:

- Analysis of local measured wave data will be performed using the following data sources:
    - Fisheries and Oceans Canada (DFO) Buoy at West Dixon Entrance (C46205)
    - Fisheries and Oceans Canada (DFO) Buoy at South Moresby (C46147)

The two buoys above are located on either end of Haida Gwaii and therefore together they represent the wave conditions approaching Dixon Entrance on the north side, and Hecate Strait on the south side.

- Offshore gridded wave datasets will also be evaluated. Table 2 shows the gridded offshore wave datasets which will be evaluated for potential inclusion as offshore wave boundary conditions.

Table 2. Gridded Wave Data Sources to be Evaluated

Dataset	Spatial Resolution	Temporal Resolution
ECMWF – ERA 40yr Interim	50 km East-West, 80 km North-South	6 hrs
WaveWatch III (WW3)	28 km East-West, 16 km North-South	3 hrs

- The spatial variability of the waves from these datasets will be evaluated and potential changes in offshore wave transformation to the site within the 3D model will be determined using sensitivity testing simulations. If wave transformation predictions can be improved using the spatially variable data, these data will be incorporated into the 3D model.

2.3 Skeena River Discharge / Sediment Load

Objective:

Improve the accuracy of freshwater and sediment load input from the Skeena River by removing input data averaging assumptions used in the previous approach to long-term morphological simulation (MORFAC approach using averaged inputs).

Approach:

Delft3D simulations will be run continuously with accurate input time series of boundary forcing for a 1-year period which will allow the full volume of river discharge and suspended sediments to be input into the model.

Methodology:

The following methodology is proposed:

- Input continuous freshwater discharge and suspended sediment data in the model. The monthly suspended sediment data will be used to produce hourly input data.
- Consistent with the prior modelling approaches, Skeena River discharges measured at the Usk Station will be increased by a factor of 1.24. This accounts for additional tributaries between the Usk measurement location and the input boundary of the model, which is further downstream.

2.4 Salinity Stratification / Sigma Layers

Objective:

Evaluate vertical salinity stratification in the vicinity of the marine structures at Flora Bank and improve initial salinity stratification conditions in the initialization of the model (ramp-up of the salinity field) in order to determine if these changes affect morphological predictions of marine structure impacts.

Approach:

Review the nearby available measured salinity data and the results from the previously modelled time series runs for the freshet to evaluate the extent of the freshwater stratification in the region and the significance of stratification on sediment transport at Flora Bank. Determine the most appropriate method to initialize the salinity conditions in the model and the number of sigma layers required to capture the stratification.

Methodology:

The following methodology is proposed to capture the impacts of stratification in the model study:

- Revise the input discharge at Usk to be 100% freshwater.
- Review the available measured salinity profiles in the region, specifically those located near the mouth of the Skeena River, Inverness Passage, and at the project site.

  The review will be used to determine the extent to which stratification exists at the location of the marine structures. If no salinity stratification exists during the majority of the time near the marine structures, the marine structures are not likely to disrupt salinity stratification and its potential effects on morphology at the site.
- In addition to analysis of previous measurements, the results from the previously modelled time series runs for the freshet time period, including those with both 5 and 10 vertical layers, will be further reviewed to evaluate the locations (horizontal and vertical extents) of stratification. If results indicate stratification is significant at the location of the marine structures, additional vertical resolution (layers) may be included within shorter-term simulations (storm events, freshets, etc.), and sensitivity testing will be performed, to evaluate stratification impacts on morphology of Flora Bank and changes caused by the marine structures.
- Additional sensitivity runs will be performed to evaluate the effect of higher resolution of vertical levels on predictions of sediment transport. Model will be tested at high resolution (e.g. 21 levels) to validate understanding and predictions of stratification.
- Subsequent time-series runs will be conducted at higher resolutions (i.e. greater than 5 layers) to the limit practical considering impacts on overall model stability and

run time. It is anticipated that run time optimizations will support full time series runs at 10 sigma layers.

- Salinity initial conditions will also be revised in the 1-year simulations. Several types of salinity initial conditions will be investigated, including:
    - Horizontally constant vertical stratification in the entire domain, specified based on local observations;
    - 3D field of calculated salinities taken from the peak fresh water input time period in the time series freshet simulations; and,
    - 3D field of calculated salinities taken from the end of the freshet time series simulation (28 days, and after high fresh water inflows).
- The initial condition will likely consist of one of the above prescribed or pre-calculated salinity fields, and selection will be based on whichever salinity field represents more highly stratified conditions and hence more potential stratification effects on the morphology of Flora Bank.
- Model input flow conditions will be reviewed to ensure they represent actual conditions at the location of the input.
- Model results will be carefully reviewed to:
    - Validate that results do not indicate development of non-physical extrema in the salinity field; and
    - Validate that stratification predictions in the vicinity of the marine structures are reasonable throughout the year.

3. Storm (Extreme Events) Modelling

Objective:

Provide additional information regarding the potential impacts of marine structures on Flora Bank during extreme event storms that occur over longer durations and arrive from different directions.

Approach:

Modify the approach for modelling the extreme events including duration and scaling of the storms, selection of tide and incorporating swell conditions. Select appropriate storm directions to model to ensure a robust understanding of the potential impacts to Flora Bank with and without the marine structures.

Methodology:

Storm simulations will be modified according to the following proposed methodology:

- Increase the duration of both the model spin-up and total run time to approximately 8-10 days total, to ensure the effects of the storm are fully captured.

- If warranted, widen the duration of storm peak winds used in the 3D model, scaled in magnitude according to wind speeds at Holland Rock.

- Define storms with return periods of approximately 1 year (base case), 5, 20, 50 and 100 years.

- During these extreme wind storm events, offshore swell from the Pacific Ocean will also be present. However these offshore waves are not directly correlated to the extreme winds. In order to generate conservative predictions of storm effects at Flora Bank, preliminarily it is proposed to specify an extreme offshore swell condition for all simulations, such as the largest waves measured at the West Dixon Entrance Buoy. Following initial simulations, this preliminary assumption will be evaluated to ensure that results are not overly conservative.

- Review input tides used in the storm simulation and ensure that tidal ranges include large tides, which produce larger morphological changes at Flora Bank. The frequency of occurrence of the tides in the simulation will be described.

- Model storms arriving from 4 realistic directions (preliminarily 170^{o}, 240^{o}, 270^{o}, 300^{o}), for 5 different return periods and with and without the marine structures in place. The highest wind speeds measured at Holland Rock, from the western and southern quadrants, will be used for the selected directions and return periods for simplicity and conservatism in prediction of morphological changes at Flora Bank.

4. Modelling of Proposed Structures

Objective:

Improve understanding of the nature and extent of any effects of the SW anchor block or SW tower on Flora Bank, specifically the hydrodynamic effects such as turbulent wakes on the leeside of the structure.

Approach:

The approach to evaluating marine structure local hydrodynamic effects consists of two components. Two independent approaches are proposed as follows to further refine the understanding of local hydrodynamics around the anchor block and tower base.

1) Improve the representation of the structure within the Delft3D model. The SW anchor block and SW tower will be represented as dry cells instead of a porous-plate (previous approach). The result of this change is that the structures will likely show greater increases in current velocity around the sides of the structures, in addition to lower-velocity areas on the downstream sides.

2) A separate, detailed hydrodynamic model of the area surrounding the anchor block and tower will be developed to simulate the fine-scale hydrodynamics, turbulent wakes, and potential for erosion/sedimentation near Flora Bank.

Methodology:

1) The following methodology is proposed to improve modelling of the structure within Delft3D:

    - Use inactive cells to represent the SW anchor block and tower as dry cells within the Delft3D model.

    - Conduct sensitivity model runs to evaluate refining the gridding near the structure. This will be evaluated to see if there is a significant difference in the results as well as the stability of the model.

2) The following methodology is proposed for a detailed model of the marine structures:

    - Multiple hydrodynamic models will be initially applied, such as 2D finite volume unstructured (MORPHO or similar) or 3D finite element (SELFE or similar) unstructured tools, and the most appropriate tool chosen based on the representation of physical processes and conservatism in representing the processes that cause an impact to Flora Bank.

    - The fine-scale model will be forced with current velocities and water levels from the Delft3D model, will be run for both existing conditions and with-structure conditions.

Safety ● Quality ● Sustainability ● Innovation

- Modelling will be performed with an unstructured finite volume/finite element model with resolution of approximately 3-5 m in the vicinity of the anchor block and tower base. The final selected resolution will be validated with a convergence study to ensure flow dynamics are adequately captured.

- Results from the separate models will be reviewed and characterized, compared with Delft3D model results, and evaluated in terms of erosion potential at Flora Bank.

- If results indicate the presence of significant currents or erosion potential, and thereby indicate potential effect on either sediment transport or morphological effects, then further efforts to couple the outputs of the high-resolution and sediment transport models will be undertaken as necessary to further quantify these effects.

- Effects of trestle piles on storm waves will be investigated with conceptual modelling.

5. Time Series Morphology Simulations

5.1 Time Series Runs (MORFAC = 1)

Objective:

To refine the simulation of hydrodynamics, sediment transport and morphological changes occurring over a minimum 1-year period to better evaluate the potential impacts of marine structures on morphology of Flora Bank.

Approach:

Run continuous simulations for an entire 1-year period without morphological acceleration and using realistic boundary condition (hourly) input. Data will be extracted after 1 year of simulations for further analyses.

One model run will simulate the baseline conditions (without the marine structures) and one will simulate the conditions with the marine structures in place.

Note: Although output from a one-year time-series will be presented to inform the CEAA assessment process, time-series runs will continue for a second year to further inform subsequent permitting and detailed design efforts.

5.2 5 Year Runs (MORFAC = 5)

Objective:

Simulate 5 years of morphological changes with and without the marine structures to support evaluation of the long-term impacts of the marine structure on Flora Bank in conjunction with other analyses.

Approach:

Note: It is acknowledged that several approaches may be appropriate to ensure confidence in longer-term morphological predictions, and this is a matter that may benefit from continued engagement with CEAA and relevant federal experts.

The anticipated approach is to run the 1-year time series input data with a morphological acceleration factor of 5, and using realistic boundary condition (hourly) inputs. One model run will simulate the baseline conditions (without the marine structures) and one will simulate the conditions with the marine structures in place. The results of these model runs will be used in conjunction with other available results to determine the 5-year long-term morphological impacts of the proposed marine structures on Flora Bank.

5.3 Prediction of Long-Term Implications

Objective:

To provide further commentary on the potential for any long-term implications of the proposed marine structures on the morphology of Agnew and Flora Banks not otherwise captured in storm and 1-year analyses.

Approach:
The results of the storm event analyses and the one-year time-series analyses will be analytically and / or mathematically integrated as necessary to assess the potential long-term trends.

Note: The specific approach to be taken will be highly dependent on what, if any, impacts or trends are evidenced in the relevant results. Further technical discussion with Federal experts will inform the specific approach adopted, as the relevant results become available.

6. Output Data Review

6.1 Quantification of Net Sediment Flux

Objective:

Summarize results from various model runs in a form which quantifies the net deposition or erosion of sediment across Flora Bank to support further evaluation of the potential impact of the proposed structures

Approach:

Results from the previous model study will be revisited to extract meaningful and relevant information to address, where possible, outstanding concerns. This review will include:

- Quantitative analysis of erosion and deposition volumes over Flora Bank from the previous 3D model study to address concerns with Figure 1 of the May 4, 2015 report *Predicted Project Effects on Fish and Fish Habitat*.
- Analysis of the volumetric changes on Flora Bank for the previous sensitivity test which modelled a 4 week period.
- Analysis of previously modelled storms to provide flux snapshots at the peak of the storm, during ramp up and ramp down, and other demonstrative information;
- Development of additional quantitative analysis and figures to demonstrate sediment flux; and,
- Presentation of representative results from existing modelling of selected events such as storms or the freshet.

Results from the updated model studies will include quantitative analysis of erosion and deposition volumes over Flora Bank provided for the 1-year and 5-year results and appropriate storm events. Results will be presented using figures and tables consistent with previous reports, supplemented with snapshots of sediment transport flux at different stages.

The net sediment erosion and accretion over Flora Bank and related habitat areas will be quantified using a TIN model over the duration of the 1-year time series and storm events.

The following outputs from the updated one-year model runs be presented and analyzed:

- Suspended sediment concentration at different stages of tidal cycles, the Skeena River discharge cycle, and durations of storms;
- Sediment transport rate and direction at different stages of tidal cycles, the Skeena River discharge cycle, and durations of storms; and,
- Net sediment transport flux and direction averaged over durations of selected modelling scenarios and over the duration of selected extreme storms.

6.2 Verification of Non-Tidal Hydrodynamics

Objective:

Evaluate the presence and relative magnitude of currents at the site not generated by tidal effects. As appropriate, evaluate their relative magnitude, potential contribution to sediment transport and morphology, and potential contribution to net transport directions.

Approach:

Analyze measured and predicted currents at the project site using various time series analysis methods to determine the relative magnitude of non-tidal hydrodynamic energy at the site based on frequencies of measured and predicted energy.

Methodology:

Analyze measured and predicted time series of currents at the site with time series analysis tools according to the following proposed methodology:

- Process time histories using a filter to remove the tidal signal, and leave only signals with periods greater than roughly one day; and,
- Perform analysis of time histories using a FFT analysis code, generating a spectrum of hydrodynamic energy, removing energy at tidal frequencies. The spectrum will be evaluated and total energy content at non-tidal frequencies will be computed relative to the total. The spectrum will be evaluated and if possible to perform accurately, time histories of non-tidal hydrodynamic components will be computed.

7. Engagement with CEAA

Hatch has structured this effort in order to foster early and ongoing technical discussion between PNW LNG and CEAA and its supporting federal experts.

Hatch's efforts will be undertaken in close cooperation with PNW LNG and its advisors, including Stantec, to ensure that the modelling results may be efficiently integrated with PNW LNG's overall consideration of the potential for significant adverse effects to fish and fish habitat.

Hatch believes the following preliminary milestones will provide the most productive opportunities to engage with CEAA and its federal experts.

7.1 Interim Workshop Presentation of Initial Analysis Results

Hatch anticipates being able to provide an interim update on the progress of its review of many of these parameters which will further inform CEAA and its experts, and foster ongoing technical discussion.

While it is not feasible to complete new "full year" hourly time series model runs during this initial period, Hatch does anticipate being able to further review hour time series runs previously undertaken and/or perform a limited number of "partial year" model runs. This should allow further investigation as to whether concerns raised by CEAA's experts are evidenced in time series data currently available.

Hatch proposes to provide an interim progress "snapshot" deliverable, followed by an interactive workshop presentation and discussion with CEAA and federal experts.

Target "Snapshot" Deliverable Date: July 3, 2015
Target Workshop Date: week of July 6, 2015

7.2 Presentation / Workshop of Results

Hatch anticipates there will be significant value in initial results from the hourly time series model runs; refined anchor block and tower modelling efforts; and related analyses once these results become available. This will include presentation of results to date, discussion of whether any preliminary results vary from the previous efforts conclusions and what if any trends are evident in the analysis.

Hatch proposes to provide an updated progress "snapshot" deliverable, followed by an interactive workshop presentation and discussion with CEAA and federal experts.

Target "Snapshot" Deliverable and Workshop Date: Early August, 2015
(preliminary and subject to change)

7.3 Supplemental Report

As modelling efforts are advanced to a point where PNW believes that CEAA's key technical concerns have been addressed, Hatch will develop a Supplemental Report for review by PNW. Once accepted by PNW, PNW will submit the Supplemental Report to CEAA.

The report will highlight new findings from the modelling studies conducted under this work plan, and will address the five key issues raised with by CEAA and the federal experts with PNW as captured in the June 4, 2015 CEAA slide deck. The report will reflect technical discussions with CEAA's technical experts subsequent to June 2, 2015.

Modelling efforts, will continue following presentation of the Supplemental Report as appropriate to support additional technical discussions, inform subsequent DFO permitting efforts, and inform final engineering design of Agnew Bank suspension bridge sub-structures, trestle and berths.

Target Date: To be confirmed following further discussion with CEAA representatives.

Appendix B:
Delft3D Model Setup

B1. Delft3D Model Setup

This appendix documents the Delft3D setup that was used for the freshet, storm and long-term simulations presented in this report and highlights differences in comparison to the setup presented in the May 5 report. Modifications were made to the May 5 Delft3D setup with assistance from Deltares to improve grid properties, increase model stability, and decrease model run times. When model settings differ from the May 5 simulation setup they are noted as such below.

B1.1 Delft3D Flow and Morphologic Grids

A modified grid with dimensions of 218 x 230 cells was generated by making moderate changes to the grid used on the simulations in the May 5 report (253 x 204 cells). Grid modifications were done in order to achieve the finest spatial resolution possible in the project area while giving consideration to recommended gridding guidelines that increase model stability (orthogonality, grid cell aspect ratio, grid cell transition smoothness, etc.) as well as to reducing overall model run times by idealizing features far from the project site. Figure B-1 shows both the May 5 (left) and modified grid (right).

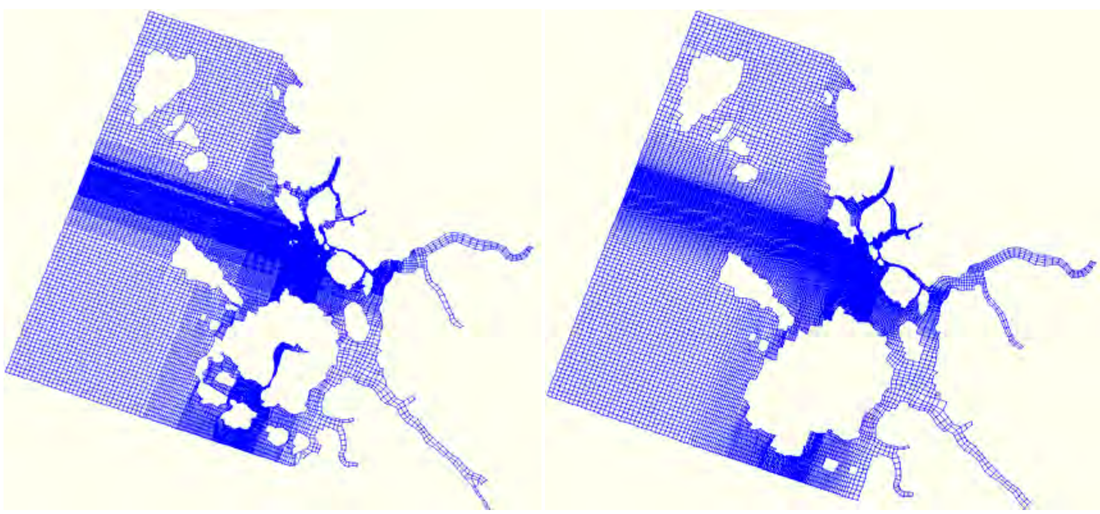


Figure B-1: May 5 Delft3D flow grid (left) and modified Delf3D flow grid (right)

The use of 10 uniform vertical sigma layers, instead of the 5 vertical sigma layers in the May 5 model, was used in order to resolve salinity stratification and accurately model sediment transport. The same bathymetric data sets used for the May 5 grid were interpolated onto the new model grid to generate a corresponding depth file. Some very minor smoothing was performed on this depth file to eliminate artificial features generated from interpolation as was done in the May 5 grid.

B1.2 Delft3D Flow Hydrodynamics Input Parameters

In order to satisfy courant number restrictions a time step of 15 s was necessary to achieve model convergence for this simulation. Tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4, and MN4) were used as hydrodynamic forcing conditions for all model boundaries except for the Skeena River which was forced using discharge time series data obtained from Environment Canada. The discharge was multiplied by 1.24 to account for the tributaries downstream of Usk station (location where the discharge was measured). The simulations in the May 5 report were conducted without the correction factor for the downstream tributaries.

Initial salinity conditions were generated by running a separate 1 year simulation (without waves, sediment transport, and morphology) in the absence of other data to obtain a well establish mixed condition for the salinity. All open ocean boundaries were given a fixed salinity of 31 ppt while the Skeena River was given a fixed freshwater value 0 ppt. The May 5 report used a homogenous condition for salinity in the entire model domain (31 ppt) and the salinity at the Skeena River boundary was considered as 10 ppt.

For the long-term simulations, the structures were modelled as porous plates to simulate the attenuating effects of the trestle pier piles. A 10 day comparison of water levels and currents at the Porpoise Channel ADCP shows there is very little difference between the May 5 setup and modified setup (both including 3-hour wave coupling) in terms of hydrodynamic results. The storm simulations assumed the SW Anchor Block and SW Tower as dry cells and the trestle as porous plate.

In addition to the general model configuration above the following important hydrodynamic parameters were used:

- Water Temperature = 9.4 °C
- Bottom Roughness = 0.03 (Manning)
- All Delft3D simulations utilized the default k-epsilon 3D turbulence closure model with a constant background horizontal and vertical eddy viscosity. A background horizontal eddy viscosity of 10 m^2/s (changed from 1 m^2/s in May 5 simulations setup to help improve model stability) and background vertical eddy viscosity of 1e-006 m^2/s were used.
- Hydrodynamic and Morphological spin-up time of 12 hours (used to smoothly transition from initial conditions)
- Boundary reflection parameter alpha = 1000 s^2
- Threshold depth = 0.1 m
- CSFR gridded winds with assimilated Holland Rock observational data used (changed from Holland Rock uniform winds in the entire model domain in the May 5 report)

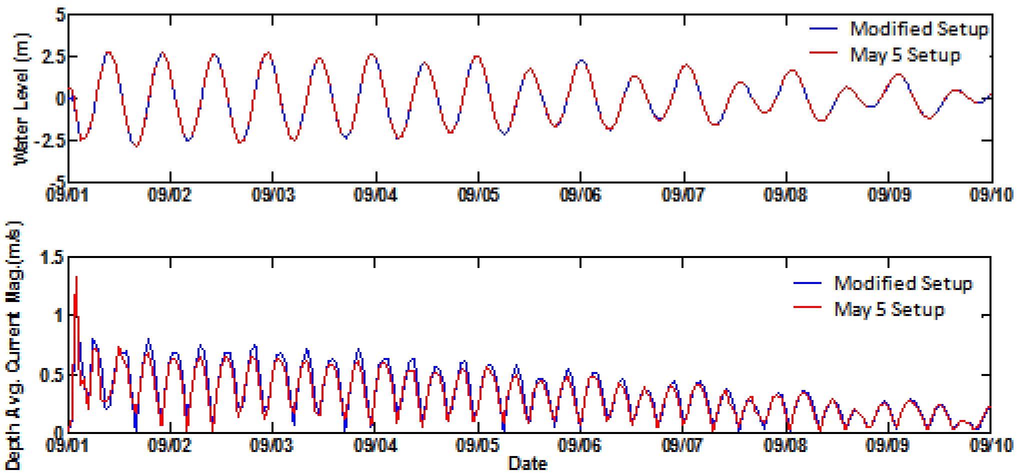


Figure B-2: 10 day time series comparison of water level and current predicted using the May 5 and modified setups

B1.3 Delft3D Flow Sediment Transport Input Parameters

A total of four sediment classes including clay, silt, fine sand and coarse sand were used to model transport and morphology. The same initial sediment bed fraction data used for the May 5 model setup was interpolated onto the modified model grid. All boundaries except for the Skeena River were assigned a fixed suspended sediment concentration of 0 kg/m^3. A time series of suspended sediment loads in the Skeena River boundary was generated from an observational data set. Initial suspended sediment concentrations were set to 0 kg/m3. In addition, the following important transport and morphology parameters were used:

- Morphologic scale factor (MORFAC) = 1 (changed from 13.55 in the May 5 report due to CEAA concern #2)
- Factor for erosion of adjacent dry cells = 0.25
- Minimum depth for sediment calculation = 0.1 m

B1.3.1 Sediment Fractions

For modelling purpose, the bottom sediments were divided into four sediment classes or fractions:

- Coarse sands and gravels, d > 2 mm (-1 ϕ); where d = mean grain size (in mm) and ϕ = unit of particle size
- Sands, d = 0.0625 to 2 mm (-1 to 4 ϕ);

- Silts, or “coarse mud”; and
- Clays, or “fine mud”.

Each type of material was specified in the model in terms of its percentage in the bed. To map the percentages of the each sediment fraction over the model grid, the following methodology was used.

At each sampling location, the percentages of sand and gravel were added together as the “sieved material” fraction f_1. The value of f_2, representing the silts and clays, was assumed to be equal to the percentage of mud at each sampling location. The grain sizes of the “sieved material” ϕ_1 and the muds ϕ_2 were estimated based on the mean grain size and sorting values, which provided two equations to estimate the two unknown values. The mean grain sizes of the sieved materials ranged from 0.14 to 2.01 mm (-1.01 to -2.84 ϕ). The mean grain sizes of the muds ranged from 0.000032 to 0.020 mm (5.66 to 14.9 ϕ).

The “sieved materials” were further divided into two sediment classes – the “coarse sand and gravel class” and the “sand class”. These sediment classes were assigned the following grain sizes based on the range of the “sieved materials”:

- Coarse sands and gravels – ϕ_{1A} = -1 ϕ (2 mm), representing “f_{1A}” percent of the bed material; and
- Sands – ϕ_{1A} = 2.84 ϕ (0.14 mm), representing “f_{1B}” percent of the bed material.

The percentages of these two fractions were estimated based on the variable grain size of the “sieved material” ϕ_1 and the percentage of the sieved material in the bed $f_1 = f_{1A} + f_{1B}$,

Likewise, the muds were divided into two sediment classes – silts and clays. These sediment classes were assigned the following grain sizes based on the range of the muddy materials:

- Silts – ϕ_{2A} = -5.66 ϕ (0.020 mm), representing “f_{2A}” percent of the bed material; and
- Clays – ϕ_{2A} = 14.9 ϕ (0.000032 mm), representing “f_{2B}” percent of the bed material.

The percentage of each sediment fraction is shown over the Delft3D model domain and locally near the project site in Figure B-3 and Figure B-4, respectively.

The resulting values of f_{1A}, f_{1B}, f_{2A}, and f_{2B}, at each sampling location were interpolated on the modelling grid used in the Delft3D-FLOW model.

The four sediment fractions were treated as shown in Table B-1.

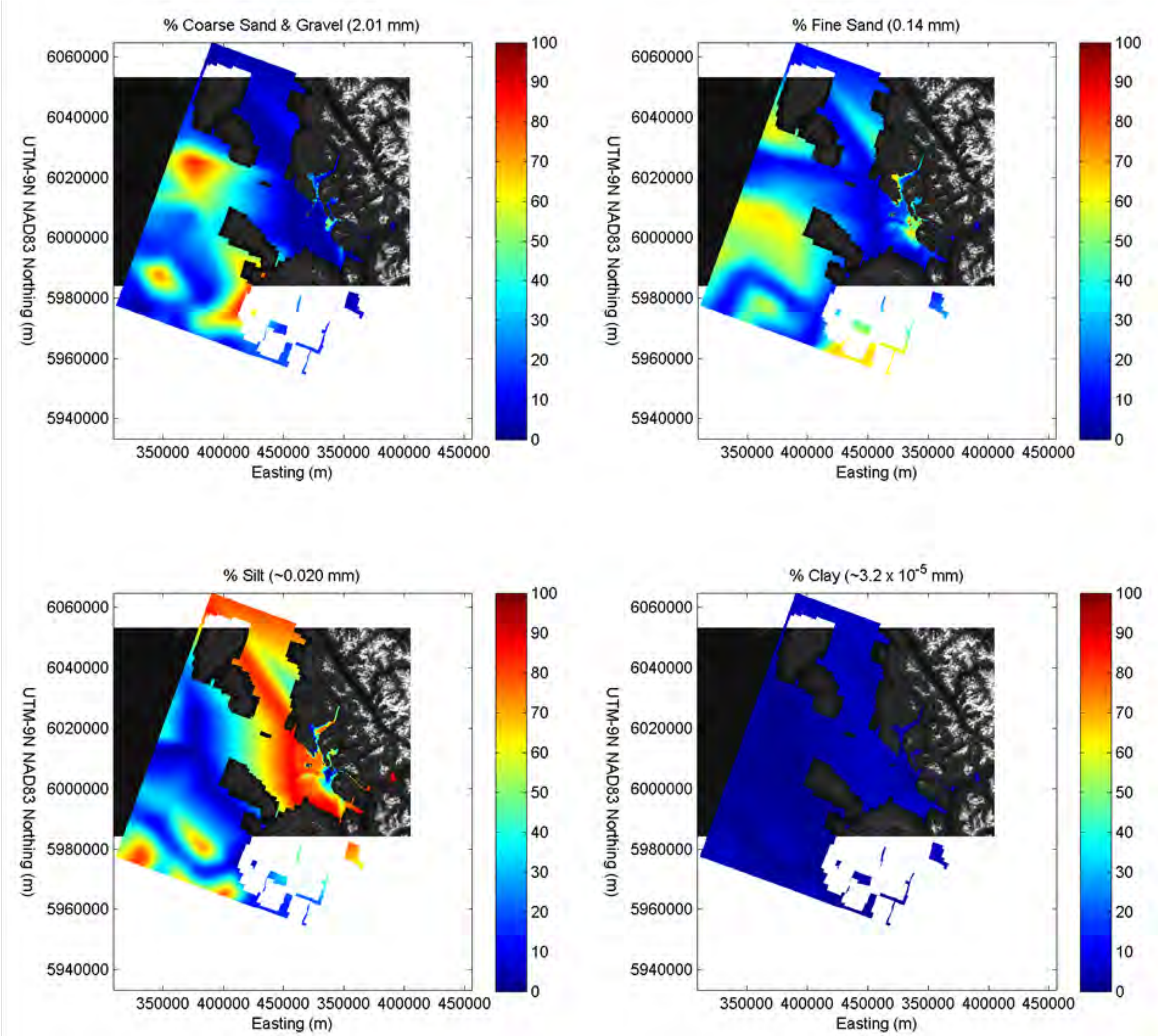


Figure B-3: Sediment Fractions over the Model Domain

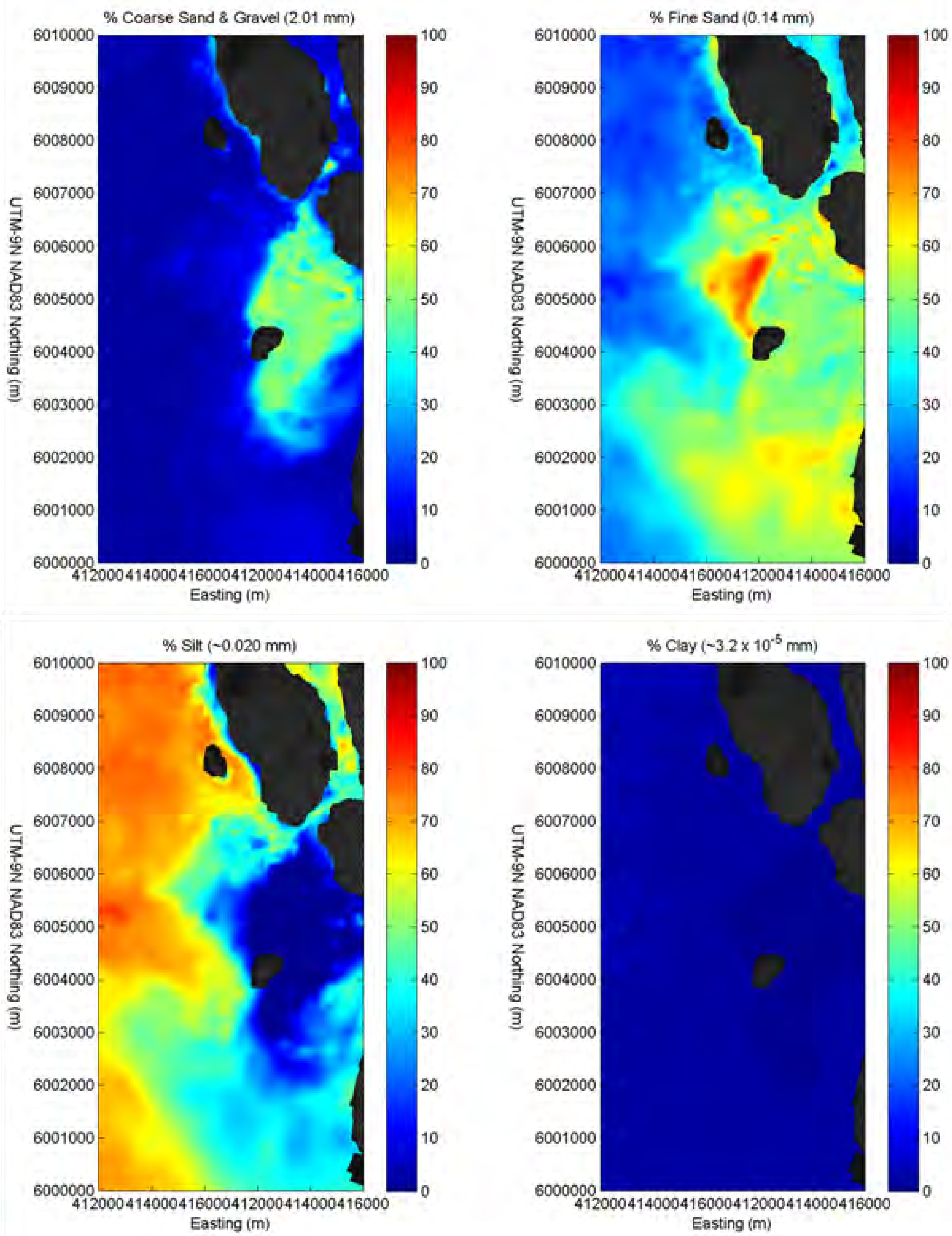


Figure B-4: Sediment Fractions over the Project Site

Table B-1: Bottom Sediment Schematization

Fraction Number	Description	Type	Grain Size (mm)
1A	Course sands and gravels	Non-cohesive	2.00 (maximum allowed)
1B	Sands	Non-cohesive	0.14
2A	Silts	Non-cohesive	0.10 (minimum allowed)
2B	Clays	Cohesive	Not Applicable

In general, silts are fine materials that do not exhibit the same degree of cohesion as clays. Ideally, the grain size of the silt fraction should be set to the size based on the samples (5.66 ϕ or 0.020 mm). The Delft3D model, however, requires a minimum grain size of 0.10 mm for a non-cohesive sediment fraction. Accordingly, the grain size of the silt fraction was set to 0.10 mm for modelling purposes.

In the Delft3D-FLOW model, cohesive materials are not characterized by grain size. Instead, the settling, deposition and erosion of the cohesive materials depend on the settling velocity, critical bottom shear stress for sedimentation, critical bottom shear stress for erosion, the erosion parameter, and dry bed density. Cohesive sediment characteristics used in the model are documented in Table B-2 along with commentary on the selection based on default values, technical literature (Winterwerp et al., 2012, USACE, 2002; and Whitehouse, et al., 2000), and previous site studies (Fugro, 2014).

Table B-2: Assumed Characteristics of the Cohesive Clay Fraction

Value	Units	Parameter Description	Comment
0.0013	m/s	Settling velocity	Estimated; range is from 0.01 mm/s to 10 mm/s
0.20	N/m^2	Critical bed shear stress for sedimentation	Estimated; from Winterwerp et al. (2012)
0.55	N/m^2	Critical bed shear stress for erosion	Estimated; from Winterwerp et al. (2012)
0.009	$kg/m^2/s$	Erosion parameter	Deltares (2014a)
1500	kg/m^3	Dry bed density	Estimated based on Fugro (2014)
36	%	Water content	Estimated based on Fugro (2014)
10	%	Plasticity Index	Estimated based on Fugro (2014)

B1.4 Delft3D Wave (SWAN) Grid

A SWAN model was used to simulate waves and it was coupled to the hydrodynamic model described above. This SWAN model consisted of a large regional scale outer grid nested with a smaller higher resolution grid that resolves the project area. The outer grid and bathymetry used for this simulation are the same as the May 5 simulations.

In the most recent setup, the nested grids (flow and waves) are identical to those used in the flow simulation. This configuration is preferred over the May 5 model configuration because it allows for improved coupling between the flow and wave modules and reduces run times. Figure B-5 shows the nested SWAN grids used in both the May 5 and modified setup. A comparison below shows that significant wave height, wave period, and wave direction near the PNW Buoy predicted using both the May 5 and modified grid (with 3-hour coupling) follow the same general trends with minor differences. These relatively minor differences are considered a worthwhile trade-off in order to obtain improved model stability and reduced run times and are not expected to impact results relative to the tolerance of other model input parameters.

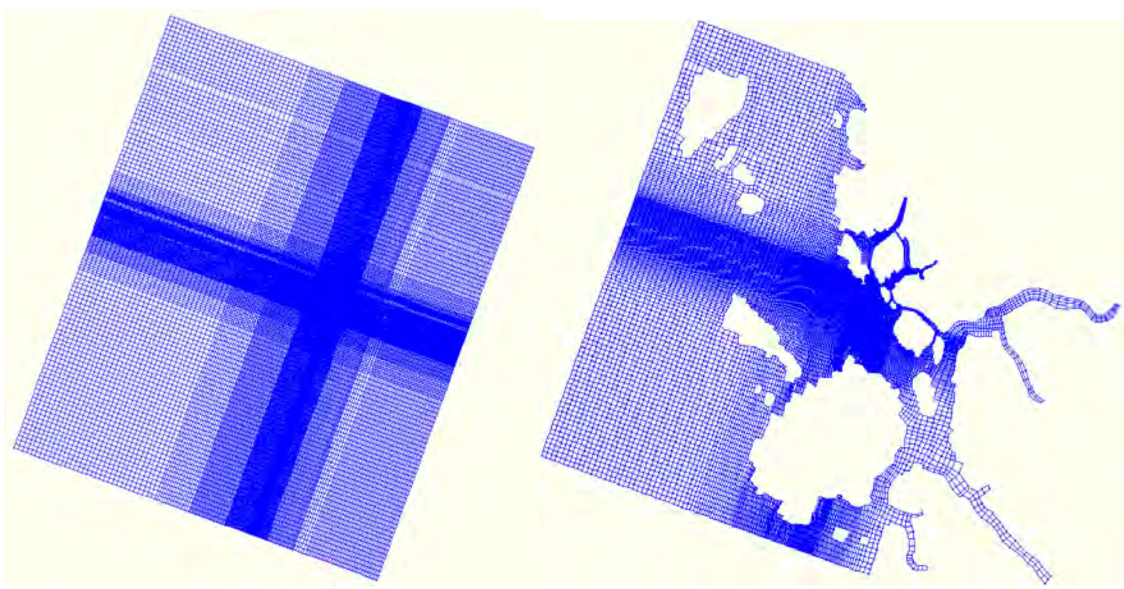


Figure B-5: May 5 nested SWAN grid (left) and modified nested SWAN grid (right)

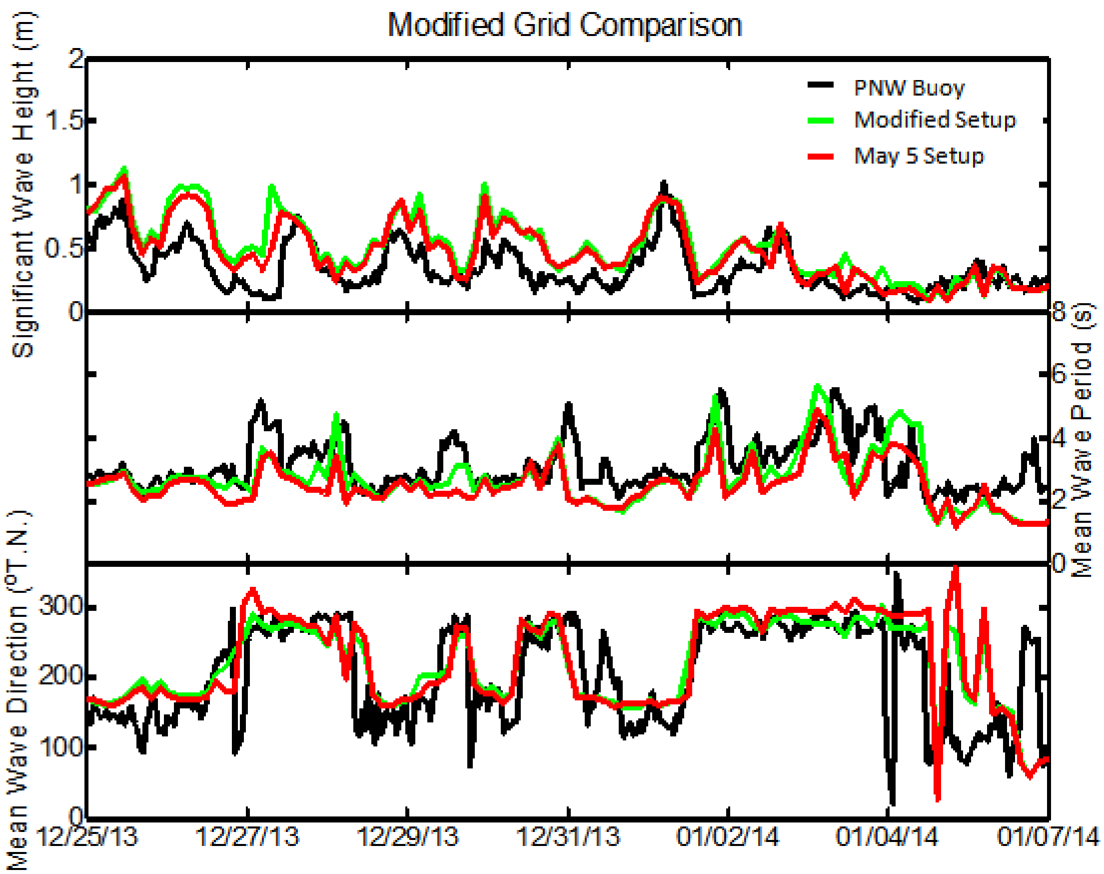


Figure B-6: A time series comparison of significant wave height, period, and direction using the May 5 and modified grids

B1.5 Delft3D Wave (SWAN) Input Parameters

The outer grid is forced using parametric wave data from WW3 at several locations along the offshore boundary (details in Appendix D). The May 5 input conditions for offshore wave heights were based on measured data at a single buoy (C46205) and the directions from WW3 as buoy 46205 doesn't have wave directions.

Both the May 5 and modified wave simulations used sheets to simulate the attenuating effects of the trestle pier piles. The wave-flow coupling interval was initially changed from 1 hour to 3 hours in an attempt to speed up model run times after calibration results showed little effect. When analysis of longer simulation results revealed unrealistic spikes in current velocities in shallow area during wetting and drying processes caused by using a 3-hour coupling interval (discussed in Appendix H) sensitivity simulations going back to 1-hour coupling were conducted to evaluate the coupling effects on currents and changes in morphology. Figure B-7 below shows a short-term comparison of wave model results both using 1-hour and 3-hour coupling. In addition, the following important wave input parameters were used for this simulation. Unless otherwise stated, these input parameters are the same as those used in the May 5 report.

- Stationary computational mode
- Frequency space = 0.05 Hz – 1 Hz using 24 bins
- Water level results from flow **used**
- Bathymetry from flow **used** (including morphological updates)
- Currents results from flow **not used**. This was changed from the May 5 settings in an attempt to speed up run times and improve stability. The impact of currents on waves is not significant near the project site. The more important impact of wave induced forces on currents is still included.
- Bottom friction = 0.067 m^2/s^3 (Default Jonswap value) (lowered from 3 m^2/s^3 in the May 5 report to allow for improved swell propagation to the project site)
- Depth-induced breaking activated
- Non-linear triad interactions activated
- Minimum depth = 0.1 m
- Wind growth activated (using same winds as flow)
- White capping activated
- Refraction activated

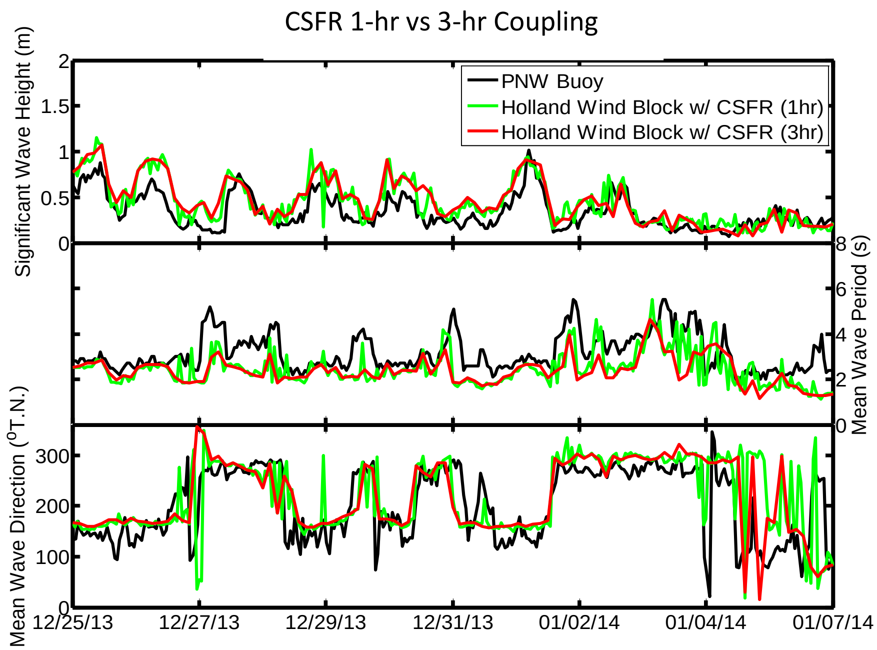


Figure B-7: Comparison of 1-hour and 3-hour coupling results

B1.6 Delft3D Wave-Flow Coupling

The simulations used 1-hour coupling between the wave and flow modules, where the only exception was the 1-year simulation that used 3-hour coupling between the wave and flow modules.

The simulations also used a full coupling between currents and waves (waves affecting currents and currents affecting waves, where the exceptions were the long-term simulations (1 year and 8 months) in which case the waves were affecting the currents but not vice versa (Table B-3). The partial coupling was used to improve the model stability during the long-term simulations. Moreover, sensitivity tests showed similar results using partial and full coupling.

Table B-3: Wave-Flow Coupling Details on Delft3D simulations

Simulation	Coupling Interval (Hour)	Wave-Currents Coupling
1 Year Time Series	3	Partial (waves affect currents but not vice versa)
8 Months Time Series	1	Partial (waves affect currents but not vice versa)
Storm Sequence (33 days)	1	Full coupling
Storm (11 days)	1	Full coupling
Freshet	1	Full coupling
Tides Only	1	Full coupling

B1.7 References

Fugro (2014). Feed-Level Geotechnical Study Nearshore Facilities Pacific Northwest Lng Project Lelu Island, British Columbia, Canada, Report No. 04.10130177-8, Pacific Northwest LNG, Vancouver, British Columbia, Canada.

U.S. Army Corps of Engineers (2002). Coastal Engineering Manual, Part III, Chapter 5, Erosion, Transport, and Deposition of Cohesive Sediments, U.S. Army Corps of Engineers, Washington, DC.

Winterwerp, J. C., W. G. M. van Kesteren, B. van Prooijen, and W. Jacobs., (2012). A Conceptual Framework for Shear Flow–induced Erosion of Soft Cohesive Sediment Beds, J. Geophys. Res., 117, C10020, doi:10.1029/2012JC008072.

Whitehouse, R., Soulsby, R., Roberts, W., Mitchener, H., (2000). Dynamics of Estuarine Muds. Thomas Telford Ltd., 210 p.

Appendix C: Wind Input

C1. Wind Input

The following section describes refinements to wind input data used in the Delft3D model for the long-term simulations.

C1.1 Wind Inputs for Long-Term Simulations

The project site is relatively sheltered from waves arriving from the Pacific Ocean; therefore local wind-generated waves in Chatham Sound dominate the wave conditions at the project site. In previous efforts, a local wind station very close to the project site (Holland Rock) was used over the entire modelling domain to generate wind-waves. Following review and comment by federal experts, additional analysis was performed to determine if more detailed wind input data could be incorporated into the model and assist in improving the wave predictions at the site. Improvements in wave predictions at the site were determined by evaluating wave model performance through comparison with measurements at the PNW Buoy which contain a wide range of wind and wave conditions.

Analysis included the following potential wind data sources:

- Local measured wind data at Environment Canada Stations including Holland Rock and Lucy Island Light Station
- Buoys including Fisheries and Oceans Canada (DFO) Buoys at North Hecate Strait (C46183), Dixon Entrance Central (C46145), West Dixon Entrance (C46205)
- Spatially variable gridded wind re-analysis datasets, including:
    - European Center for Medium Range Weather Forecasting (ECMWF, Dee et al 2011)
    - North American Regional Reanalysis (NARR, Mesinger et al 2006)
    - NOAA Wave Watch III (Chawla et al, 2013).
    - Climate Forecast System Version 2 (CFSRv2, Saha et al 2010).

Analysis included comparing wind datasets with local buoy and fixed station measurements, and evaluating the spatial and temporal resolution of the datasets to determine which would provide more accurate wave predictions. Figure C-1 shows the grid resolution of the four gridded wind datasets included in the analysis. Significant attention was paid to the potential for local winds to undergo channelization effects from local topography, in particular for southerly winds. Analysis of Holland Rock wind data in relation to other local wind sources indicates that some southerly wind speed increases are possible due to local topography. The channelization appears to be captured in the local data such that use of those data would incorporate these local effects as desired. In addition, wind events from the south generate waves that arrive at Flora Bank prior to the marine structures; therefore, the potential uncertainty in topographic effects on the predictions of marine structure impacts is not significant.

Due to its higher spatial and temporal resolution and good representation of local (Chatham Sound) wind patterns, the CFSR gridded wind dataset was selected, and improved locally using assimilation of Holland Rock winds with equivalent duration of 90 minutes. Figure C-2 shows the CFSR grid resolution and comparison with local buoy measurements for Calibration Period 1. Equivalent duration for winds used in the modelling system was developed using the measured fetch lengths in Chatham Sound and equivalent durations provided in Resio et al (1982).

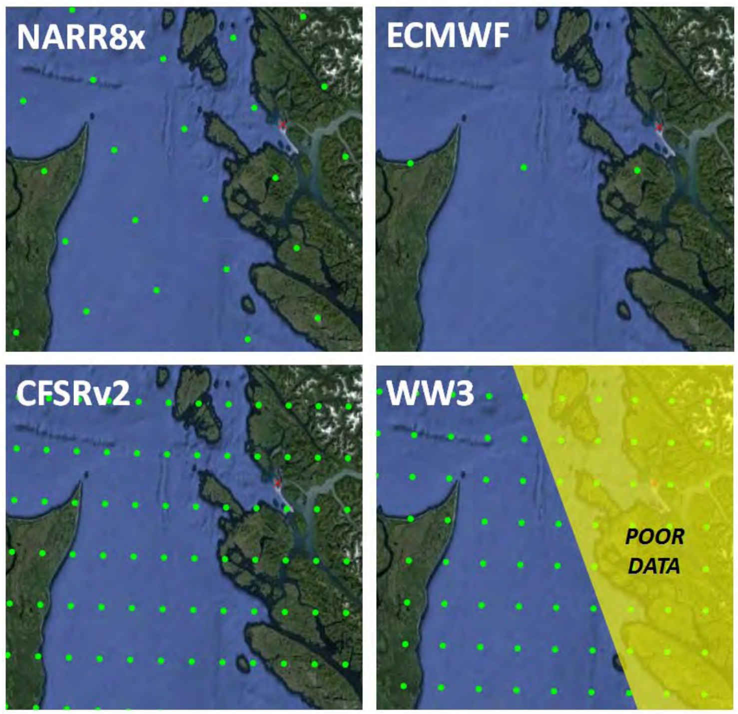


Figure C-1: Resolution of gridded wind datasets

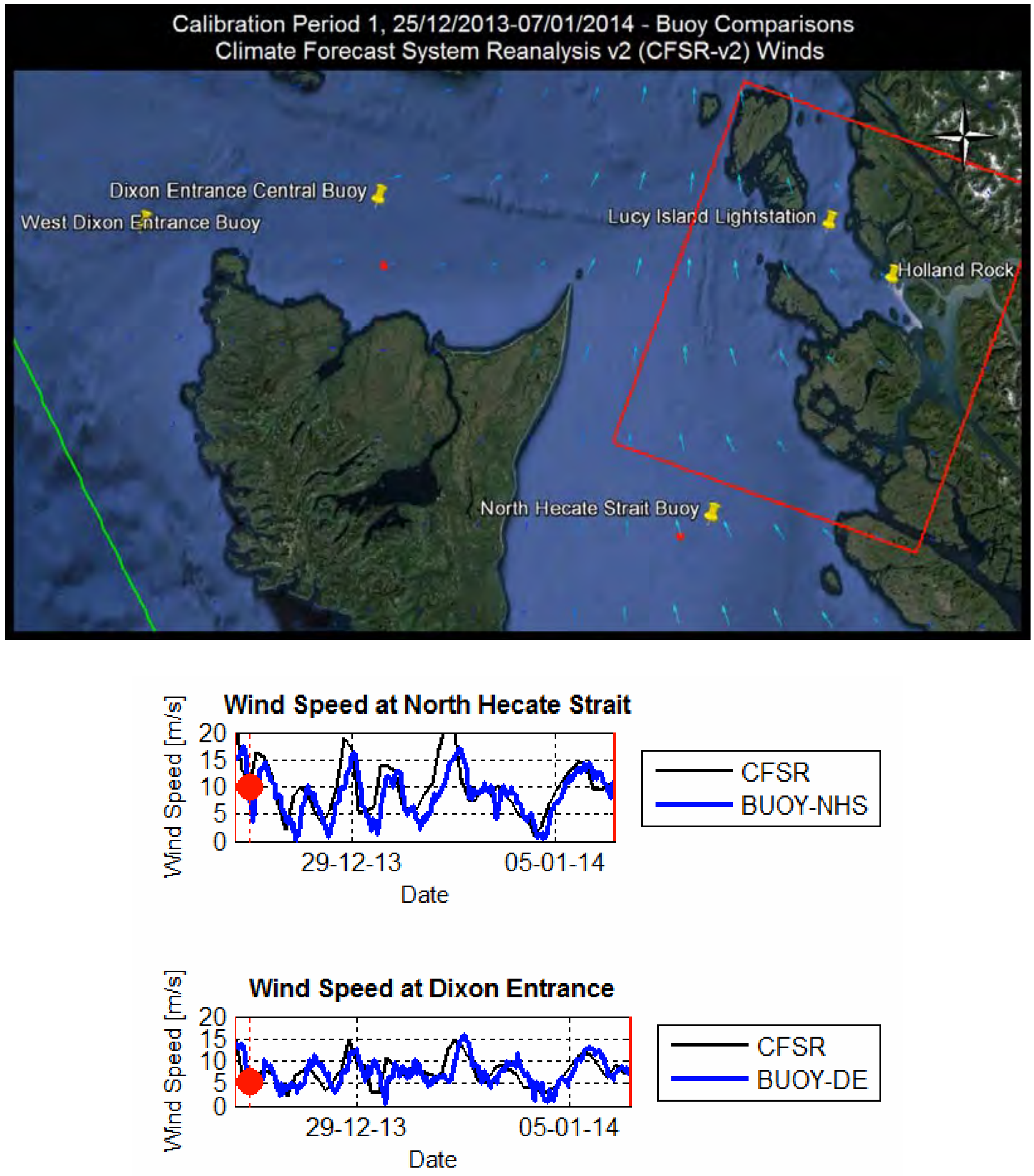


Figure C-2: Example CFSR wind field (top) and data comparison with local buoy measurements (bottom)

Wave model validations for three different time periods were performed using this wind data source and default wave model parameters (no calibration), and the best wave model predictions were produced. Figure C-3 shows the extent of the large-scale and nested wave models, which were run at 1-hour intervals to generate waves at the project site. Offshore wave conditions were taken from the Wave Watch III dataset and interpolated to the offshore boundary at the maximum resolution available.

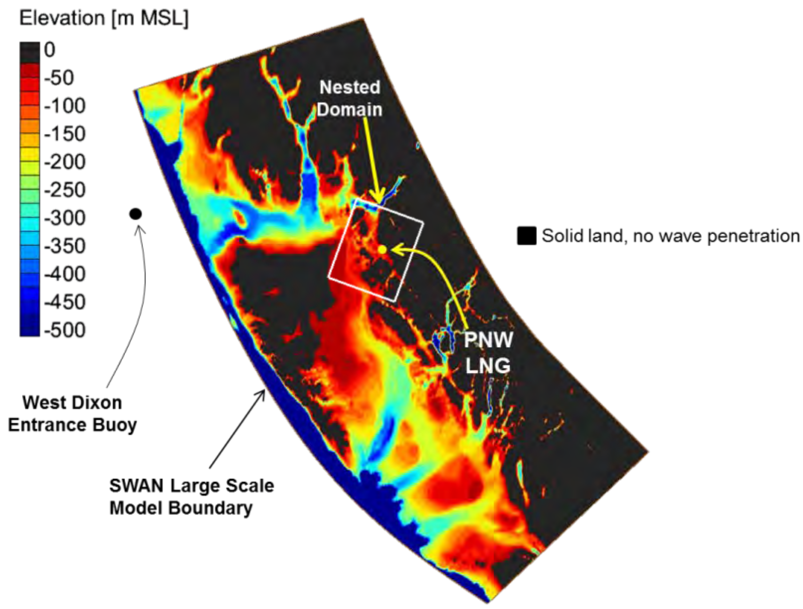


Figure C-3: Wave Model Large-scale and Nested Modelling Domains

Figure C-4 shows wave model calibration results using the combined CFSR gridded wind input dataset with local data assimilation for Calibration Period 1. This period of time was also used previously. The May 5 wave model calibration and modified wave model calibration are shown. Analysis indicates that in general, the modified wave model calibration better represents wave conditions at the site, in particular the mean wave periods. Calibration Period 1 is considered a rigorous test for the wave model, as it includes several wind events from several directions, with varying level of offshore wave contribution. Figure C-5 shows wave model calibration results for Calibration Period 2 (left) and Calibration Period 3 (right). No modification of any wave model parameters were made (all default model parameters were used).

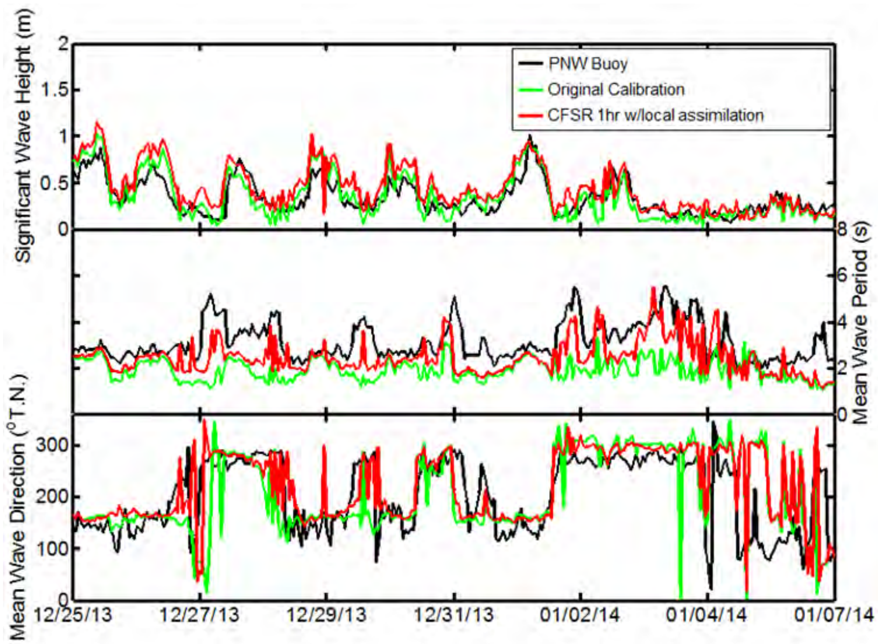


Figure C-4: Wave Model Calibration for Calibration Period 1

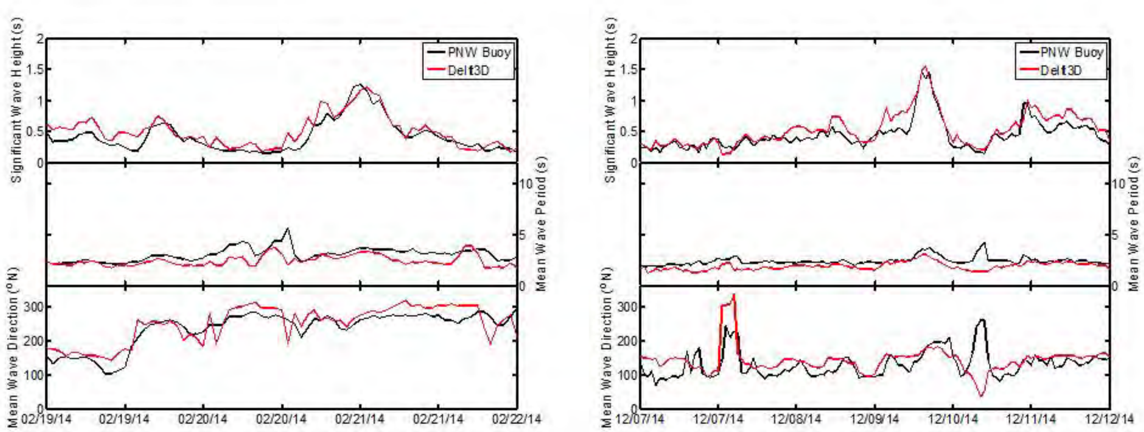


Figure C-5: Wave Model Calibration for Calibration Period 2 (left) and 3 (right)

C1.2 Summary

Wind input datasets available in the industry were evaluated and tested, and the most suitable dataset for long-term simulations was selected. Wave model calibration results indicate a slight improvement in wave predictions at the project site but not a significant departure from previous wave model calibration results. 3D model predictions of morphological changes on Flora Bank and the impacts of the marine structures are not likely to be significantly affected by the use of new input wind data to the model.

C1.3 References

Chawla, A., Spindler, D., and H. Tolman. 2013. “Validation of a Thirty Year Wave Hindcast using the Climate Forecast System Reanalysis Winds”. Ocean Modelling, Volume 70.

Dee, D., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hersbach, H., Holm, E., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A., Monge-Sanz, B., Morcrette, J., Park, B., Peubey, C., Rosnay, P., Tavolato, C., Thepaut, J., and F. Vitart. 2011. “The ERA-Interim reanalysis: configuration and performance of the data assimilation system”. Quarterly Journal of the Royal Meteorological Society, April 2011, Part A.

Fedor Mesinger, Geoff DiMego, Eugenia Kalnay, Kenneth Mitchell, Perry C. Shafran, Wesley Ebisuzaki, Dušan Jović, Jack Woollen, Eric Rogers, Ernesto H. Berbery, Michael B. Ek, Yun Fan, Robert Grumbine, Wayne Higgins, Hong Li, Ying Lin, Geoff Manikin, David Parrish, and Wei Shi, 2006. “North American Regional Reanalysis”. Bull. Amer. Meteor. Soc., 87, 343-360.

Resio, D. T., and Vincent, C. L. 1982. “A Comparison of Various Numerical Wave Prediction Techniques,” Proc. 11th Annual Offshore Technology Conf., Houston, TX, pp 2471-2485.

Suranjana Saha, Shrinivas Moorthi, Hua-Lu Pan, Xingren Wu, Jiande Wang, Sudhir Nadiga, Patrick Tripp, Robert Kistler, John Woollen, David Behringer, Haixia Liu, Diane Stokes, Robert Grumbine, George Gayno, Jun Wang, Yu-Tai Hou, Hui-Ya Chuang, Hann-Ming H. Juang, Joe Sela, Mark Iredell, Russ Treadon, Daryl Kleist, Paul Van Delst, Dennis Keyser, John Derber, Michael Ek, Jesse Meng, Helin Wei, Rongqian Yang, Stephen Lord, Huug Van Den Dool, Arun Kumar, Wanqiu Wang, Craig Long, Muthuvel Chelliah, Yan Xue, Boyin Huang, Jae-Kyung Schemm, Wesley Ebisuzaki, Roger Lin, Pingping Xie, Mingyue Chen, Shuntai Zhou, Wayne Higgins, Cheng-Zhi Zou, Quanhua Liu, Yong Chen, Yong Han, Lidia Cucurull, Richard W. Reynolds, Glenn Rutledge, and Mitch Goldberg, 2010. “The NCEP Climate Forecast System Reanalysis”. Bull. Amer. Meteor. Soc., 91, 1015-1057.

Appendix D: Offshore Waves

D1. Offshore Waves

The following section describes refinements to offshore wave input data used in the Delft3D model for the long-term simulations.

D1.1 Input for Long-Term Simulations

Pacific Ocean waves have only a minor contribution to the wave climate at the project site. Significant energy dissipation occurs during transformation from offshore to the site, which is relatively sheltered within Chatham Sound. It was desired, however, to utilize an offshore wave dataset that was likely to provide the most reliable input data and a dataset that generates larger waves at the site so as to result in a conservative prediction of morphology and morphological impacts of the marine structures on Flora Bank. Analysis included the following potential wave data sources:

- Fisheries and Oceans Canada (DFO) Buoy at West Dixon Entrance (C46205)
- Fisheries and Oceans Canada (DFO) Buoy at South Moresby (C46147)
- Gridded wave datasets, including:
  - European Center for Medium Range Weather Forecasting (ECMWF) ERA Interim Reanalysis (Dee et al, 2011).
  - NOAA Wave Watch III Alaskan Waters (Chawla et al, 2013).

Figure D-1 shows a comparison of the model resolution offered by the NOAA Wave Watch III and ECMWF datasets. The Wave Watch III dataset was selected because it provides higher spatial and temporal resolution than ECMWF, and contains larger wave heights overall, resulting in conservative predictions of Pacific Ocean waves at the project site.

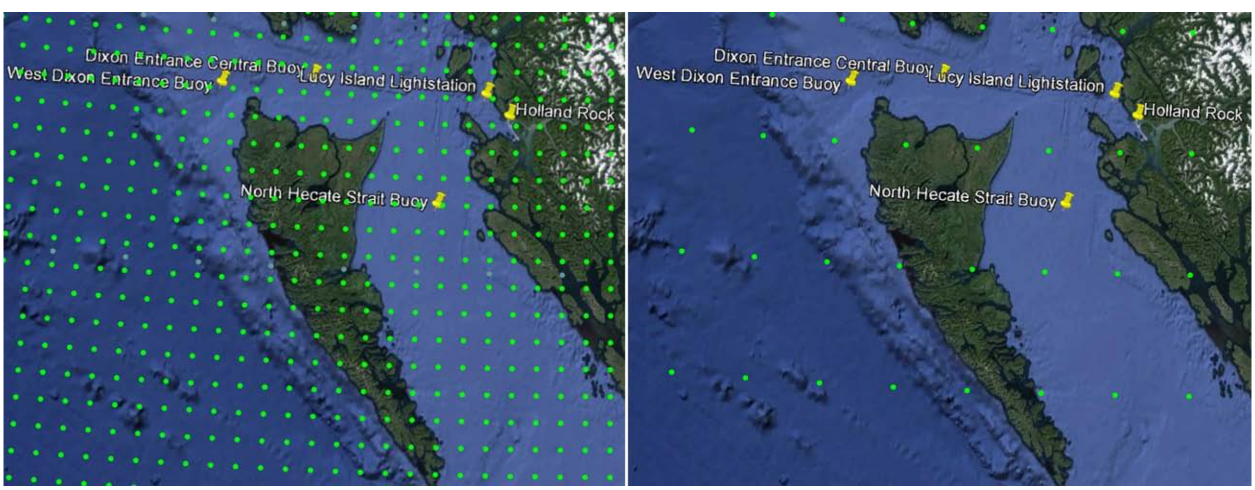


Figure D-1: Gridded wave dataset resolution for NOAA Wave Watch III (left) and ECMWF 40-yr Interim (right)

Figure D-2 shows the Wave Watch III model resolution and comparison with local buoy measurements during Calibration Period 1 as an example. Wave model validations for three different time periods were performed using the NOAA Wave Watch III offshore wave data source and default wave model parameters (no calibration).

Figure D-3 and Figure D-4 show the wave model calibration using the Wave Watch III offshore waves during all three calibration periods. Model results indicate an excellent representation of waves at the project site. Sensitivity analysis was also performed using the two datasets, and it was determined that the selection of offshore wavedata results in very minor differences in predicted wave conditions at the project site (which is dominated by local wind-waves).

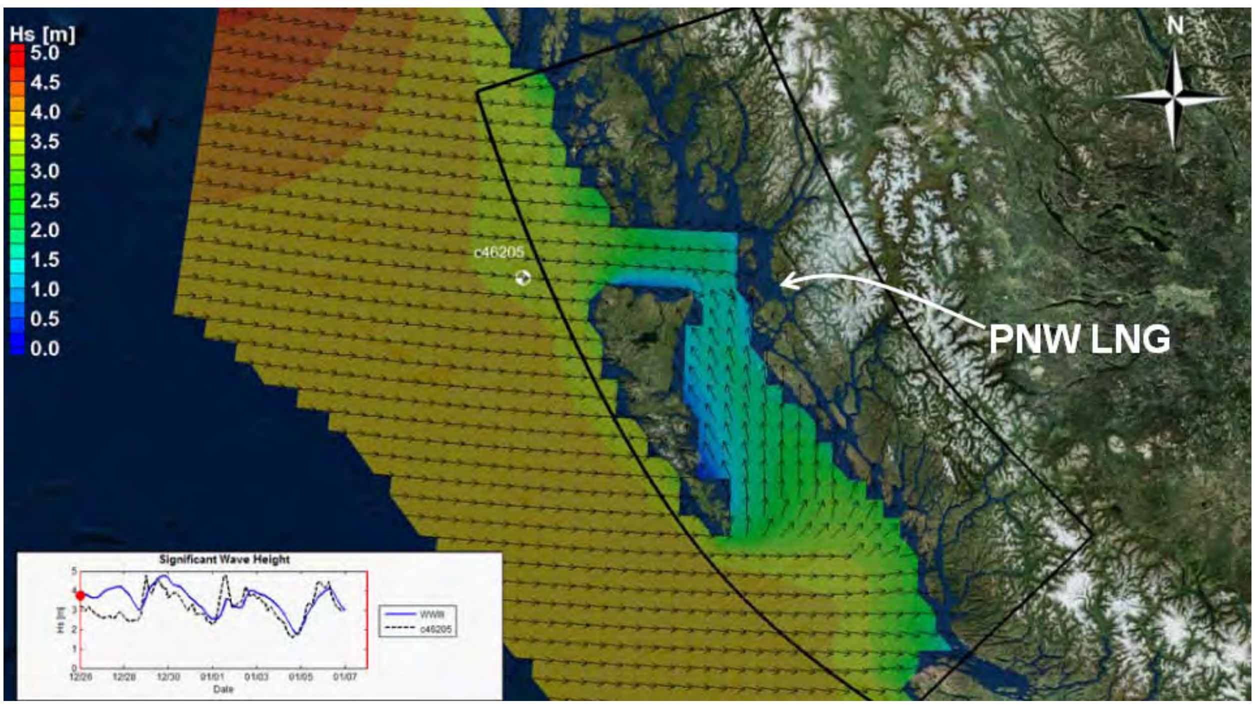


Figure D-2: Snapshot of significant wave heights from NOAA Wave Watch III gridded wave dataset and comparison with local buoy wave measurements

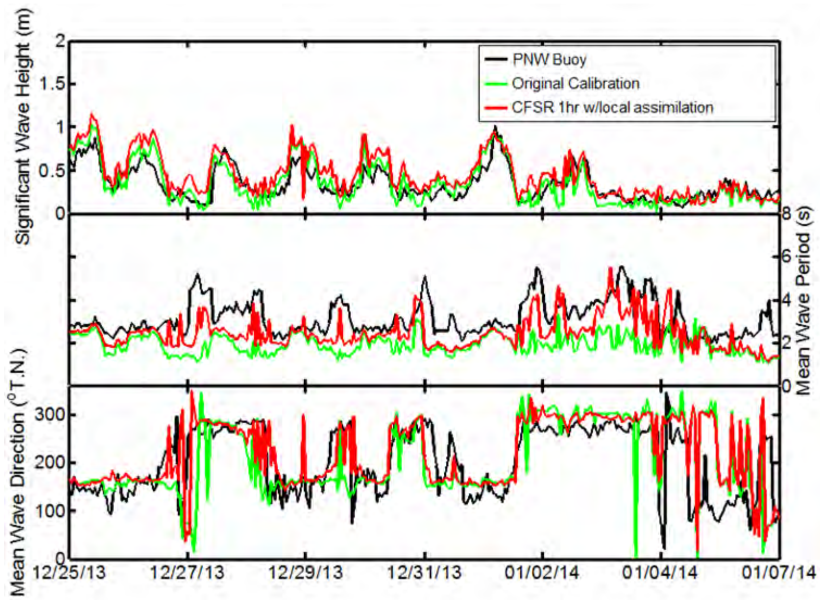


Figure D-3: Wave model calibration for Calibration Period 1

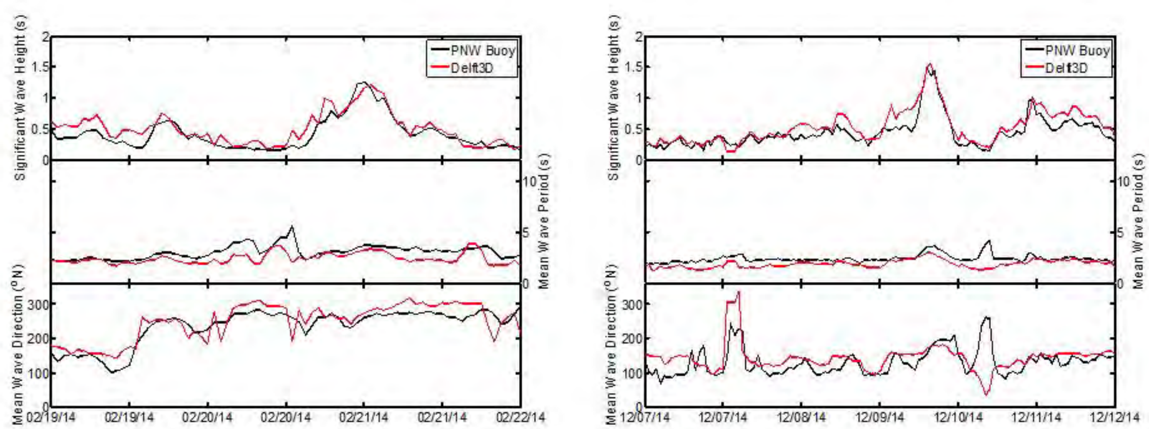


Figure D-4: Wave model calibration for Calibration Period 2 (left) and 3 (right)

D1.2 Summary

Offshore wave input datasets available in the industry were evaluated and tested, and the most suitable dataset for long-term simulations was selected. Wave model calibration results indicate a slight improvement in wave predictions at the project site but not a significant departure from previous wave model calibration results. 3D model predictions of morphological changes on Flora Bank and the impacts of the marine structures are not likely to be significantly affected by the use of new input offshore wave data to the model.

Safety • Quality • Sustainability • Innovation

D1.3 References

Chawla, A., Spindler, D., and H. Tolman. 2013. “Validation of a Thirty Year Wave Hindcast using the Climate Forecast System Reanalysis Winds”. Ocean Modelling, Volume 70.

Dee, D., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hersbach, H., Holm, E., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A., Monge-Sanz, B., Morcrette, J., Park, B., Peubey, C., Rosnay, P., Tavolato, C., Thepaut, J., and F. Vitart. 2011. “The ERA-Interim reanalysis: configuration and performance of the data assimilation system”. Quarterly Journal of the Royal Meteorological Society, April 2011, Part A.

Appendix E:
Vertical Resolution/Stratification

E1. Vertical Resolution/Stratification

The 3D model simulations include salinity from the ocean, and freshwater discharge and sediment load from the Skeena River. Inclusion of Skeena River discharge and sediment load within the time series simulations is expected to result in realistic river inputs based on the location of the river boundary and estimates of discharge and total suspended solids (TSS) from measurements. Concerns remain, however, as to whether the model represents site conditions in terms of vertical stratification of salinity and its effects on Flora Bank morphology and the potential impacts of the proposed marine structures. It was also suggested that higher vertical resolution (more sigma layers) could provide better simulation of stratification effects, therefore potentially affect (improve) predictions of morphological changes on Flora Bank.

E1.1 Field Observations of Salinity and Stratification

Field data analysis and a series of sensitivity analyses were performed to determine what salinity stratification is present at the site and whether it affects morphology. Stantec has recently collected field salinity and turbidity data at a number of locations around the project site on a monthly basis. Figure E-1 shows the data collection points and measured salinity profiles at Location #3 which is the location of the largest marine structure (SW Anchor Block). Analysis shows that the May 19, 2015 survey captured a portion of the freshet with the lowest measured salinities of the year to date. Figure E-2 shows a series of vertical salinity and turbidity profiles taken at the location of the SW Anchor Block on a monthly basis starting with the January 27, 2015 survey and ending with the June 6, 2015 survey. It should be noted that no conversion of turbidity (FTU) to total suspended solids (TSS) can be made at this time because the conversion process has not been completed by Stantec.

The May 19 profile clearly demonstrates the freshet processes described by federal experts, namely a thin surface lens of less saline water arriving at the site, combined with higher levels of turbidity within that thin surface layer. Generally speaking, however, vertical stratification is minimal at this location, as bottom salinities range from 23 to 30 PSU, and salinity varies more than a few PSU only in the top 0.5 m of the water column.

Given how thin this surface layer appears, the turbidity is likely due to very fine sediments delivered from the Skeena River, and not related to the coarser sediments found near Flora Bank. Also, it should be noted that the thin surface lens of fresh water and associated higher turbidity levels are not found in any of the other profiles taken at the same location. Within 18 days of the May 19 profile, the June 06 profile shows that this feature is no longer present; therefore this feature appears to be present only a few weeks per year, and during calm periods with relatively low wave activity, resulting in minor changes to morphology.

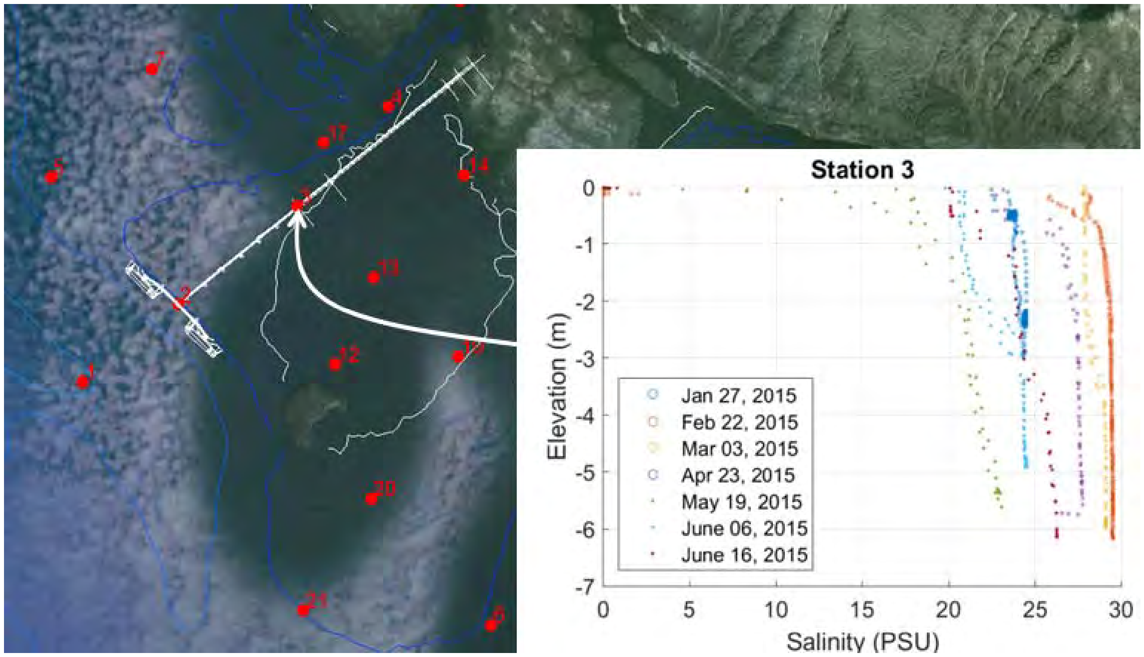


Figure E-1: Location of salinity and turbidity data collection locations from Stantec, and salinity profiles measured at the SW Anchor Block location in 2015

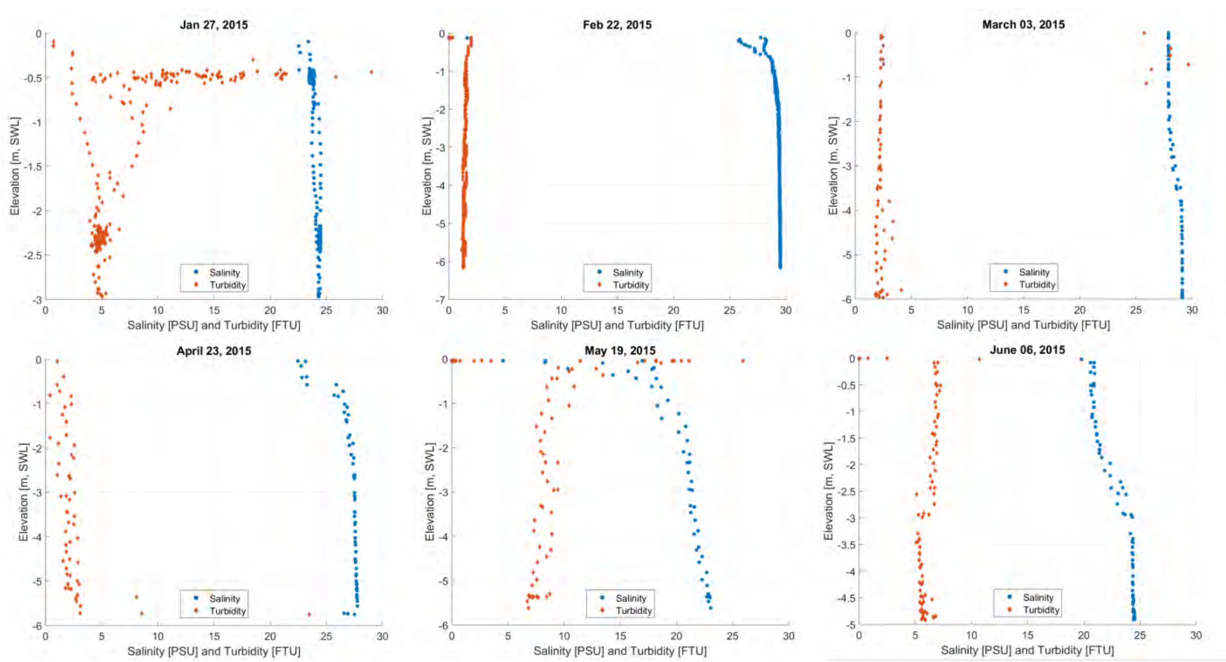


Figure E-2: Measured salinity and turbidity profiles at the SW Anchor Block location, beginning January 27, 2015 and ending June 6, 2015

Based on analysis of the field measurements, the following conclusions were reached regarding the stratification of salinity at the site:

- At the peak of the freshet a thin surface lens of freshwater and elevated turbidity was observed, and was no longer present less than 18 days later.
- The surface turbidity is likely due to very fine silts and clays delivered from the Skeena River and not material found in field sediment samples taken on Flora Bank.

E1.2 Comparison of Field Observations and Model Results

Measured salinity profiles were evaluated through a visual comparison of measured and predicted profiles. Field measurements during the peak of the freshet as shown in Figure E-3 and Figure E-4 indicate that surface salinity is highly variable even at the same time during the peak of the freshet, with values between 5 and 18 PSU within the top 0.2 m at the surface. It appears there are isolated pockets of very low salinity water moving on the surface. Since no modelling results were available for the 2015 field data collection period, time histories of salinity at surface, mid-depth and bottom were extracted from the 2011 simulation (10 sigma layers) to observe the overall fluctuation and relative levels of stratification from surface to bottom. During the peak of the modelled freshet period, the surface salinities reach down to approximately 20 PSU, which is only a few PSU higher than the field measurements for the majority of the measurements in the top 0.5 m of the water column.

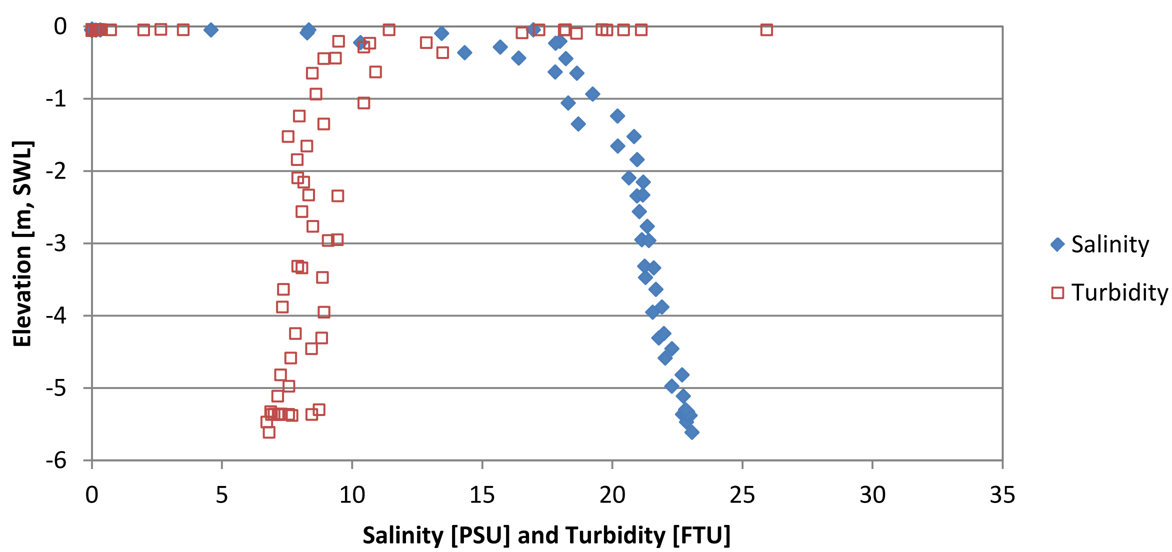


Figure E-3: Salinity and turbidity measured near the peak of the freshet in the field at the location of the SW Anchor Block on May 19, 2015

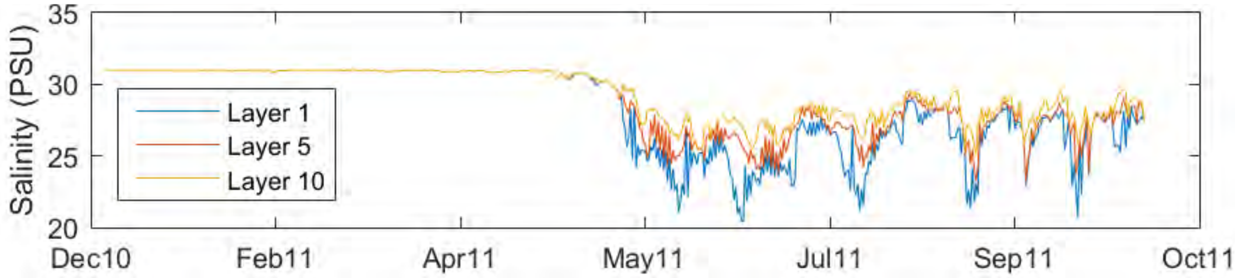


Figure E-4: Time histories of 3D model salinity at the surface (layer 1), mid-depth (layer 5) and bottom (layer 10)

The following conclusions can be made regarding the comparison between measured and predicted salinities:

- Generally speaking, during the peak of the freshet, the model over-predicts average near-surface salinities by a 3-5 PSU. Isolated pockets of very low salinity water which are present in the measurements were not reproduced in the model.
- However, the model includes stratification effects and reasonable salinity predictions in the project area the vast majority of the time (freshet effects only last few weeks per year).
- Additional simulations have indicated that if Skeena River flows are actually higher than estimated, or other local freshwater sources are contributing, surface salinity predictions would be closer to the measured values.

E1.3 Sensitivity Analysis for Vertical Resolution (# of Sigma Layers)

E2. In order to provide further confidence in the physical processes included in the 3D model, sensitivity testing was also performed to determine if 1) the vertical resolution in the 3D model (number of sigma layers) has a significant effect on transport of freshwater to the project area, and 2) if the vertical resolution in the 3D model (sigma layers) has any significant effect on morphological changes at Flora Bank. The sensitivity test consists in running the same simulation (same input conditions) only changing the number of sigma (vertical) layers from 10 to 21. Salinity and morphology were evaluated with both 10 and 21-sigma layers for the 2014 freshet period (28-day simulation).

Figure E-5 and Figure E-6 show vertical profiles of salinity over time at the SW Anchor Block location for 10-layers and 21-layers. The timing and general magnitudes of freshwater and salinity stratification in the vertical profiles are very similar.

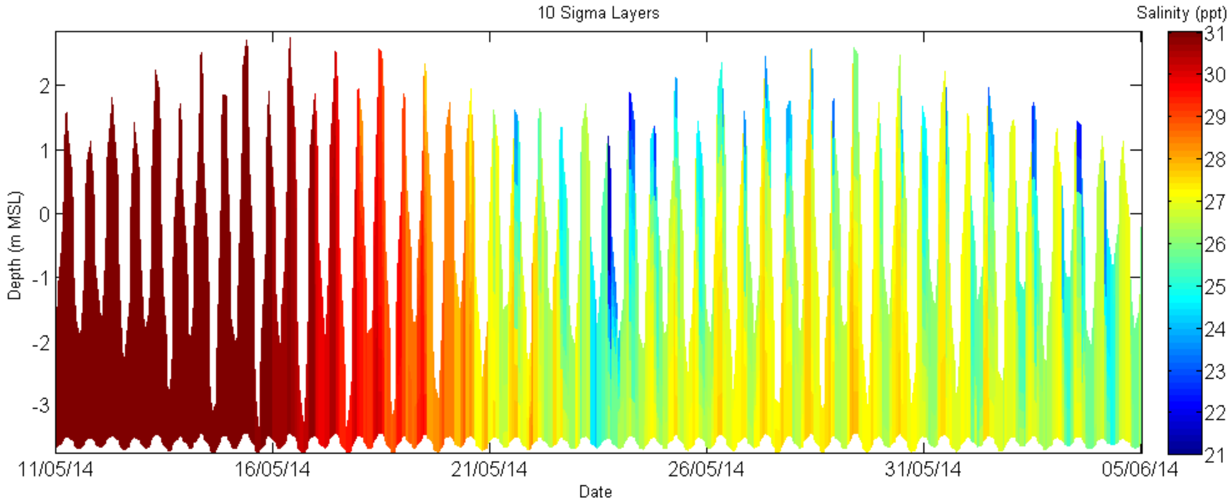


Figure E-5: Vertical profiles of salinity at the location of the SW Anchor Block during the 28-day freshet simulation using 10 sigma layers

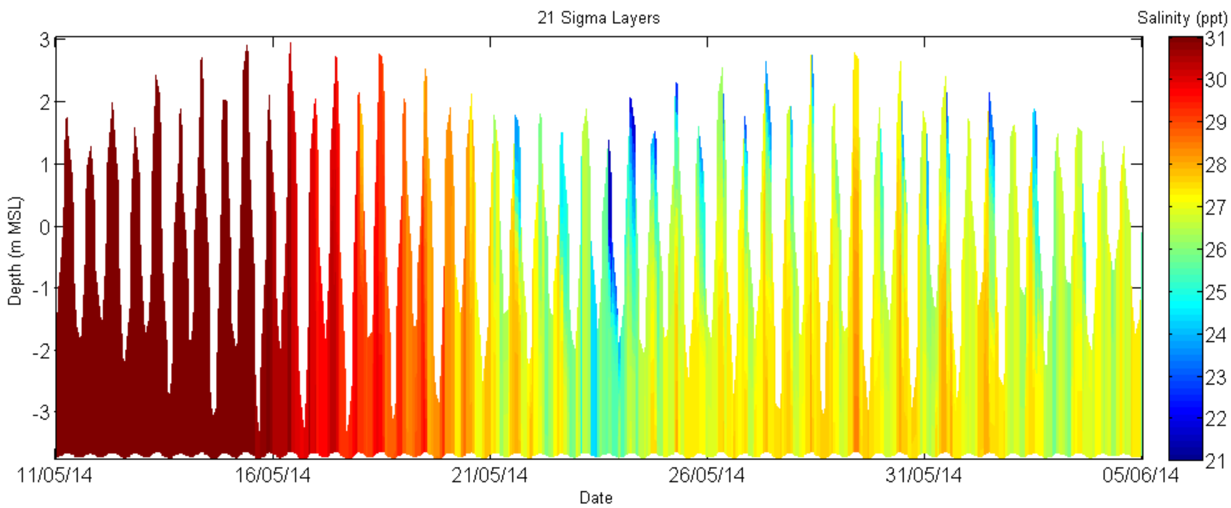


Figure E-6: Vertical profiles of salinity at the location of the SW Anchor Block during the 28-day freshet simulation using 21 sigma layers

Figure E-7 shows profiles of salinity at three different times during the freshet simulation for 10 and 21 layers for low tide conditions (left), mid-tide conditions (middle) and high tide conditions (right). Each figure includes profiles at Agnew Bank, in deeper water, and at the location of the trestle (SW Anchor Block). Results indicate some differences in stratification, with the 21-layer simulation more stratified (vertically variable) in general. At many times during the simulation, however, the 10-layer simulation is more stratified and/or demonstrates lower salinity (more fresh water) in the surface layer. In general the profiles are similar over time, and during the freshet period the bottom salinities reach similar levels. Overall the results indicate that regardless of vertical resolution (sigma layers), similar levels of freshwater and salinity stratification are present at the project site.

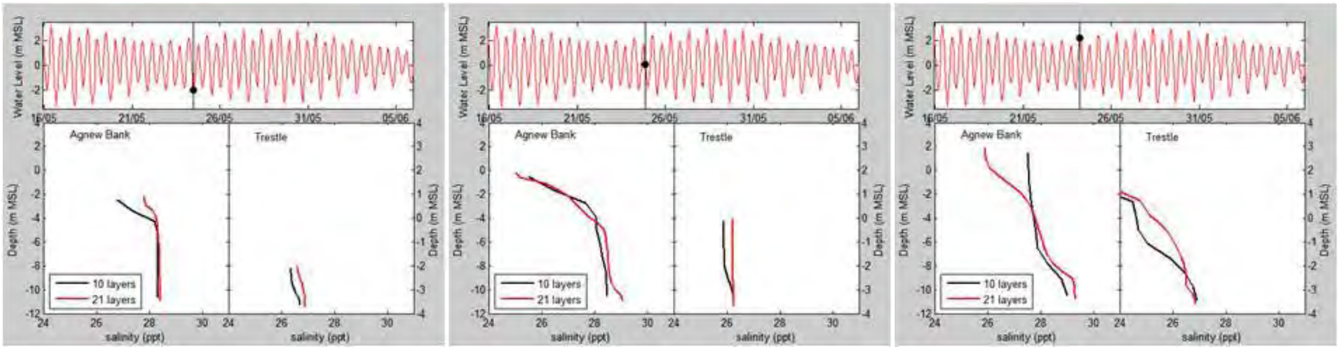


Figure E-7: Vertical profiles of salinity in deeper water over Agnew Bank (left side of each frame) and near the SW Anchor Block (right side of each frame) for 10 and 21 sigma layers. Left frame represents low tide conditions, middle frame represents mid-tide conditions, and the right frame represents high tide conditions.

The 28-day freshet simulation was also used to predict morphological changes in the project area and any differences that could be found using a higher level of sigma layers. Figure E-8 shows the differences in morphological change in the project area for the 10 and 21-layer simulations. The changes in morphology due to the higher vertical resolution are negligible in the vicinity of Flora Bank. There are minor differences found in Porpoise Channel, where currents are significantly stronger than at Flora Bank. These results indicate that the increase in sigma layers from 10 to 21 has a negligible impact on predictions of morphological changes at Flora Bank.

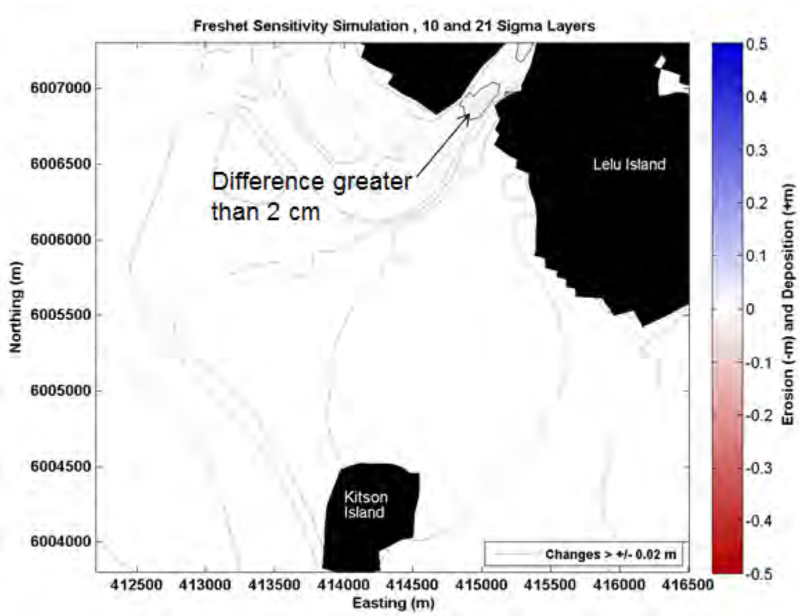


Figure E-8: Differences in morphological change caused by increasing the vertical resolution from 10 to 21 sigma layers

Safety • Quality • Sustainability • Innovation

E1.1 Salinity Initial Conditions

Full 1-year spin-up hydrodynamic/salinity simulation (starting on January 1, 2011) was performed to develop a set of salinity initial conditions to be used to initialize Delft3D model in the 1-year time series simulations.

The results of the 1-year spin-up hydrodynamic/salinity simulation on September 1, 2011 (after 8 months of simulation) were used as the initial condition for the 1-year time series simulation (including hydrodynamics, salinity, morphology, waves, etc), as this simulation started on September 1, 2012. Other initial conditions that were considered included the peak freshwater time period within the 2014 freshet simulation; however, it was determined that the longer spin-up inherent in the 2011 full year simulation (8 months) was most appropriate.

E1.2 Annual Changes in Salinity

The 1-year simulation presented in Section 3.3.4 of the main report was extended for another year to evaluate if the salinity field used for the long-term simulations had already reached an equilibrium. The second year simulation was also used to observe if the same interannual changes on the salinity field observed in the first year occurred in the second year. The same discharge from Skeena River used during the first year of simulation was repeated in the second year.

Figure E-9 shows the surface salinity during four seasons in the first year of simulation (same as Figure 3-22 in the main report). The surface salinity during the second year is presented in Figure E-10. The comparison between both figures shows some differences in the salinity distribution only during the spring. This happened because the model was still spinning up in the first year spring (before the Skeena River discharge peak), with all initial salinity at the model equal to 31 ppt and the river boundary salinity with fresh water or 0 ppt. After that, the large discharge of fresh water observed during the late spring and summer months (freshet) contribute to mix the water and the results from the first and second year of simulation are practically the same. The results obtained on the first and second year of simulation during the fall and winter were very similar, where the influence of the fresh water from Skeena River is only observed at the river mouth. Figure E-11shows the salinity at the surface and bottom layers have very similar patterns during the first and second year of simulations (e.g. with more input of freshet water during the freshet period and minimum values).

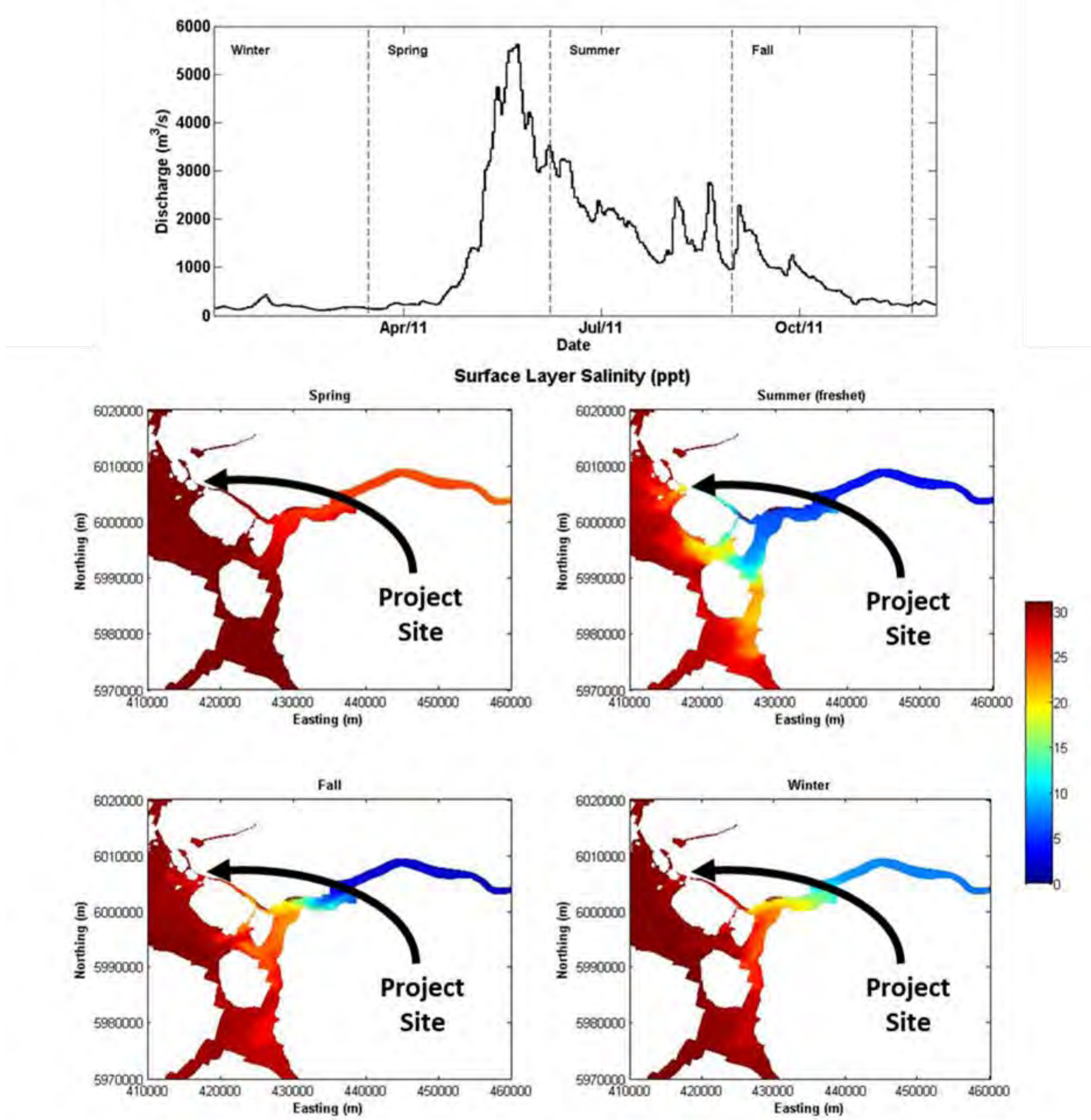


Figure E-9: Model snapshots showing surface salinities indicative of spring, summer, fall and winter during the first year of simulation

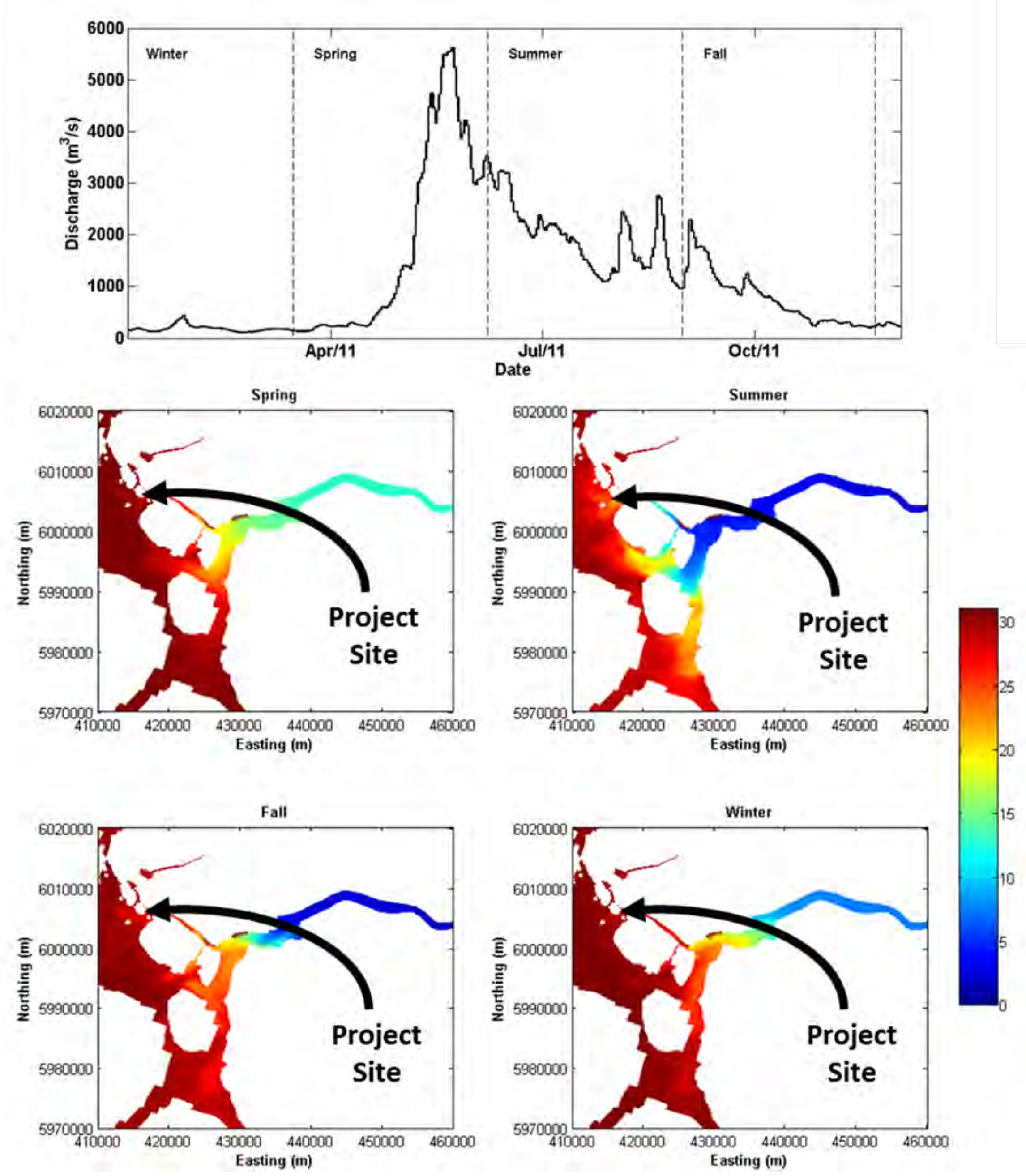


Figure E-10: Model snapshots showing surface salinities indicative of spring, summer, fall and winter during the second year of simulations

This results indicate that salinity field were in equilibrium at the end of the first year of simulation and using the end of the 1-year hydrodynamic/salinity as initial condition for the model is a good approximation to start the model with stratified conditions.

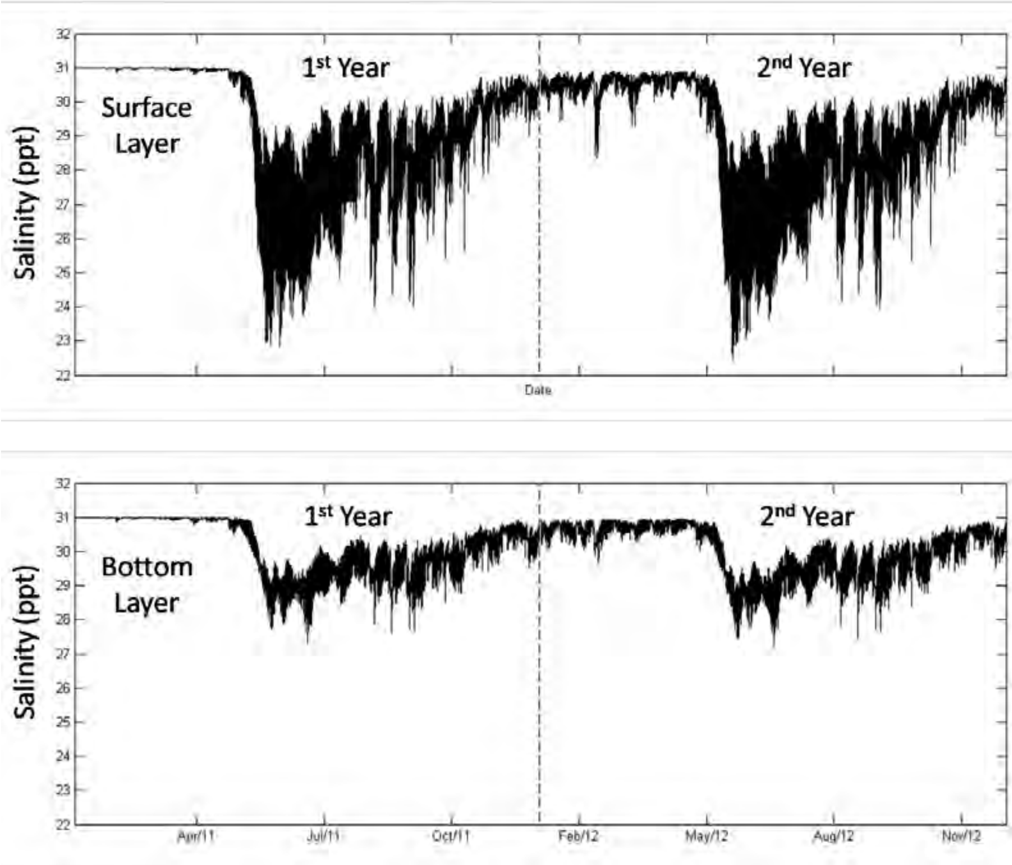


Figure E-11: Time series during the 2 years of simulations showing the salinity changes at the surface and bottom layers

E1.3 Sensitivity Testing – Skeena River Influence

Section 5.2.2 in the main report presented the comparison between the depth averaged velocity during the freshet period (May 11, 2014 to June 8, 2014) using the normal river discharge and a simulation with no discharge from Skeena River.

Further analyses, comparing the surface and bottom velocities during these two simulations, showed that the surface velocity is more affected by the river discharge (Figure E-12, left), as the fresh water moves as a thin layer on top of the salt water. The velocities at the bottom layer (Figure E-12, right), responsible for suspending the sediments, were very similar in both simulations.

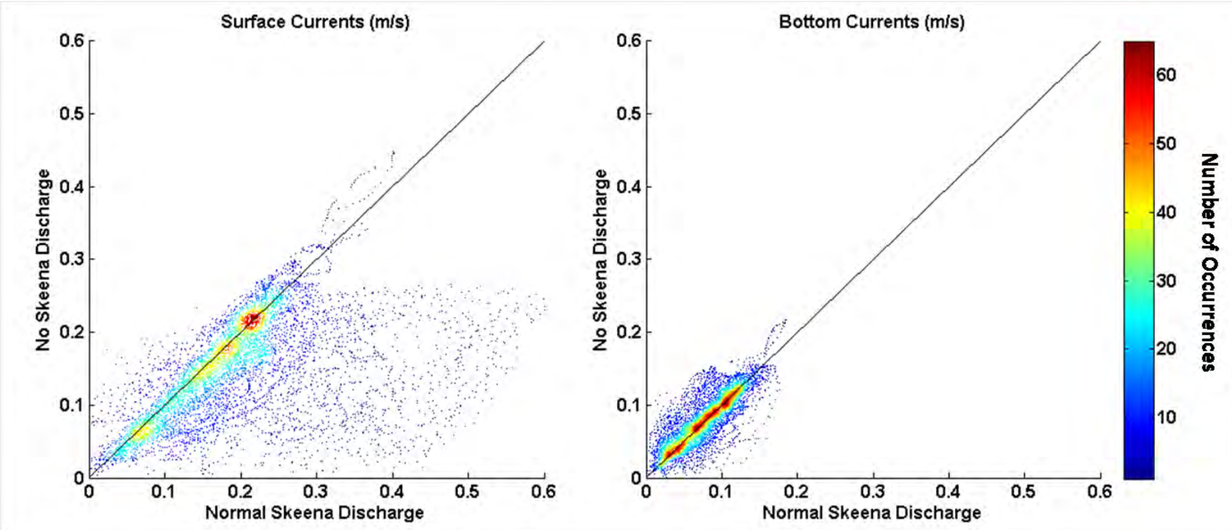


Figure E-12: Surface (left) and bottom (right) current velocities during the 28-days freshet simulation using normal and zero discharge from Skeena River

This sensitivity testing shows that the model is able to represent changes in the current velocity caused by the Skeena River discharge, but also that the discharge has a negligible effect changing the morphology.

E1.4 Skeena River Influence on Currents

Also, two other simulations were compared to assess the influence of the river discharge on the residual currents. The simulation during the freshet period without winds, waves and river discharge and the same simulation, but including the normal river discharge from Skeena River.

The net current for the simulations without the river discharge (Figure E-13, top), with the river discharge (Figure E-13, middle) and the difference (Figure E-13, bottom) show the Skeena River is more effective changing the net currents on Inverness Passage, where the changes due to the river discharge are about 0.1 m/s. The net current changes due to the river discharge are smaller on Flora Bank (about 0.05 m/s), during the freshet period. It is important to note that this is the period with largest potential to cause changes induced by the river and it is restricted to few weeks of the year when the river discharge is high.

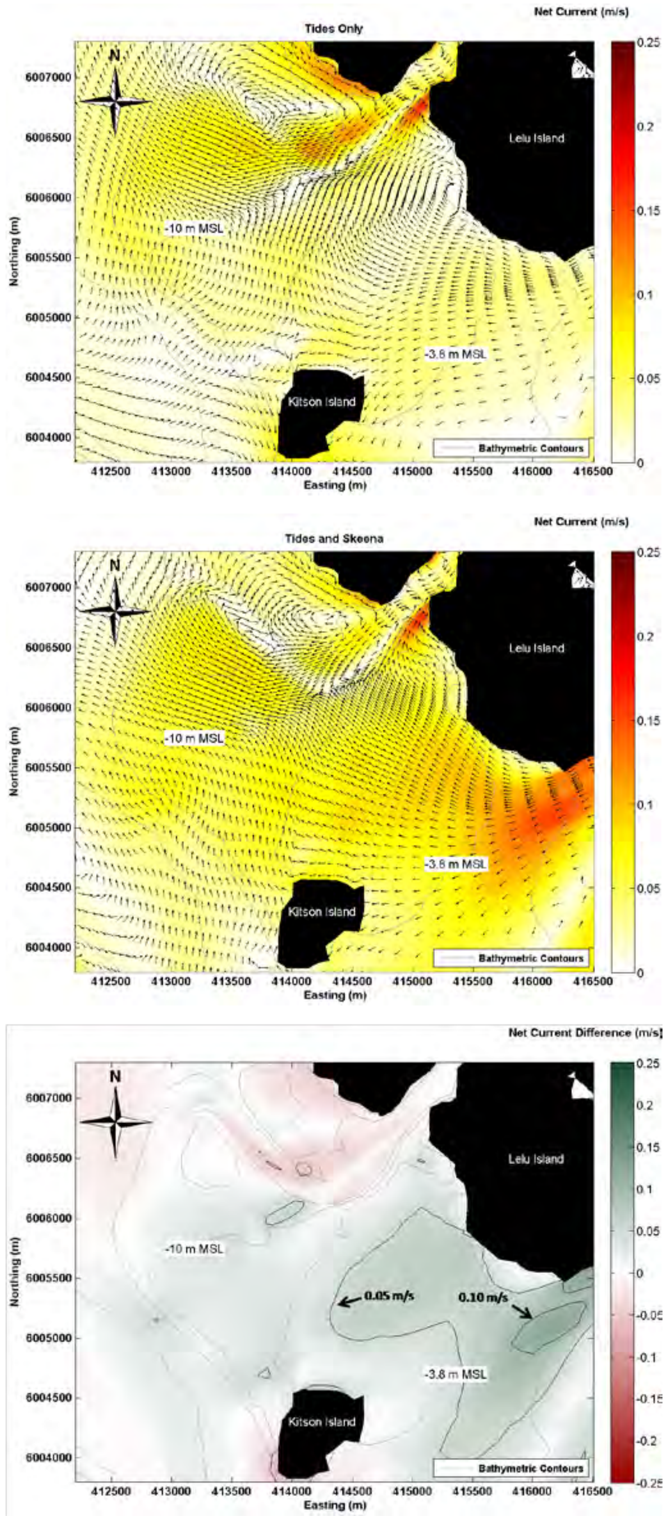


Figure E-13: Net current velocity during the simulation with tides only (top), simulation with tides and river discharge (middle) and the net current difference (bottom)

E1.5 Summary: Stratification, Sigma Layers and Salinity Initial Conditions

Field data analysis and sensitivity tests indicate the following:

- At the peak of the freshet, several processes described by federal experts have been observed:
    1. A thin freshwater lens is present on the surface, with salinity values varying significantly only in the top 0.5 m of the water column.
    2. The thin freshwater lens has elevated turbidity, with turbidity values varying significantly only in the top 0.5 m of the water column.
    3. The conditions described above (greater salinity stratification and surface turbidity) are only present a few weeks out of the entire year.
- The 3D model over-predicts the surface salinity at the peak of the freshet by 3-4 PSU overall, and with slightly less variation vertically.
- Sensitivity testing and analysis indicates that increased vertical resolution and salinity stratification effects have a negligible effect on the morphology of Flora Bank.
- Salinity initial conditions for the 1-year time series simulations were generated using stratified conditions obtained from the 1-year hydrodynamic/salinity simulation.

The morphological changes on Flora Bank are episodic and only occur during large wave conditions. During freshet simulations or even during 1-year storm events, morphological changes on Flora Bank are negligible. Only during large storm events the morphological changes expected, and therefore the only time when any potential impacts of the marine structures could occur. Therefore, since no significant wave events occur during the periods when heavy stratification is present (freshet period), these processes are likely to have a negligible effect on the morphology of Flora Bank or any potential impacts of the marine structures on Flora Bank.

Appendix F:
Delft3D Model Calibration and Validation

F1. Delft3D Model Calibration and Validation

Once the model was setup and running, calibrations and then validations were conducted to refine the Delft3D input parameters and achieve results which were consistent with the available measured data. To calibrate the model, time series runs were conducted for a certain time period and compared to the measured field data for the same time period. The model variables, parameters, geometry and domain were then reviewed and adjusted iteratively until the model results produced results that compared well with measured values.

The modelled data was then compared with measurements from a different time period or location to validate that the model performed consistently for scenarios outside the calibration dataset.

F1.1 Water Levels

The water levels at Prince Rupert Tide Gauge (Figure F–1) were used to compare modelled and measured data. The results from this calibration using the modelled and observed water levels at the Prince Rupert Tide Gauge are presented in Figure F–2. The results indicate that the model well represents the water level changes in this area dominated by large tides (tidal range up to 7 m).

Delft3D estimates both currents and water levels at the same time. Therefore, parameters such as horizontal and vertical Eddy Viscosity and Manning's n were used to calibrate water level and current simultaneously. For this study the main parameter used for calibration was Manning's n, which defines roughness.

Figure F–1: Local Data Source Locations (Source: bing)

Safety • Quality • Sustainability • Innovation

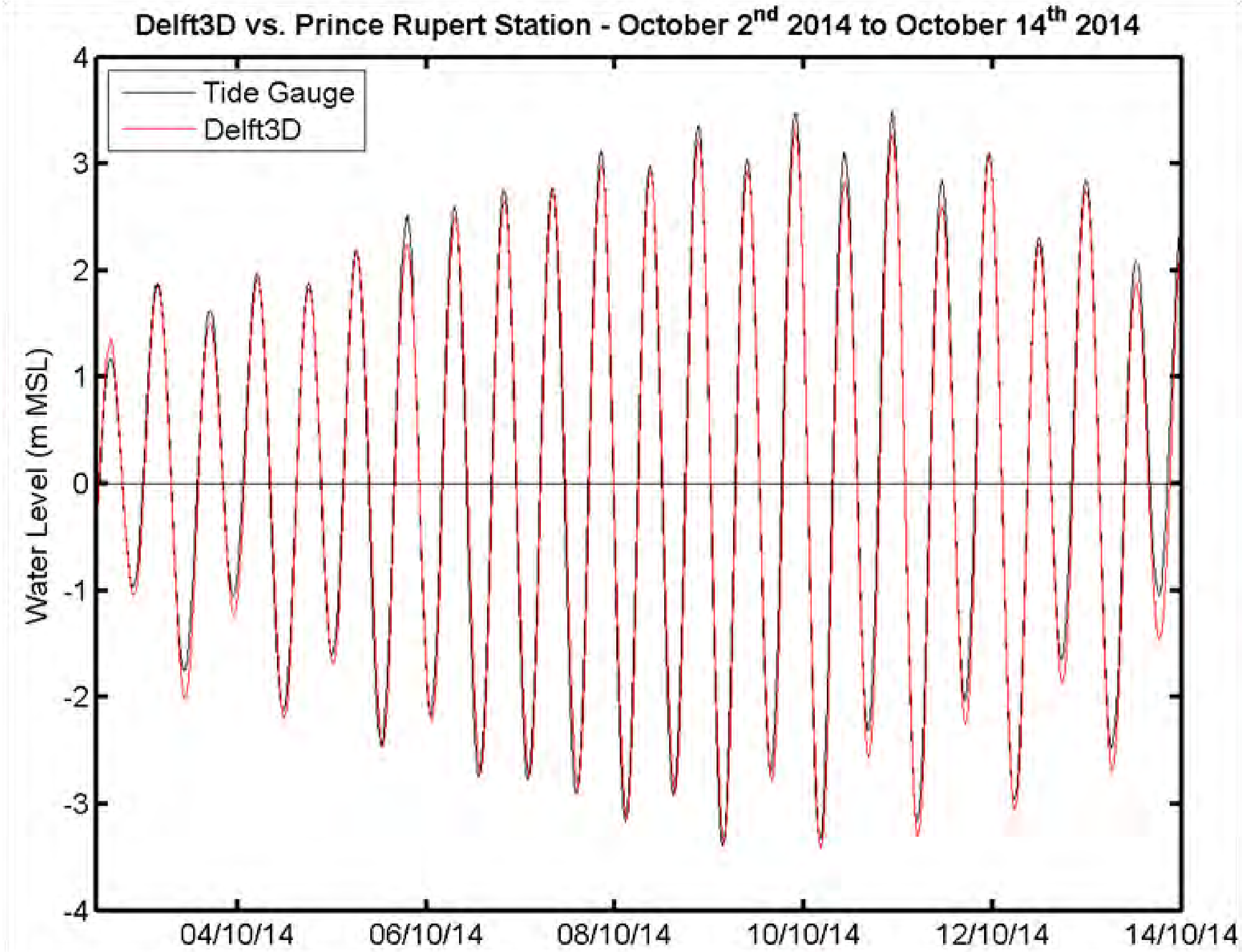


Figure F–2: Measured vs. Delft3D Modelled Water Levels at Prince Rupert Tide Gauge

The modelled water levels were in phase with the observed water levels at Prince Rupert tide gauge and the tide range compared well. In some instances, Delft3D slightly underestimated peak high tide level by up to 0.15 m and overestimated low tide by a slightly smaller amount. However, the overall difference is negligible considering the 6 m to 7 m tide range.

The model was checked against the water levels at the Inverness Passage ADCP for the same time period (Figure F–3) to validate the model. See Figure F–1 for the location of the Inverness Passage ADCP.

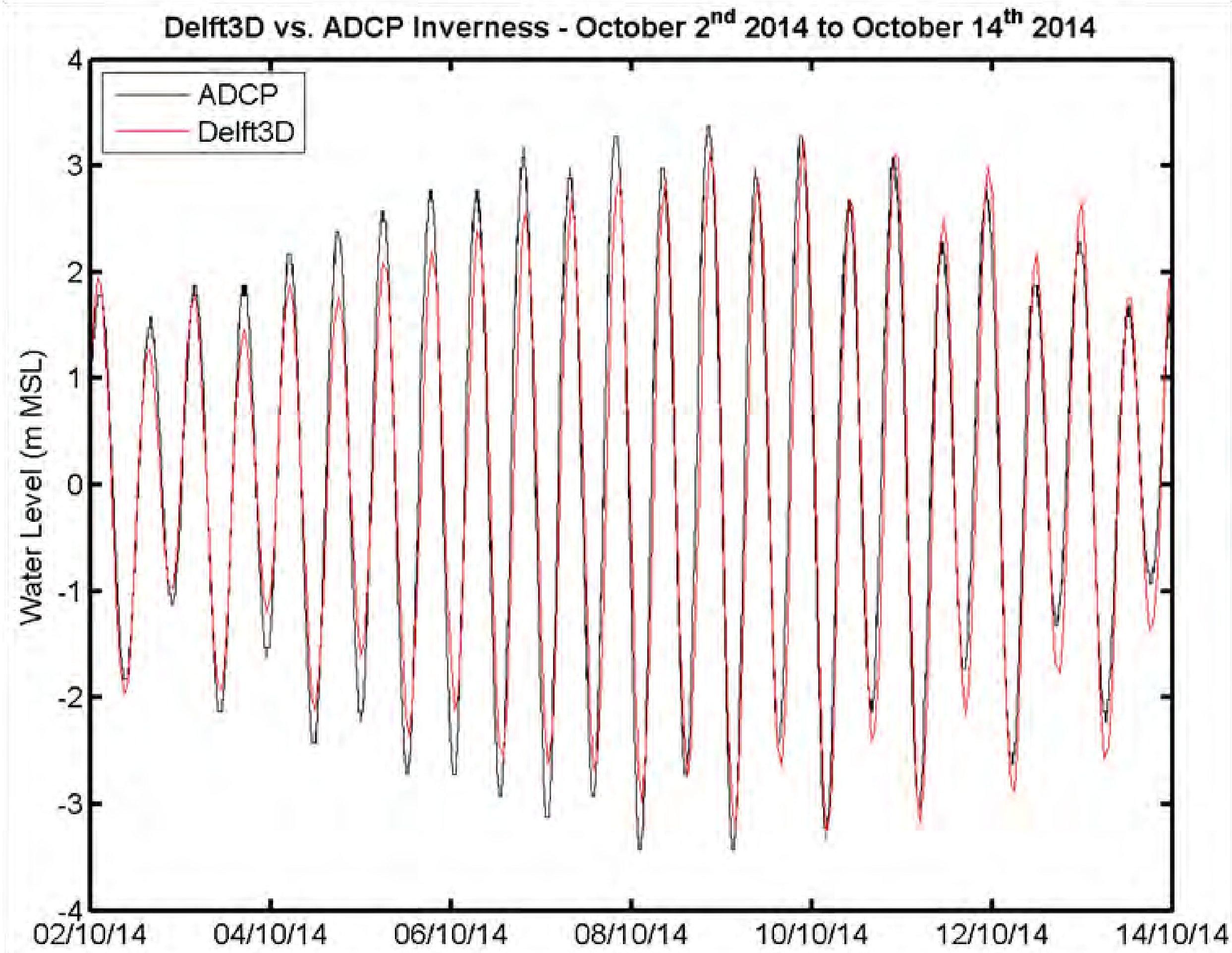


Figure F–3: Measured vs. Delft3D Modelled Water Levels at the Inverness ADCP (PH2 1A)

Similar to the calibration data at Porpoise Channel, Figure F–3 also demonstrates good correlation between modelled and observed water levels at Inverness Passage. At this location the model slightly underestimated the tide range during the initial neap tide cycle, matches well during the spring tide cycle, and slightly overestimates the tide range in the subsequent neap cycle.

F1.2 Currents

F1.2.1 Currents Calibration

Thirteen (13) days of modelled results were calibrated with the measured data from PNW LNG's Porpoise Channel ADCP until a good comparison was achieved (Figure F–4).

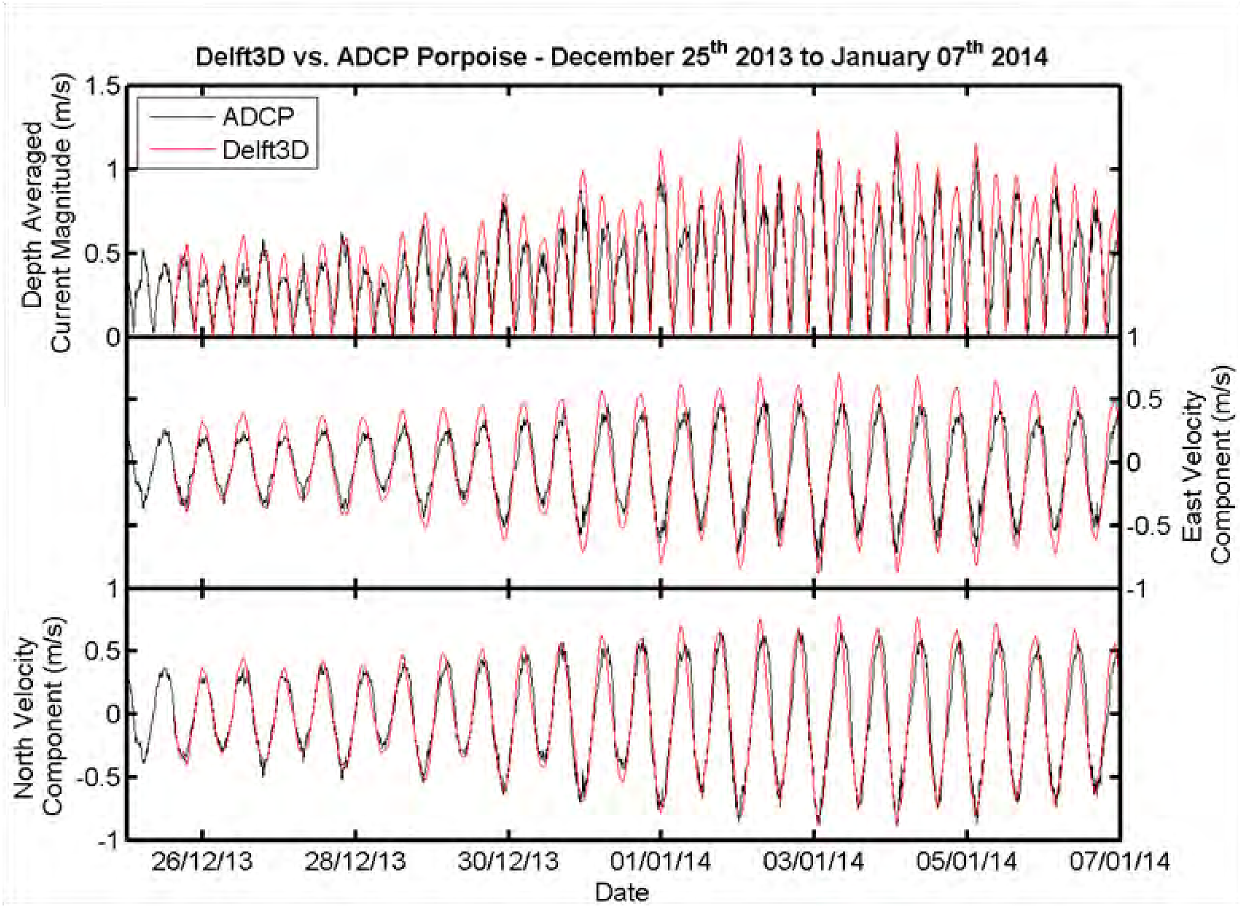


Figure F–4: Measured vs. Deltf3D Modelled Currents at Porpoise Channel

The Delft3D and the ADCP in Porpoise Channel compared well. Overall the model slightly overestimates peak currents at Porpoise Channel. Furthermore, the time series of depth averaged currents produced in the Delft3D results and observed by ADCP at Porpoise Channel were analyzed and compared within the frequency domain, using spectral analysis, as shown in Figure F–5. This comparison demonstrates that the semi-diurnal variations are dominant in the power spectra of the tidal currents associated sediment transport and morphological changes in this area dominated by the semi-diurnal tidal currents. The model derived semi-diurnal tidal current amplitude was five times greater than the diurnal tidal component, with more than 20 times the power (amplitude squared).

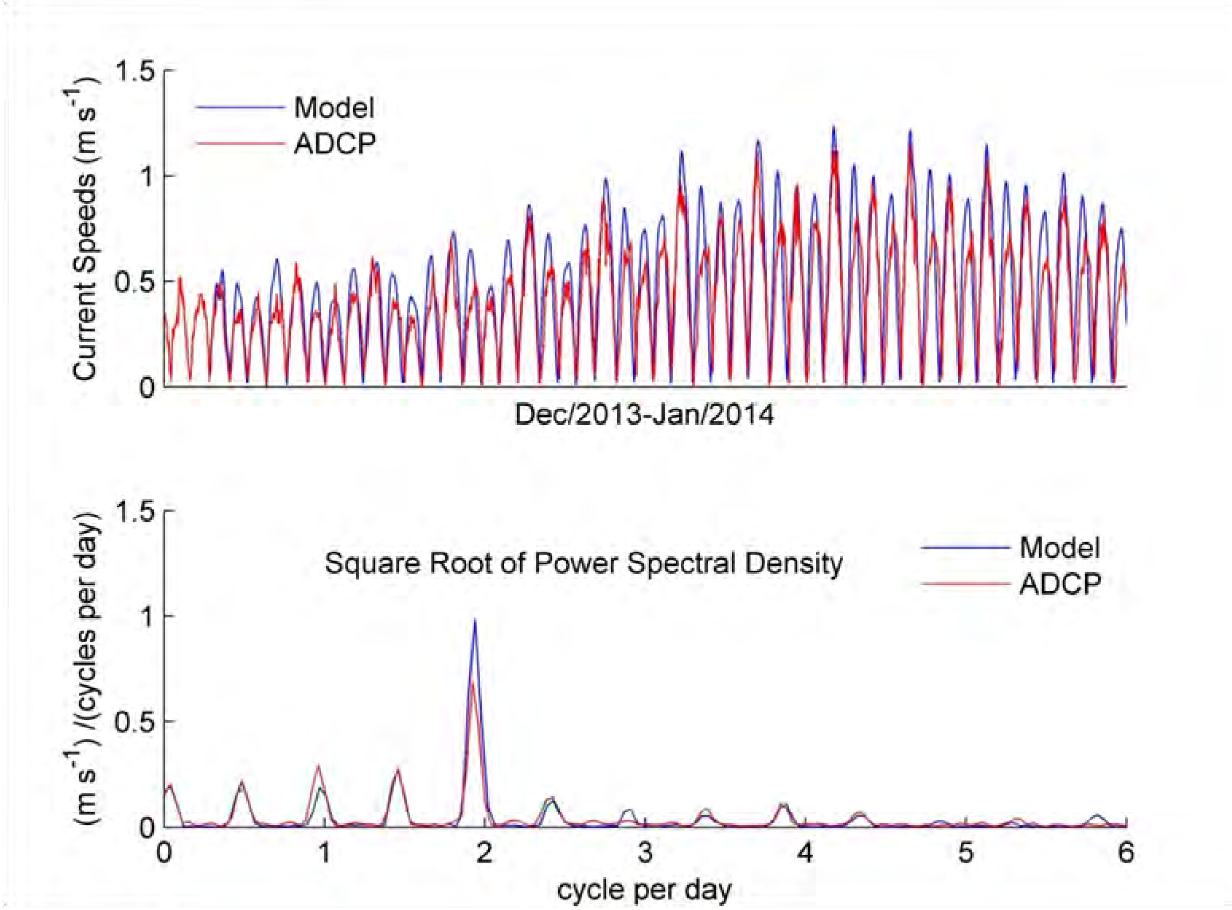


Figure F–5: Distribution of Modelled and ADCP Currents at Porpoise Channel (Depth Averaged) in Frequency Domain

Measured and predicted significant currents at Porpoise Channel are compared in Figure F–6 for the east component (top right), the north component (top left), and magnitude (bottom). The color of the scatter points indicates density, with warm/hot colors showing the most common measured and predicted current speeds. The correlations, compared to 1.0, between modelled and measured currents are 0.90 for the east component, 0.91 for the north component and 0.70 for the magnitude. The magnitude match is not as good as the components due to phase differences in the currents. The model's Mean Square Skill Score (MSSS), or Nash Sutcliffe Model Efficiency (ME), is approximately 0.85 for the east component, 0.85 for the north component and 0.60 for the magnitude. These scores rate as "excellent" for the components and "very good" for the magnitudes according to rating of results in Carniello et al (2011).

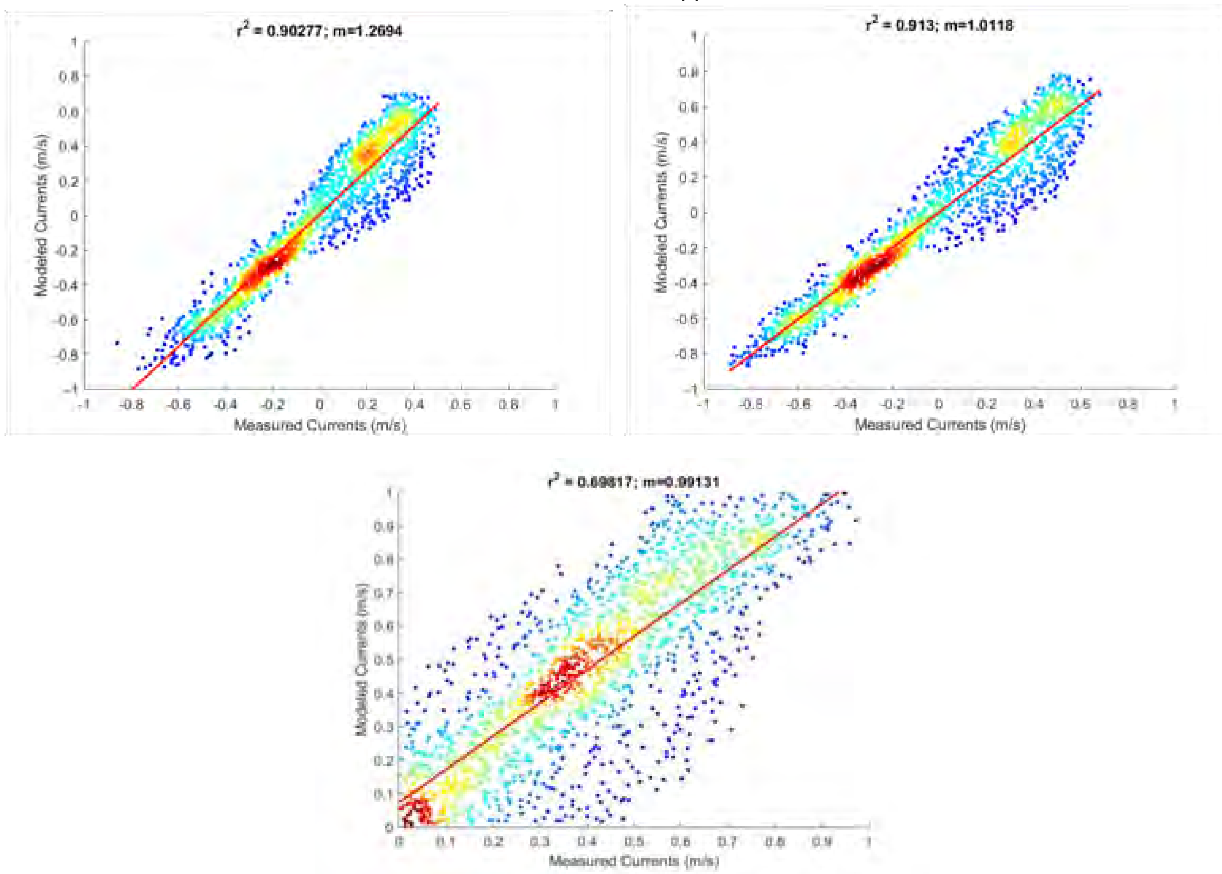


Figure F–6: Correlation between measured and modelled depth averaged current data at Porpoise Channel. East component (top left), north component (top right) and depth averaged current magnitude (bottom).

The modelled results were also compared with the measured results along the five sigma (vertical) layers at the Porpoise Channel between December 25, 2013 and January 07, 2014. The results are presented from Figure F–7 to Figure F–11.

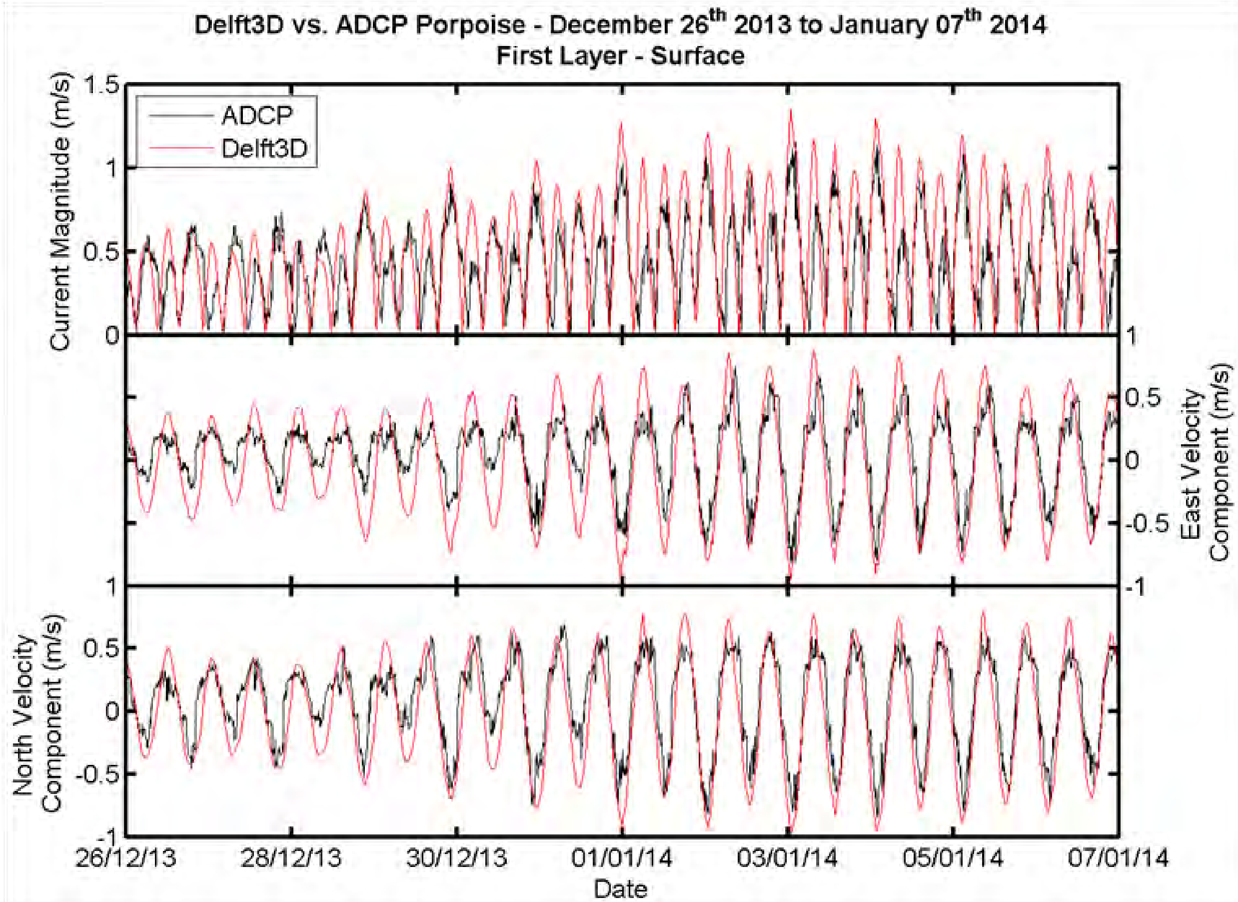


Figure F–7: Measured vs. Modelled Currents on the First Sigma Layer (Surface)

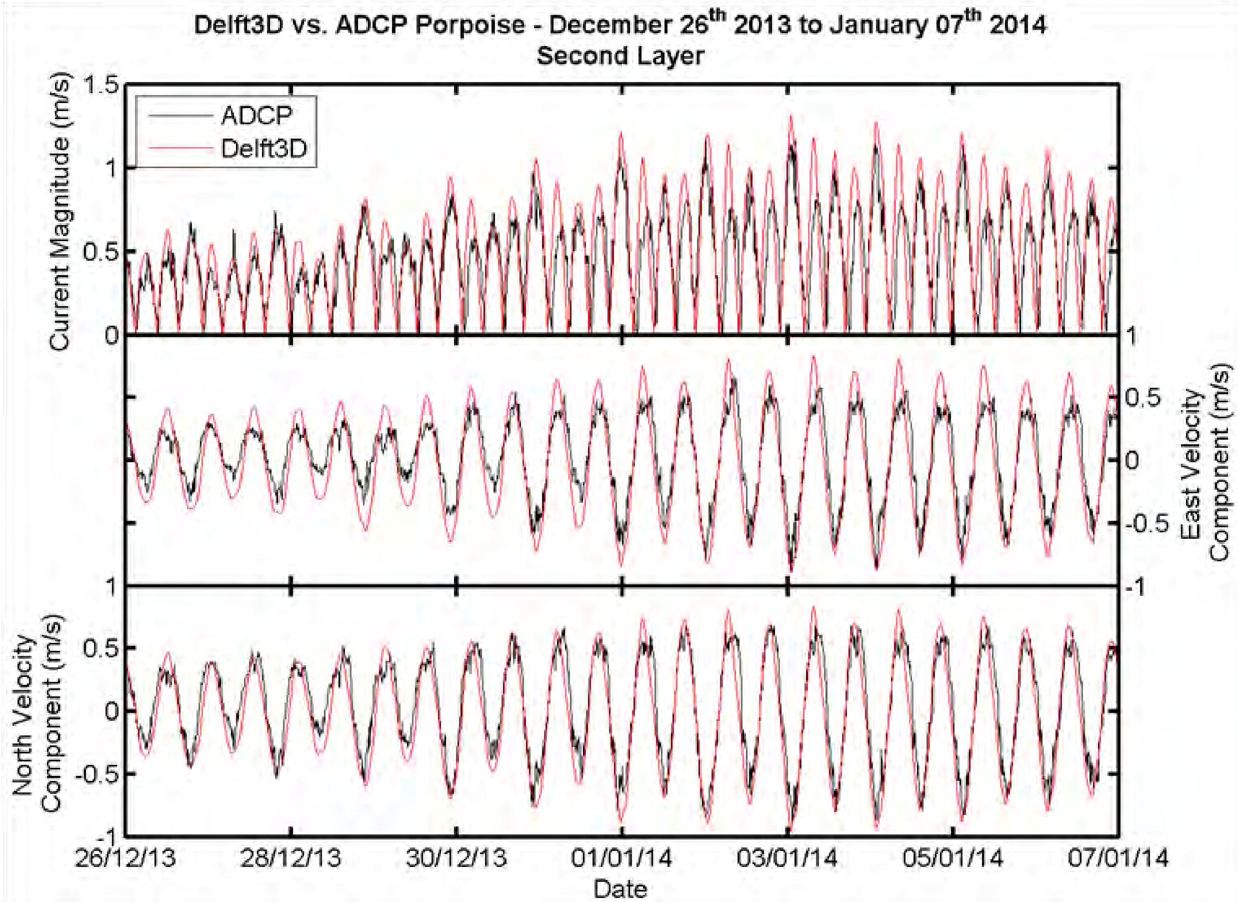


Figure F–8: Measured vs. Modelled Currents on the Second Sigma Layer

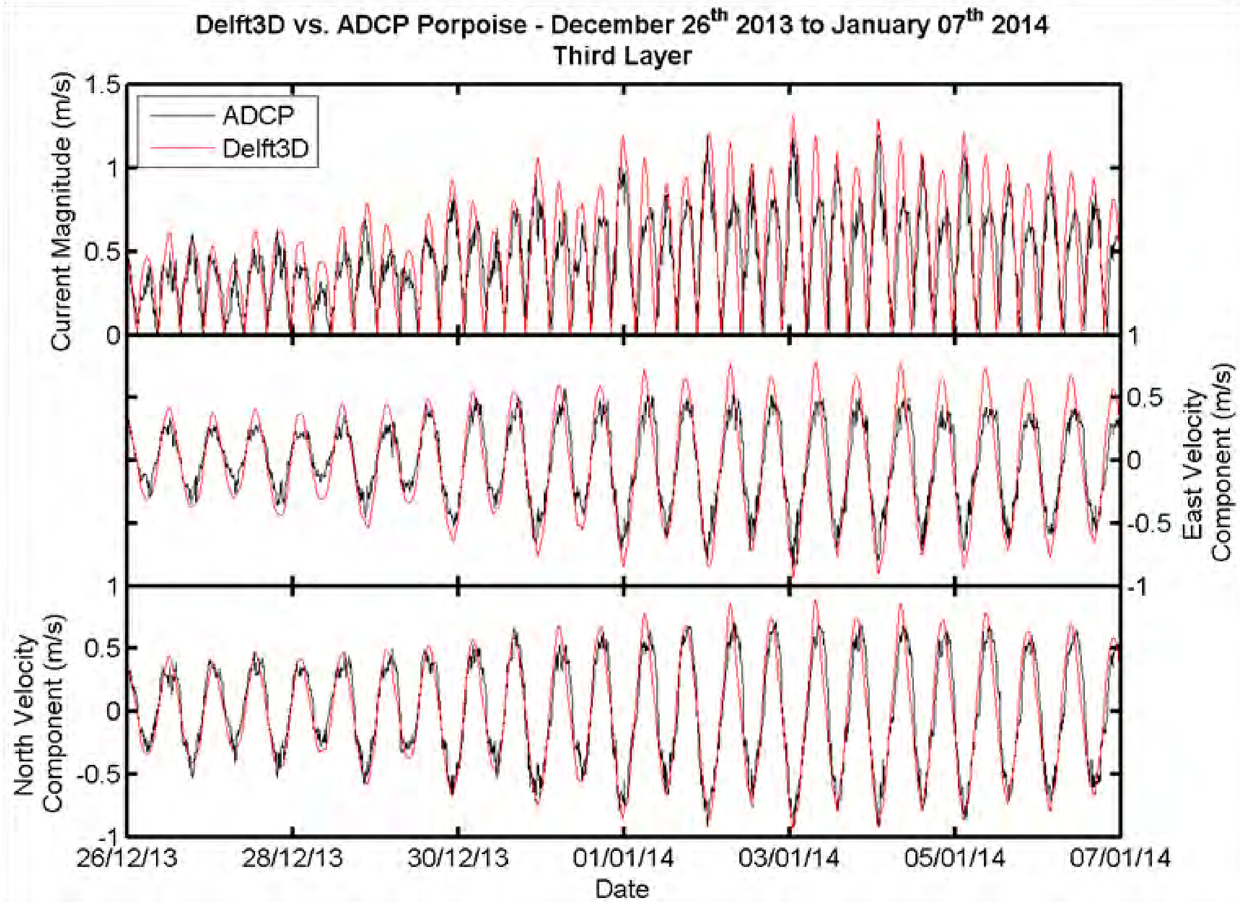


Figure F–9: Measured vs. Modelled Currents on the Third Sigma Layer

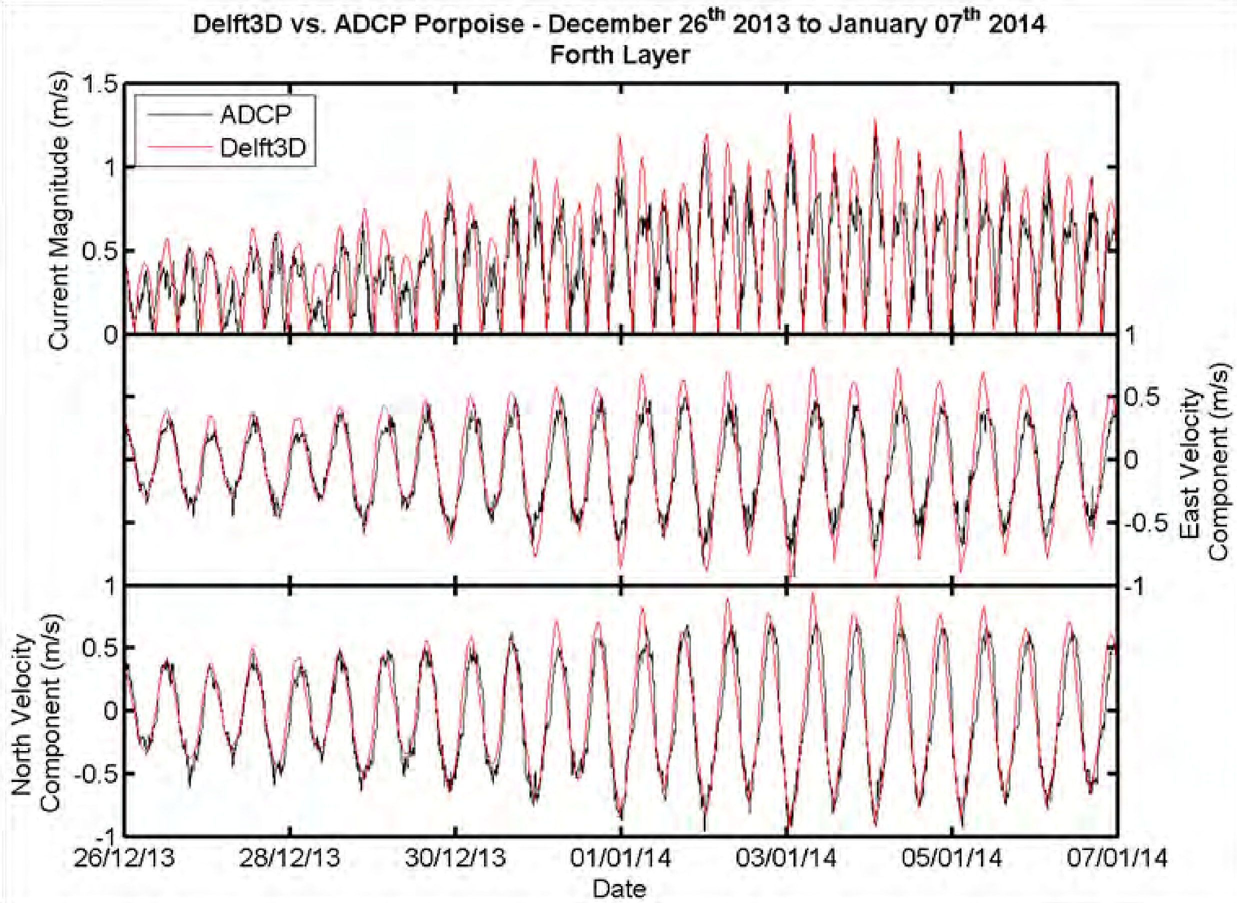


Figure F–10: Measured vs. Modelled Currents on the Fourth Sigma Layer

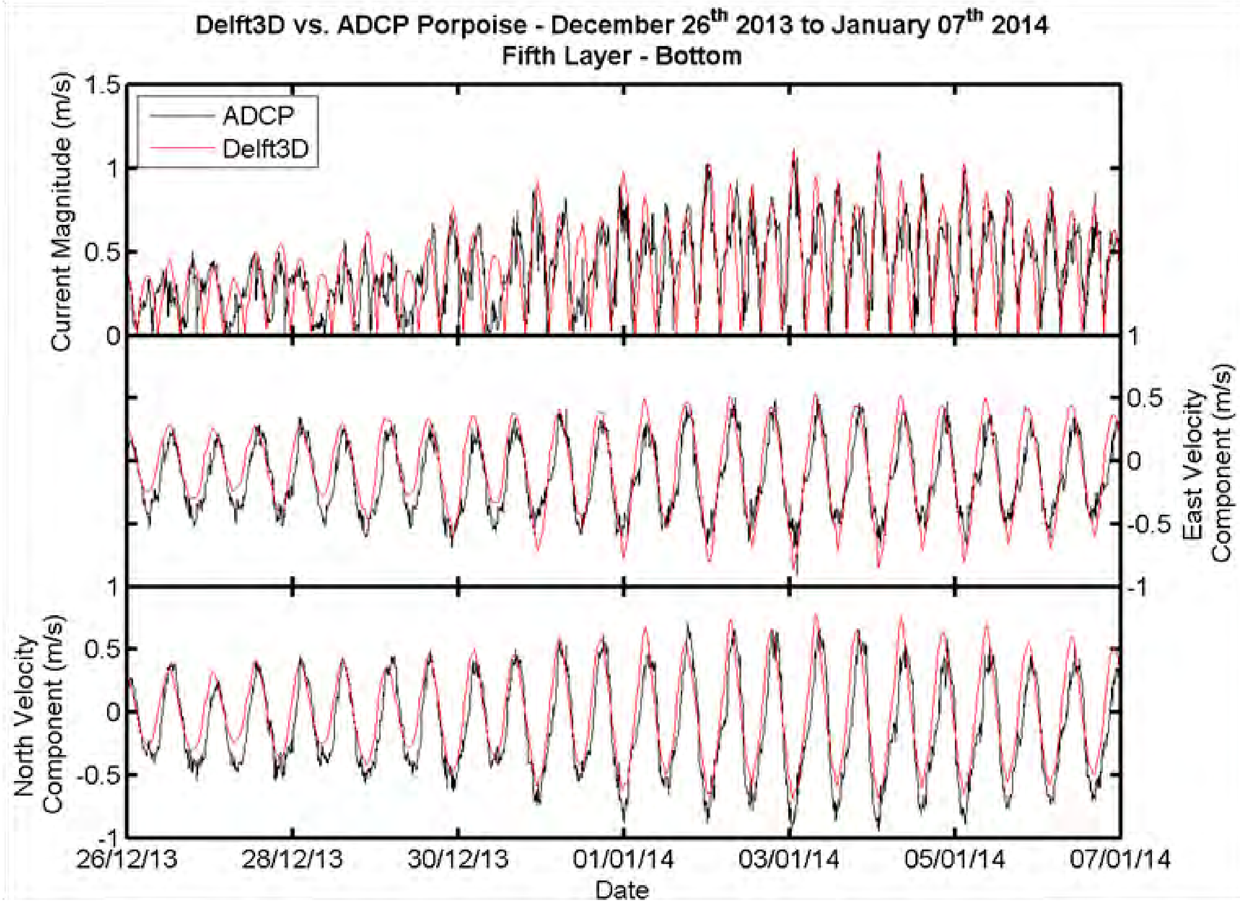


Figure F–11: Measured vs. Modelled Currents on the Fifth Sigma Layer (Bottom)

Figure F–7 to Figure F–11 show a very strong correlation between modelled and measured currents at the Porpoise Channel ADCP through the five vertical layers. Similarly to the depth averaged velocities, the Delft3D model currents were typically stronger than the measured values. Both modelled and measured currents are lower at the bottom layer, due to the friction with the seabed that decreases the current speeds, among other factors.

Thirteen days of modelled results were compared with the measured data from the Inverness Passage ADCP (Figure F–12) for validation of currents throughout the water column.

Safety ● Quality ● Sustainability ● Innovation

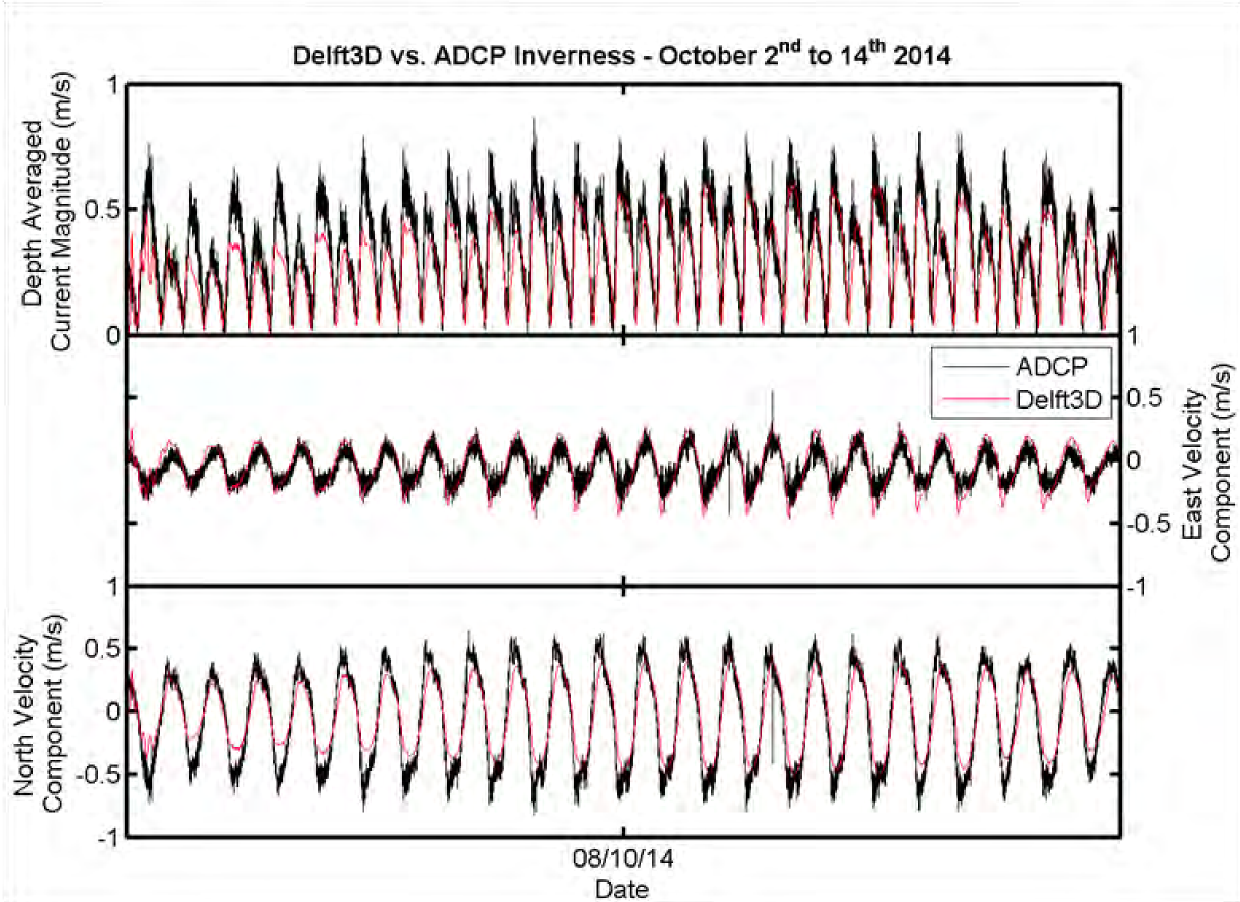


Figure F–12: Measured vs. Modelled Currents at Inverness Passage

Again, the modelled and measured currents at the Inverness Passage ADCP compare well. The modelled currents are smaller in magnitude, however, to the measured currents at Inverness Passage.

Correlation between measured and modelled currents at Inverness Passage is presented in Figure F–13. The correlation at Inverness Passage was also good, with values of 0.69, 0.81 and 0.89 for the current magnitude, east and north velocity components, respectively.

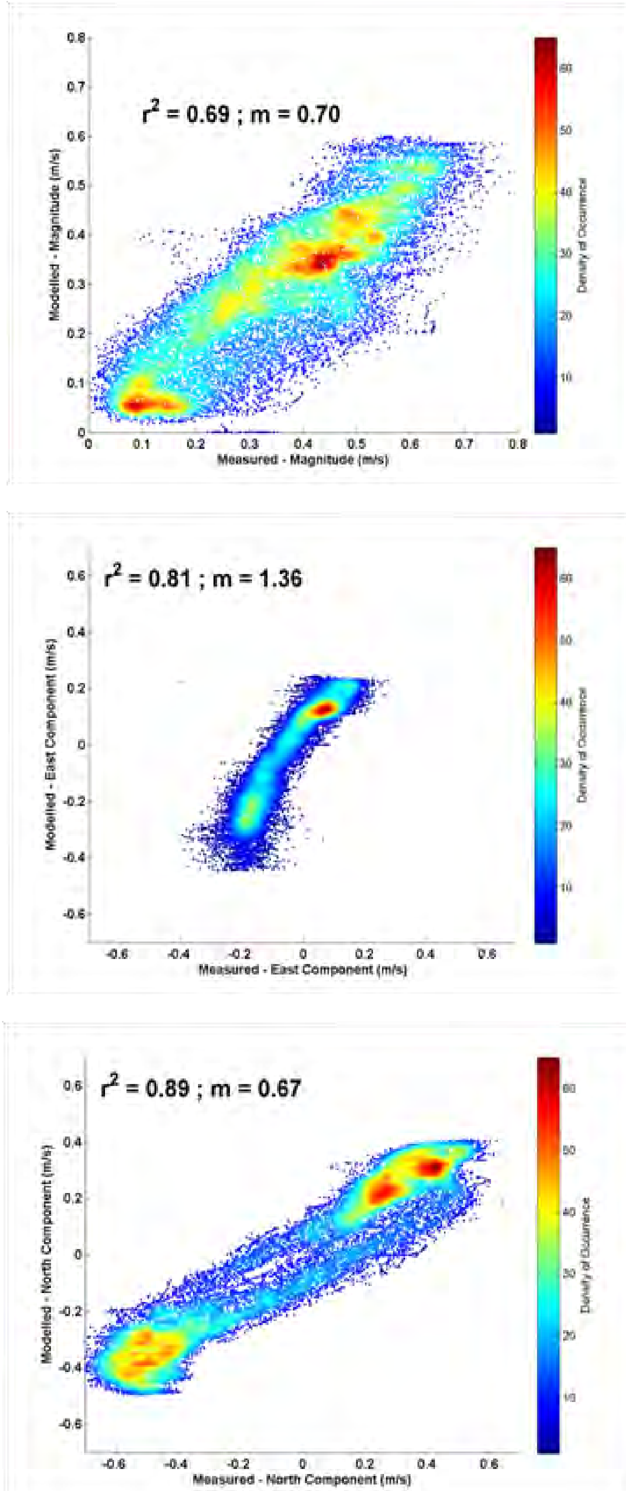


Figure F–13 Correlation between measured and modelled depth averaged current data at Inverness Passage, specifically current magnitude (top), east component (middle), north component (bottom).

F1.2.2 Currents Validation

A longer period of data measured at Porpoise Channel was used to validate Delft3D modelled. The period was almost three months between October 15, 2013 and January 07, 2014.

The time series results at the ADCP location are presented at 5 different sigma layers (1st at the surface, 3rd, 5th, 7th and 10th layer at the bottom). Figure F–14 to Figure F–18 present the comparison of the current magnitude (top), east (middle), and north (bottom) velocity components. Modelled and measured currents presented higher currents at the surface and lower currents at the bottom. The results showed a good correlation between measured and modelled results on different layers along the water column.

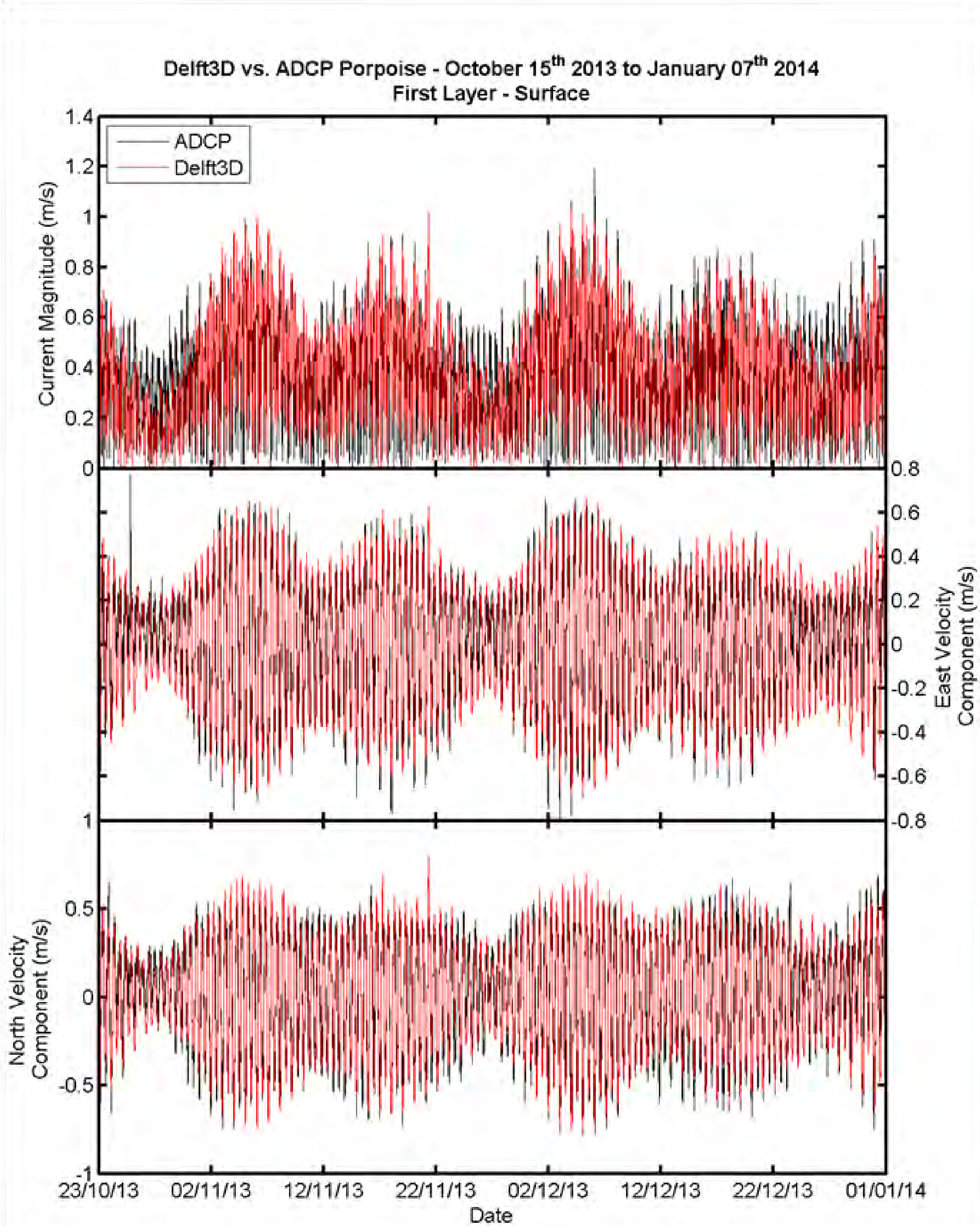


Figure F–14: Measured vs. Modelled Currents on the First Sigma Layer (Surface)

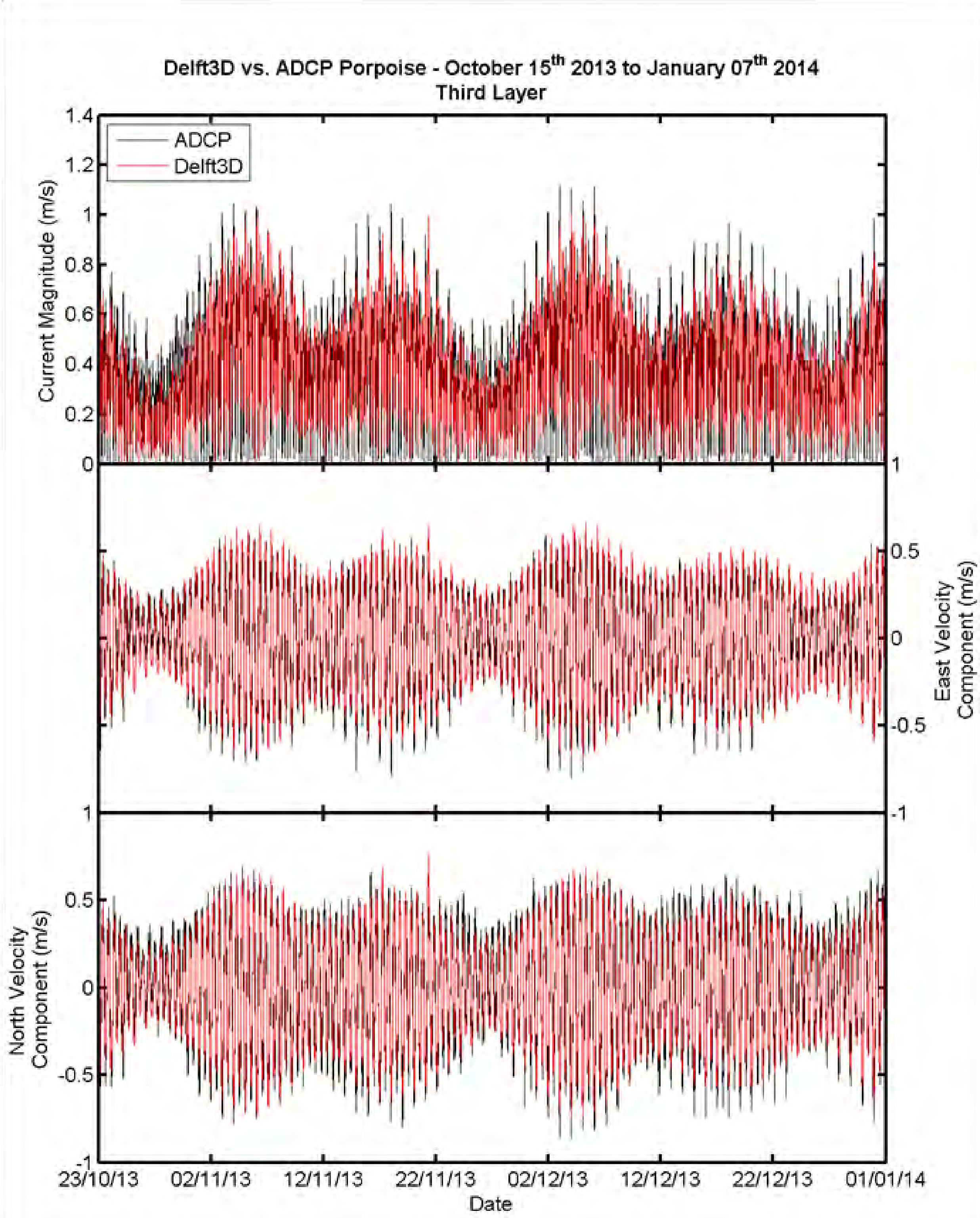


Figure F–15: Measured vs. Modelled Currents on the Third Sigma Layer

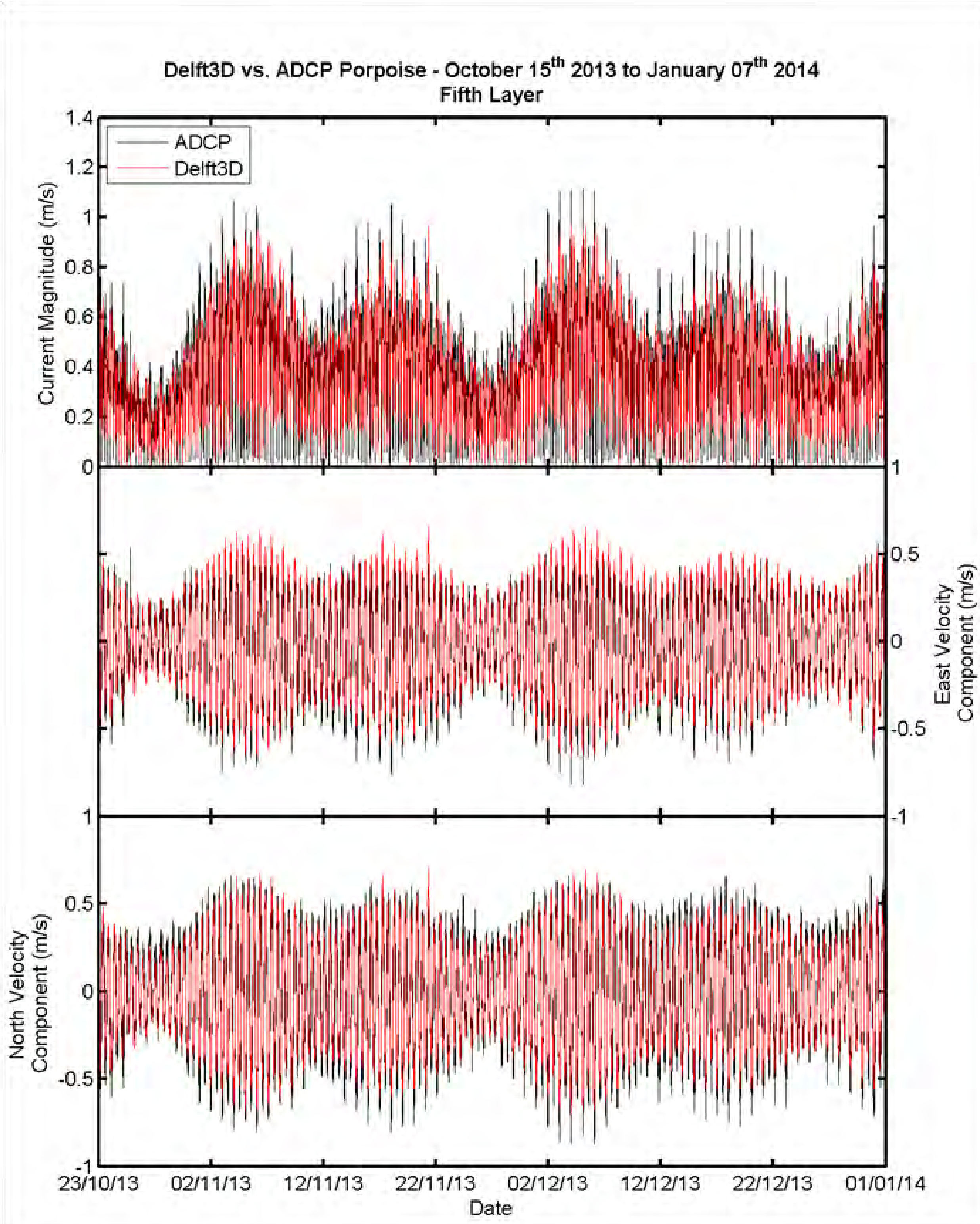


Figure F–16: Measured vs. Modelled Currents on the Fifth Sigma Layer

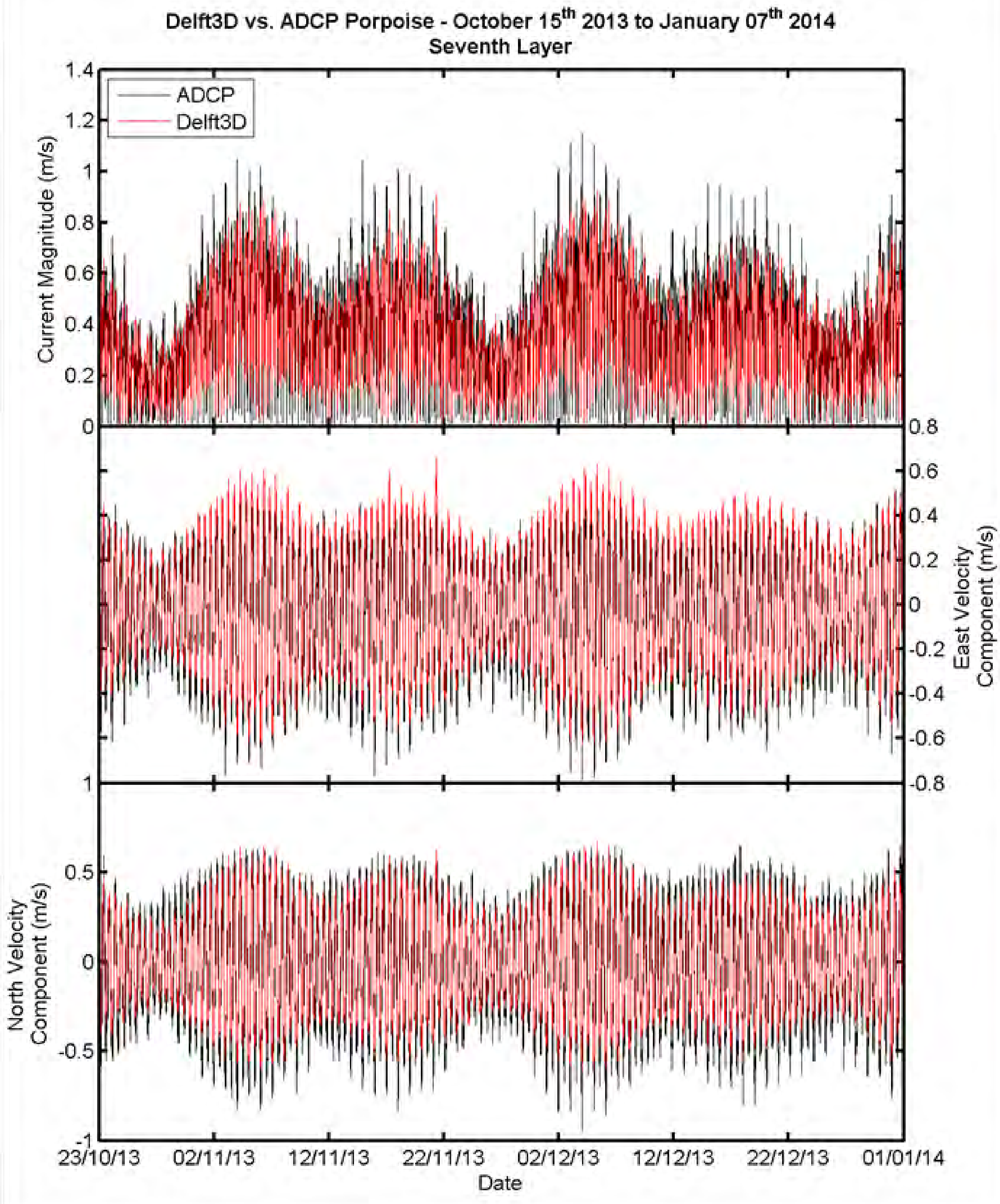


Figure F–17: Measured vs. Modelled Currents on the Seventh Sigma Layer

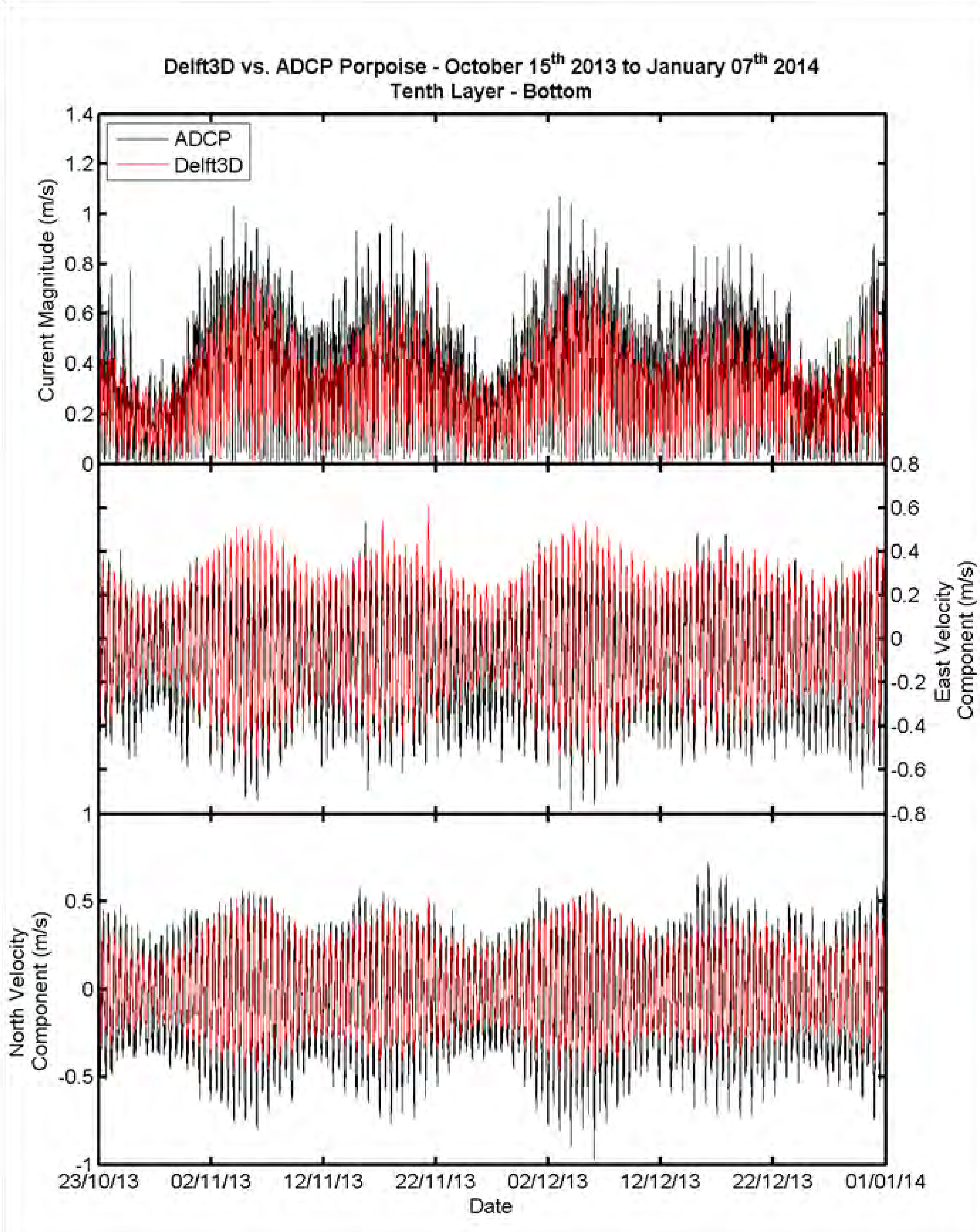


Figure F–18: Measured vs. Modelled Currents on the Tenth Sigma Layer (Bottom)

The correlation between measured and modelled currents at Porpoise Channel is presented in Figure F–19 for 5 different vertical layers.

The MSSS for the east component and north components are presented on Table F-1. Smaller MSSS values are observed at the bottom layer on the east (0.48) and north (0.66) components of the velocity. The MSSS values are between 0.72 and 0.87 for the other vertical layers. These scores rate as “good” at the bottom and from “very good” to “excellent” for the other layers according to rating of results in Carniello et al (2011).

Table F-1: Statistics of Measured vs. Modelled Currents on Different Sigma Layers

Layer	1	3	5	7	10
East Vel Comp - R^2	0.82	0.85	0.84	0.83	0.73
East Vel Comp - Slope	1.05	1.00	1.00	0.97	0.95
East Vel Comp - MSSS	0.72	0.82	0.80	0.76	0.48
North Vel Comp - R^2	0.85	0.88	0.86	0.81	0.72
North Vel Comp - Slope	0.97	0.89	0.84	0.75	0.65
North Vel Comp - MSSS	0.81	0.87	0.86	0.80	0.66

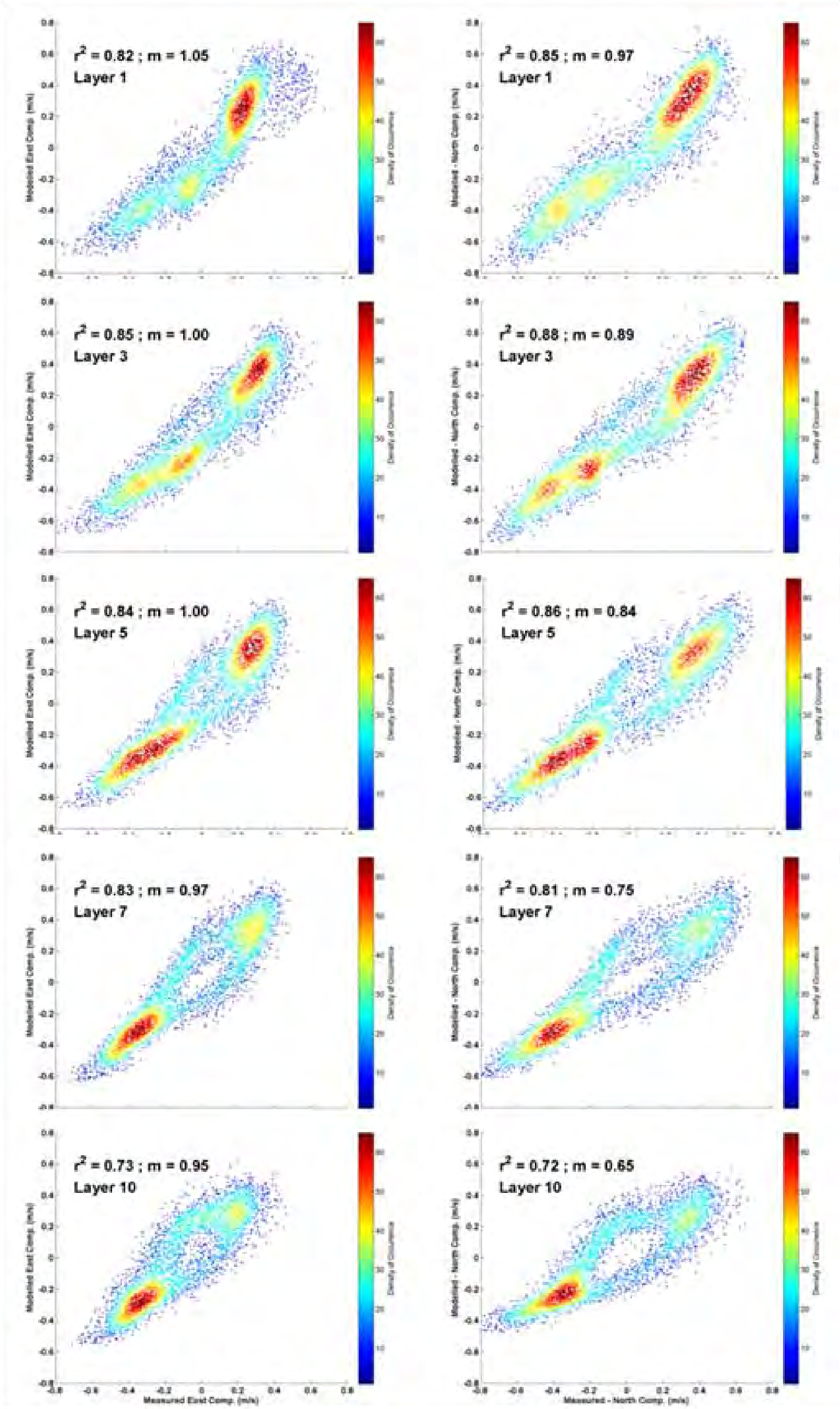


Figure F–19: Correlation between measured and modelled current velocity at Porpoise Channel. East component (left) and north component (right) at different sigma levels in the water column from the surface (top) towards the bottom (bottom).

F1.3 Waves

The Delft3D wave model was used to reproduce measured waves during three separate time periods. Wind data used for input to the wave model are described in Appendix A. The following three time periods were simulated:

- Calibration Period 1: December 25, 2013 – January 7, 2014 (Figure F–20)
- Calibration Period 2: February 19, 2014 – February 22, 2014 (Figure F–21)
- Calibration Period 3: December 7, 2014 – December 12, 2014 Figure F–22)

Calibration Period 1 was selected to include simultaneous wave (PNW Buoy) and current (Porpoise Channel ADCP) measurements. Calibration Period 2 was selected to include the third most severe storm measured by PNW Buoy and the highest waves from west-northwest. Calibration Period 3 was selected to include the most severe storm measured by the PNW Buoy, with waves approaching from the south-southeast. Figure F–20 to Figure F–22 displays the model results (SWAN coupled with Delft3D) and the measured waves at the PNW Buoy. The wave model reproduces the measured wave conditions, with an overall accurate prediction of significant wave height, mean wave period and mean wave direction.

Mean wave periods are an extremely difficult measure to validate, given that they represent a brutal average of energy from distinctly different directions and at different frequencies (swell vs. local seas). Time periods of increase in mean wave period represent a calm period where the small background swell represents a greater portion of the mean.

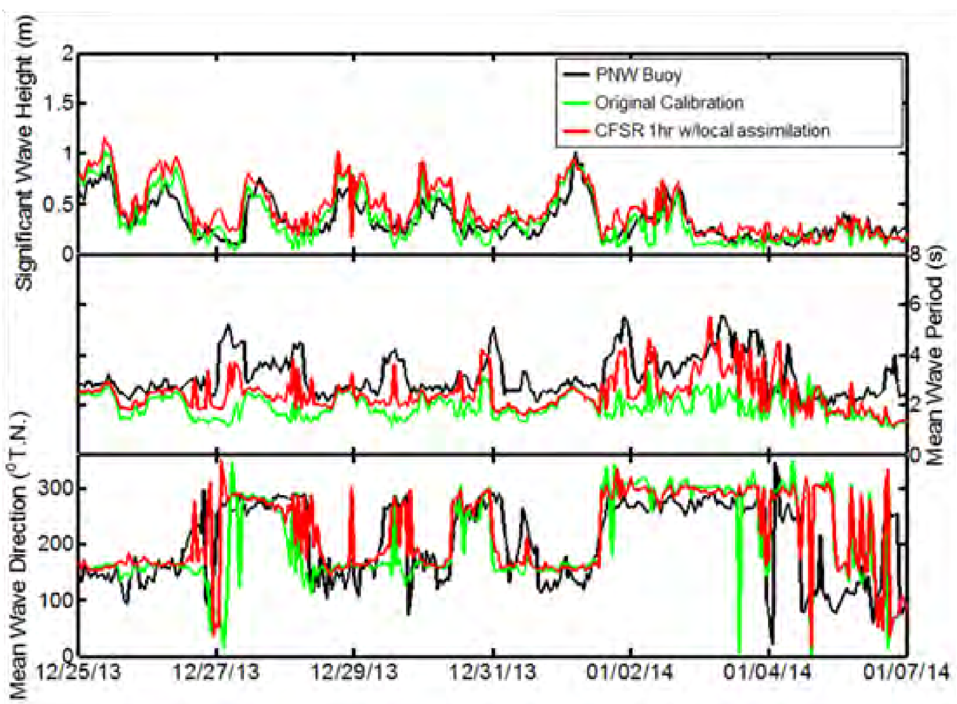


Figure F–20: Wave Model Calibration for Calibration Period 1

Safety • Quality • Sustainability • Innovation

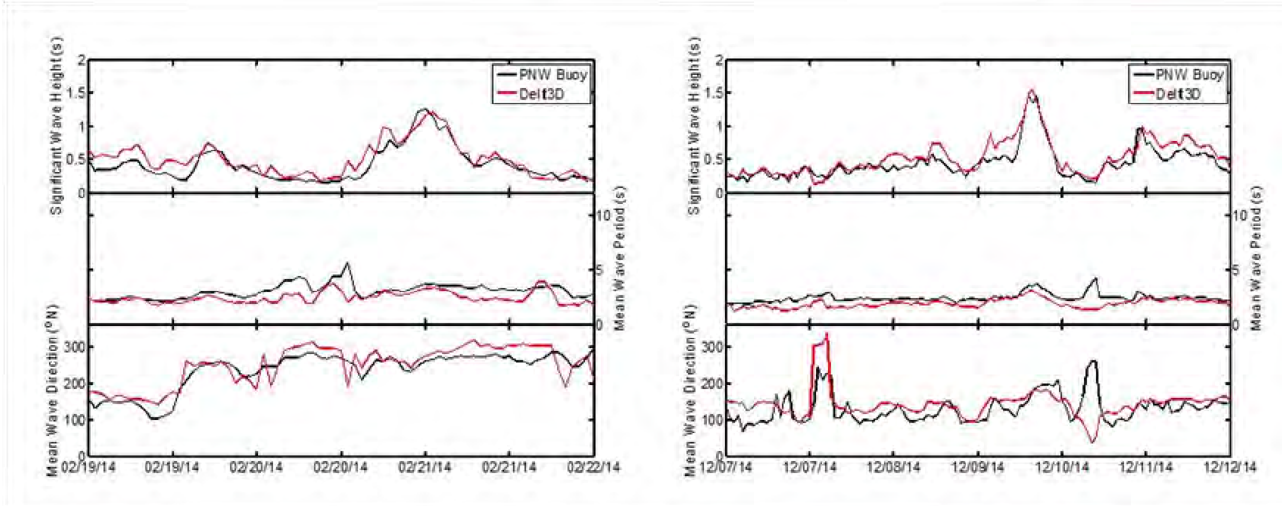


Figure F–21: Wave Model Calibration for Calibration Period 2 (left) and 3 (right)

Measured and predicted significant wave heights from all three simulations are compared in Figure F–22. The color of the scatter points indicates density, with warm/hot colors showing the most common measured and predicted wave heights. The correlation between modelled and measured significant wave heights is 0.76. The model slightly over-predicts wave heights on average (slope 1.0178). The model's Mean Square Skill Score (MSSS), or Nash Sutcliffe Model Efficiency (ME) is approximately 0.47, which rates between "good" and "excellent" according to rating of results in Carniello et al (2011).

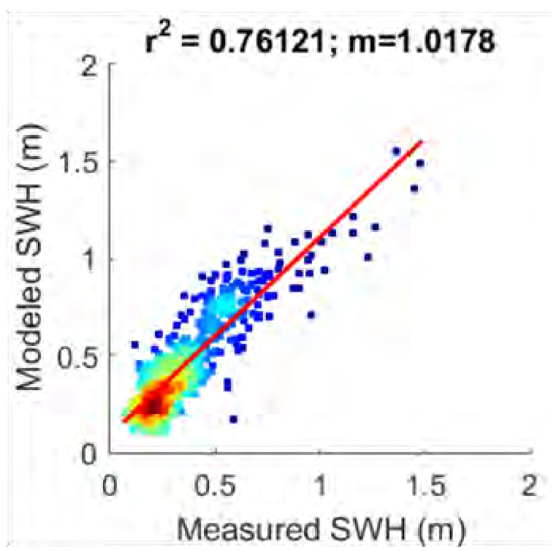


Figure F–22: Model Performance in Prediction of Significant Wave Height

F1.4 References

Carniello, L., D'Aplaos, A. and A. Defina. 2011. Modelling wind waves and tidal flows in shallow micro-tidal basins. Estuarine, Coastal and Shelf Science. Vol. 92 (2): 263-276.

Appendix G:
Storm Condition Development

G1. Storm Condition Development

This section outlines the setup of the storm simulations. The storm simulation were conducted over an 11-day period. Three days were allotted for the ramp-up period and eight days for the morphological simulation.

In order to model conservative storm conditions a large tide range was applied over the 11-day period with the highest water level occurring at the peak of the storm. This water level corresponds to the highest 1% water level.

G1.1 Winds

The locally generated wind driven waves dominate the wave climate at the project site. In order to establish storm events, winds from the Holland Rock station (Figure G-1) were analysed. Hourly wind data has been recorded at Holland Rock since 1994. As discussed in Appendix C, Holland Rock is a good representation of wind conditions in Chatham Sound and the resulting generation of waves affecting the project site.

Figure G-1:Holland Rock Station (looking southwest Jan. 20, 2015)

The wind rose shown in Figure G-2 displays the wind directions and speeds measured at Holland Rock. The wind rose demonstrates that while a significant portion of the wind is concentrated from the southeast, an important northwest component is present, where the waves can develop over a longer fetch.

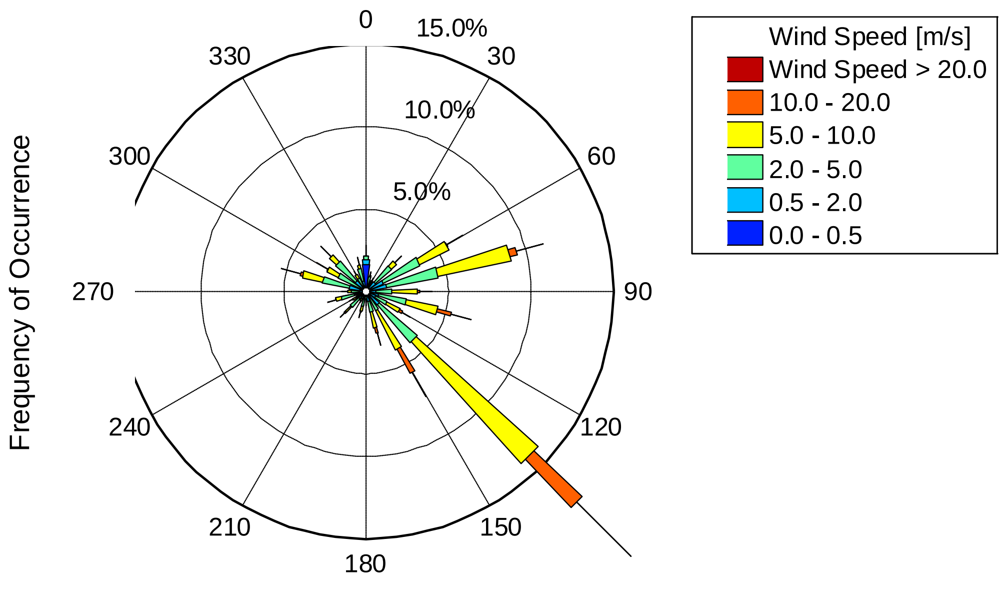


Figure G-2: Wind speeds and directions measured at Holland Rock station

The storm modelling focuses on three wind directions from the west: southwest (240^{o}N), west (270^{o}N), and the northwest (300^{o}N). These directions were selected as the resulting waves will interact with the structure before reaching Flora Bank.

A wind direction from the south-southeast (170^{o}N) was also selected as the largest and most prominent wind speeds are measured from the southeast.

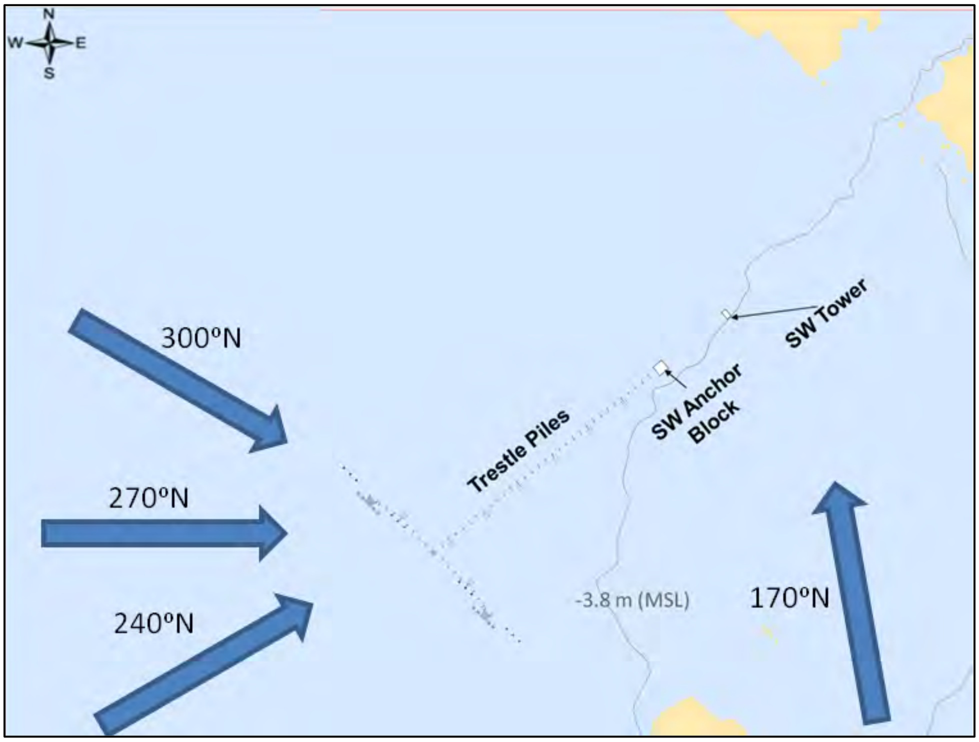


Figure G-3: Wind Directions for Storm Conditions

The modelled winds in the storm simulation were run as a wind field over the model domain with a constant direction for the full duration of the 11-day simulation. This increases the conservatism in the storm simulations as naturally the wind would shift directions over the course of a storm. The constant wind in one direction will result in the generation of larger waves.

G1.1.1 Westerly Winds

Wind speeds with the peak event between 225°N and 360°N were ranked and an extreme event analysis was conducted. Independent storms, or extreme events, were distinguished by a minimum interval of 24-hours between independent events and then ranked the magnitude of the wind speed.

The wind magnitude return periods were determined with Gumbel distribution based on the measured data at Holland Rock (Table G-1).

Table G-1: Wind Speeds and Return Periods (Holland Rock)

Return Period (years)	Wind Magnitude (m/s)
1	13.5
5	18.7
10	20.9
20	23.1

Return Period (years)	Wind Magnitude (m/s)
50	26.1
100	28.3

It is noted that it is standard practice to determine return periods up to three times the length of the measured record (Leenknecht, 1992). The Holland Rock dataset is approximately 21 years long and therefore the 1 to 50-year return period events are consistent with standard practice. The statistical accuracy of the 100-year event is limited by the length of the measured record at Holland Rock.

As a conservative approach, a Gaussian curve was used to reproduce the wind growth time series with the peak of the curve corresponding to the return period determined in the extreme value analysis. This created a wider distribution than is expected to occur naturally and allows for a more conservative generation of the wind driven waves.

Further, these long-term distributions are developed for a single parameter, the wave height. Since wave height is normally the most important wave parameter in design, it is common to calculate the wave height distribution and then relate other wave parameters to wave height using joint distributions. An example of a joint distribution would be the wave height-duration distribution, which would have smaller probability (less chance) of occurrence than the Hs-distribution. For the Gaussian curve storm durations, long-term return periods have a smaller percent chance of occurrence than the ones derived for wave height only, as the real storm event durations are smaller, as shown in Figure G-4. In this report, however, the return periods used were defined for the wave height distribution only.

The maximum duration for a recorded westerly storm at Holland Rock with winds over 10 m/s and a minimum interval between storms of 24-hours is 115 hours. The average duration of storms is 14 hours.

Figure G-4 displays the time series of the winds used for the storm simulations. The orange line shows an example of the measured wind speeds at Holland Rock during a westerly storm event which occurred in December 1998.

Figure G-5 displays the input wind conditions time series as well as the corresponding water levels used in the simulation. The peak of the storm occurs at high tide.

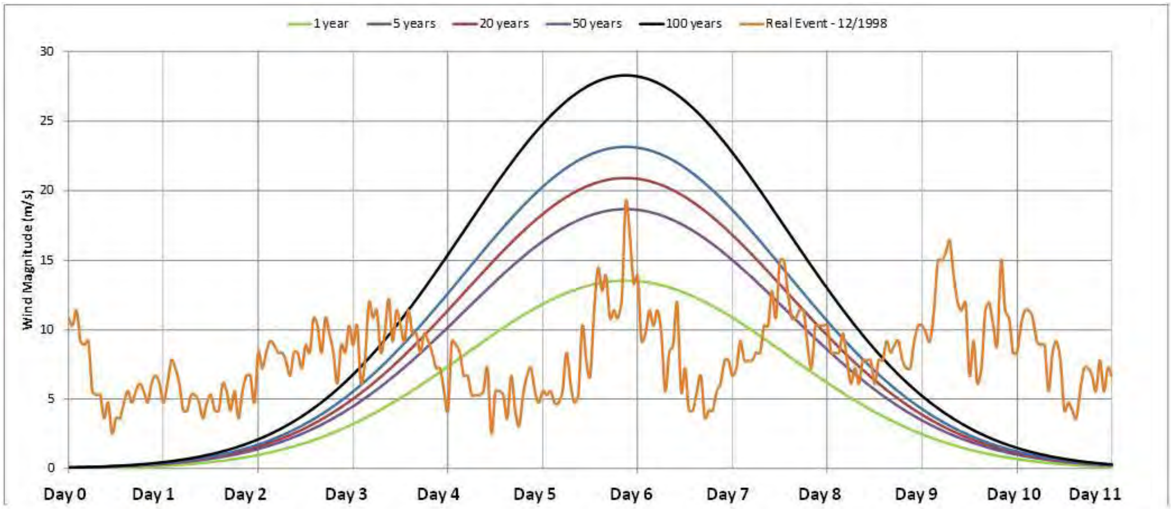


Figure G-4: Input wind conditions based Gaussian curve and example of wind speeds measured at Holland Rock during a storm

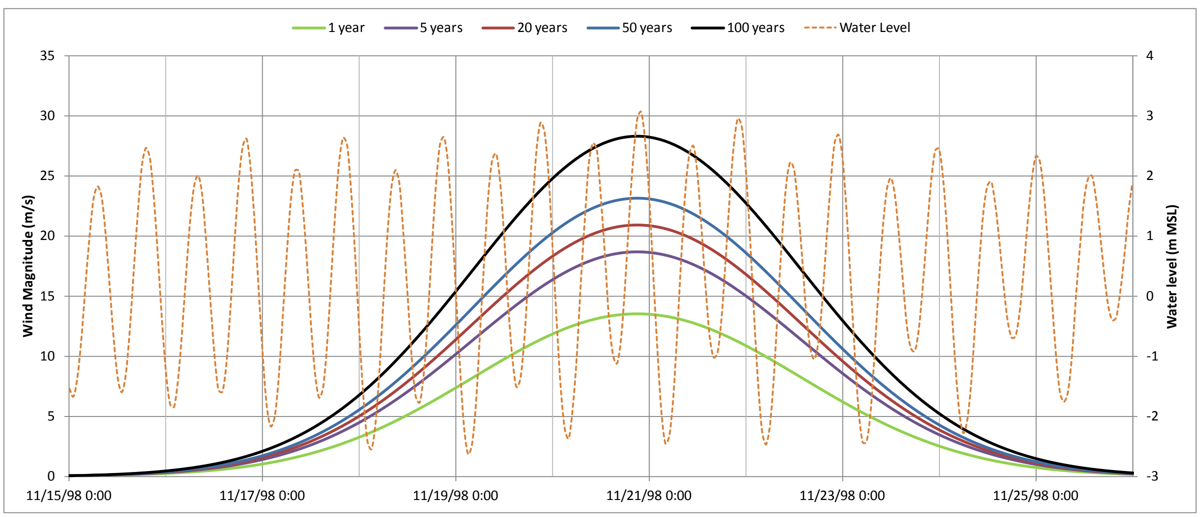


Figure G-5: Input wind conditions based Gaussian curve and corresponding water levels

G1.1.2 South-Southeast Winds

Wind speeds with peak events between 255^{o}N and 285^{o}N were ranked and an extreme event analysis was completed. Independent storms were distinguished by a minimum interval of 24-hours between independent events and then ranked by severity.

The wind magnitude return periods were determined with Gumbel distribution based on the measured data at Holland Rock (Table G-2).

Safety • Quality • Sustainability • Innovation

Table G-2: Wind Speeds and Return Periods for Waves from 170° (Holland Rock)

Return Period (years)	Wind Magnitude (m/s)
1	22.8
5	26.4
20	29.4
50	31.4
100	32.9

Similarly to the westerly waves, a Gaussian curve was used to produce the wind growth time series with the peak corresponding to the return period's listed in Table G-2. Figure G-5 displays the input wind condition time series for the 170°N storm simulations. The orange line shows an example of the measured wind speeds at Holland Rock during a westerly storm event which occurred in December 1997.

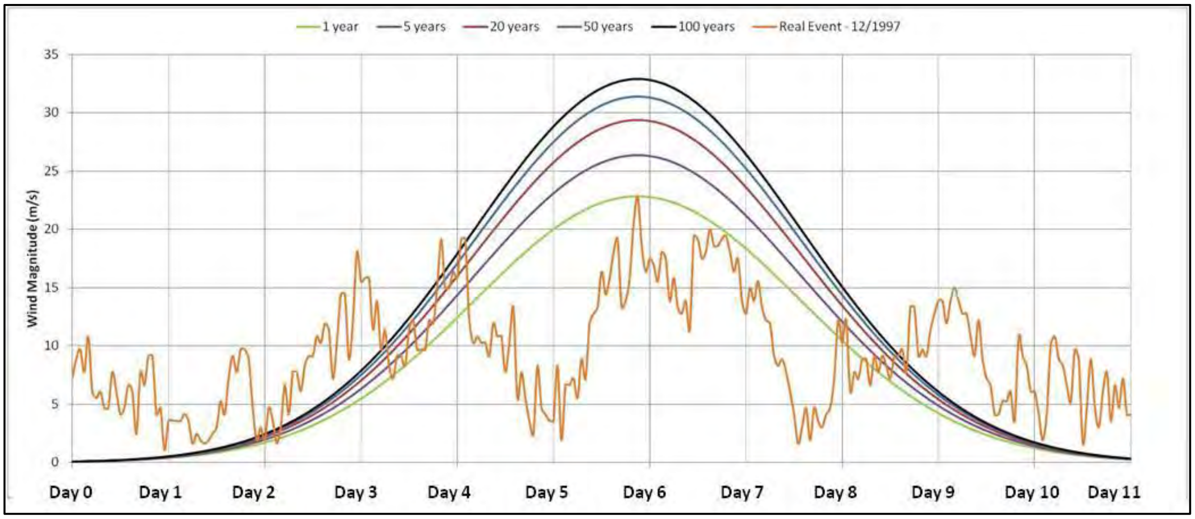


Figure G-6: Input wind conditions from 170° True North based Gaussian curve

Safety ● Quality ● Sustainability ● Innovation

G1.2 Offshore Waves

In addition to the extreme wind storm and resulting wind generated waves, offshore wave conditions (swell) were also used for the simulation.

Offshore data from the Wave Watch III dataset was analyzed from 1979 to 2014. The largest offshore swell event in the dataset was selected with a significant wave height (Hs) equal to 11.2 m and a corresponding peak period (Tp) equal to 14.3 s and peak direction equal to 270°N.

A Gaussian curve was then used to define the incoming swell heights. The peak wave height occurs simultaneously to the peak wind magnitude in the simulations. These swell conditions were applied to all of the storm simulations. Figure G-7 displays the swell wave input conditions time series.

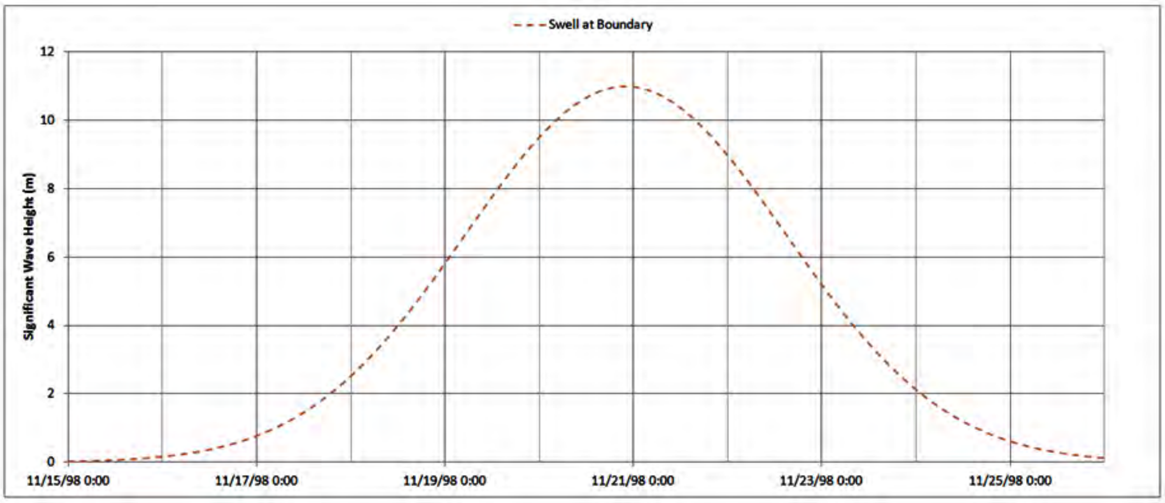


Figure G-7: Input swell conditions at offshore boundary (Dir = 270°N and Tp = 14.3 s)

G1.3 Summary

The conservative storm simulations are run for five return periods (1, 5, 20, 50, and 100-year) and for four directions (300°N, 270°N, 240°N, and 170°N). All storm simulations are conducted for existing and proposed conditions (with and without the marine structures) to analyse the impact of the marine structures. The results of these simulations are presented in the main report and Appendix H and Appendix J.

G1.4 References

Leenknecht, D., Szuwalski, A., & Sherlock, A. (1992). Extremal Significant Wave Height Analysis. Automated Coastal Engineering System.

Appendix H:
Regional Scale Modelling Results

H1. Regional Scale Modelling Results

This appendix provides additional results and analysis from the regional Delft3D simulations to supplement the information presented in the main report.

This includes wave and morphology results for a range of extreme event directions and return periods. Additional data for the 3 month stormy period presented in the main report and a closer look at a 6 day period during the 3 months. Supplementary data for the 4 month calmer period as well as a closer look at the freshet and tides-only simulations are also provided. Extra data for the 1 year 1–hour wave-flow coupling run is included as well as the results from two year-long simulations which used 3–hour wave-flow coupling is included.

H1.1 Extreme Events

Additional results, including wave conditions and morphology, from the following 11 day extreme event (storm) simulations (40 total) are provided.

- Directions 300^o, 270^o, 240^o, 170^o True North
- Wind return periods 1, 5, 20, 50, 100 years
- Existing and proposed conditions

These results are provided to supplement the discussion of the extreme events provided in the main report. The development of the extreme events are described in Appendix G.

H1.1.1 Waves

The following figures display the significant wave height (H_s) at the peak of the storm event (equivalent to the peak in wind speed) for the various storm directions and return periods for the existing conditions (without the marine structures) and the proposed conditions (with the marine structures). Additional figures showing the difference between the significant wave height of the proposed and existing conditions for the 20 and 50-year return period are also included.

In general, the storms results showed a slight and localized reduction (negative values) in the significant wave height at the peak of the storm around the trestle, SW Anchor Block, and SW Tower.

H1.1.1.1 1-Year Return Period Storms

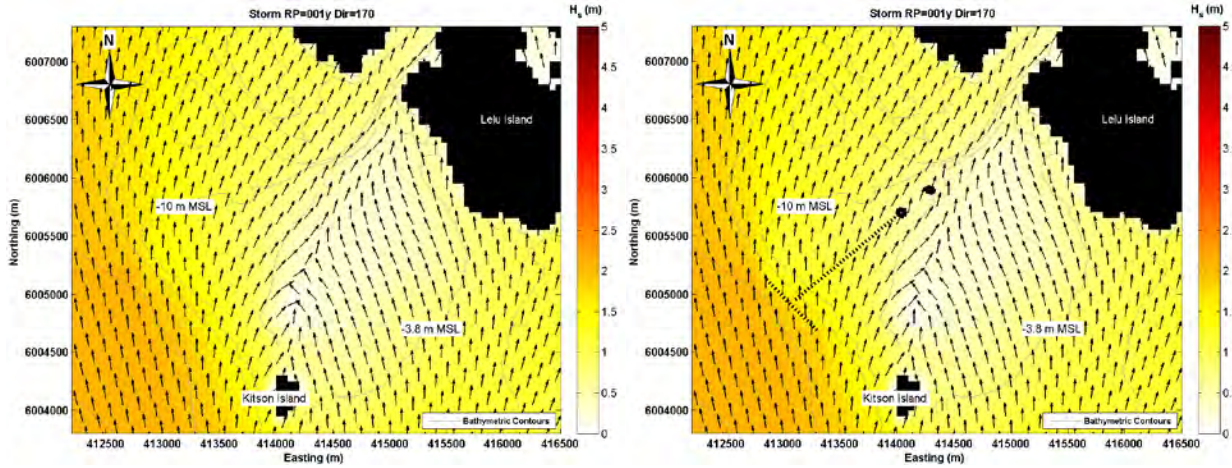


Figure H– 1: Significant wave height at the peak of the 1-year storm from 170° True North for existing (left) and proposed (right) conditions.

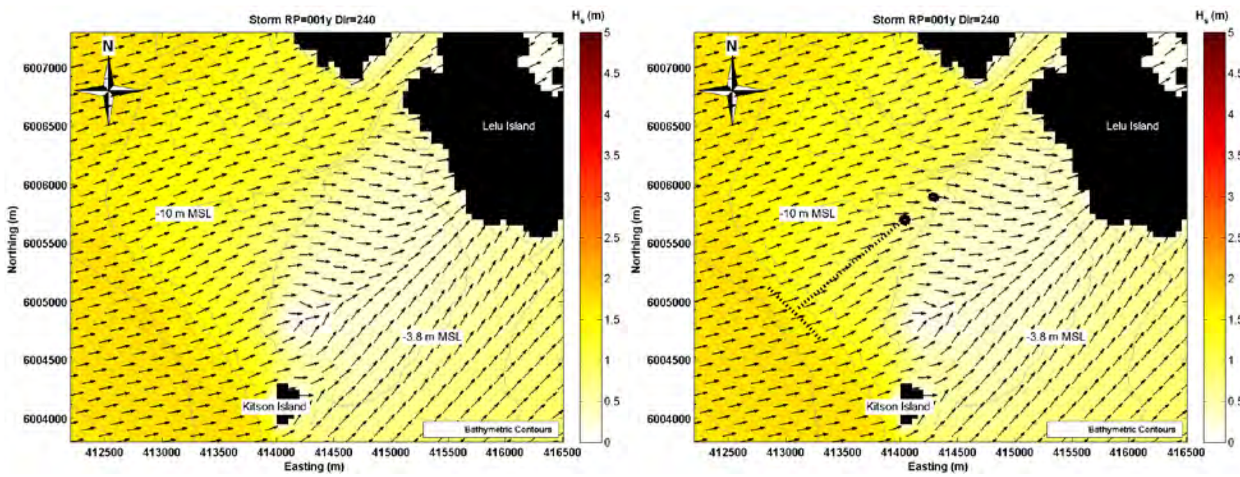


Figure H–2: Significant wave height at the peak of the 1-year storm from 240° True North for existing (left) and proposed (right) conditions.

Safety ● Quality ● Sustainability ● Innovation

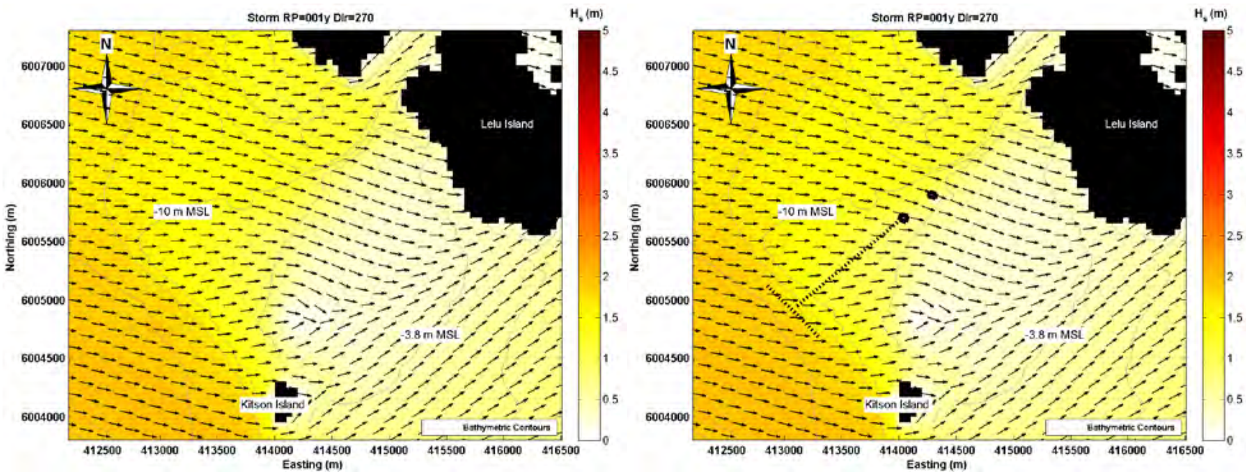


Figure H–3: Significant wave height at the peak of the 1-year storm from 270^o True North for existing (left) and proposed (right) conditions.

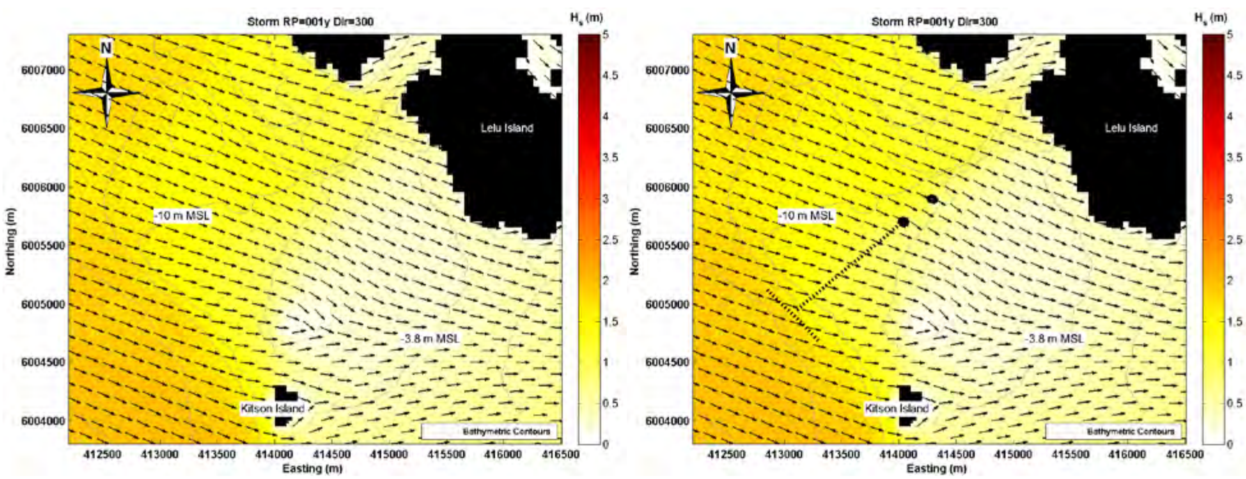


Figure H–4: Significant wave height at the peak of the 1-year storm from 300^o True North for existing (left) and proposed (right) conditions.

H1.1.1.2 5-Year Return Period Storms

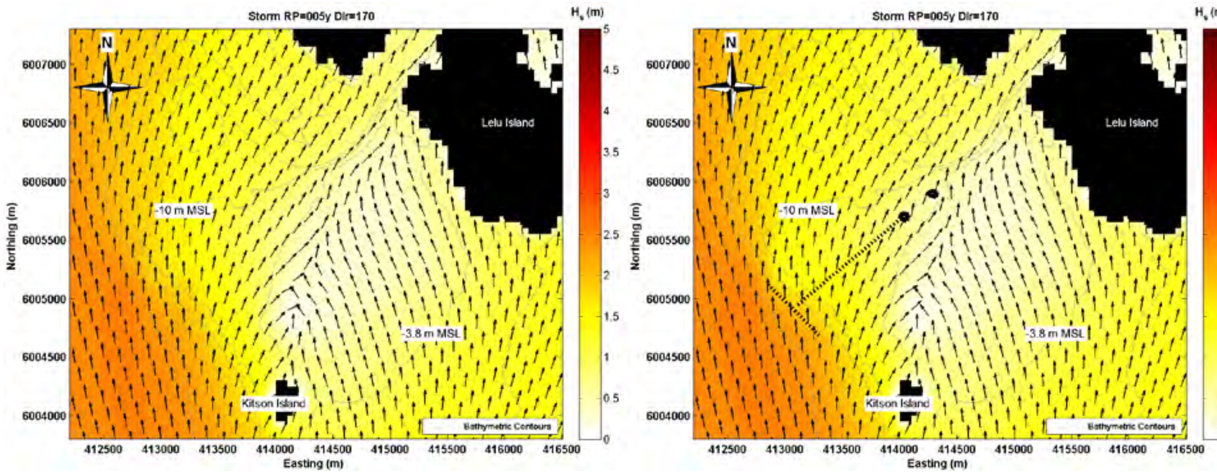


Figure H–5: Significant wave height at the peak of the 5-year storm from 170° True North for existing (left) and proposed (right) conditions.

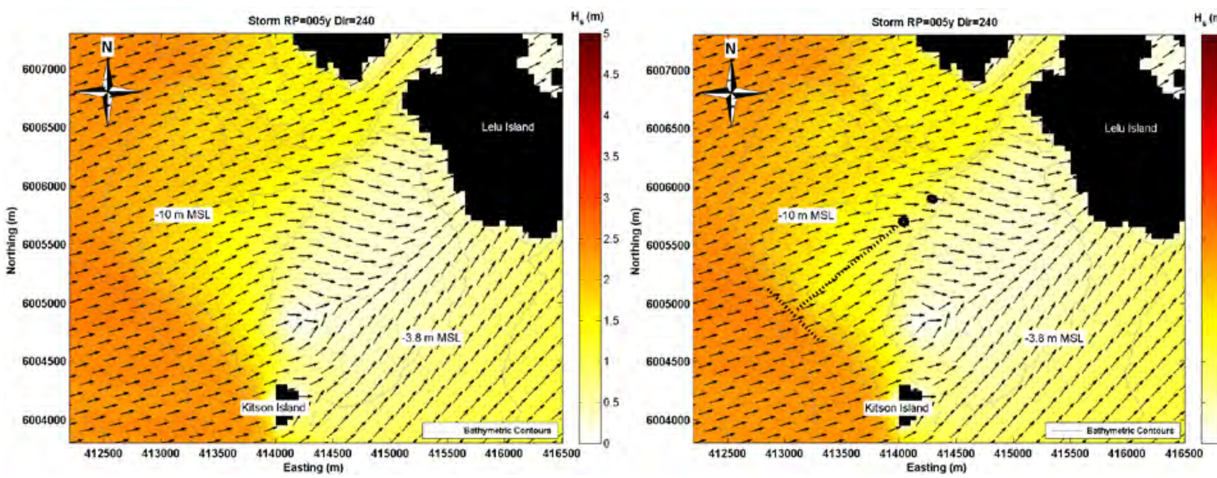


Figure H–6: Significant wave height at the peak of the 5-year storm from 240° True North for existing (left) and proposed (right) conditions.

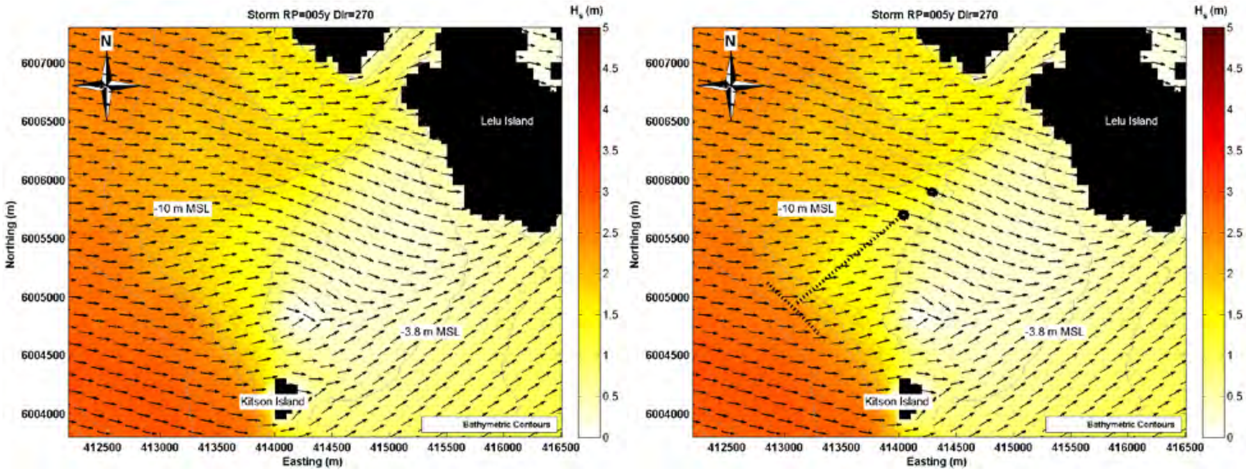


Figure H–7: Significant wave height at the peak of the 5-year storm from 270° True North for existing (left) and proposed (right) conditions.

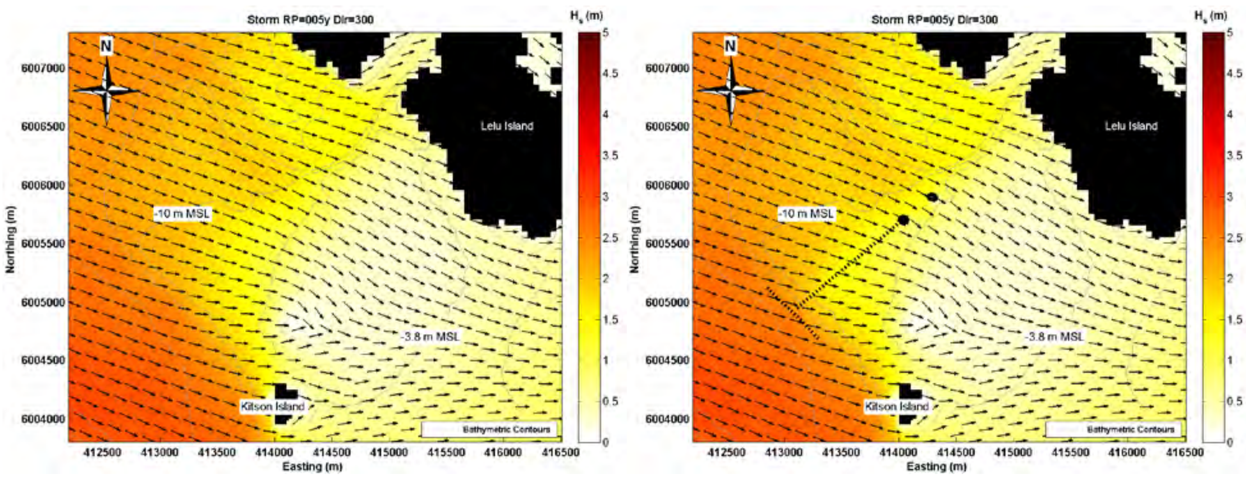


Figure H–8: Significant wave height at the peak of the 5-year storm from 300° True North for existing (left) and proposed (right) conditions.

H1.1.1.3 20-Year Return Period Storms

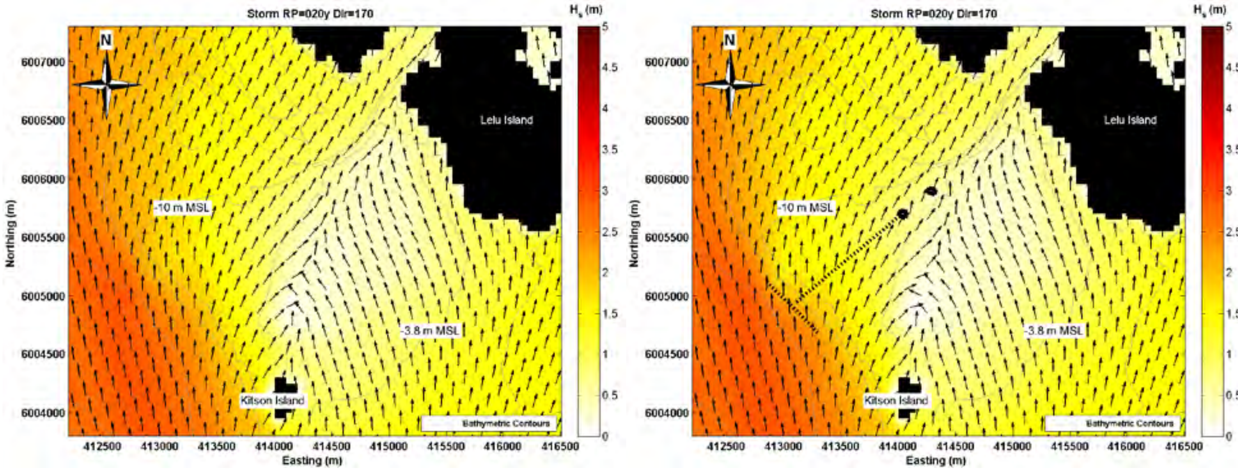


Figure H–9: Significant wave height at the peak of the 20-year storm from 170° True North for existing (left) and proposed (right) conditions.

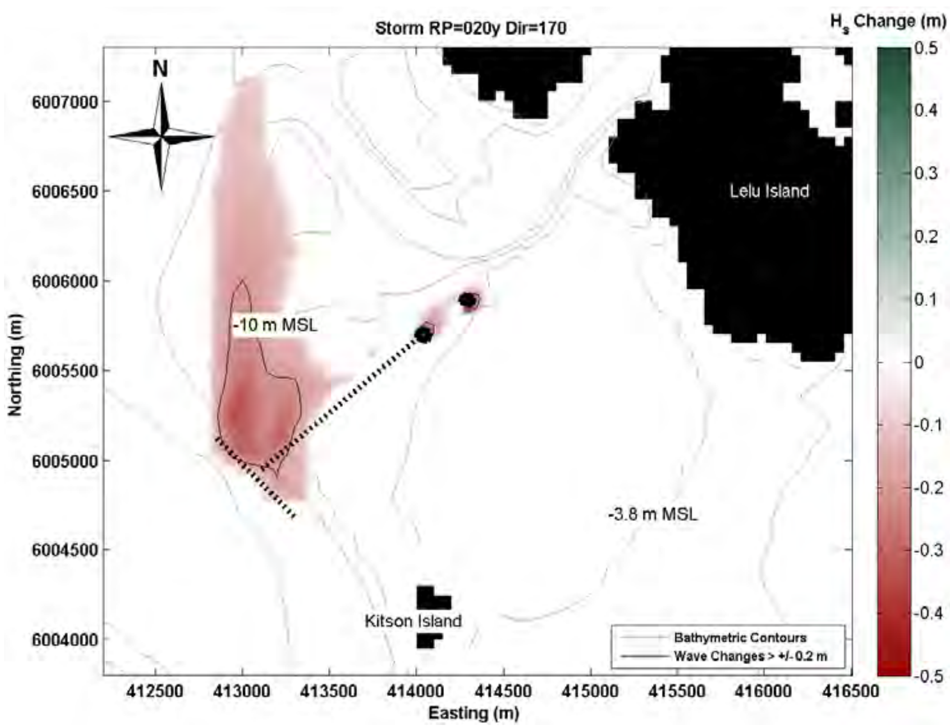


Figure H–10: Difference between significant wave height at the peak of the 20-year storm from 170° True North.

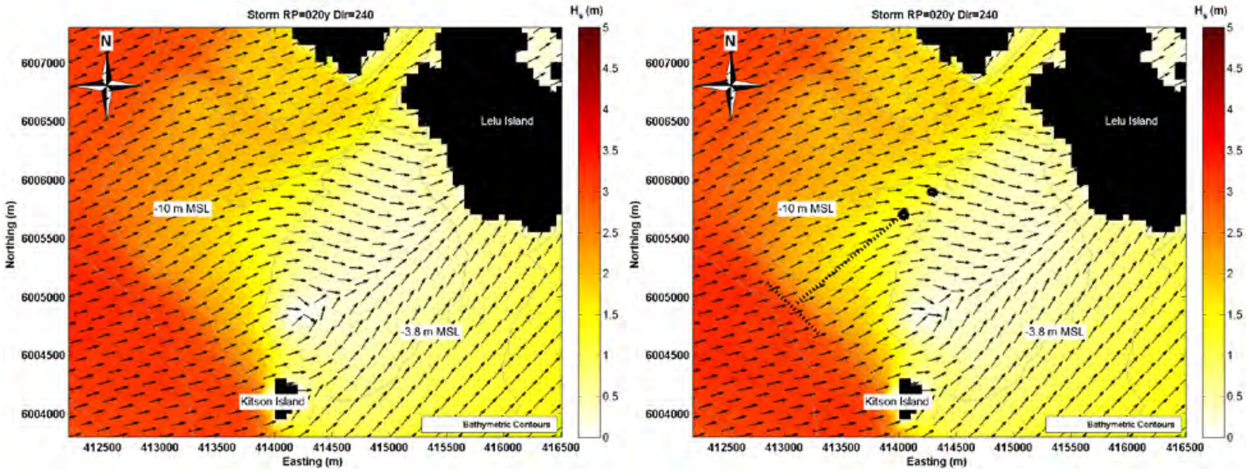


Figure H–11: Significant wave height at the peak of the 20-year storm from 240° True North for existing (left) and proposed (right) conditions.

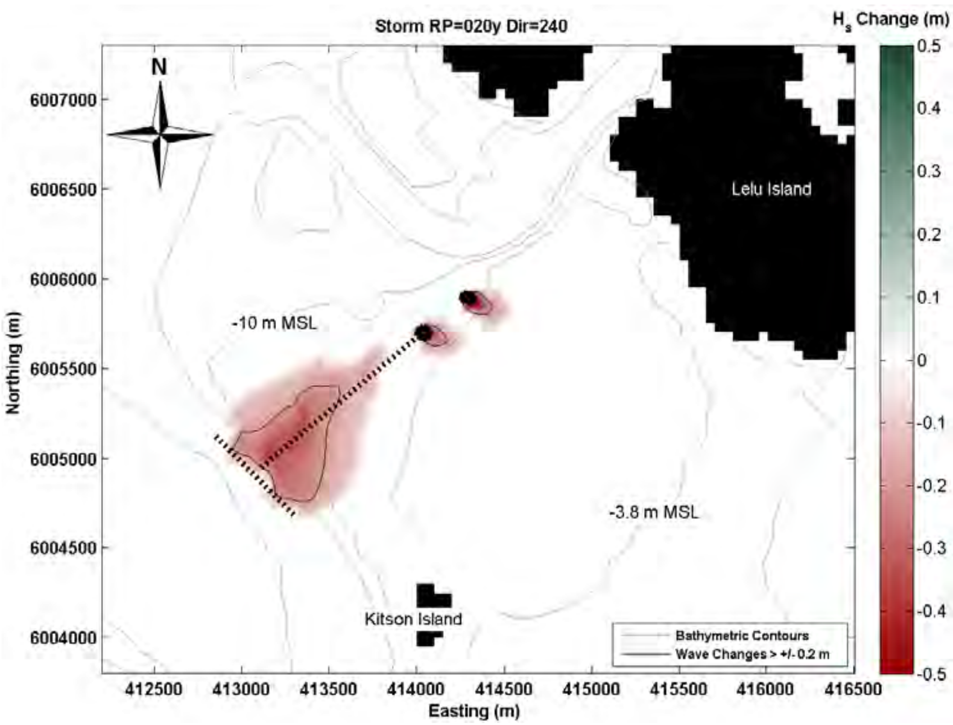


Figure H–12: Difference between significant wave height at the peak of the 20-year storm from 240° True North.

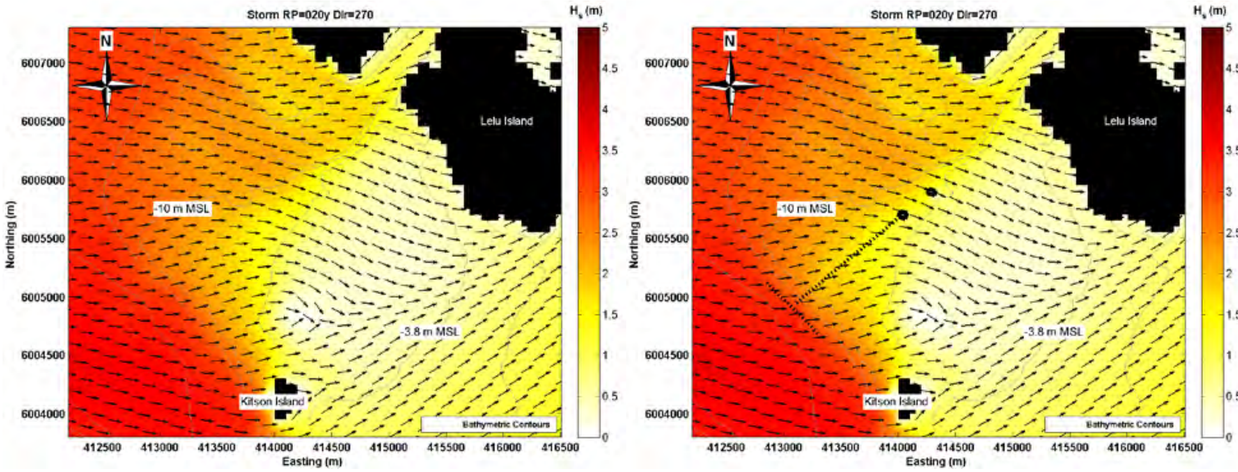


Figure H–13: Significant wave height at the peak of the 20-year storm from 270^o True North for existing (left) and proposed (right) conditions.

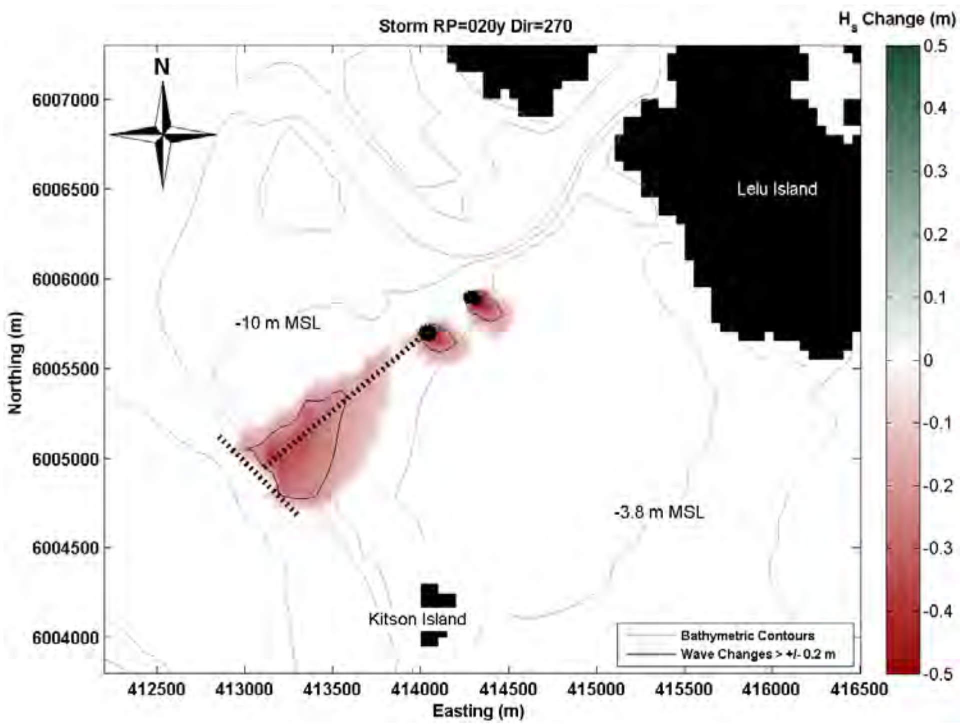


Figure H–14: Difference between significant wave height at the peak of the 20-year from 270^o True North.

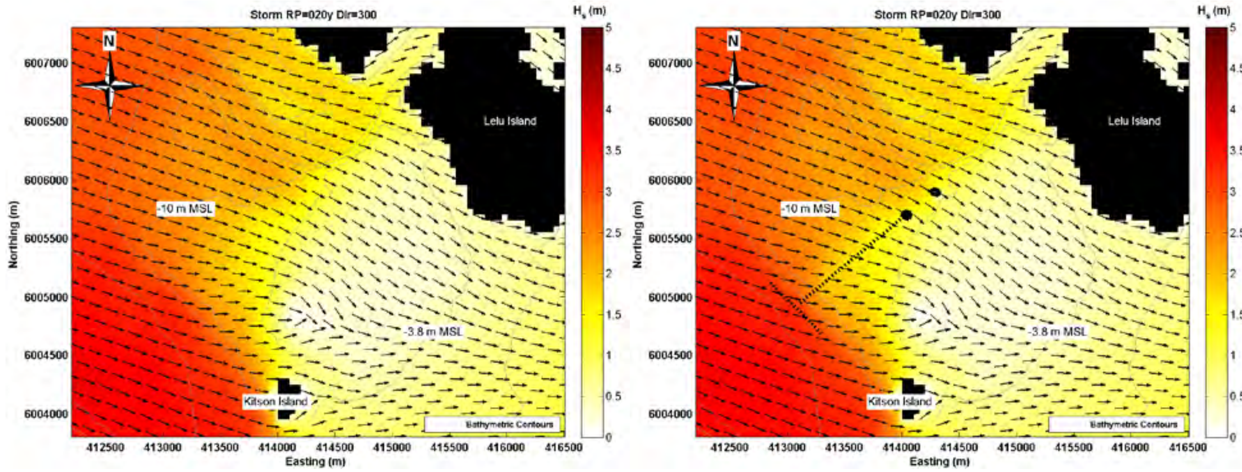


Figure H–15: Significant wave height at the peak of the 20-year storm from 300° True North for existing (left) and proposed (right) conditions.

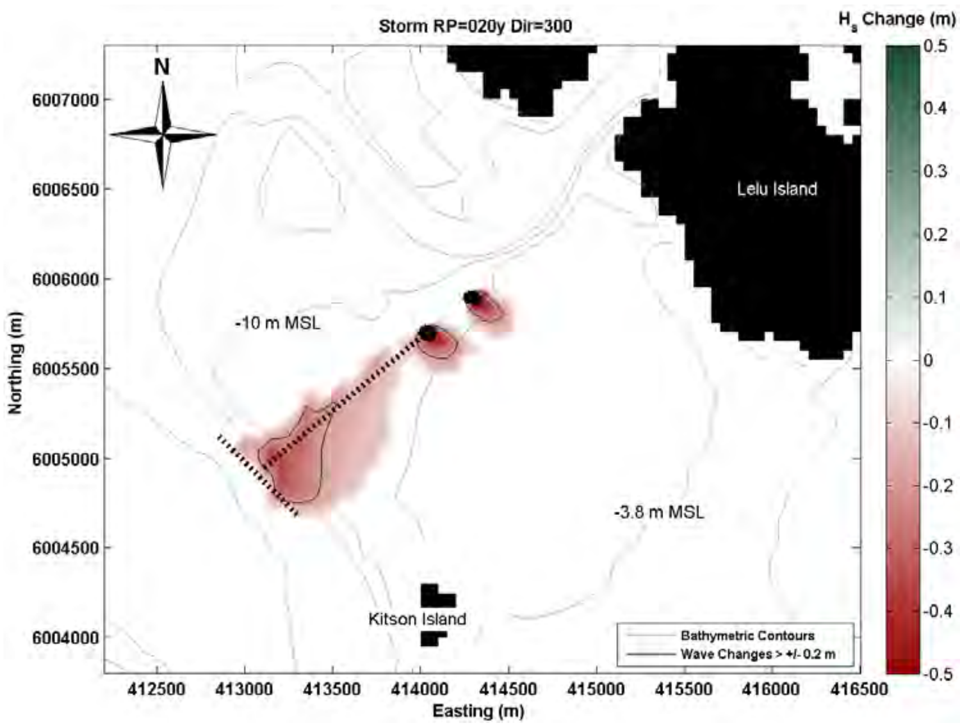


Figure H–16: Difference between significant wave height at the peak of the 20-year storm 300° True North.

H1.1.1.4 50-Year Return Period Storms

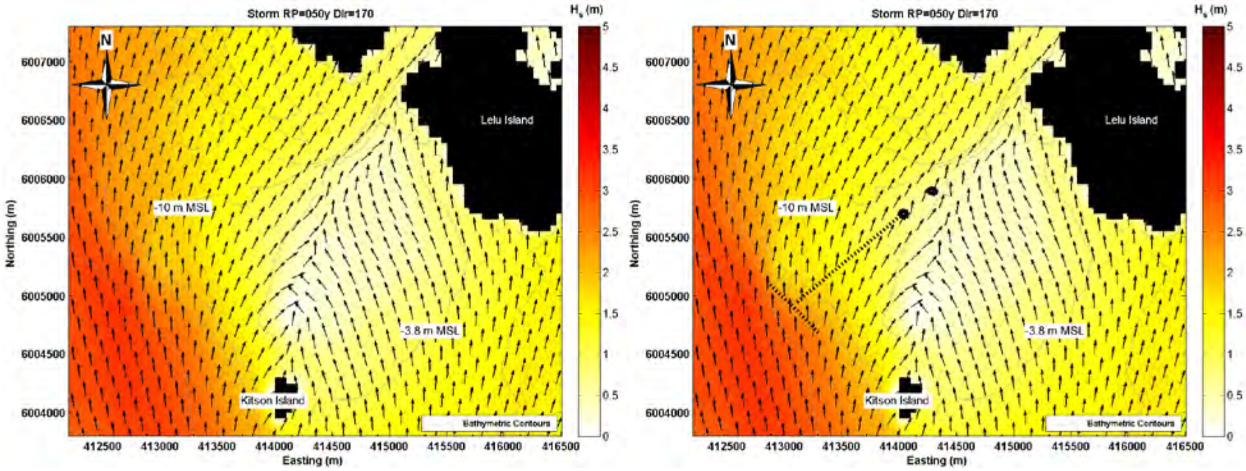


Figure H–17: Significant wave height at the peak of the 50-year storm from 170° True North for existing (left) and proposed (right) conditions.

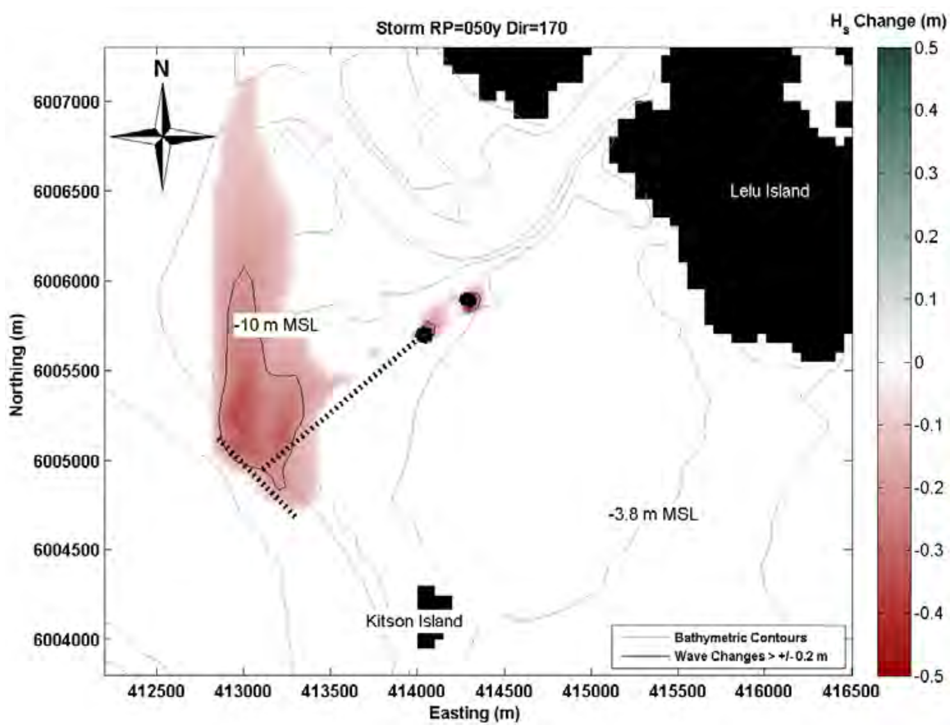


Figure H–18: Difference between significant wave height at the peak of the 50-year from 170° True North.

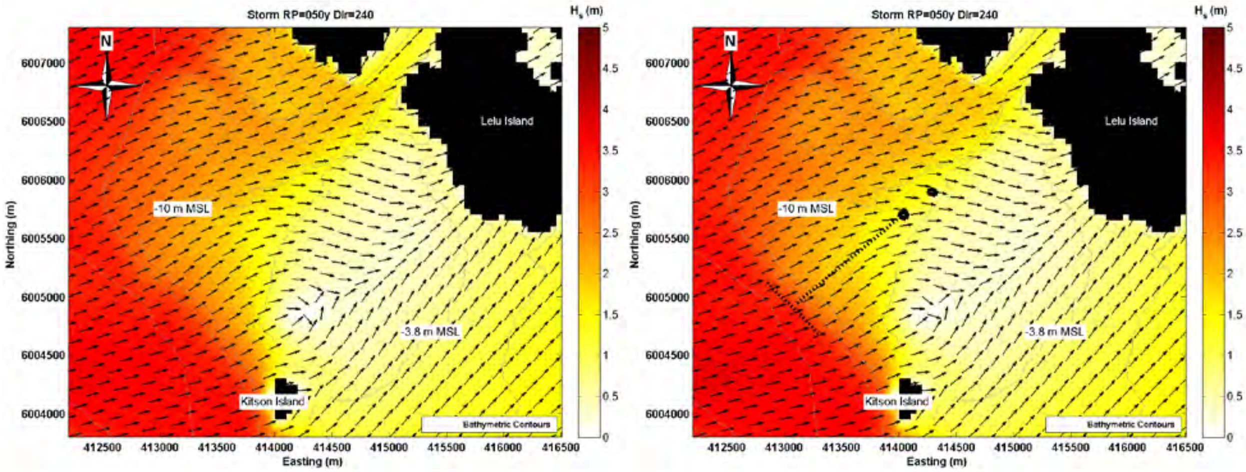


Figure H–19: Significant wave height at the peak of the 50-year storm from 240° True North for existing (left) and proposed (right) conditions.

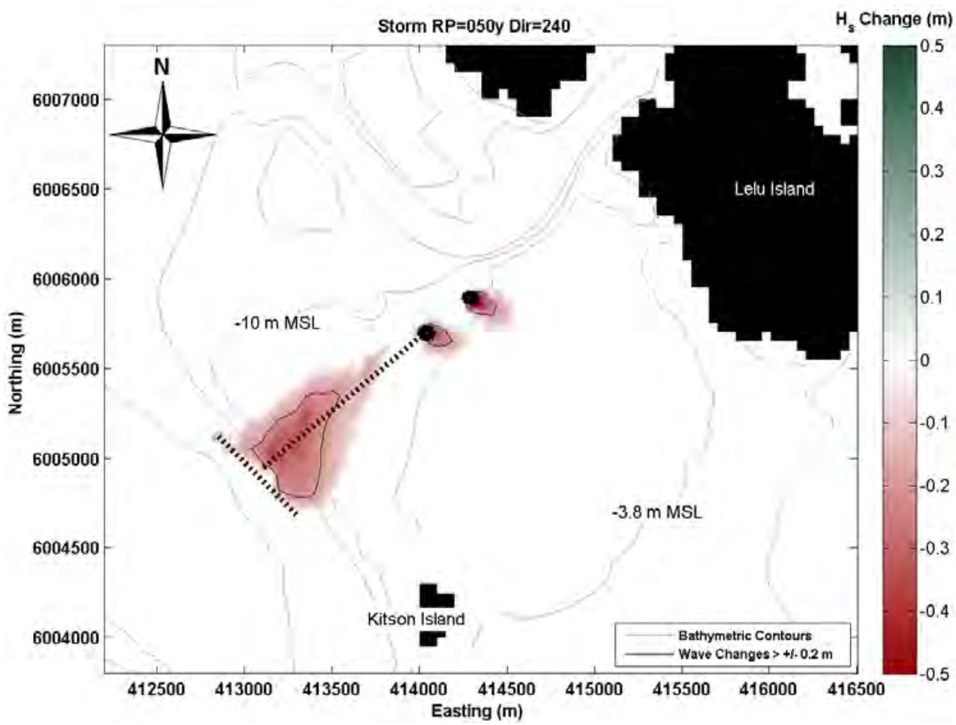


Figure H–20: Difference between significant wave height at the peak of the 50-year from 240° True North.

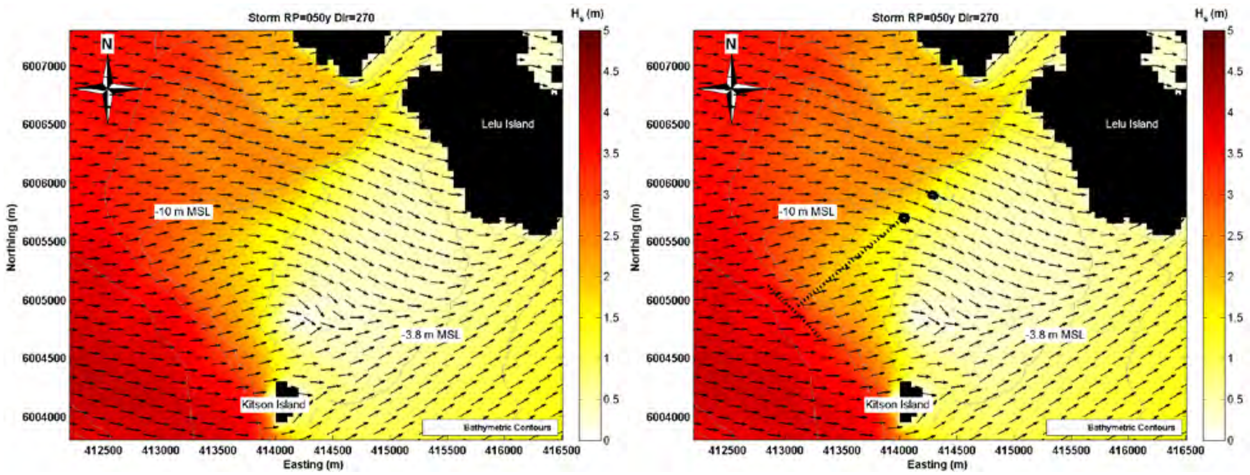


Figure H–21: Significant wave height at the peak of the 50-year storm from 270° True North for existing (left) and proposed (right) conditions.

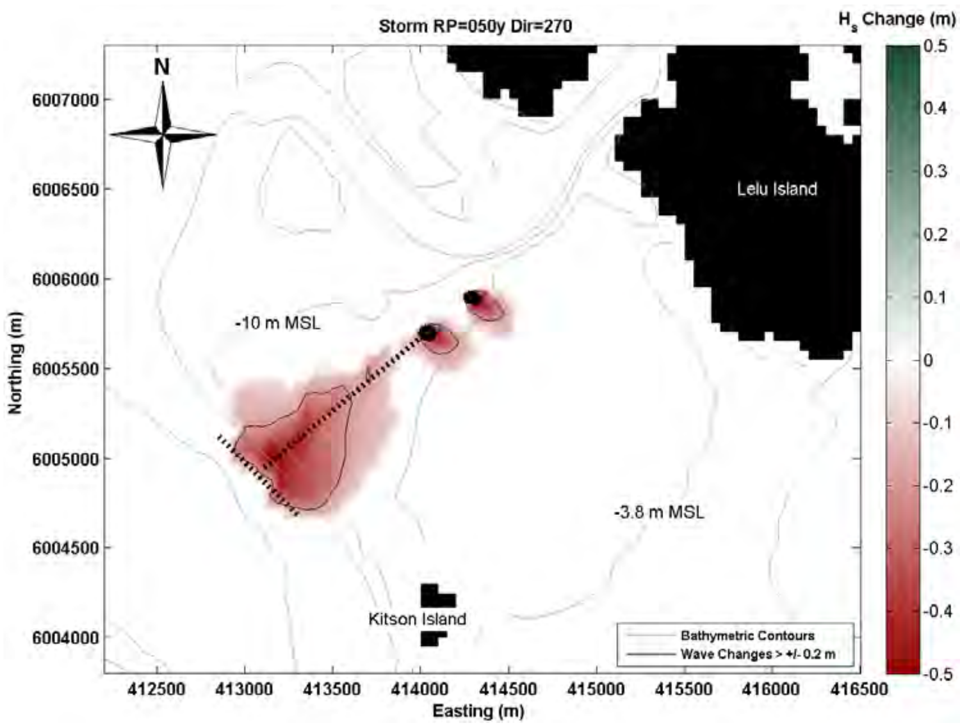


Figure H–22: Difference between significant wave height at the peak of the 50-year storm from 270° True North.

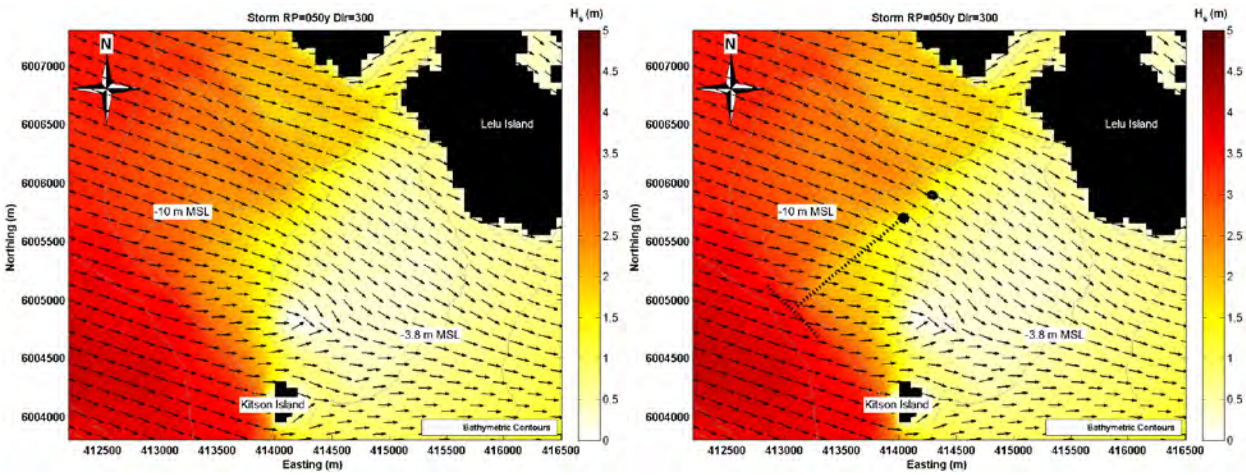


Figure H–23: Significant wave height at the peak of the 50-year storm from 300° True North for existing (left) and proposed (right) conditions.

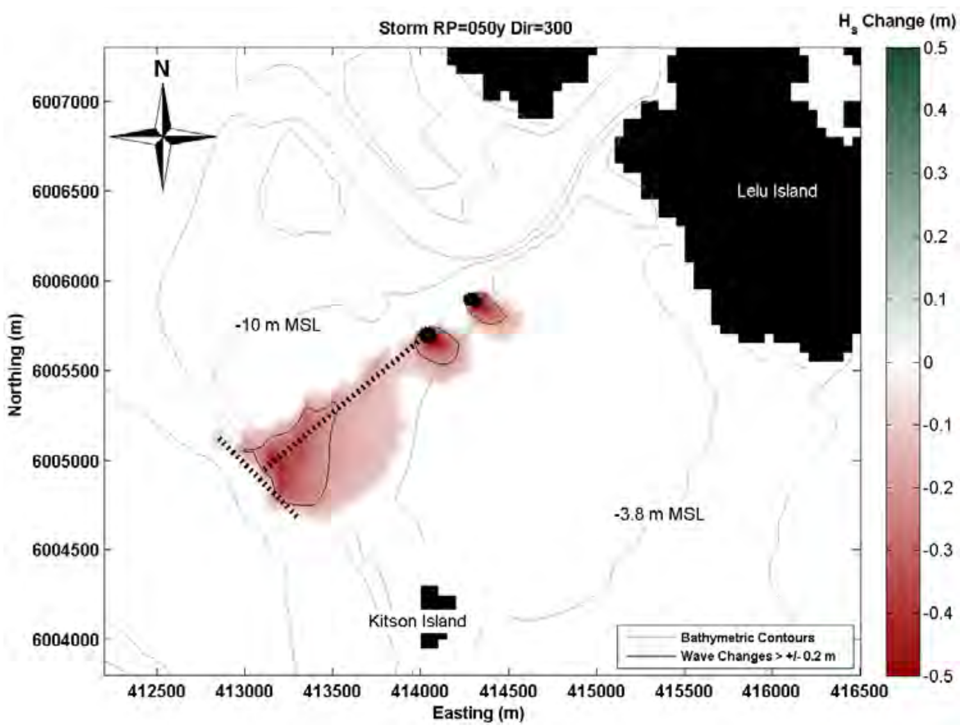


Figure H–24: Difference between significant wave height at the peak of the 50-year from 300° True North.

H1.1.1.5 100-Year Return Period Storms

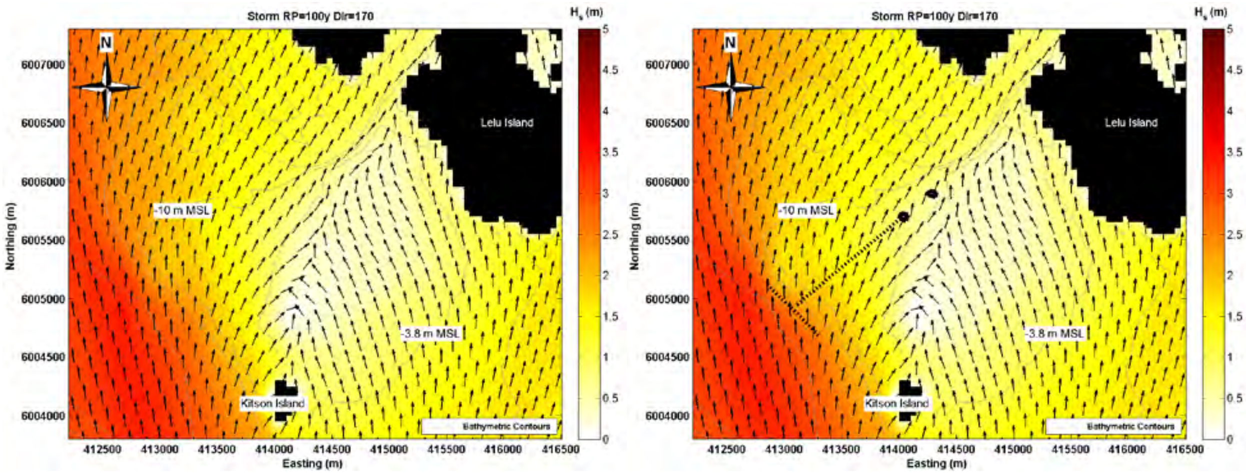


Figure H–25: Significant wave height at the peak of the 100-year storm from 170^{o} True North for existing (left) and proposed (right) conditions.

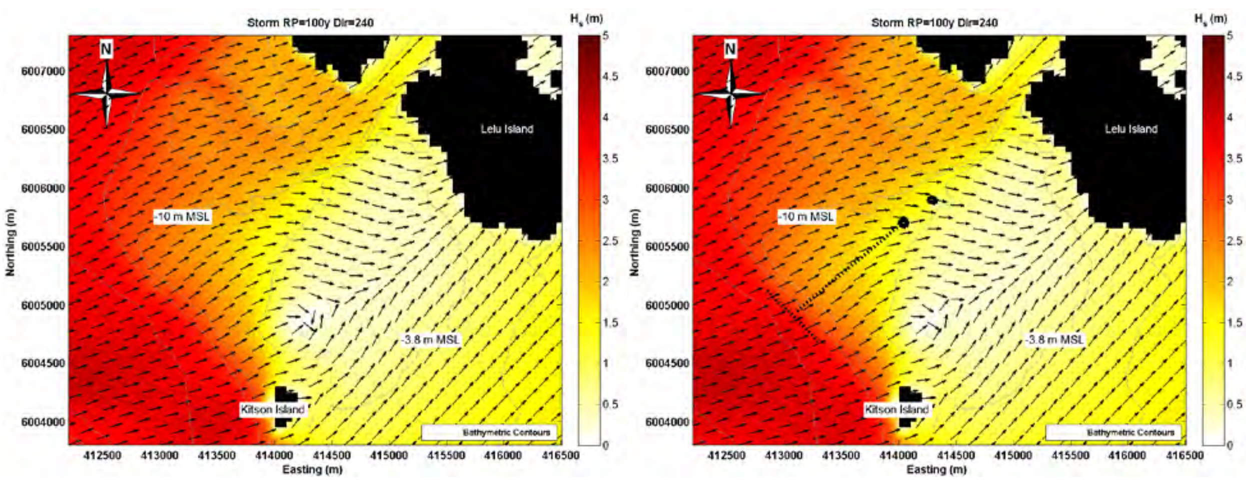


Figure H–26: Significant wave height at the peak of the 100-year storm from 240^{o} True North for existing (left) and proposed (right) conditions.

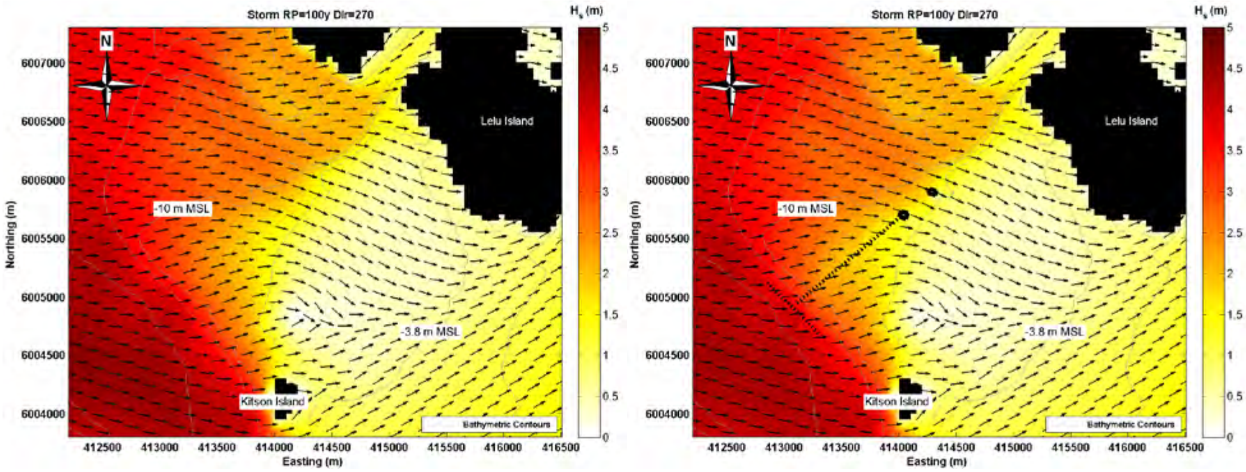


Figure H–27: Significant wave height at the peak of the 100-year storm from 270^{o} True North for existing (left) and proposed (right) conditions.

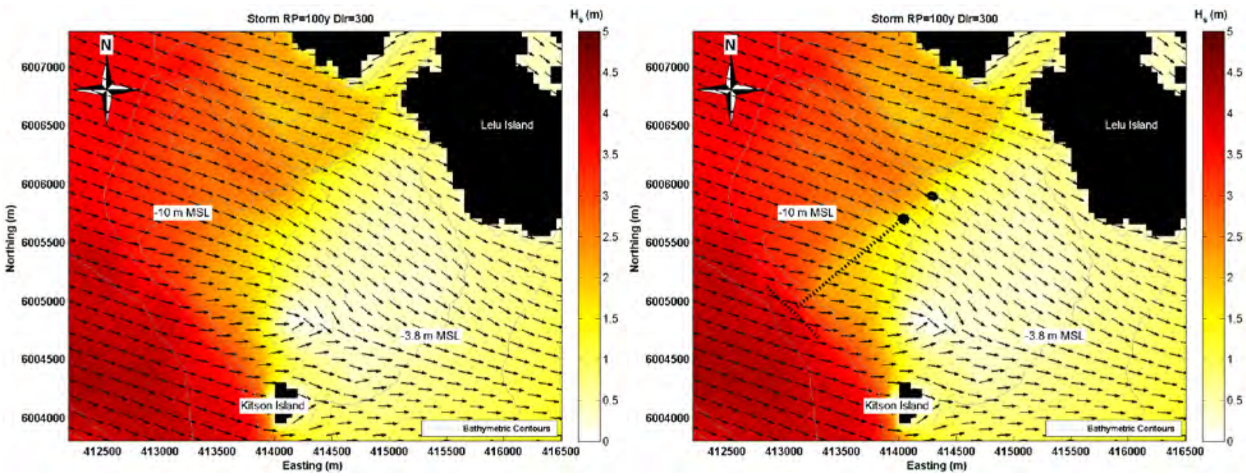


Figure H–28: Significant wave height at the peak of the 100-year storm from 300^{o} True North for existing (left) and proposed (right) conditions.

H1.1.2 Morphology

The following figures and tables display the morphological changes during the storm simulation for the various directions and return periods for both the existing and proposed conditions.

The morphological volumetric changes are determined using the morphology results from Delft3D and calculated using AutoCAD Civil3D 2014 (Civil3D). The following method was used to compute the volumetric changes over Flora Bank:

1. The seabed elevations were extracted from the Delft3D simulation of interest at the start of the simulation (time zero) and at the time of interest (usually simulation end).

Safety • Quality • Sustainability • Innovation

2. The seabed elevations were imported into Civil3D as a set of XYZ data points. The data points were then used to create two TIN surfaces: the base surface and the comparison surface. The base surface is the one created using the data from time zero.
3. Long, large and unrealistic triangulation within the network were removed. Any triangulation networks spanning over a known landmass were removed from the TIN surfaces. This was accomplished by defining polyline outlines of the landmasses as hide boundaries which removed these spaces from all volume and area calculations.
4. The comparison surface was subtracted from base surface to create a TIN surface volume bounded by both surfaces. The surface volume was also given an outer boundary defined by the -3.8 m MSL contour line. The volume surface displays the morphological changes.
5. The surface volume properties were set to compute the volumetric change and the corresponding footprint area of that volumetric change. These calculations were made between horizontal boundaries at intervals of 0.05 m of elevation change (from 0.00 m) and output as a table of values. Note that the sum of all areas is 3,247,120 m^2.
6. A colour gradient was also applied to these elevation changes to provide a pictorial representation of the changes.
7. The tabulated volumetric changes and corresponding footprint areas were extracted from Civil3D into Microsoft Excel 2010. The volumes and areas were summed into erosional and depositional volume and areas.
8. The summed volumes were divided by the area of Flora Bank, 3,247,120 m^2, to produce a net average elevation change.

H1.1.2.1 1-Year Return Period Storms

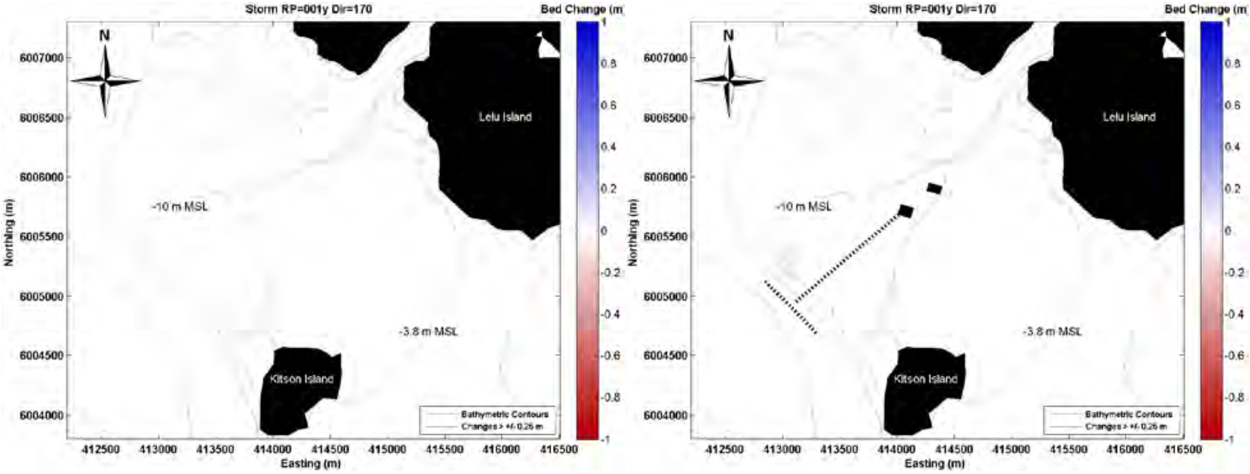


Figure H–29: Morphological changes during 1-year storm from 170^{o} True North for existing (left) and proposed (right) conditions.

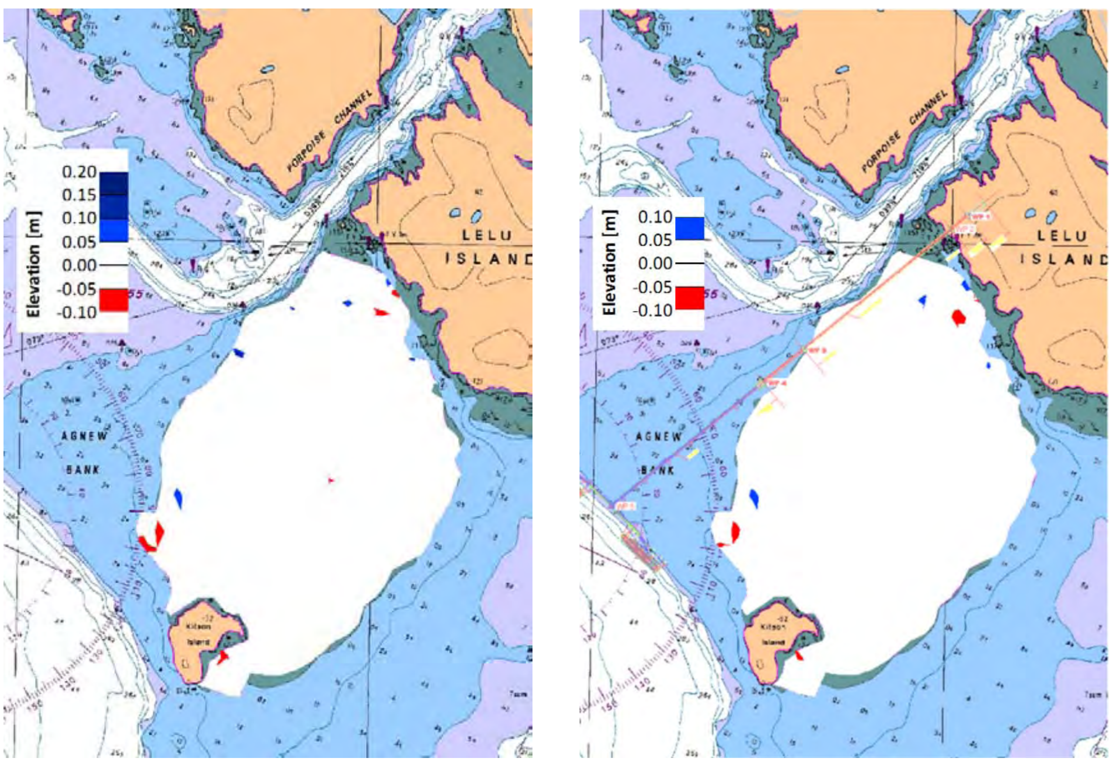


Figure H–30: Morphological changes on Flora Bank during 1-year storm from 170^{o} True North for existing (left) and proposed (right) conditions.

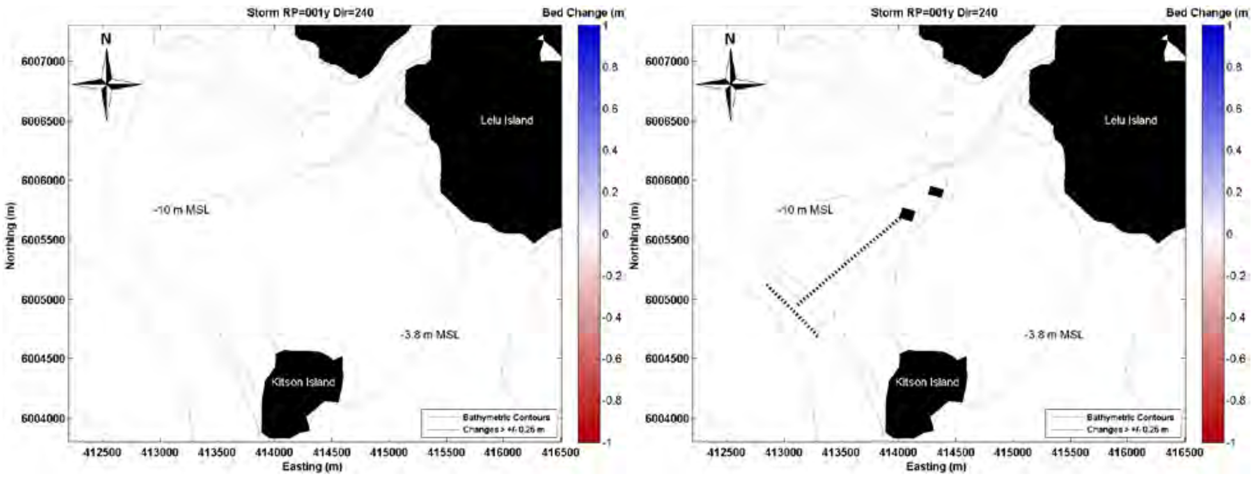


Figure H–31: Morphological changes during 1-year storm from 240° True North for existing (left) and proposed (right) conditions.

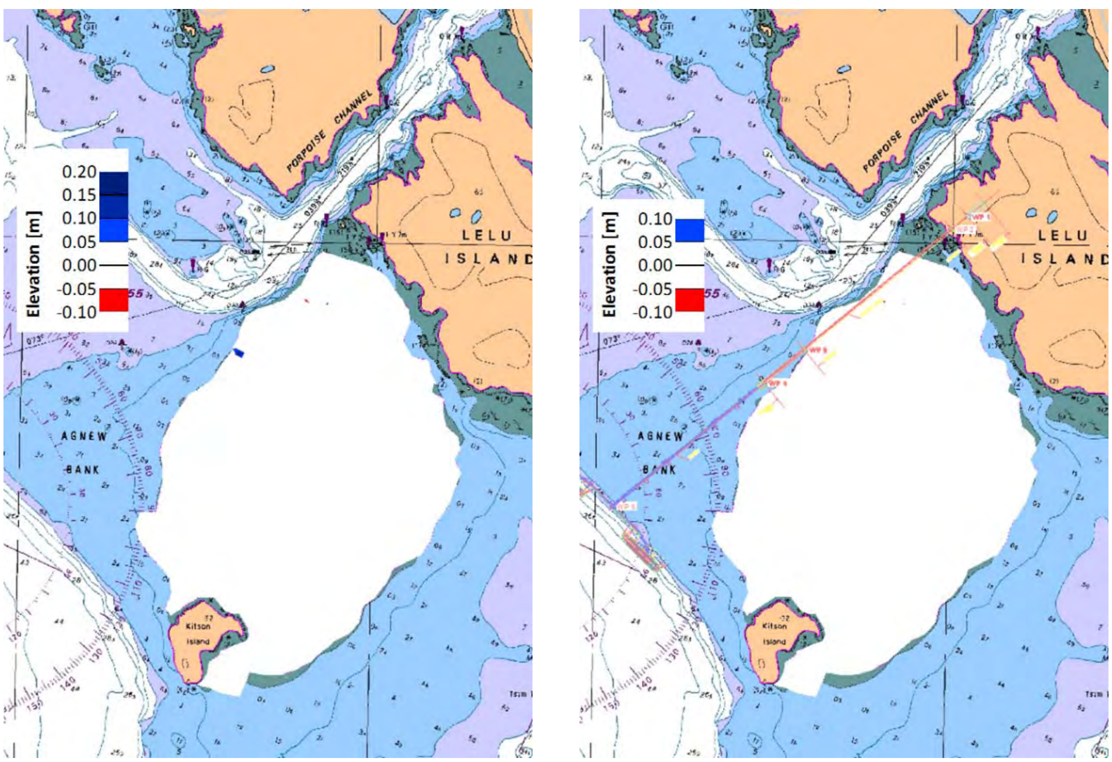


Figure H–32: Morphological changes on Flora Bank during 1-year storm from 240° True North for existing (left) and proposed (right) conditions.

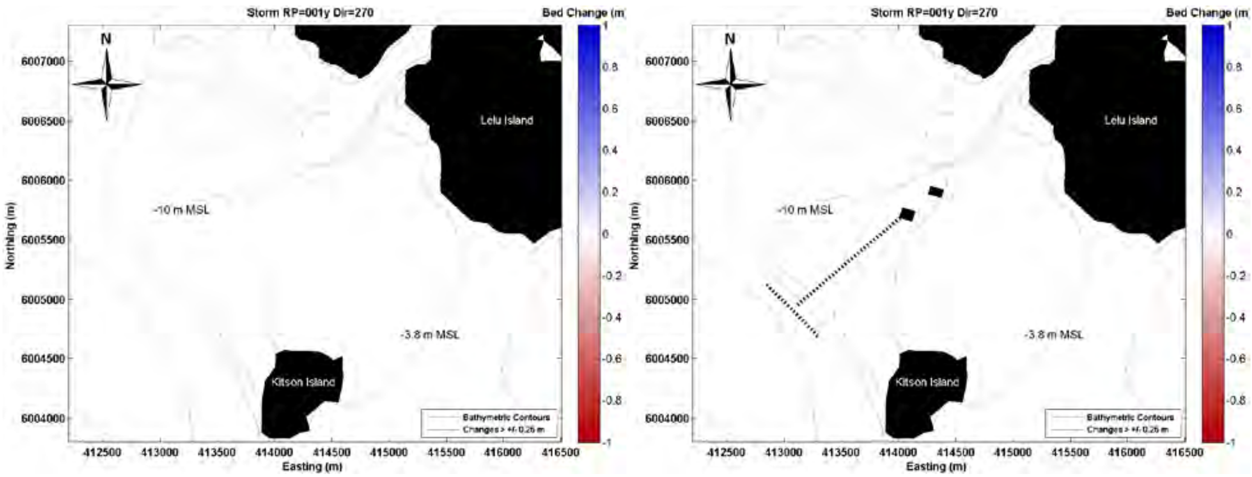


Figure H–33: Morphological changes during 1-year storm from 270° True North without marine structures (left) and with marine structures (right).

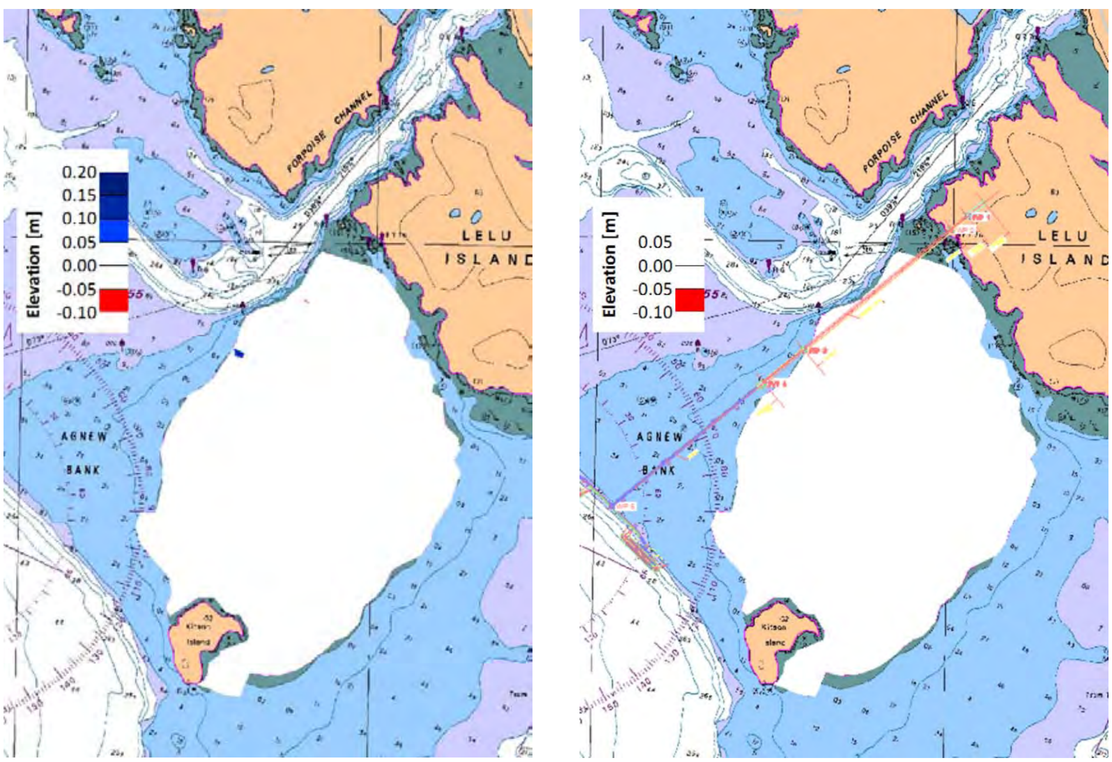


Figure H–34: Morphological changes on Flora Bank during 1-year storm from 270° True North for existing (left) and proposed (right) conditions.

Safety • Quality • Sustainability • Innovation

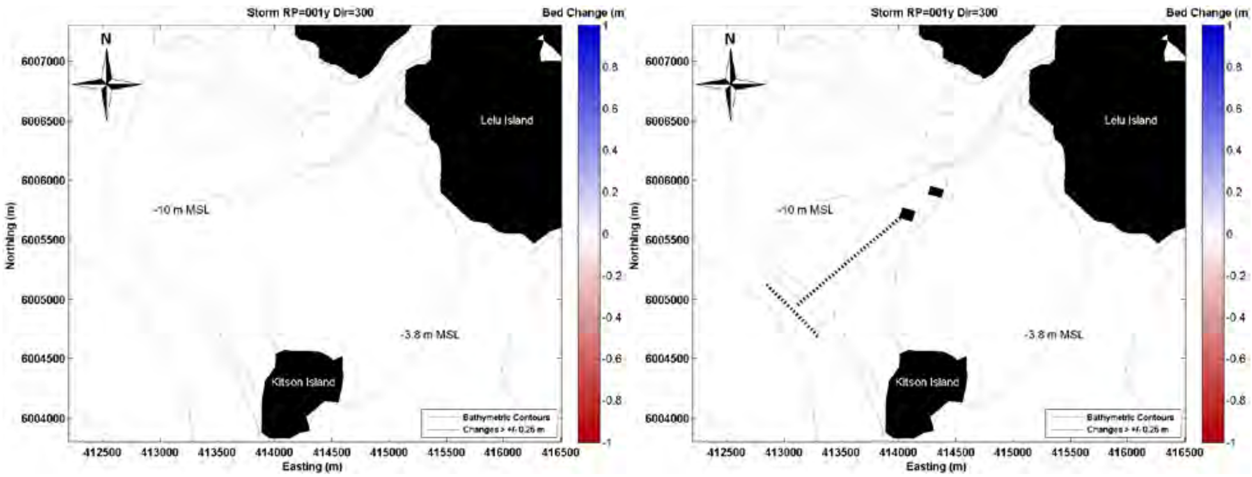


Figure H–35: Morphological changes during 1-year storm from 300^o True North for existing (left) and proposed (right) conditions.

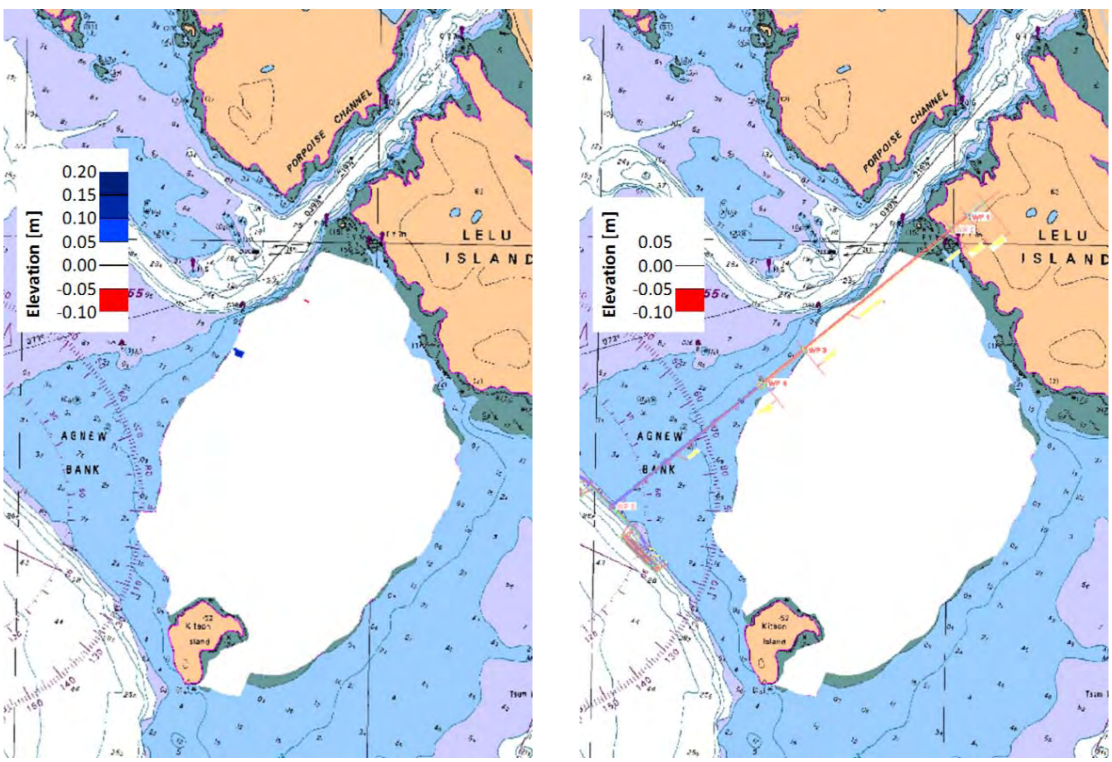


Figure H–36: Morphological changes on Flora Bank during 1-year storm from 300^o True North for existing (left) and proposed (right) conditions.

Safety ● Quality ● Sustainability ● Innovation

Table H-1: Volumetric and area changes over Flora Bank during the 1-year Storm (170°, 240°, 270° and 300° True North)

Extreme Event Incoming Direction [°N]	Presence of Marine Structures	Erosion Volume [m³]	Deposition Volume [m³]	Net Volume [m³]	Erosion Area [m²]	Deposition Area [m²]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
170	**Without**	-20,940	15,400	-5,540	19,140	6,620	-0.01	0.00	-0.01
	With	-20,490	14,770	-5,720	13,970	5,370	-0.01	0.00	-0.01
240	**Without**	-4,590	3,560	-1,030	390	1,860	0.00	0.00	0.00
	With	-4,280	3,070	-1,210	250	0	0.00	0.00	0.00
270	**Without**	-5,350	4,510	-840	500	1,730	0.00	0.00	0.00
	With	-4,900	3,810	-1,090	290	0	0.00	0.00	0.00
300	**Without**	-5,340	4,440	-900	460	1,760	0.00	0.00	0.00
	With	-4,890	3,770	-1,120	390	0	0.00	0.00	0.00

H1.1.2.2 5-Year Return Period Storms

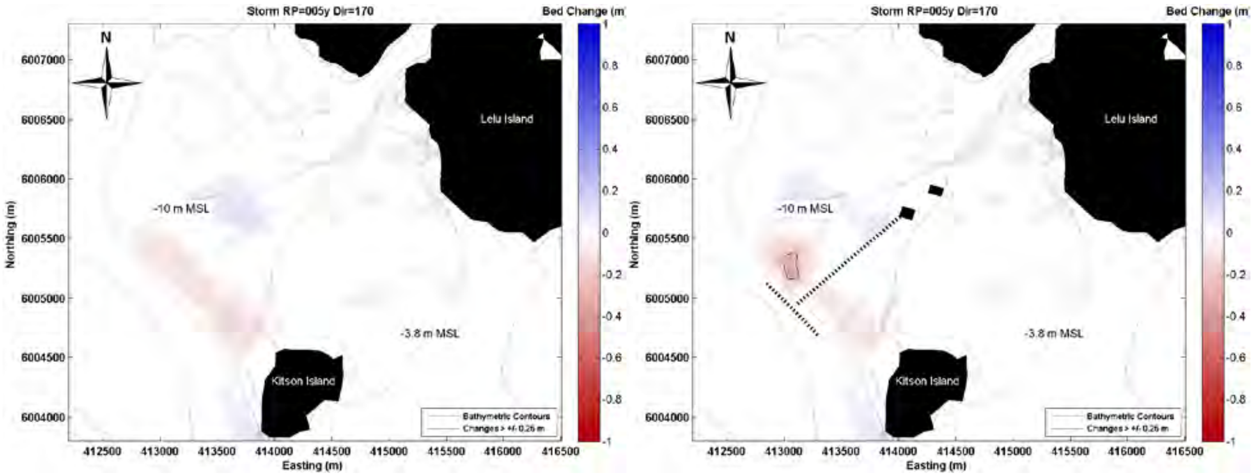


Figure H–37: Morphological changes during 5-year storm from 170° True North for existing (left) and proposed (right) conditions.

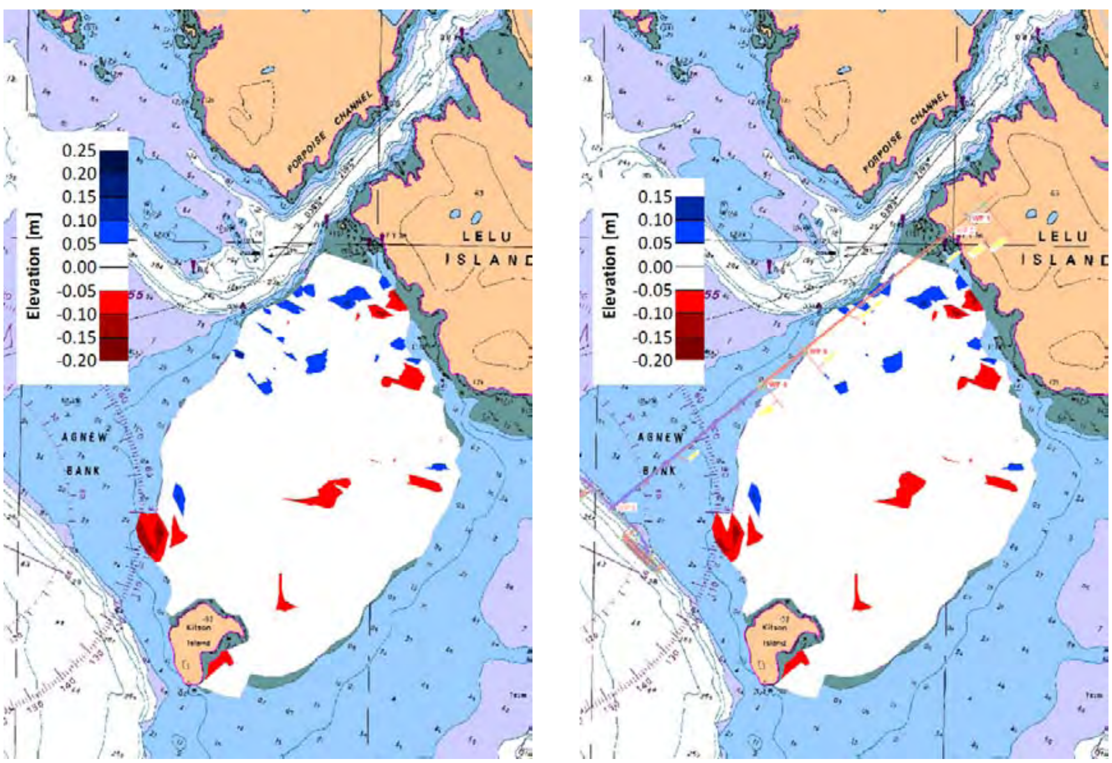


Figure H–38: Morphological changes on Flora Bank during 5-year storm from 170° True North for existing (left) and proposed (right) conditions.

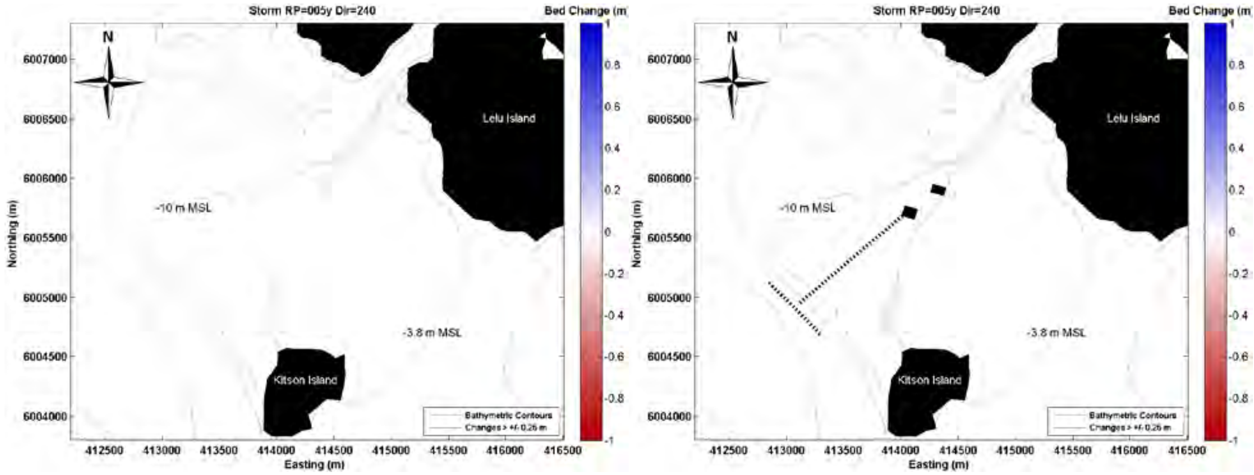


Figure H–39: Morphological changes during 5-year storm from 240° True North for existing (left) and proposed (right) conditions.

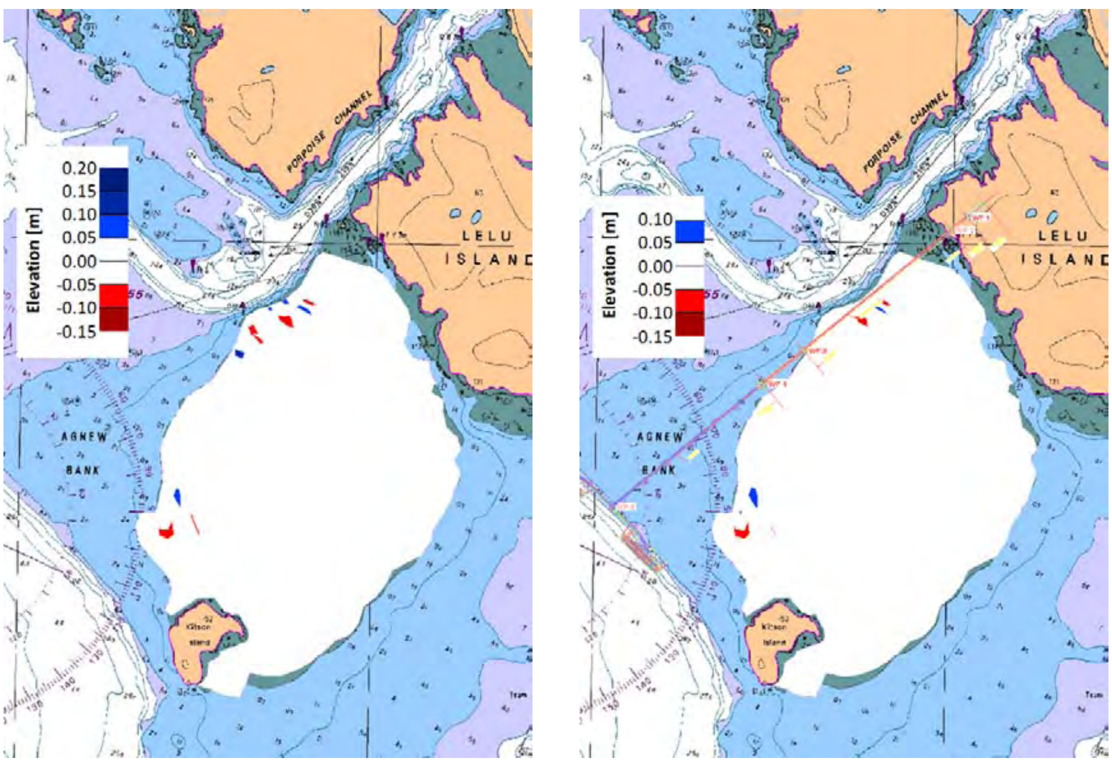


Figure H–40: Morphological changes on Flora Bank during 5-year storm from 240° True North for existing (left) and proposed (right) conditions.

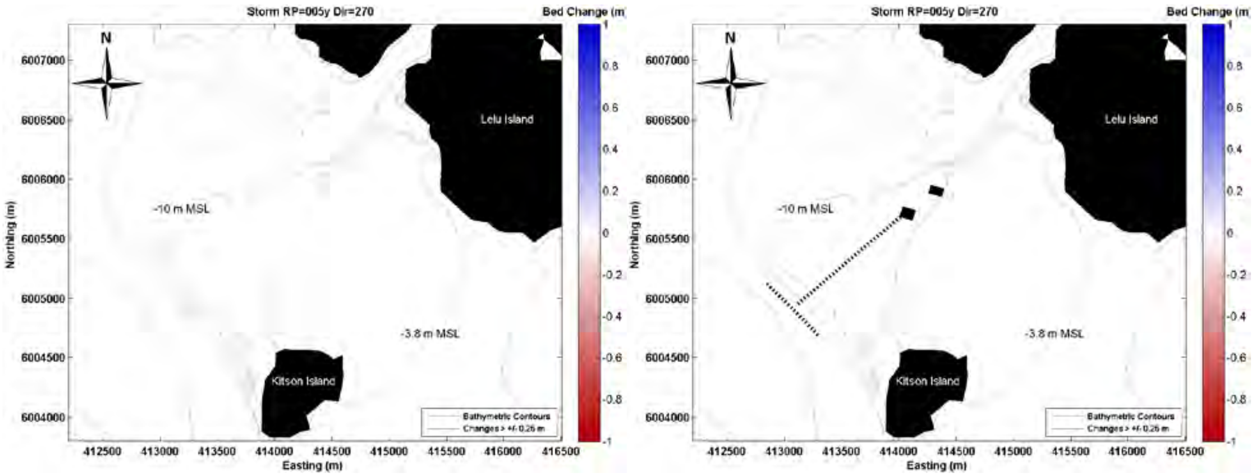


Figure H–41: Morphological changes during 5-year storm from 270° True North for existing (left) and proposed (right) conditions.

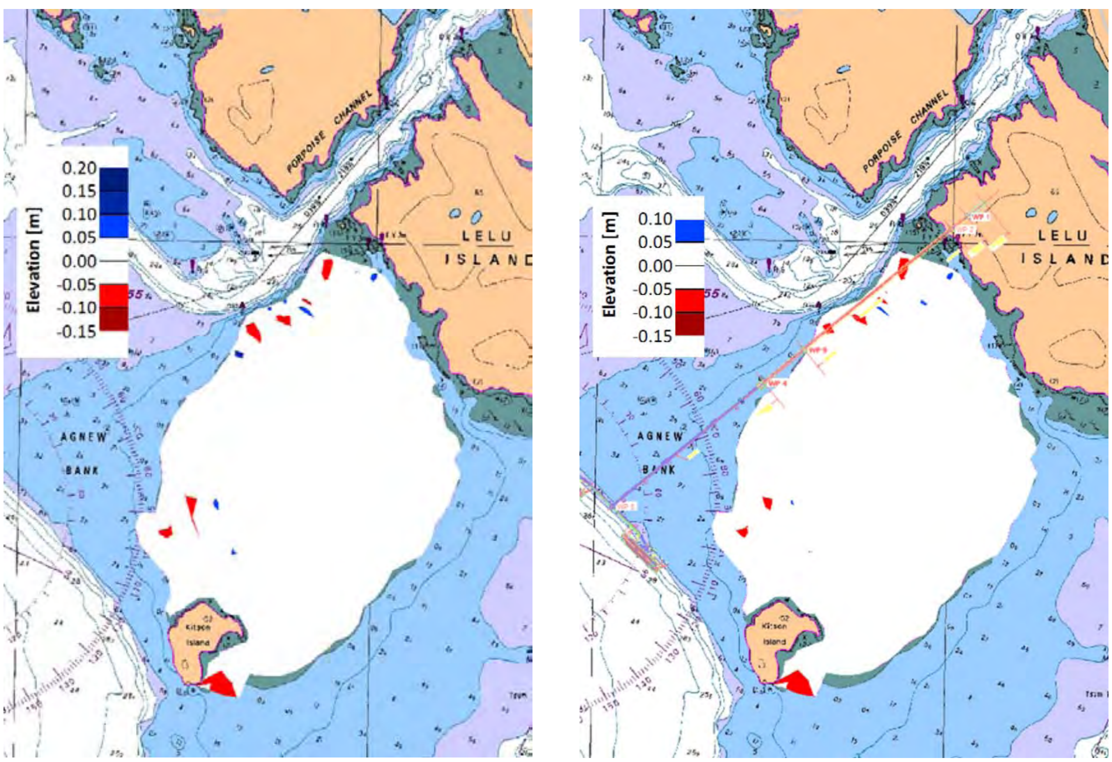


Figure H–42: Morphological changes on Flora Bank during 5-year storm from 270° True North for existing (left) and proposed (right) conditions.

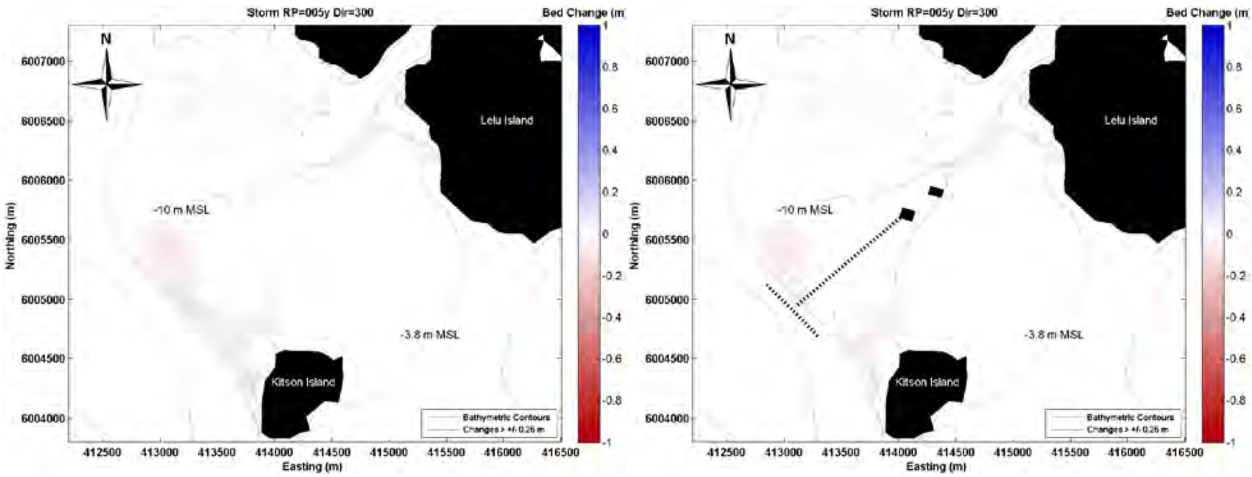


Figure H–43: Morphological changes during 5-year storm from 300° True North for existing (left) and proposed (right) conditions.

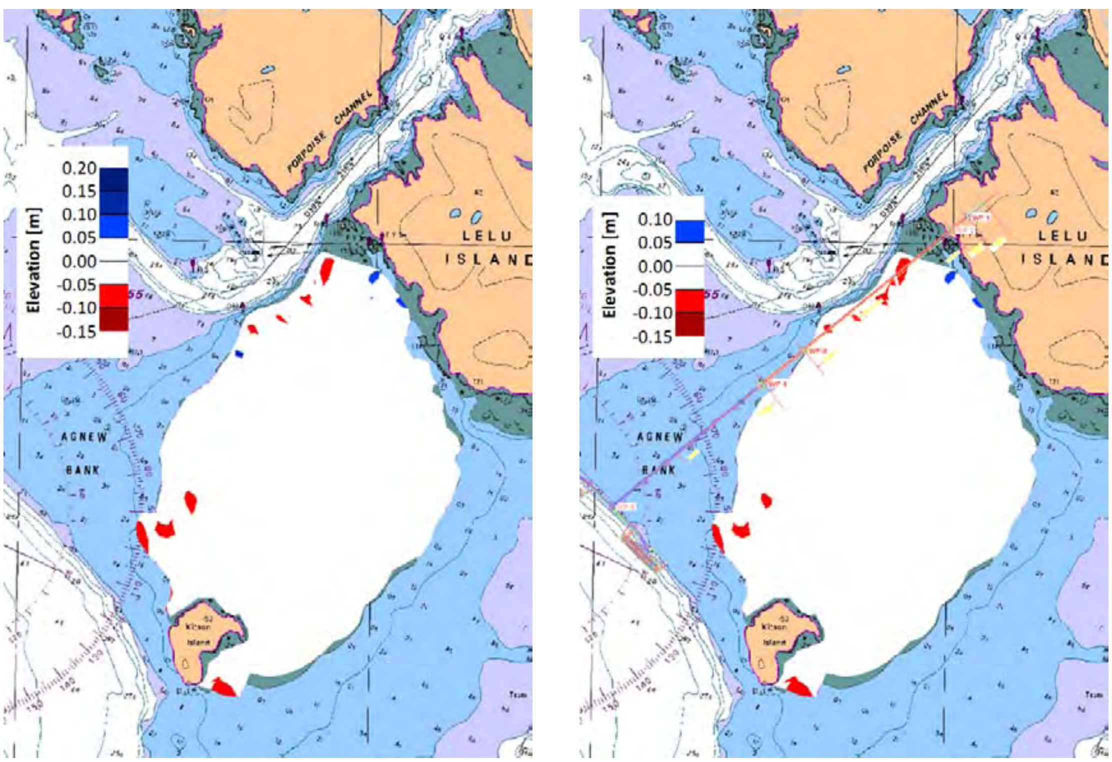


Figure H–44: Morphological changes on Flora Bank during 5-year storm from 300° True North for existing (left) and proposed (right) conditions.

Table H-2: Volumetric and area changes over Flora Bank during 5-year Storm (170^o, 240^o, 270^o and 300^o True North)

Extreme Event Incoming Direction [^{o}N]	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
170	**Without**	-41,170	28,270	-12,900	165,990	74,980	-0.01	0.01	0.00
	With	-39,960	26,790	-13,170	158,810	68,120	-0.01	0.01	0.00
240	**Without**	-11,730	10,880	-850	16,440	5,880	0.00	0.00	0.00
	With	-10,870	9,660	-1,210	10,090	4,130	0.00	0.00	0.00
270	**Without**	-14,610	13,310	-1,300	49,750	5,930	0.00	0.00	0.00
	With	-13,660	12,110	-1,550	41,430	2,060	0.00	0.00	0.00
300	**Without**	-17,090	13,890	-3,200	55,140	5,700	-0.01	0.00	-0.01
	With	-15,850	12,250	-3,600	52,740	4,440	0.00	0.00	0.00

H1.1.2.3 20-Year Return Period Storms

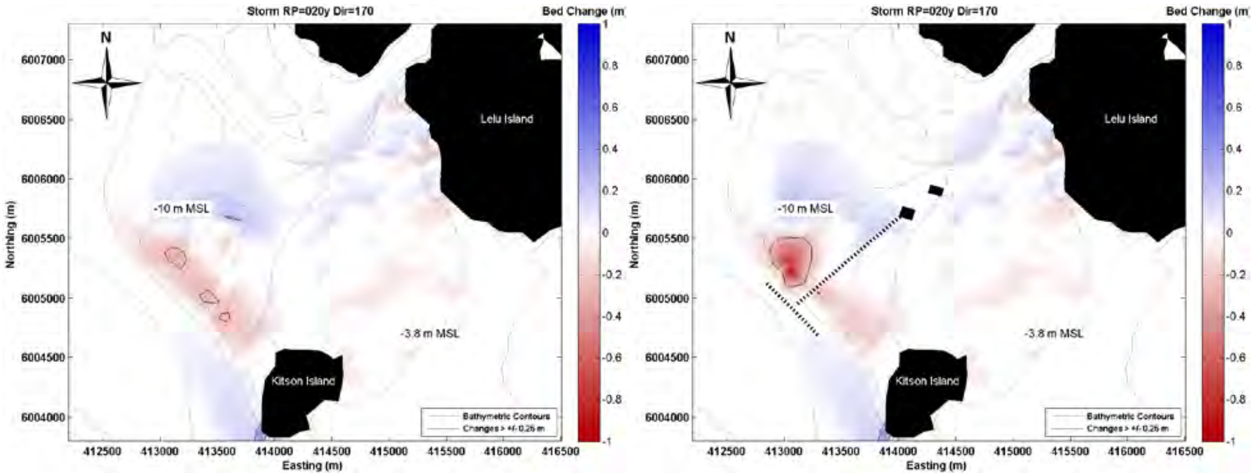


Figure H–45: Morphological changes during 20-year storm from 170° True North for existing (left) and proposed (right) conditions.

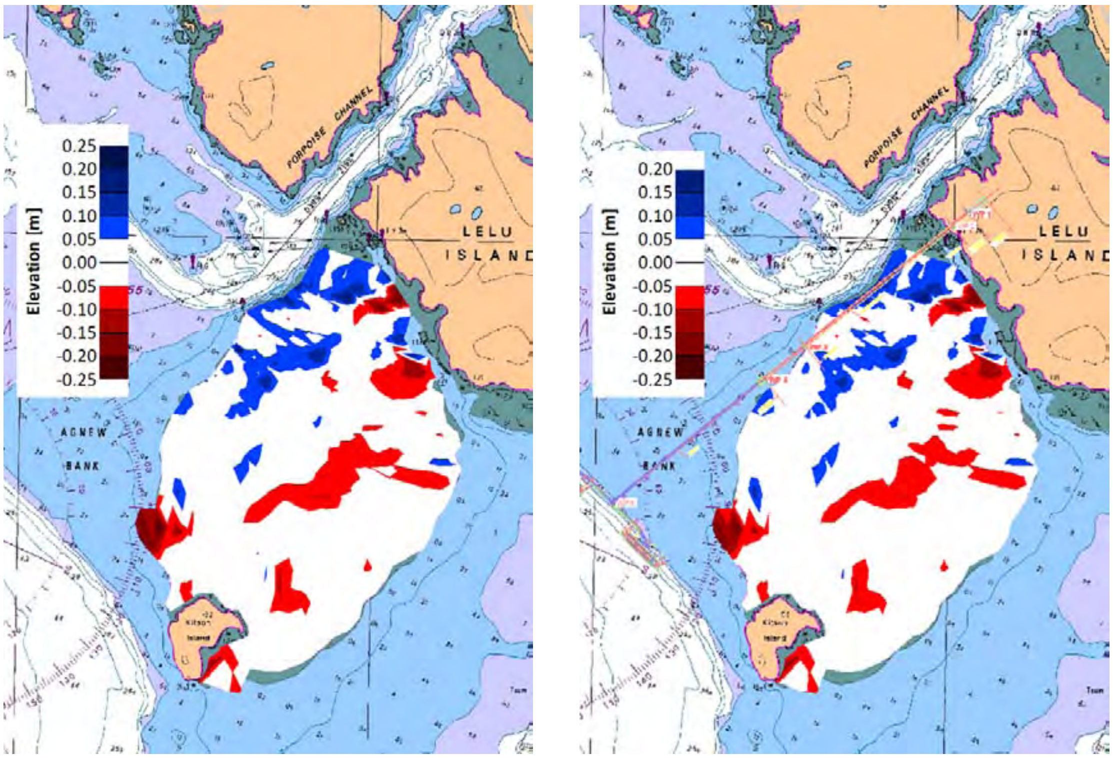


Figure H–46: Morphological changes on Flora Bank during 20-year storm from 170° True North for existing (left) and proposed (right) conditions.

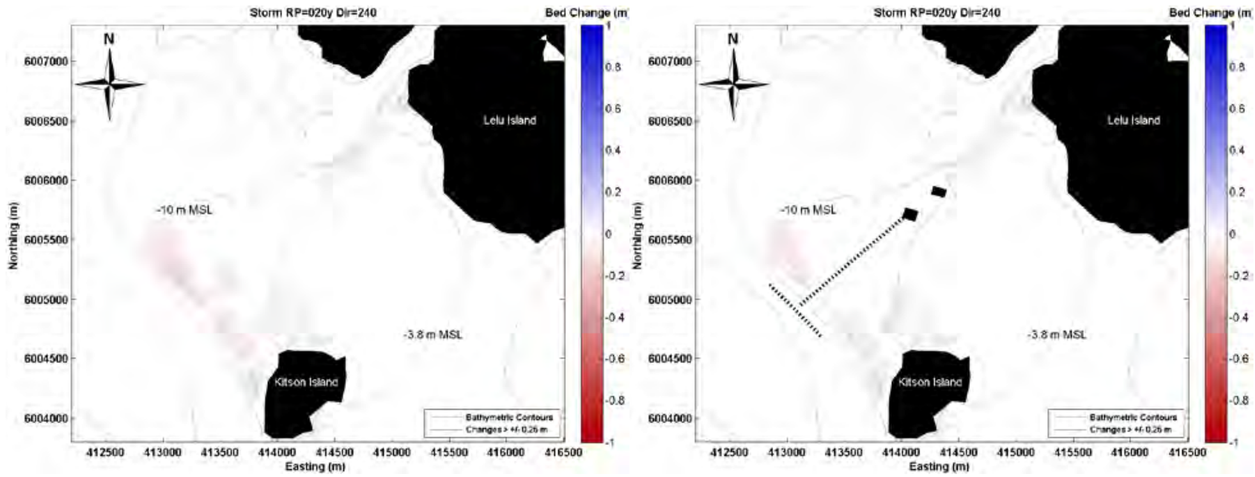


Figure H–47: Morphological changes during 20-year storm from 240° True North for existing (left) and proposed (right) conditions.

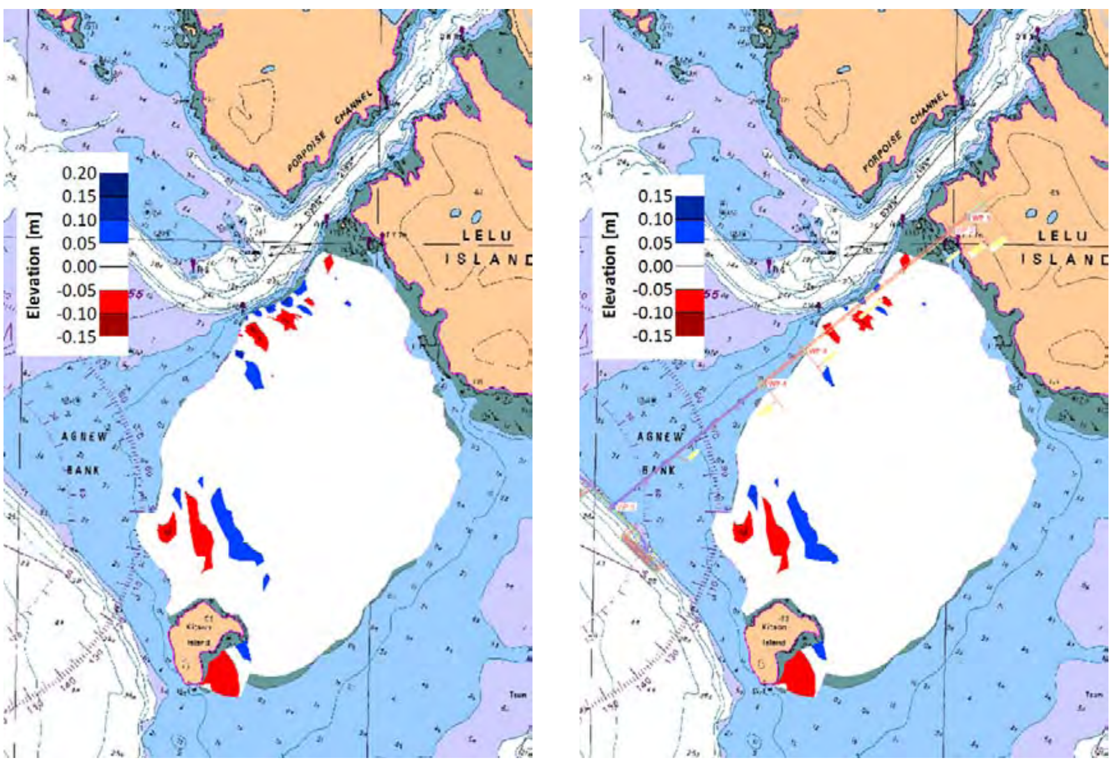


Figure H–48: Morphological changes on Flora Bank during 20-year storm from 240° True North for existing (left) and proposed (right) conditions.

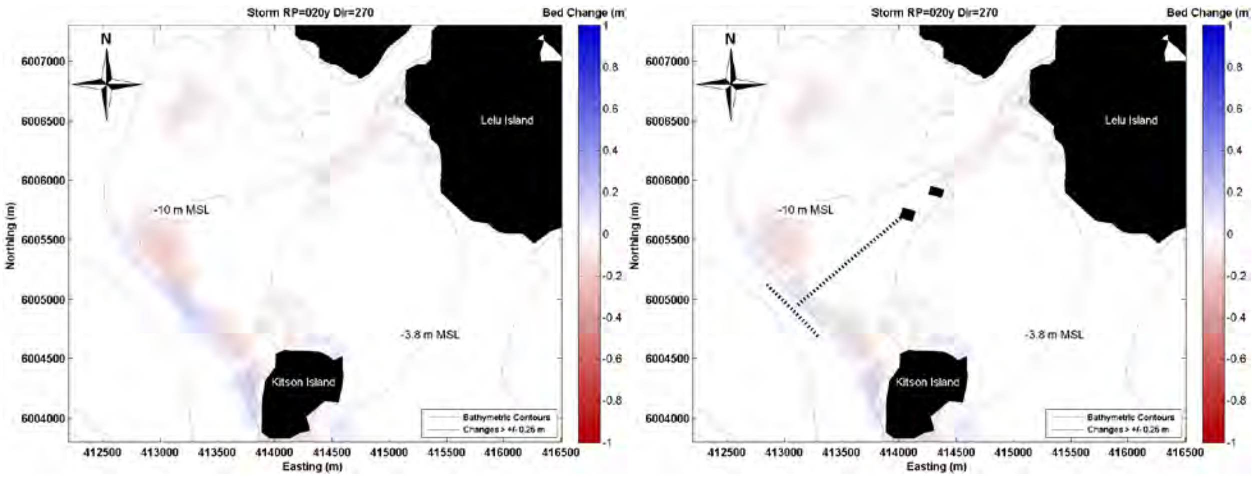


Figure H–49: Morphological changes during 20-year storm from 270° True North for existing (left) and proposed (right) conditions.

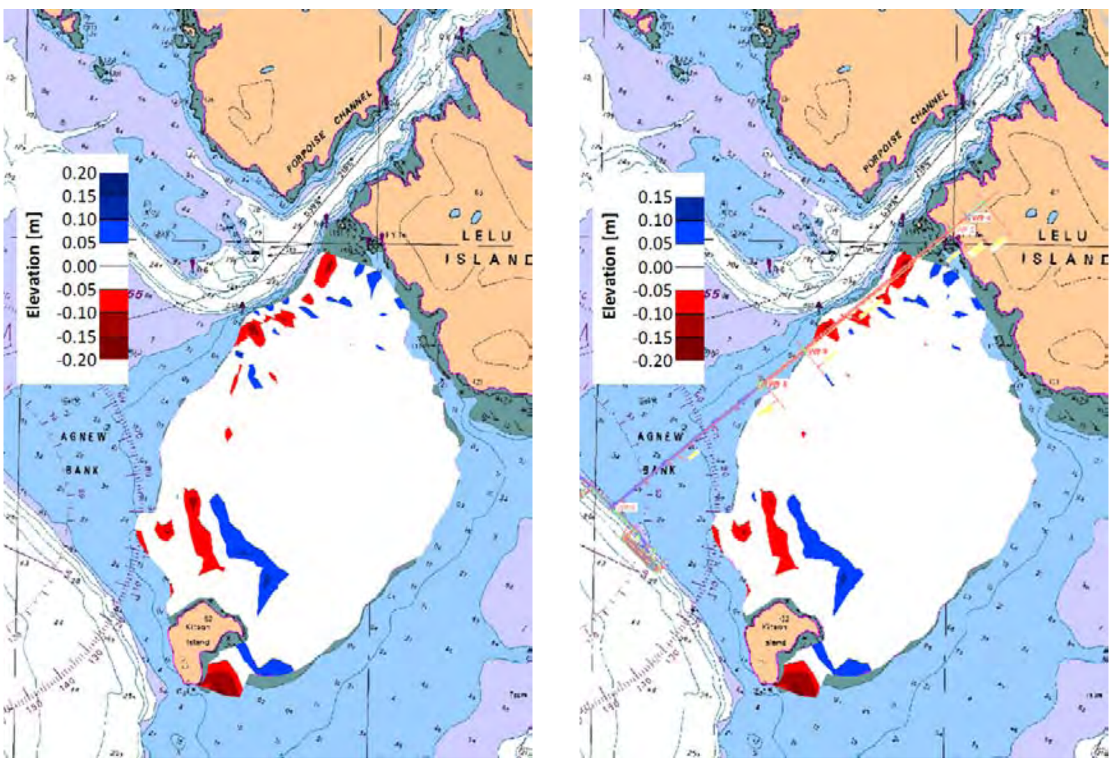


Figure H–50: Morphological changes on Flora Bank during 20-year storm from 270° True North for existing (left) and proposed (right) conditions.

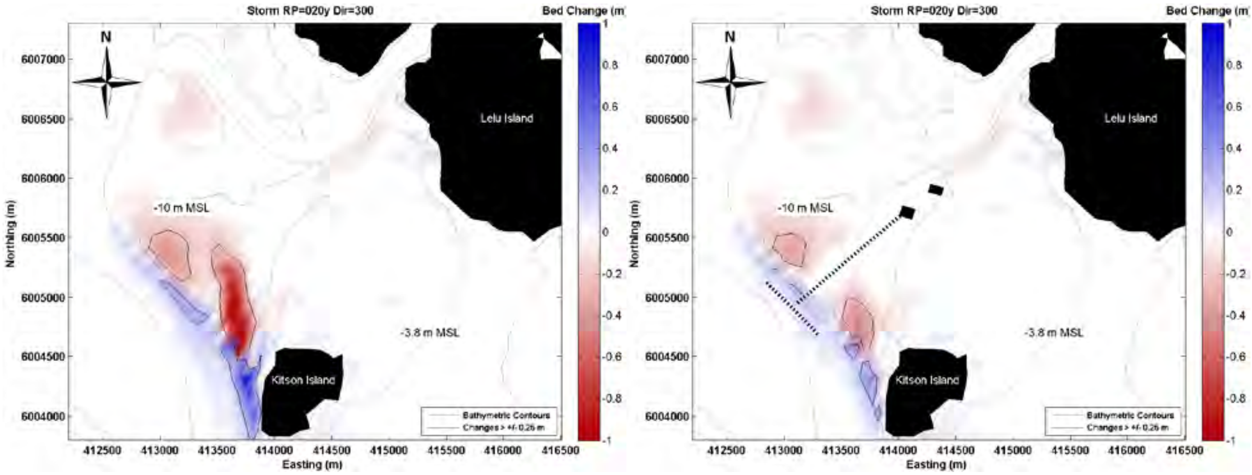


Figure H–51: Morphological changes during 20-year storm from 300° True North for existing (left) and proposed (right) conditions.

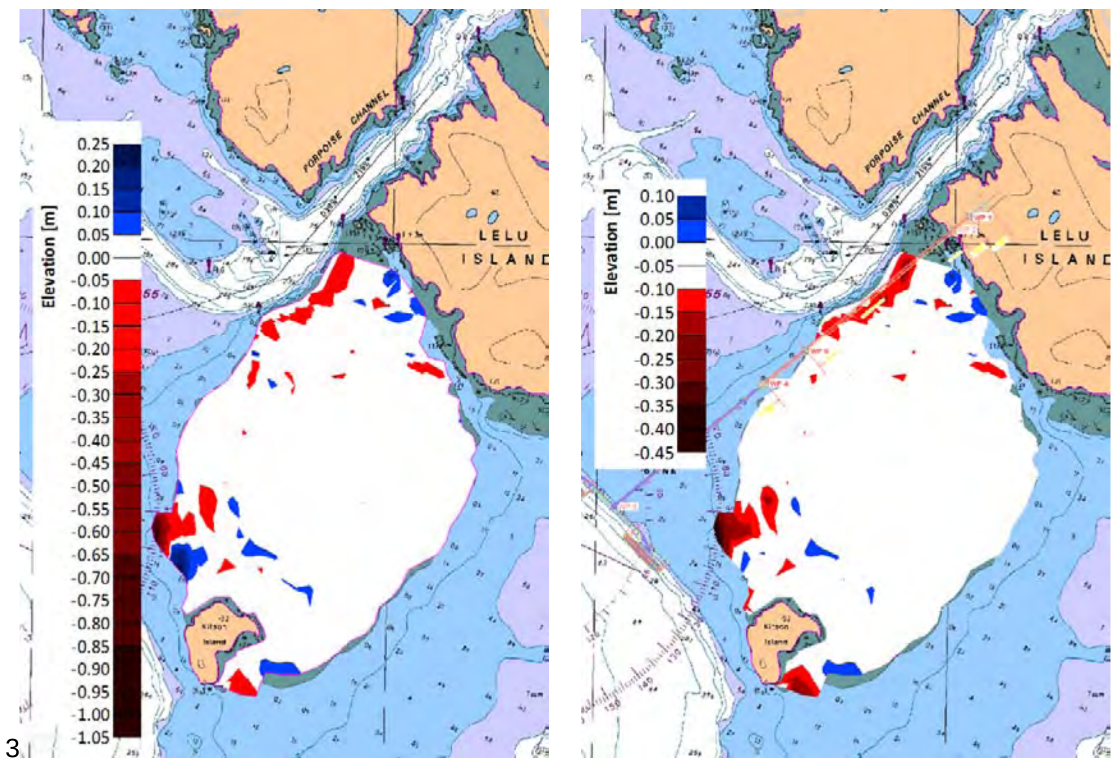


Figure H–52: Morphological changes on Flora Bank during 20-year storm from 300° True North for existing (left) and proposed (right) conditions.

Table H-3: Volumetric and area changes over Flora Bank during 20-year Storm (170°, 240°, 270° and 300° True North)

Extreme Event Incoming Direction [°N]	Presence of Marine Structures	Erosion Volume [m³]	Deposition Volume [m³]	Net Volume [m³]	Erosion Area [m²]	Deposition Area [m²]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
170	**Without**	-73,570	45,790	-27,780	496,910	321,990	-0.02	0.01	-0.01
	With	-70,970	43,480	-27,490	480,290	283,410	-0.02	0.01	-0.01
240	**Without**	-22,510	24,890	2,380	132,780	82,860	-0.01	0.01	0.00
	With	-20,810	21,640	830	122,080	60,830	-0.01	0.01	0.00
270	**Without**	-29,620	29,970	350	172,420	132,460	-0.01	0.01	0.00
	With	-28,810	27,360	-1,450	162,270	117,460	-0.01	0.01	0.00
300	**Without**	-45,620	36,520	-9,100	198,290	104,700	-0.01	0.01	0.00
	With	-41,690	30,030	-11,660	220,330	60,230	-0.01	0.01	0.00

H1.1.2.4 50-Year Return Period Storms

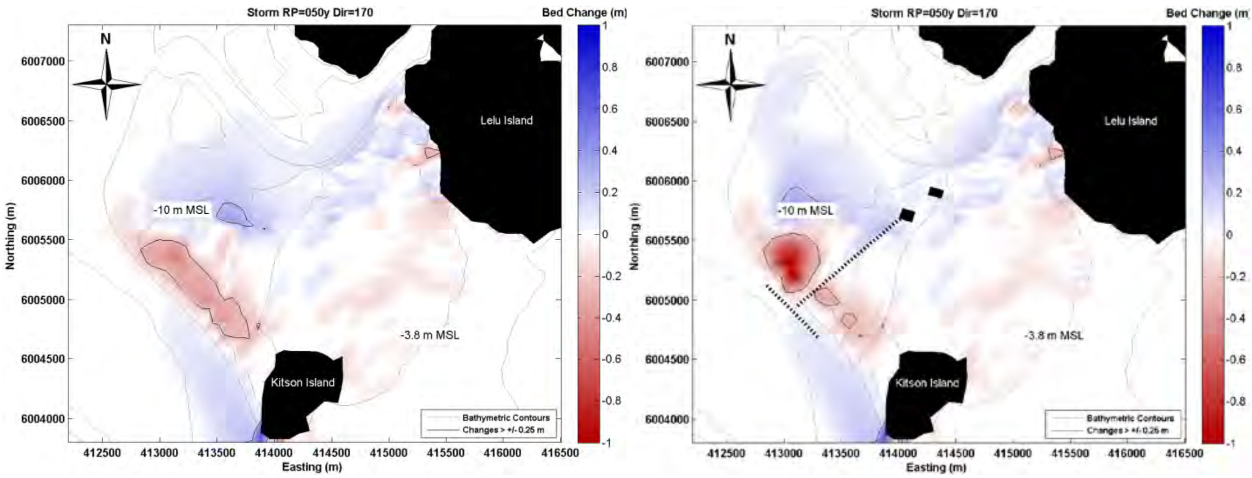


Figure H–53: Morphological changes during 50-year storm from 170° True North for existing (left) and proposed (right) conditions.

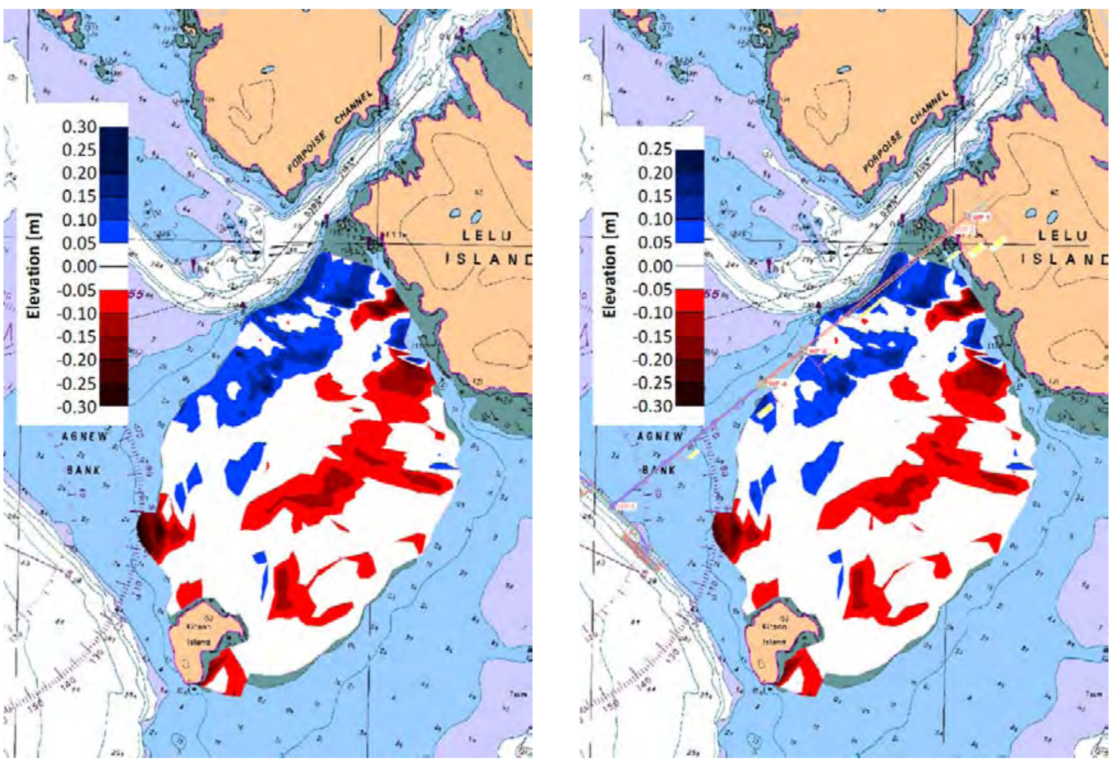


Figure H–54: Morphological changes on Flora Bank during 50-year storm from 170° True North for existing (left) and proposed (right) conditions.

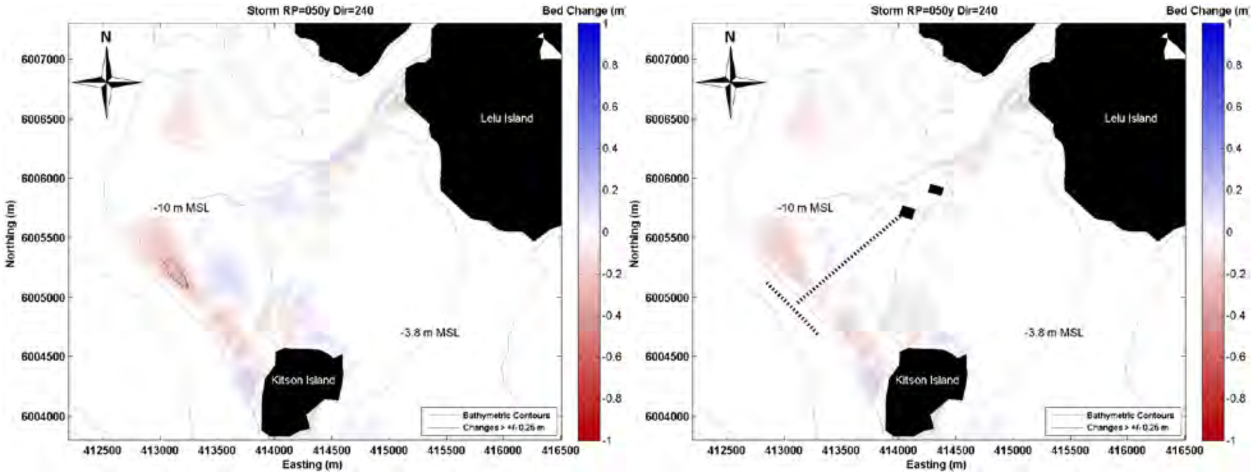


Figure H–55: Morphological changes during 50-year storm from 240° True North for existing (left) and proposed (right) conditions.

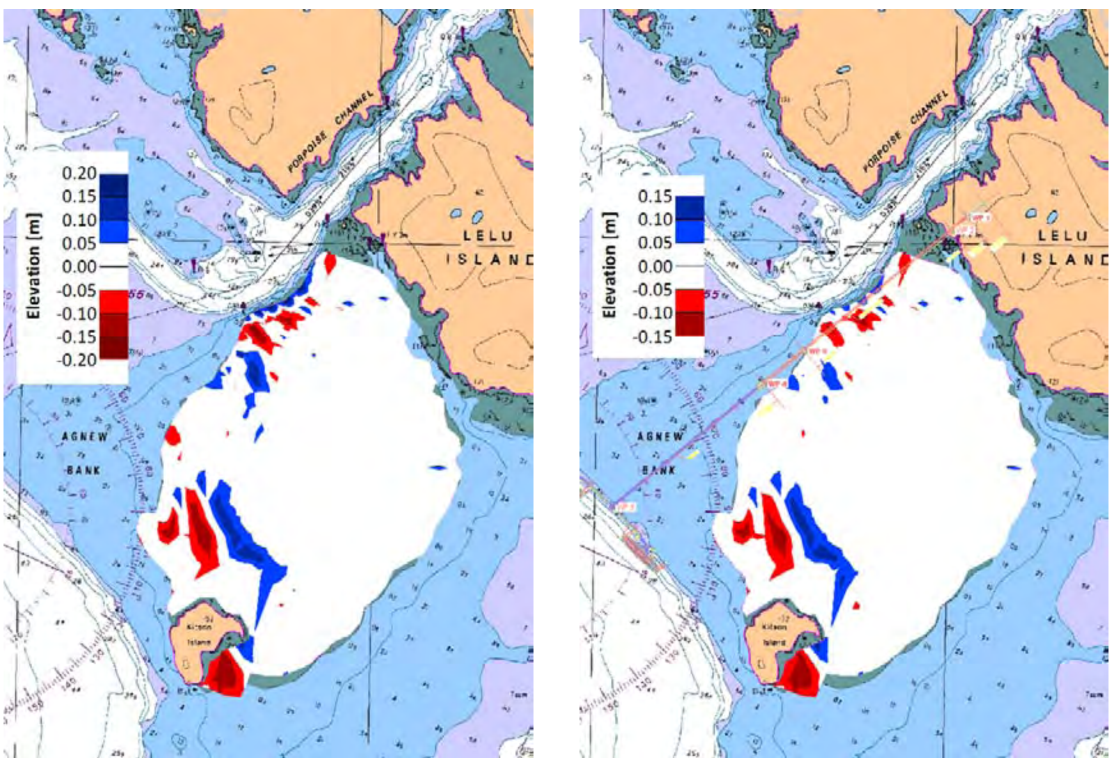


Figure H–56: Morphological changes on Flora Bank during 50-year storm from 240° True North for existing (left) and proposed (right) conditions.

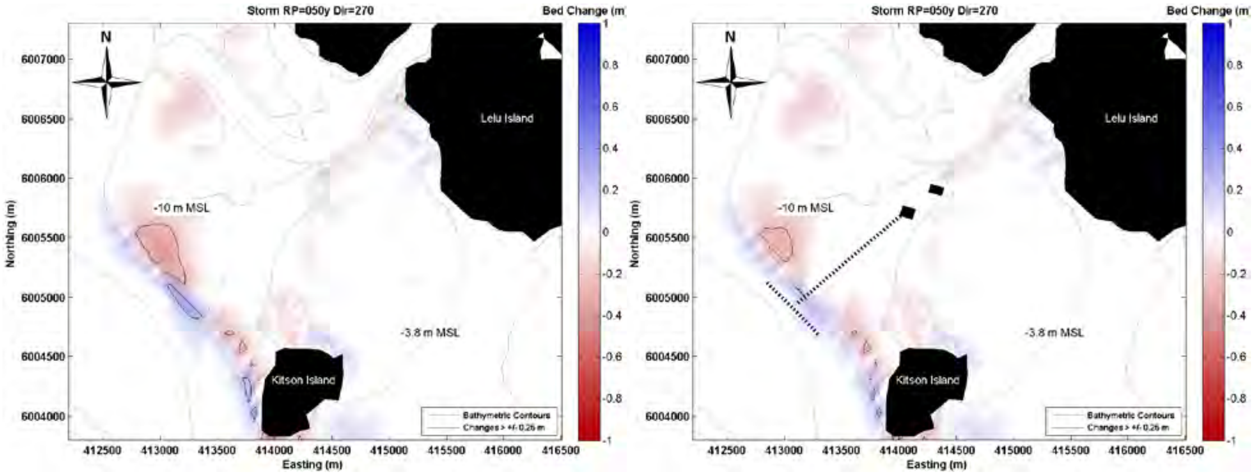


Figure H–57: Morphological changes during 50-year storm from 270^{o} True North for existing (left) and proposed (right) conditions.

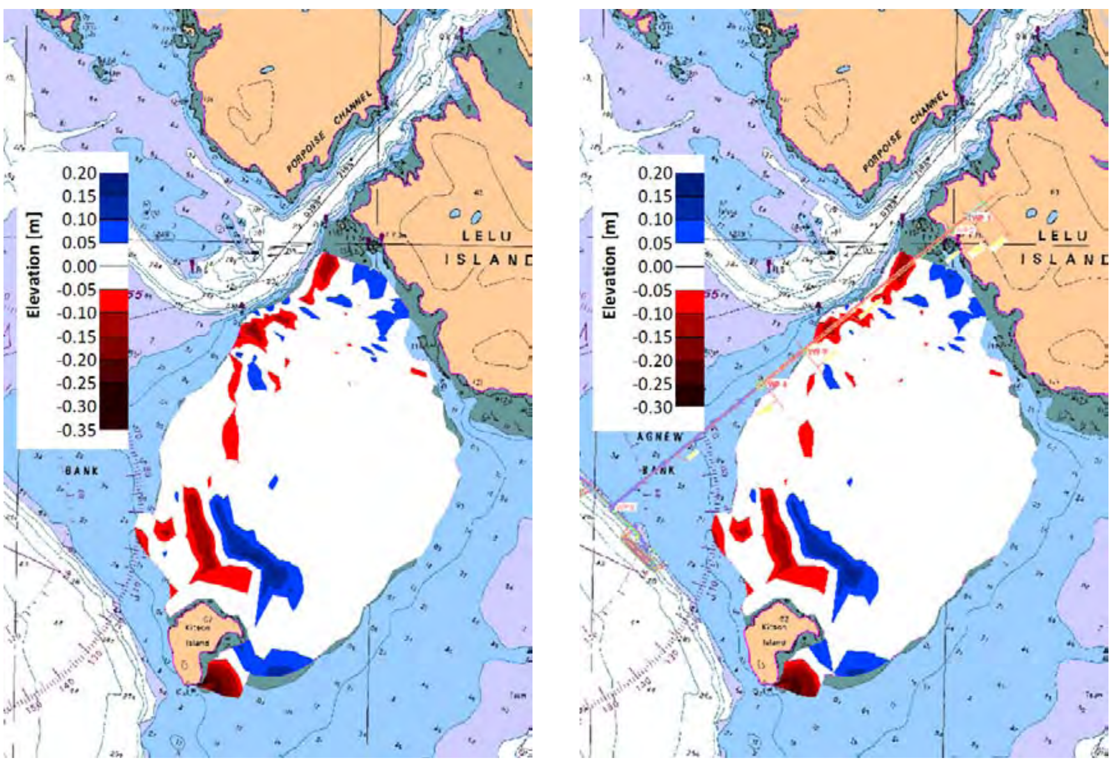


Figure H–58: Morphological changes on Flora Bank during 50-year storm from 270^{o} True North for existing (left) and proposed (right) conditions.

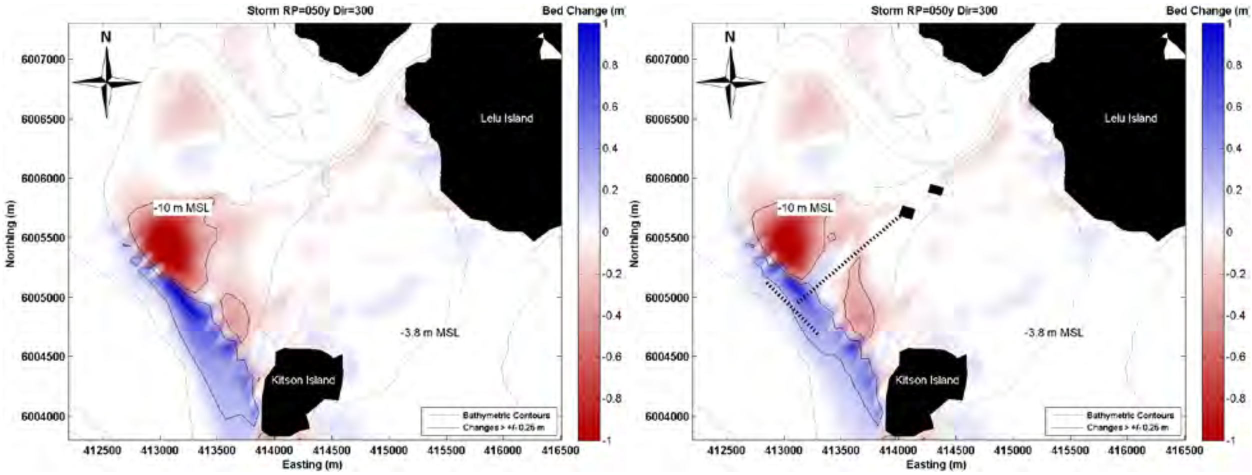


Figure H–59: Morphological changes during 50-year storm from 300° True North for existing (left) and proposed (right) conditions.

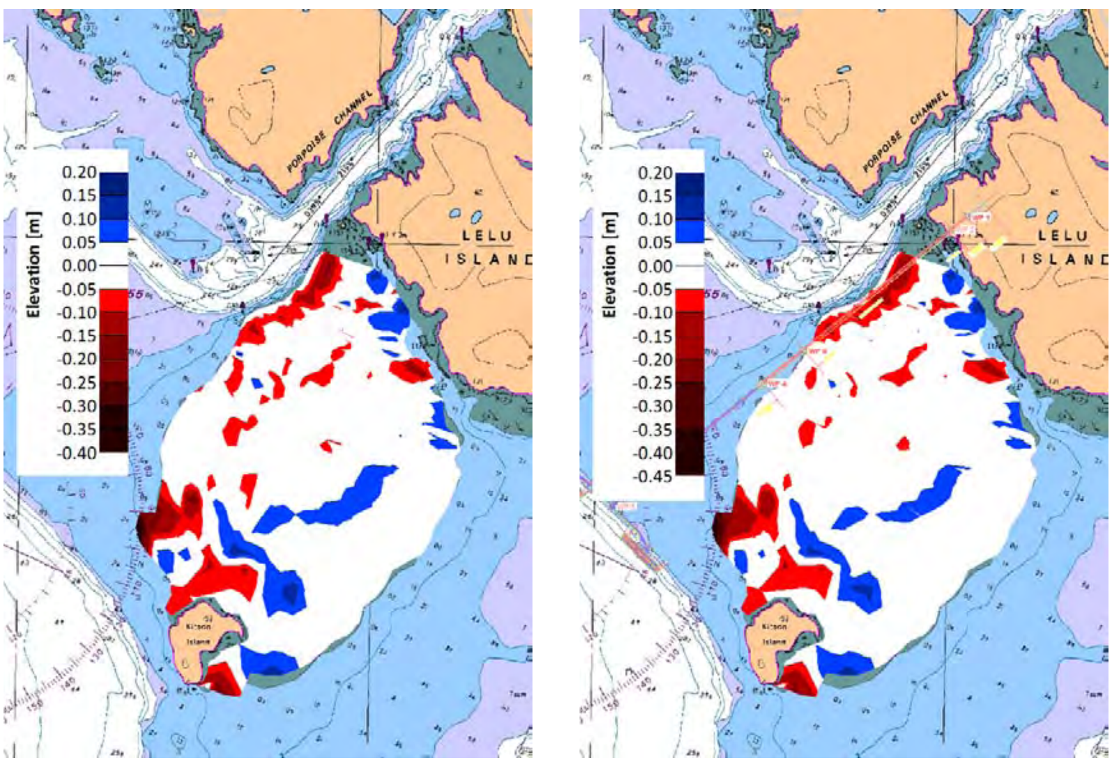


Figure H–60: Morphological changes on Flora Bank during 50-year storm from 300° True North for existing (left) and proposed (right) conditions.

Table H-4: Volumetric and area changes over Flora Bank during 50-year Storm (170°, 240°, 270° and 300° True North)

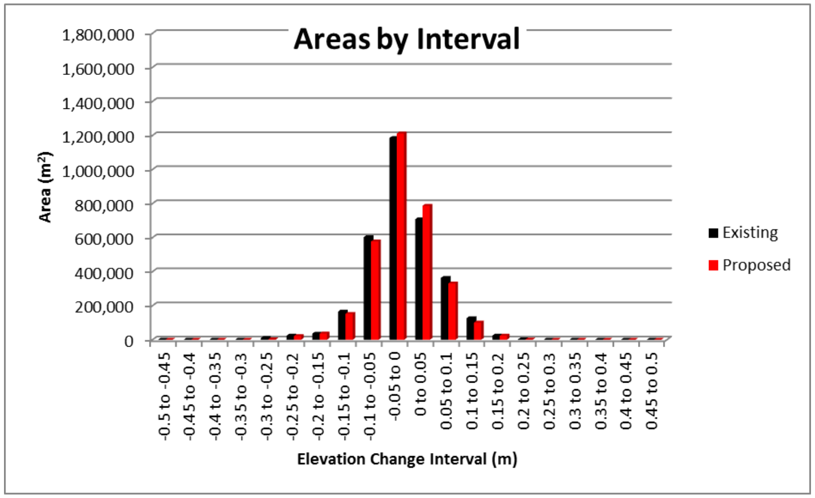
Extreme Event Incoming Direction [°N]	Presence of Marine Structures	Erosion Volume [m³]	Deposition Volume [m³]	Net Volume [m³]	Erosion Area [m²]	Deposition Area [m²]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
170	**Without**	-106,480	61,590	-44,890	838,140	516,640	-0.03	0.02	-0.01
	With	-101,560	57,770	-43,790	791,560	456,920	-0.03	0.02	-0.01
240	**Without**	-31,930	39,370	7,440	202,490	188,000	-0.01	0.01	0.00
	With	-29,900	34,230	4,330	185,460	145,830	-0.01	0.01	0.00
270	**Without**	-47,340	50,140	2,800	308,920	278,860	-0.01	0.02	0.01
	With	-45,460	43,860	-1,600	287,910	233,160	-0.01	0.01	0.00
300	**Without**	-67,010	55,760	-11,250	491,430	354,360	-0.02	0.02	0.00
	With	-66,040	50,370	-15,670	446,750	297,110	-0.02	0.02	0.00

Two-extreme event (storm) cases were selected for further evaluation; the 50-year storm from 270° True North and the 50-year storm from 170° True North. Tables listing the statistics for erosion and deposition intervals for both existing and proposed conditions on Flora Bank have been included in Table H-5 and Table H-6. These tables reflect the volumetric change and the footprint area computed from the surface volume as described above.

The figures for both the 170° and 270° 50-year storms (Figure H–61 and Figure H–62) demonstrate similar results for both the existing and proposed conditions. The volume change for the 270° storm is slightly less for the proposed conditions than the existing conditions indicating that the marine structures slightly attenuate the morphology change on Flora Bank. The total erosion, deposition and net volume and area for both directions are listed in Table H-4. In both cases the majority of morphological change on Flora Bank are between -0.05 m and 0.05 m, with minimal changes greater than outside of ±0.15 m. Note that the sum of all the areas is 3,247,120 m². Therefore, the proposed conditions is slightly attenuated compared to the existing conditions shown in by the fact that the proposed conditions is greater in area than the existing conditions between -0.05 m and 0.05 m and less elsewhere.

Table H-5: Volume and Area Changes on Flora Bank for the 50-year, 170° True North Storm

	Area [m²]		Volumes [m³]		Absolute Volumes [m³]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.5 to -0.45	0	0	0	0	0	0
-0.45 to -0.4	0	0	0	0	0	0
-0.4 to -0.35	0	0	0	0	0	0
-0.35 to -0.3	0	0	0	0	0	0
-0.3 to -0.25	10,060	2,970	-110	-50	110	50
-0.25 to -0.2	23,930	22,180	-1,040	-600	1,040	600
-0.2 to -0.15	36,120	36,890	-2,550	-2,090	2,550	2,090
-0.15 to -0.1	164,980	152,010	-6,390	-5,790	6,390	5,790
-0.1 to -0.05	603,050	577,510	-23,850	-22,270	23,850	22,270
-0.05 to 0	1,185,300	1,211,610	-72,530	-70,770	72,530	70,770
0 to 0.05	707,030	787,040	41,700	40,730	41,700	40,730
0.05 to 0.1	363,270	330,380	15,420	13,090	15,420	13,090
0.1 to 0.15	126,560	100,850	3,910	3,450	3,910	3,450
0.15 to 0.2	24,090	23,860	520	480	520	480
0.2 to 0.25	2,720	1,830	40	20	40	20
0.25 to 0.3	10	0	0	0	0	0
0.3 to 0.35	0	0	0	0	0	0
0.35 to 0.4	0	0	0	0	0	0
0.4 to 0.45	0	0	0	0	0	0
0.45 to 0.5	0	0	0	0	0	0



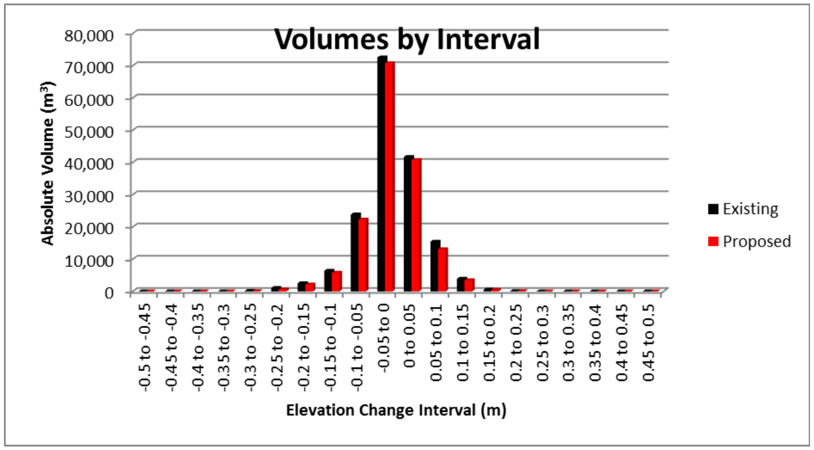


Figure H–61: Area Changes (top) and Absolute Volume Changes (bottom) on Flora Bank for the 50-year, 170° True North Storm

Table H-6: Volume and Area Changes on Flora Bank for the 50-year, 270° True North Storm

	Area [m²]		Volumes [m³]		Absolute Volumes [m³]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.5 to -0.45	0	0	0	0	0	0
-0.45 to -0.4	0	0	0	0	0	0
-0.4 to -0.35	0	0	0	0	0	0
-0.35 to -0.3	120	0	0	0	0	0
-0.3 to -0.25	2,150	450	-40	0	40	0
-0.25 to -0.2	7,930	9,120	-290	-180	290	180
-0.2 to -0.15	18,460	17,130	-870	-920	870	920
-0.15 to -0.1	78,480	73,440	-3,150	-2,840	3,150	2,840
-0.1 to -0.05	201,780	187,780	-9,370	-8,820	9,370	8,820
-0.05 to 0	1,001,120	1,059,870	-33,630	-32,700	33,630	32,700
0 to 0.05	1,658,220	1,666,180	41,070	36,660	41,070	36,660
0.05 to 0.1	215,520	182,900	7,600	6,110	7,600	6,110
0.1 to 0.15	57,350	46,490	1,420	1,070	1,420	1,070
0.15 to 0.2	5,990	3,760	50	20	50	20
0.2 to 0.25	0	0	0	0	0	0
0.25 to 0.3	0	0	0	0	0	0
0.3 to 0.35	0	0	0	0	0	0
0.35 to 0.4	0	0	0	0	0	0
0.4 to 0.45	0	0	0	0	0	0
0.45 to 0.5	0	0	0	0	0	0

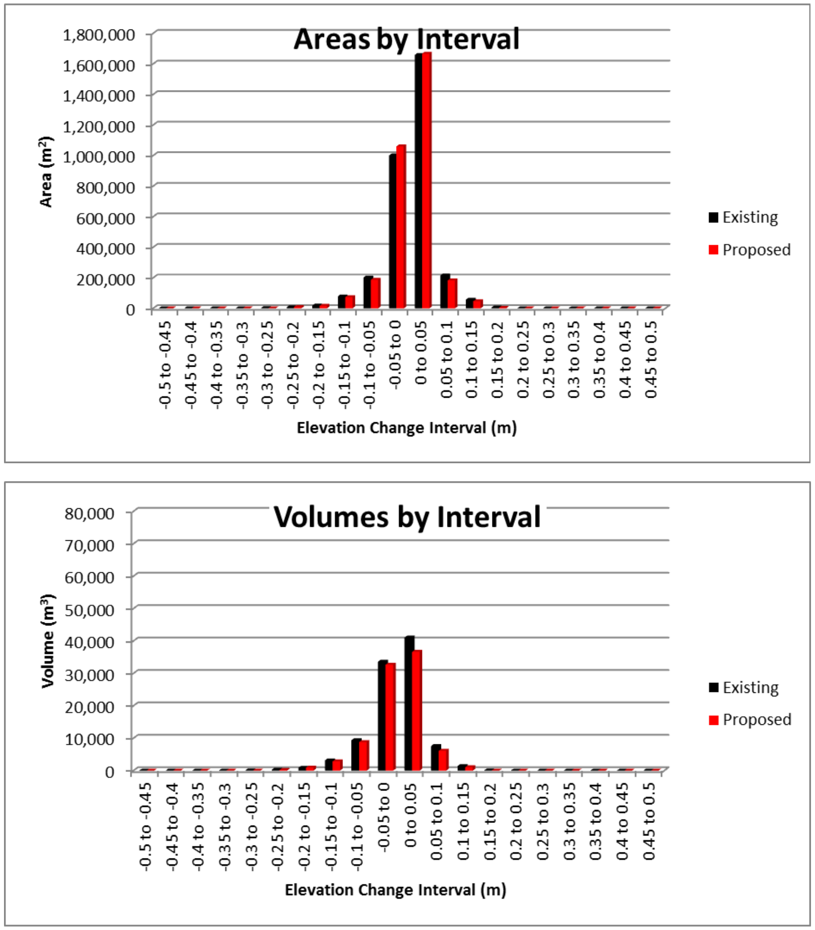


Figure H–62: Area Changes (top) and Absolute Volume Changes (bottom) on Flora Bank for the 50-year, 270° True North Storm

H1.1.2.5 100-Year Return Period Storms

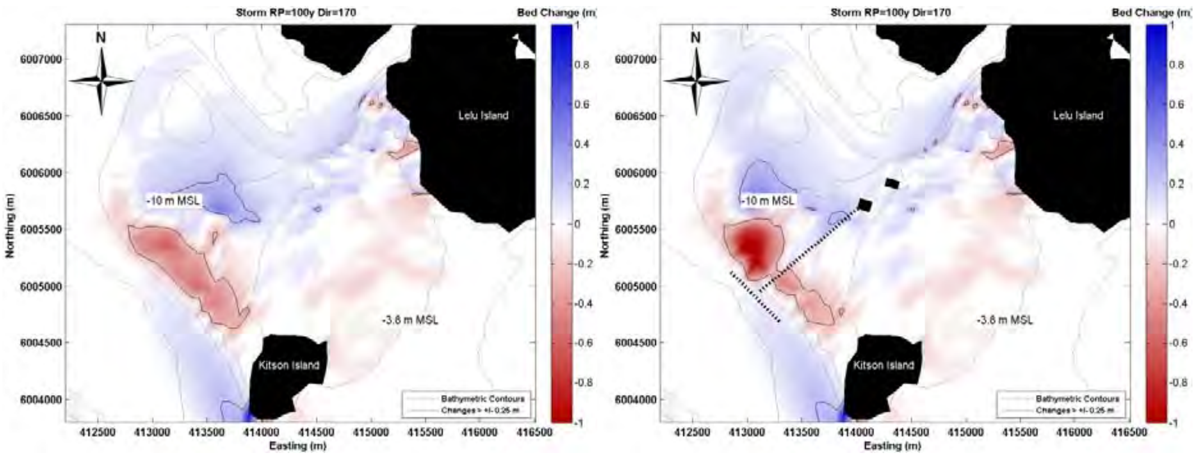


Figure H–63: Morphological changes during 100-year storm from 170° True North for existing (left) and proposed (right) conditions.

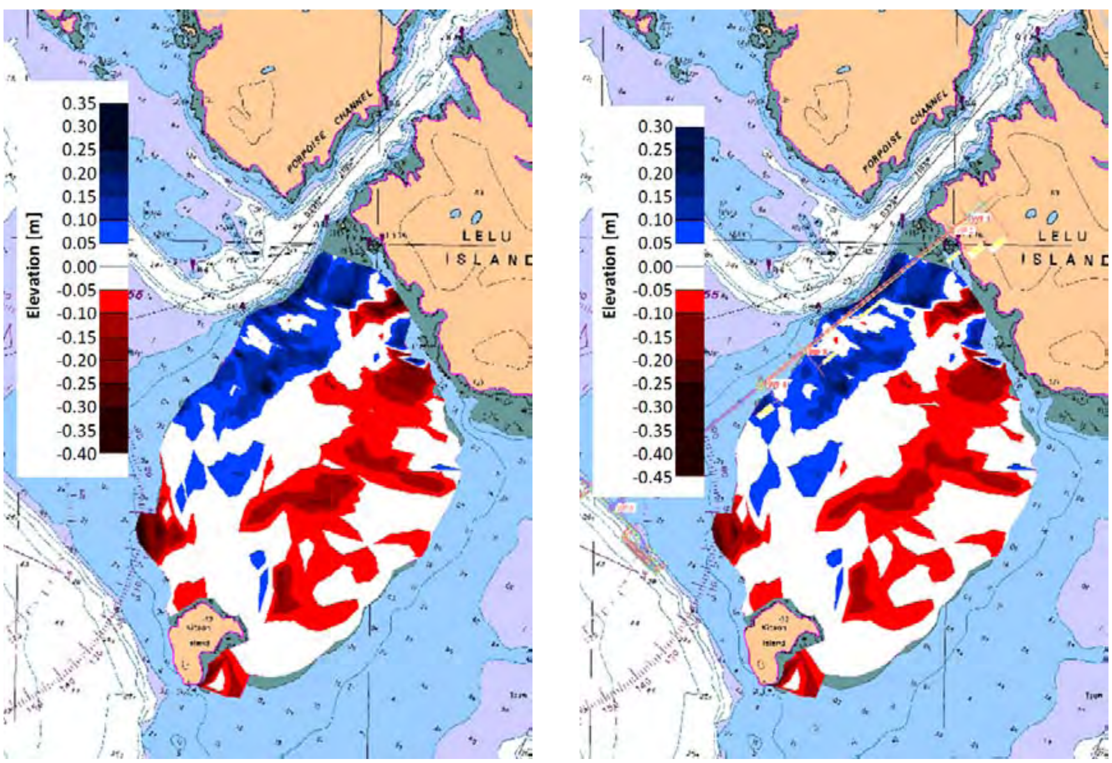


Figure H–64: Morphological changes on Flora Bank during 100-year storm from 170° True North for existing (left) and proposed (right) conditions.

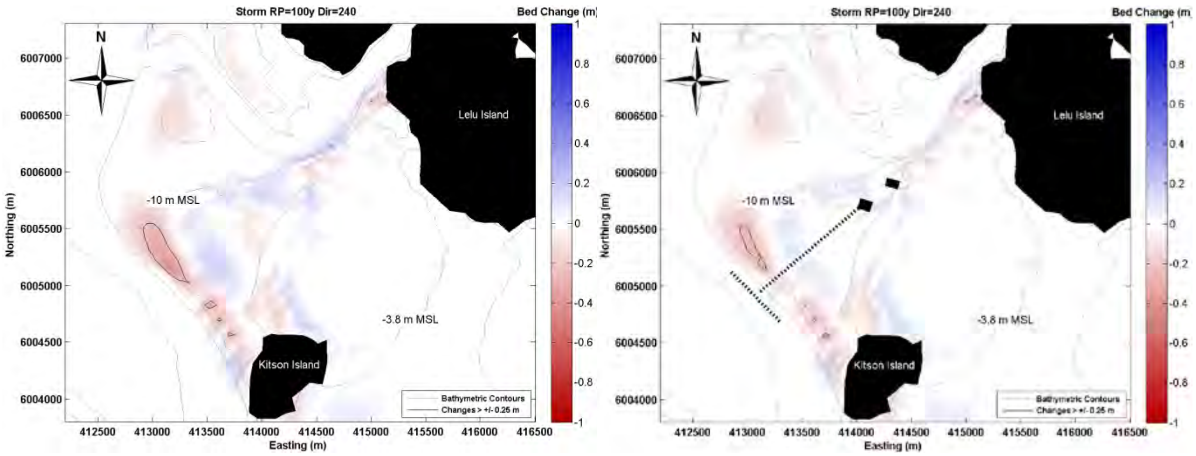


Figure H–65: Morphological changes during 100-year storm from 240° True North for existing (left) and proposed (right) conditions.

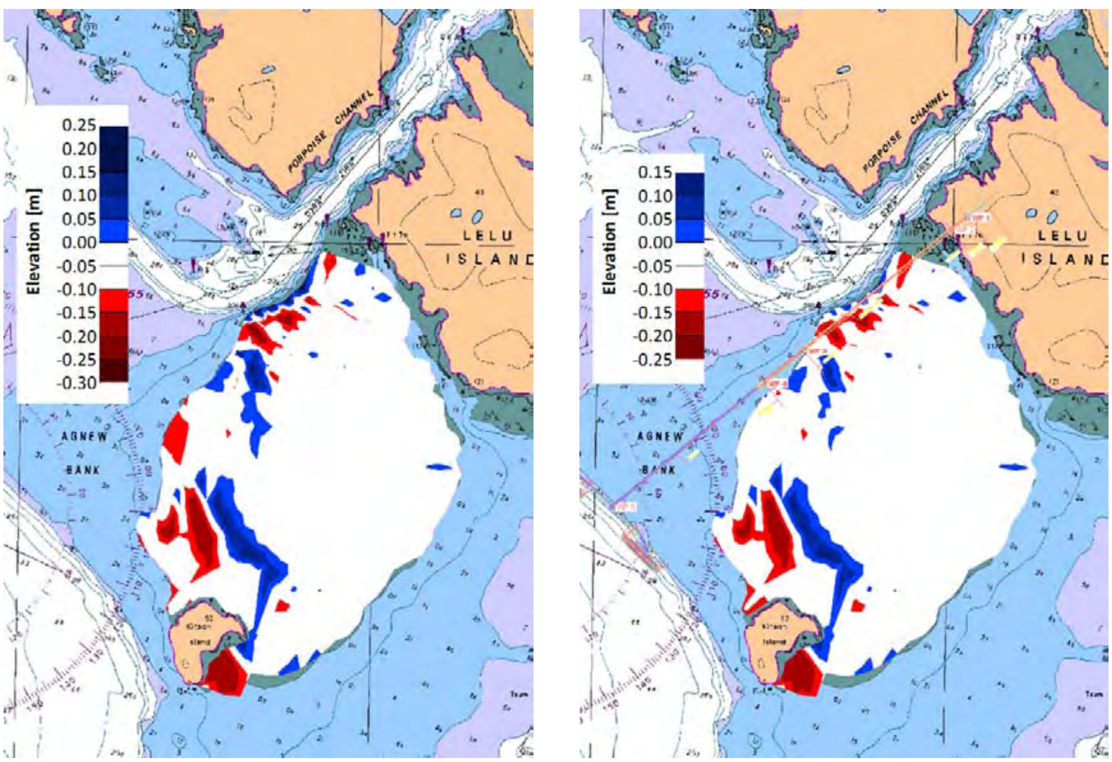


Figure H–66: Morphological changes on Flora Bank during 100-year storm from 240° True North for existing (left) and proposed (right) conditions.

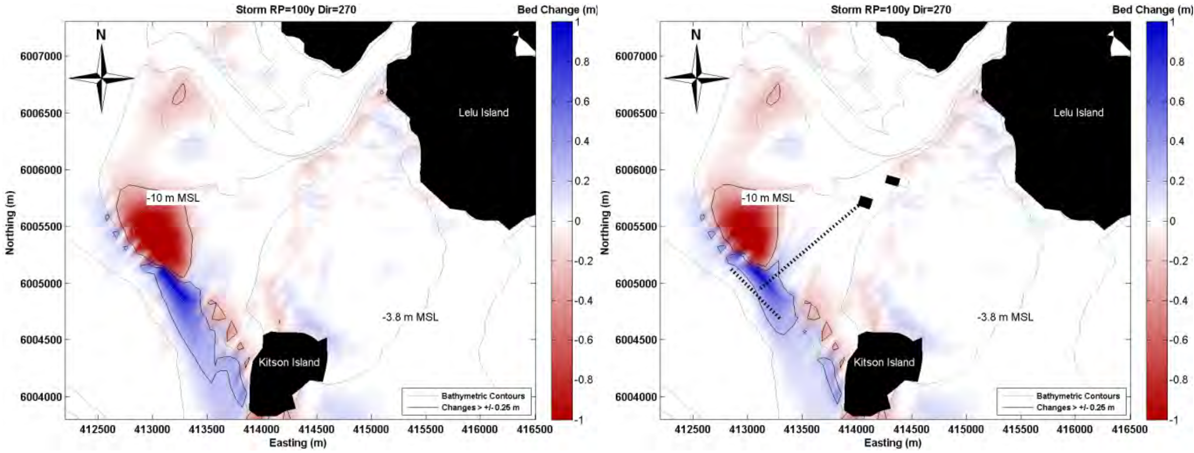


Figure H–67: Morphological changes during 100-year storm from 270° True North for existing (left) and proposed (right) conditions.

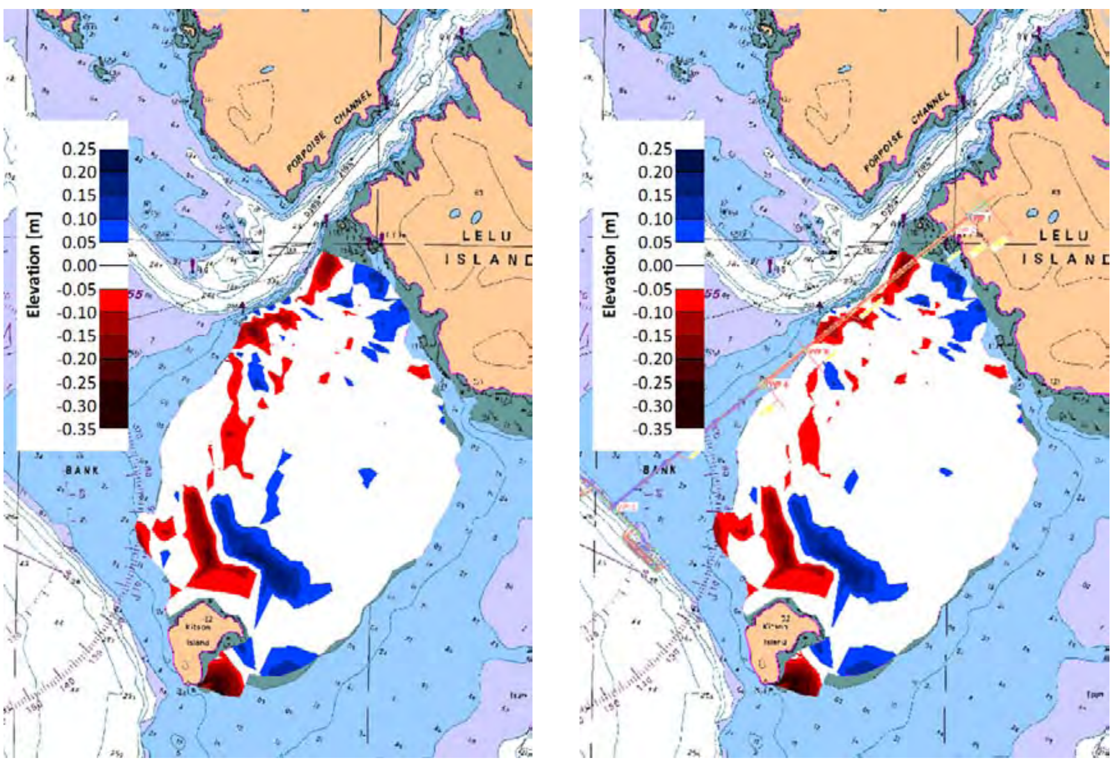


Figure H–68: Morphological changes on Flora Bank during 100-year storm from 270° True North for existing (left) and proposed (right) conditions.

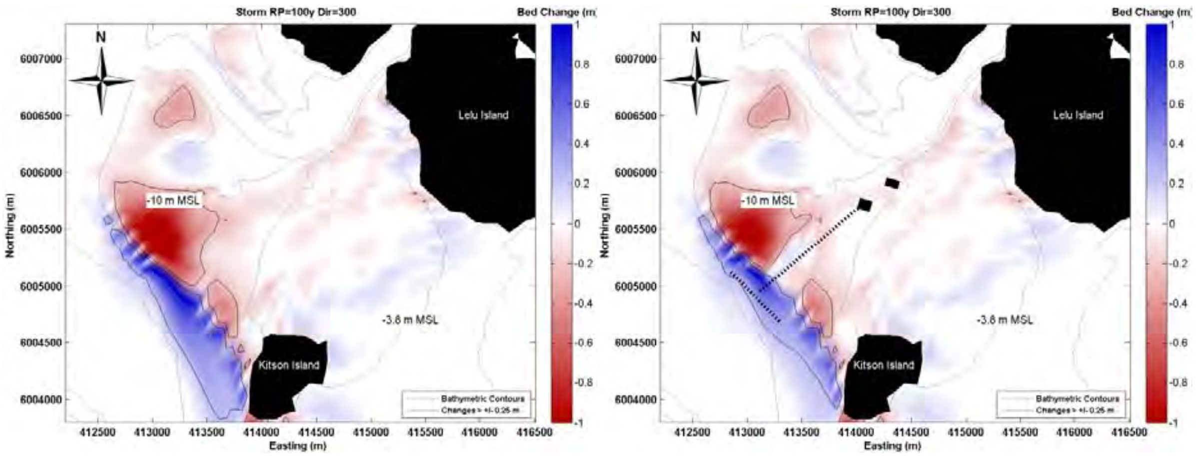


Figure H–69: Morphological changes during 100-year storm from 300° True North for existing (left) and proposed (right) conditions.

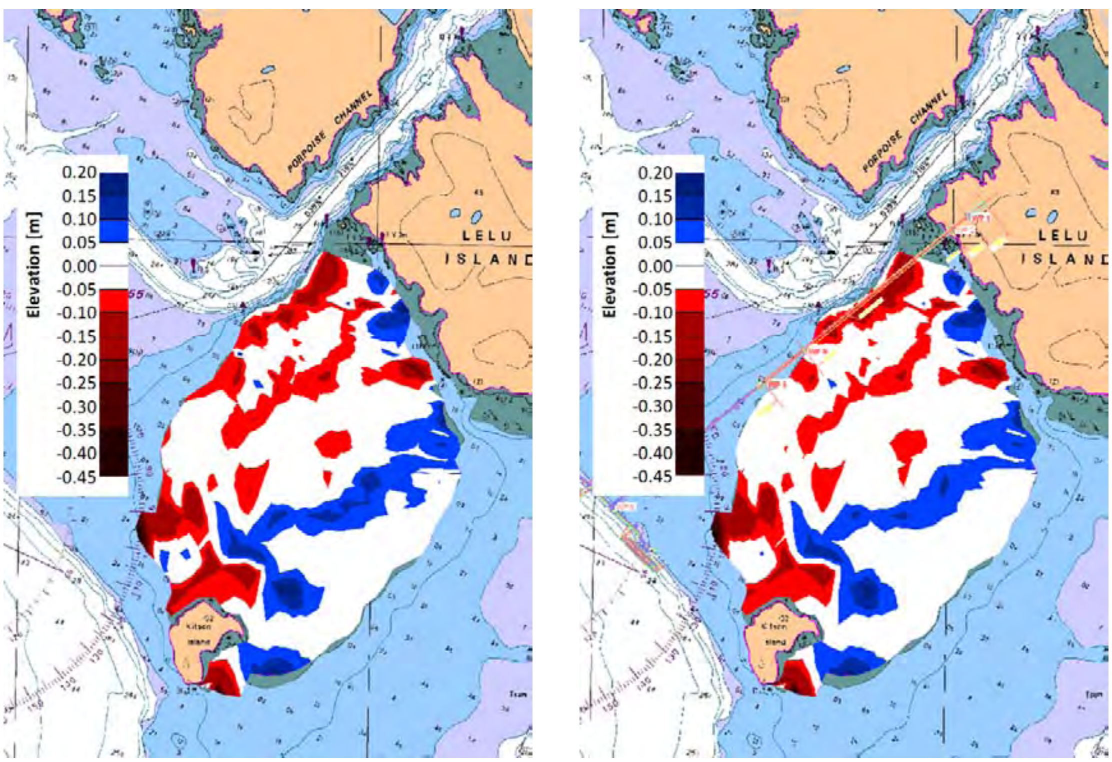


Figure H–70: Morphological changes on Flora Bank during 100-year storm from 300° True North for existing (left) and proposed (right) conditions.

Table H-7: Volumetric and area changes over Flora Bank during 100-year Storm (170°, 240°, 270° and 300° True North)

Extreme Event Incoming Direction [°N]	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
170	**Without**	-137,380	74,280	-63,100	1,153,230	600,150	-0.04	0.02	-0.02
	With	-130,510	68,800	-61,710	1,079,220	554,510	-0.04	0.02	-0.02
240	**Without**	-38,460	49,570	11,110	259,630	275,650	-0.01	0.02	0.01
	With	-36,970	44,290	7,320	239,230	229,500	-0.01	0.01	0.00
270	**Without**	-61,260	66,210	4,950	425,130	386,520	-0.02	0.02	0.00
	With	-59,540	58,830	-710	405,160	328,100	-0.02	0.02	0.00
300	**Without**	-98,780	75,730	-23,050	810,290	602,480	-0.03	0.02	-0.01
	With	-95,160	69,770	-25,390	761,720	544,790	-0.03	0.02	-0.01

H1.1.2.6 Summary of Morphology Trends

Plots depicting the total area where erosion and deposition occurred over the area of Flora Bank for the extreme event cases are shown in Figure H–71 and Figure H–72, respectively. The total area of bed change decreases in order of 170°, 300°, 270°, and 240°. This trend correlates with the strength of the south-southeast and westerly winds and the storms' corresponding fetches, which is described in Appendix G. It is also apparent that the area where erosion and deposition occurs for the existing and proposed conditions result is very similar (almost overlapping in these figures).

Plots depicting the net volume of erosion and deposition for the extreme event cases are shown in Figure H–73 and Figure H–74, respectively. These volumes were divided by the area of Flora Bank to produce a net average elevation change. The net average elevation change of erosion and deposition for the existing and proposed conditions is very similar. The slight attenuation in the proposed conditions compared to the existing conditions is more apparent with the increase in storm return period.

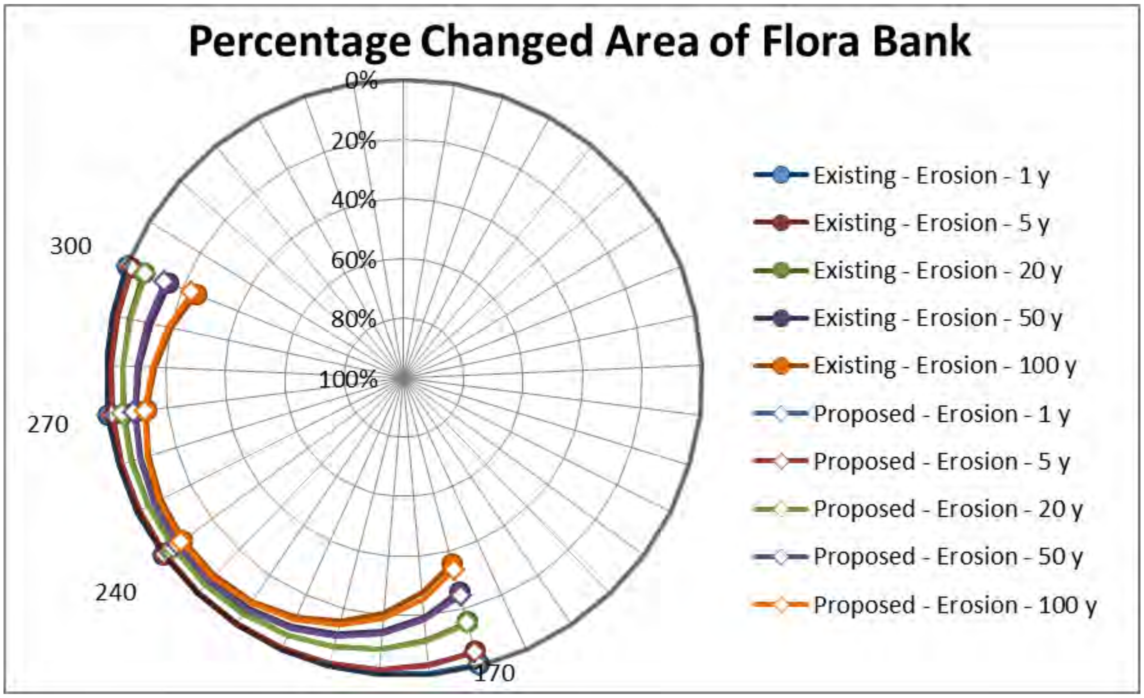


Figure H–71: Percentage Changed Area of Flora Bank due to Erosion for Existing and Proposed Conditions

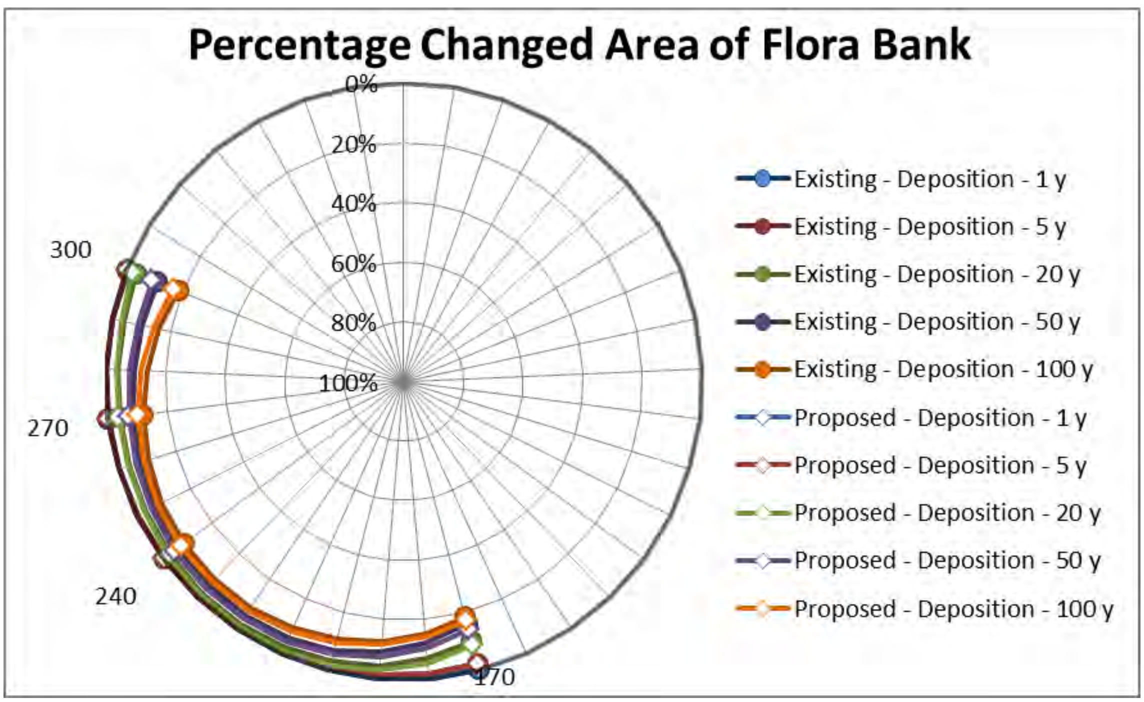


Figure H–72: Percentage Changed Area of Flora Bank due to Deposition for Existing and Proposed Conditions

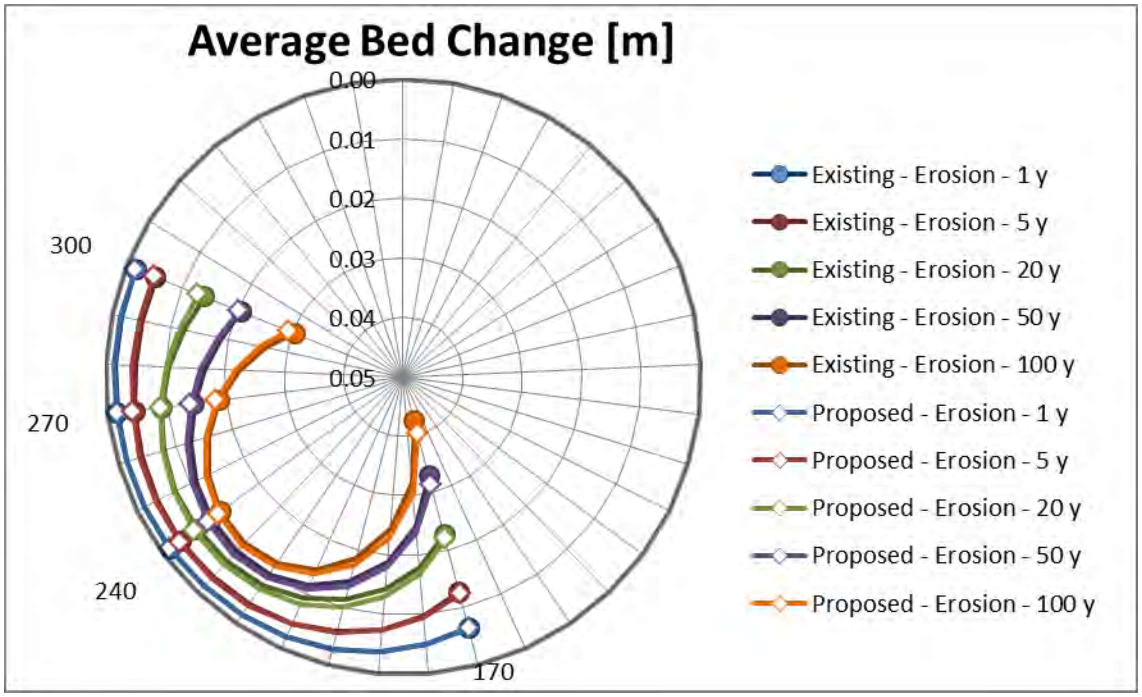


Figure H–73: Average Bed Change due to Erosion for Existing and Proposed Conditions

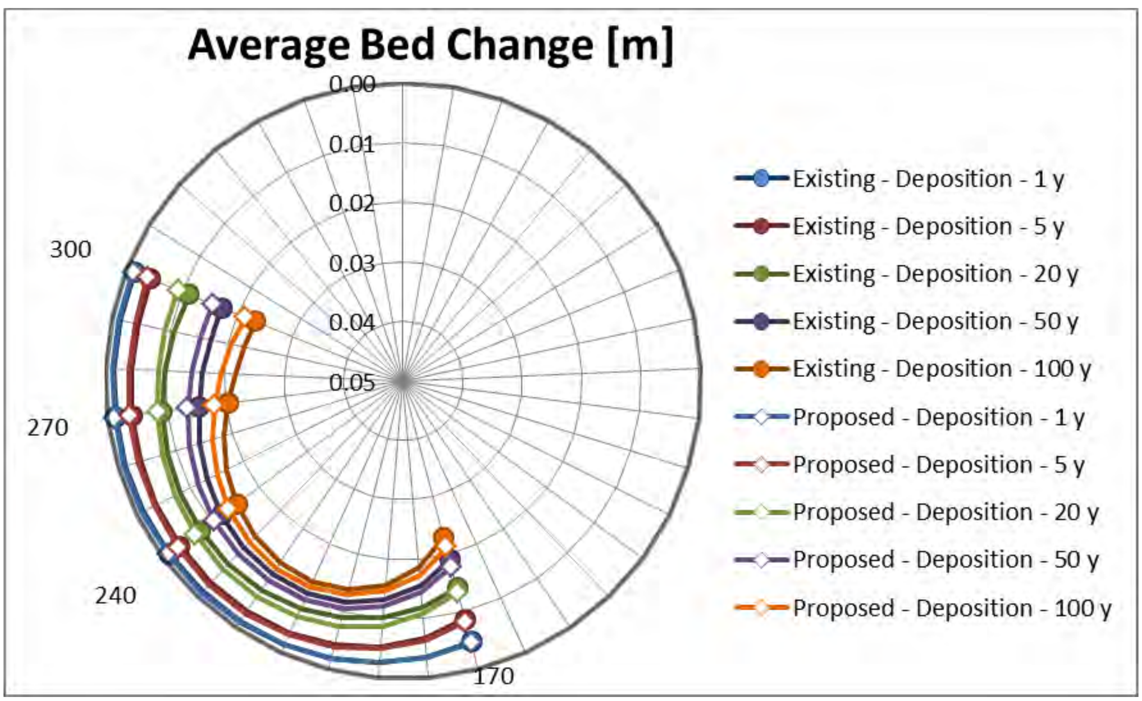


Figure H–74: Absolute Average Bed Change due to Deposition for Existing and Proposed Conditions

H1.1.3 Currents during Slack Tide 50-year Storm from 270°

The 50-year storm simulation from 270° was used to evaluate the currents during slack tides. At this stage of the tide, the current velocities induced by the tidal component are minimum, giving an approximation and understanding of the currents induced by winds and waves, minimizing the tidal effects.

Three difference moments when the wave heights were high during the simulation were evaluated (red dots in Figure H–75). The depth averaged current velocity patterns were similar during those stages, indicating that the current velocities are mostly induced by winds and waves (about 0.7 m/s) on Flora Bank and slightly higher north of Kitson Island. The currents are low at Porpoise Channel during the slack tides (transient period between ebb and flood).

The same storm, but with the marine structures in place, was analyzed during the slack tide (Figure H–76) and the results were very similar to the existing conditions. The proposed condition showed a localized decrease in the currents near the trestle.

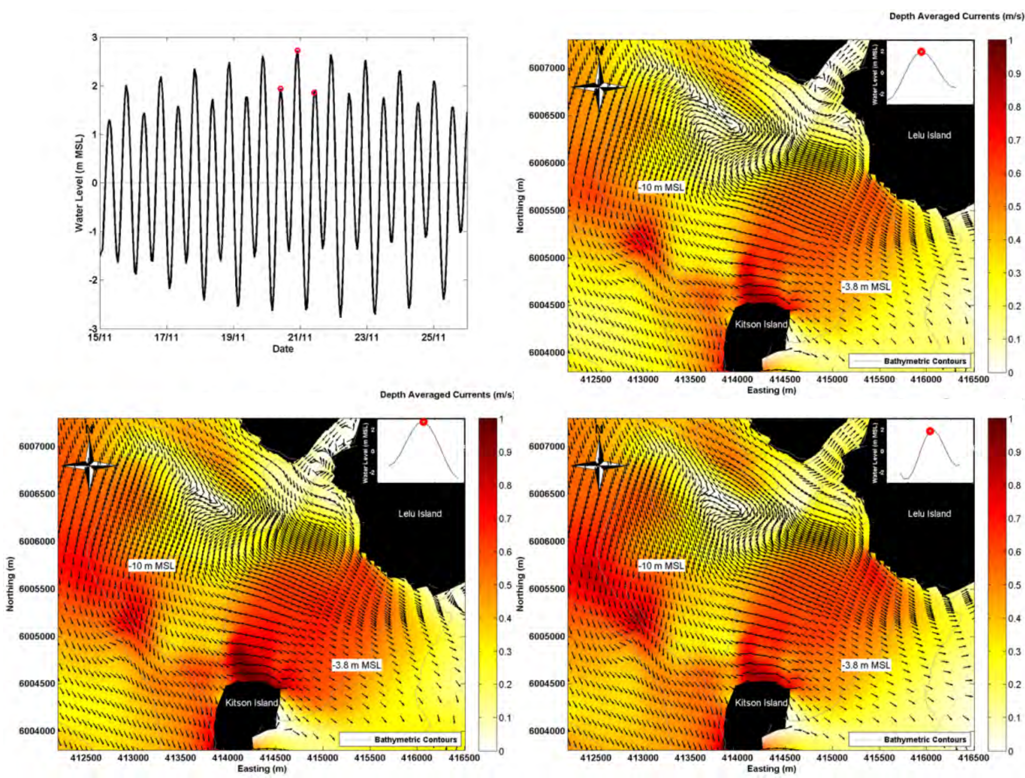


Figure H–75: Instantaneous depth averaged currents during the 50-year storm from 270° True North during three different slack tide for the existing conditions.

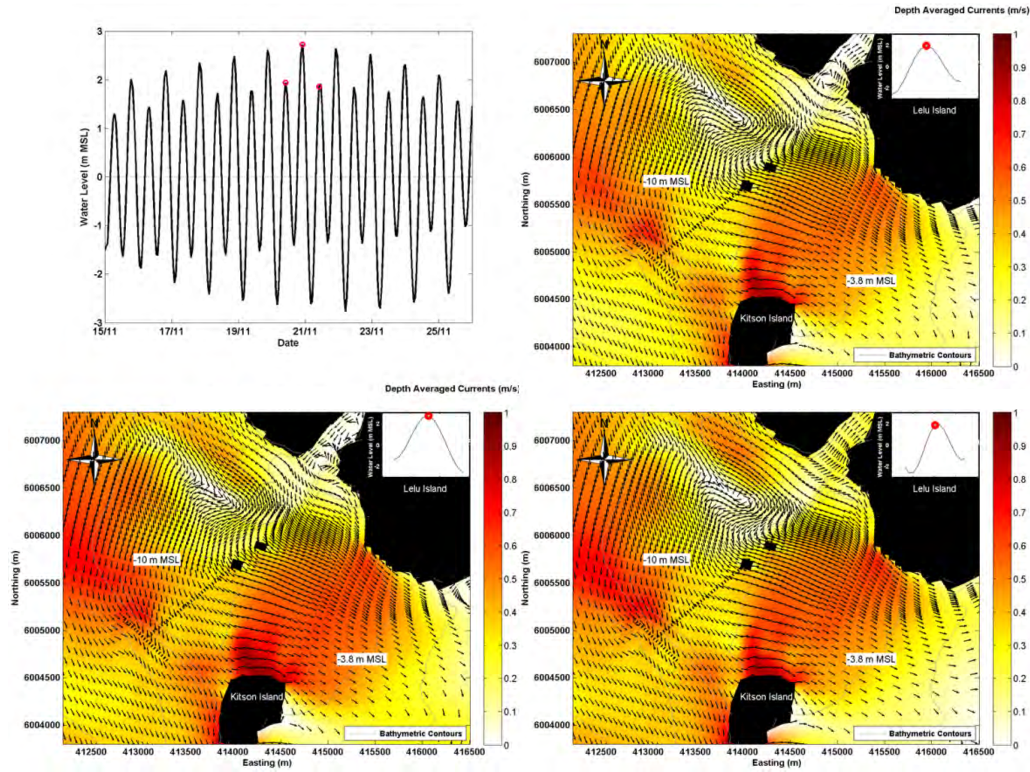


Figure H–76: Instantaneous depth averaged currents during the 50-year storm from 270^{o} True North during three different slack tide for the proposed conditions.

H1.2 Annual Stormy Period (3 months)

In contrast with the extreme events examined in Section H1.1, the simulation results provided in this section evaluate typical stormy conditions through 3 months of the annual stormy season. The 3 month period from September 1, 2012 to December 31, 2012 was selected to further evaluate the impacts of the proposed marine structures during a typical stormy period. This 3 month period is discussed within the main report in Section 5.3.4.1 and Section 6.1.4.1 and additional morphology (Table H-8) and TSS data are is provided in this section.

Table H-8: Volume and Area Changes on Flora Bank for 3 Month Stormy Period (1-hr Coupling).

	Area [m²]		Volumes [m³]		Absolute Volumes [m³]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.5 to -0.45	0	0	0	0	0	0
-0.45 to -0.4	0	0	0	0	0	0
-0.4 to -0.35	0	0	0	0	0	0
-0.35 to -0.3	0	0	0	0	0	0
-0.3 to -0.25	3,210	0	-40	0	40	0
-0.25 to -0.2	13,510	5,070	-460	-70	460	70
-0.2 to -0.15	24,030	18,600	-1,390	-660	1,390	660
-0.15 to -0.1	46,280	35,400	-3,020	-1,960	3,020	1,960
-0.1 to -0.05	143,390	111,280	-7,480	-5,090	7,480	5,090
-0.05 to 0	1,349,280	1,472,880	-28,660	-24,510	28,660	24,510
0 to 0.05	1,525,700	1,514,480	28,260	23,150	28,260	23,150
0.05 to 0.1	122,710	80,590	3,060	1,570	3,060	1,570
0.1 to 0.15	17,360	8,830	440	100	440	100
0.15 to 0.2	1,640	0	10	0	10	0
0.2 to 0.25	0	0	0	0	0	0
0.25 to 0.3	0	0	0	0	0	0
0.3 to 0.35	0	0	0	0	0	0
0.35 to 0.4	0	0	0	0	0	0
0.4 to 0.45	0	0	0	0	0	0
0.45 to 0.5	0	0	0	0	0	0

Four observation points over Flora Bank were selected to analyse TSS during the 3 month stormy period. The location of the observation points are displayed in Figure H-77.
Figure H-78 shows a time series of the depth averaged TSS concentration over the 3 month stormy period for both the existing and proposed conditions at four observations points over Flora Bank. The time series illustrate that TSS concentrations are very similar for both the existing and proposed conditions. However, because of the attenuating effect the proposed marine structures have on waves propagating toward Flora Bank the proposed conditions appear to produce, in general, slightly lower TSS concentrations.

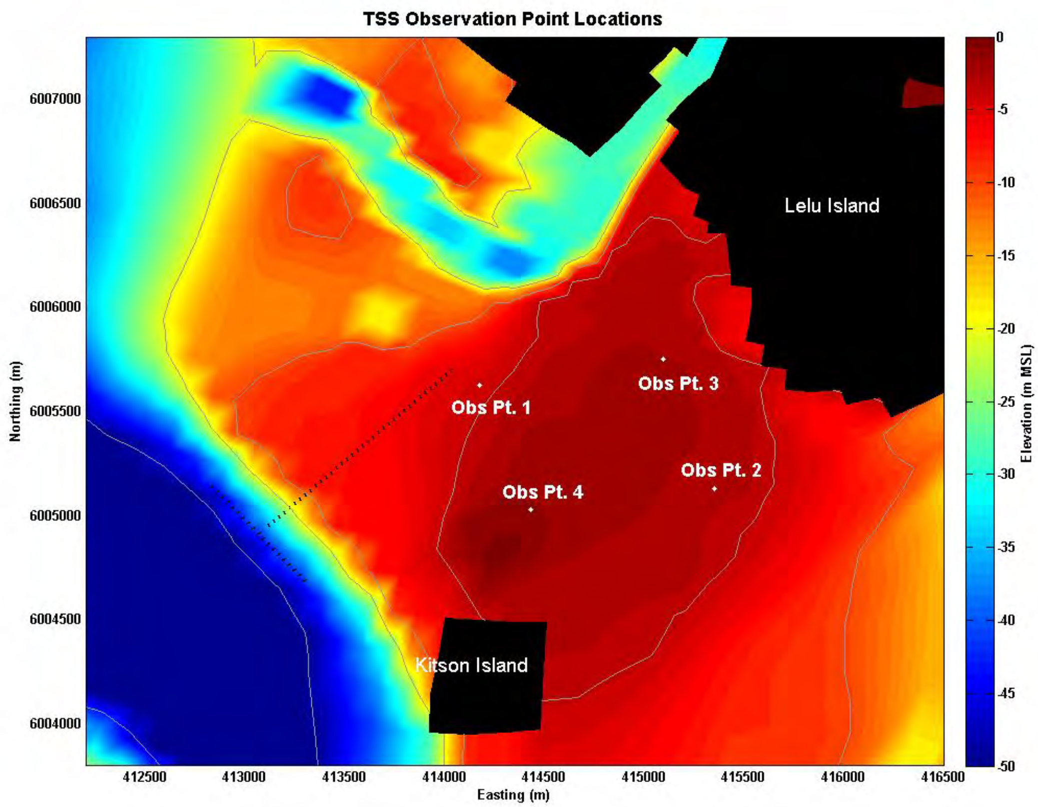


Figure H-77: Location of TSS Observation Points.

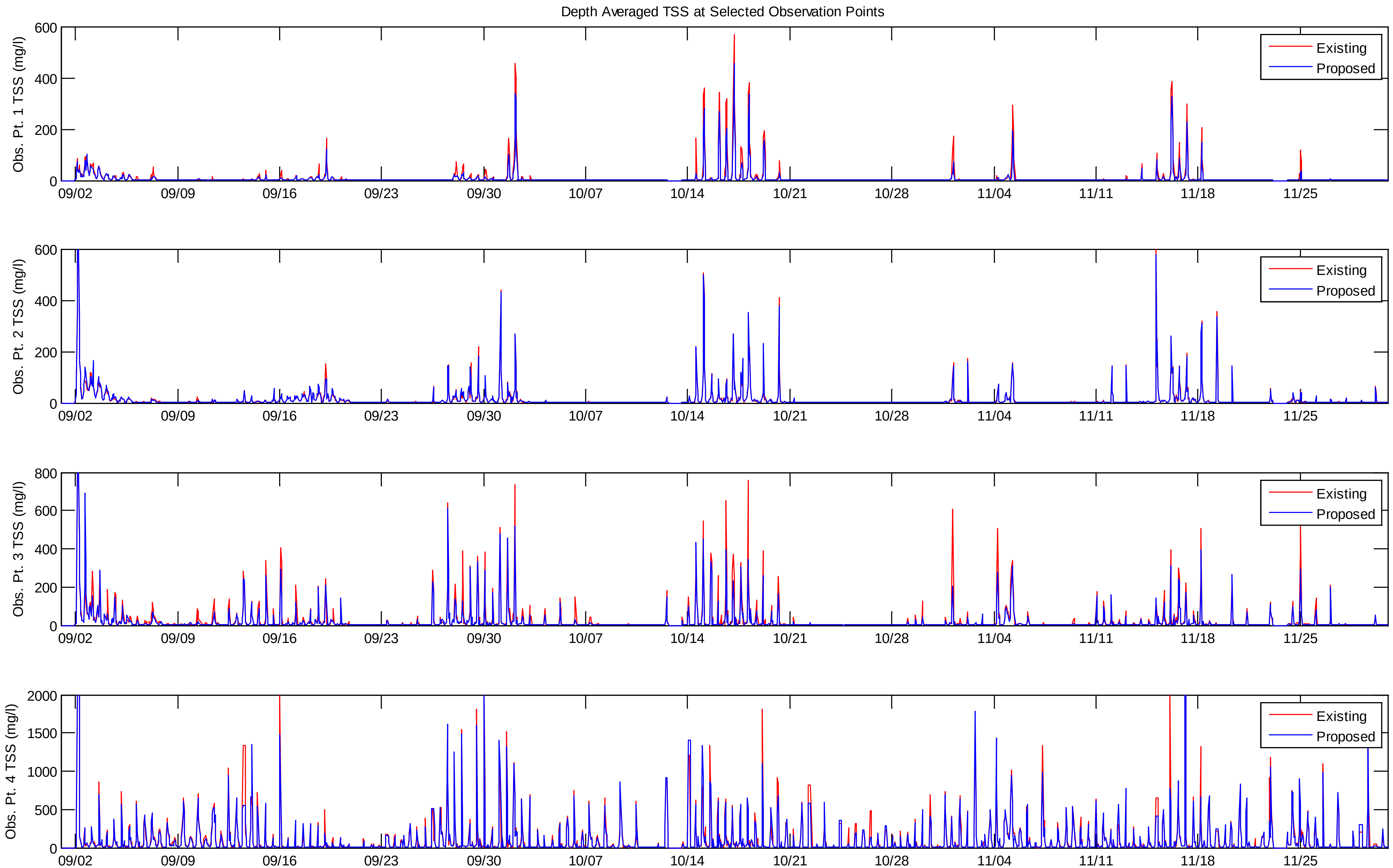


Figure H-78: 3 Month Stormy Period Time Series (Note the different scale for each observation point).

Safety • Quality • Sustainability • Innovation

Statistics on the above time series data were also analyzed to more quantitatively describe potential impacts of TSS changes. Table H-9 provides percentages of time over the 3 month stormy period that either existing or proposed conditions generated TSS concentrations that were 5 mg/l or 25 mg/l greater than the other. This again illustrates that the existing conditions produce larger TSS concentrations more often than the proposed conditions. This table also highlights the larger difference in TSS concentrations that occur in locations with more wave energy such as the Observation Point 4 just above Kitson Island.

Table H-9: 3 Month Stormy Period Time Series Exceedance Statistics.

3 month 1–hour coupling "stormy" run	Percent of time Proposed TSS is 5 mg/l greater than Existing TSS	Percent of time Proposed TSS is 25 mg/l greater than Existing TSS	Percent of time Existing TSS is 5 mg/l greater than Proposed TSS	Percent of time Existing TSS is 25 mg/l greater than Proposed TSS
Obs. Point 1: East, near mid-trestle	0.4	0.0	7.7	3.2
Obs. Point 2: Eastern edge	3.3	0.4	2.8	0.3
Obs. Point 3: Northern central	2.7	0.8	18.4	6.7
Obs. Point 4: Above Kitson Island	12.4	5.5	26.1	12.2

Finally, histograms showing the duration of events causing an increase in TSS over 5 mg/l and 25 mg/l were generated for each observation station and are presented in Figure H–79 to Figure H–82. These histograms indicate that increases in TSS are typically not sustained for very long periods of time.

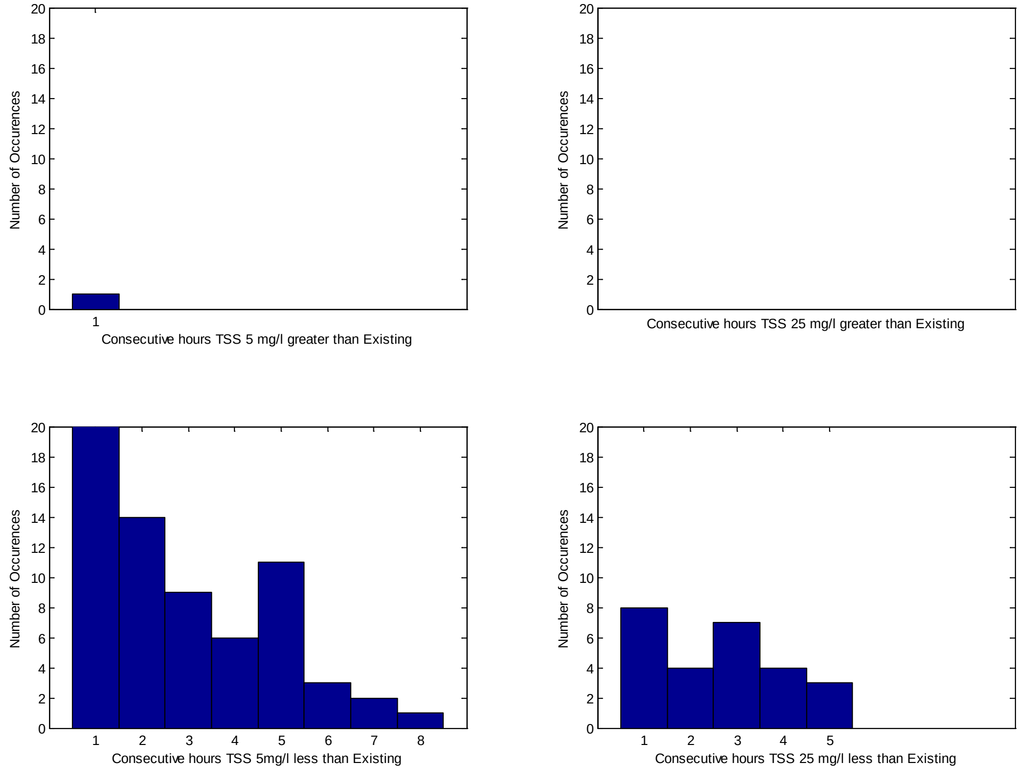


Figure H–79: Observation Point 1 Histogram

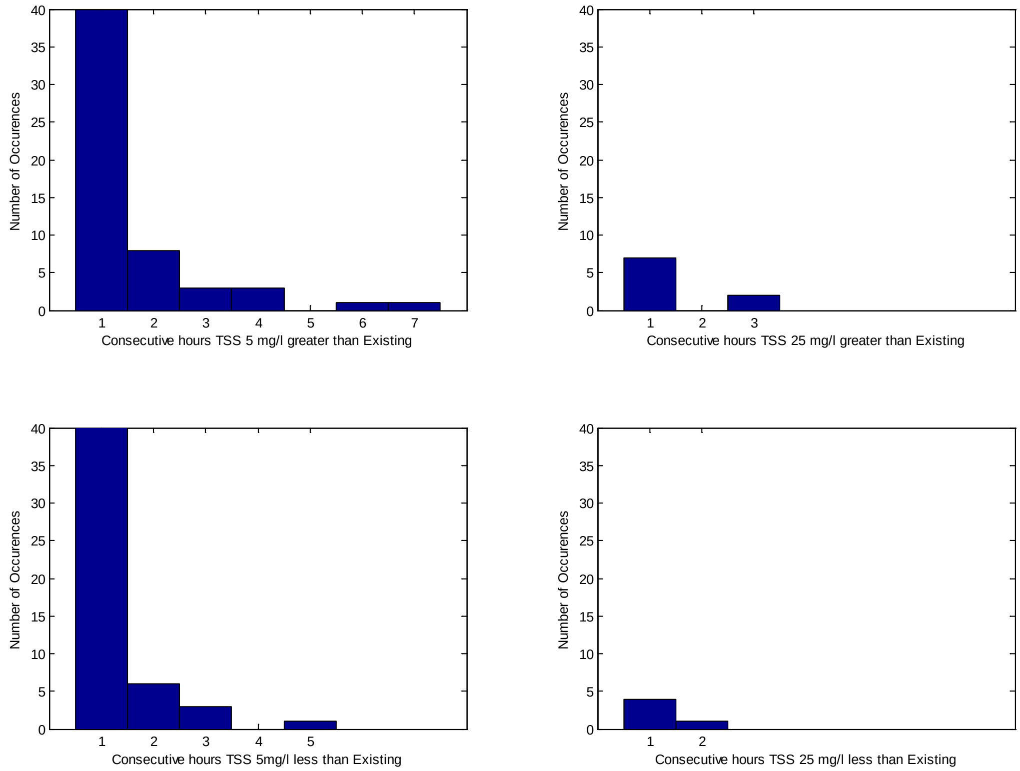


Figure H–80: Observation Point 2 Histogram

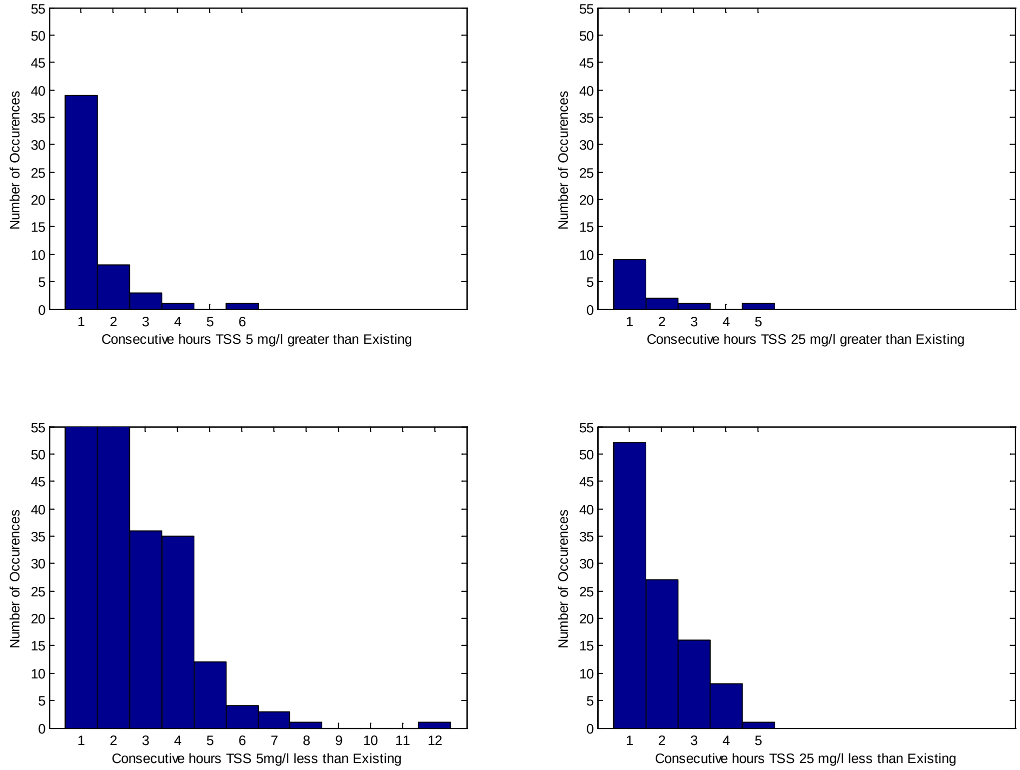


Figure H–81: Observation Point 3 Histogram

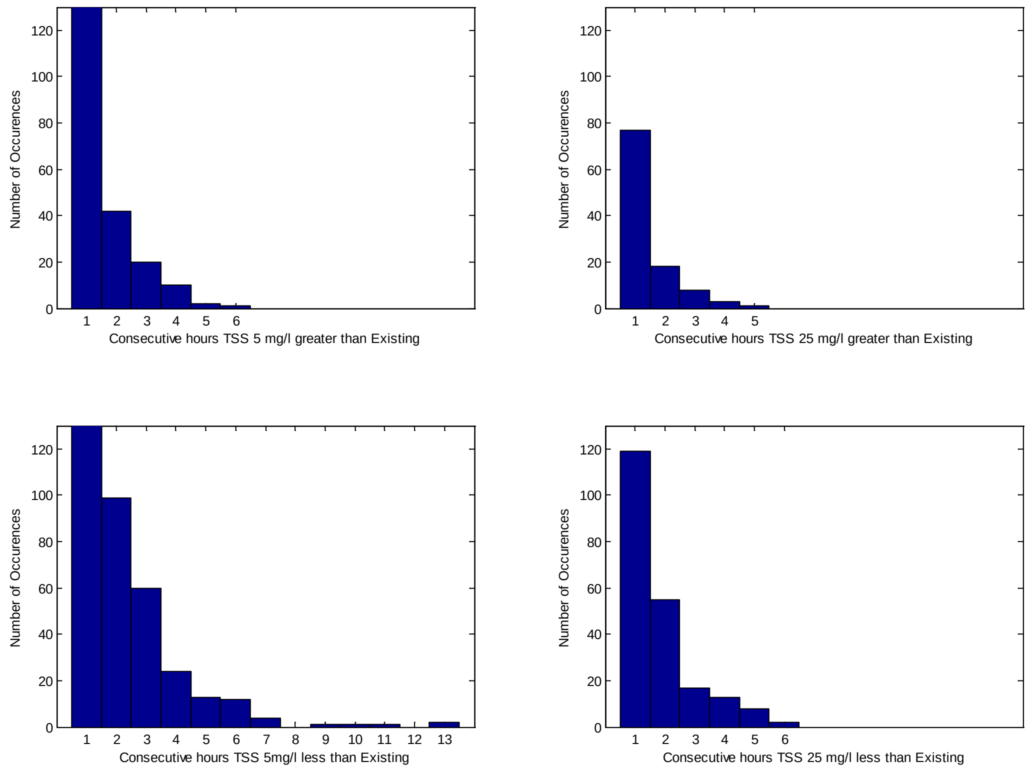


Figure H–82: Observation Point 4 Histogram

H1.2.1 Largest Storm in Annual Stormy Period

In order to further evaluate the impacts of the marine structures during the stormy season a naturally occurring storm was selected. An additional shorter-term simulation of a 6 day stormy period (October 13, 2012 to October 18, 2012) was analyzed to quantify the impact of marine structures on the coastal processes.

As an example of the complete range of background hydrodynamic conditions that are present during the 6 day simulation Figure H–84 shows a time history of water depth, velocity, and wave heights at the west side of Flora Bank (location shown Figure H–83).

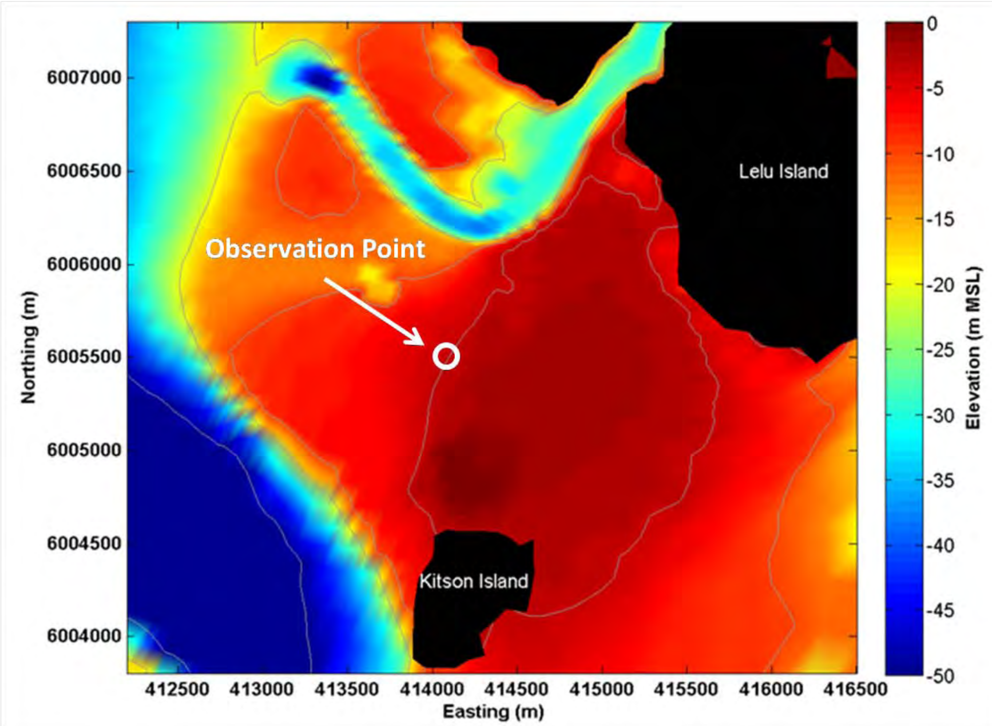


Figure H–83:Location of observation point for time histories shown in Figure H–84.

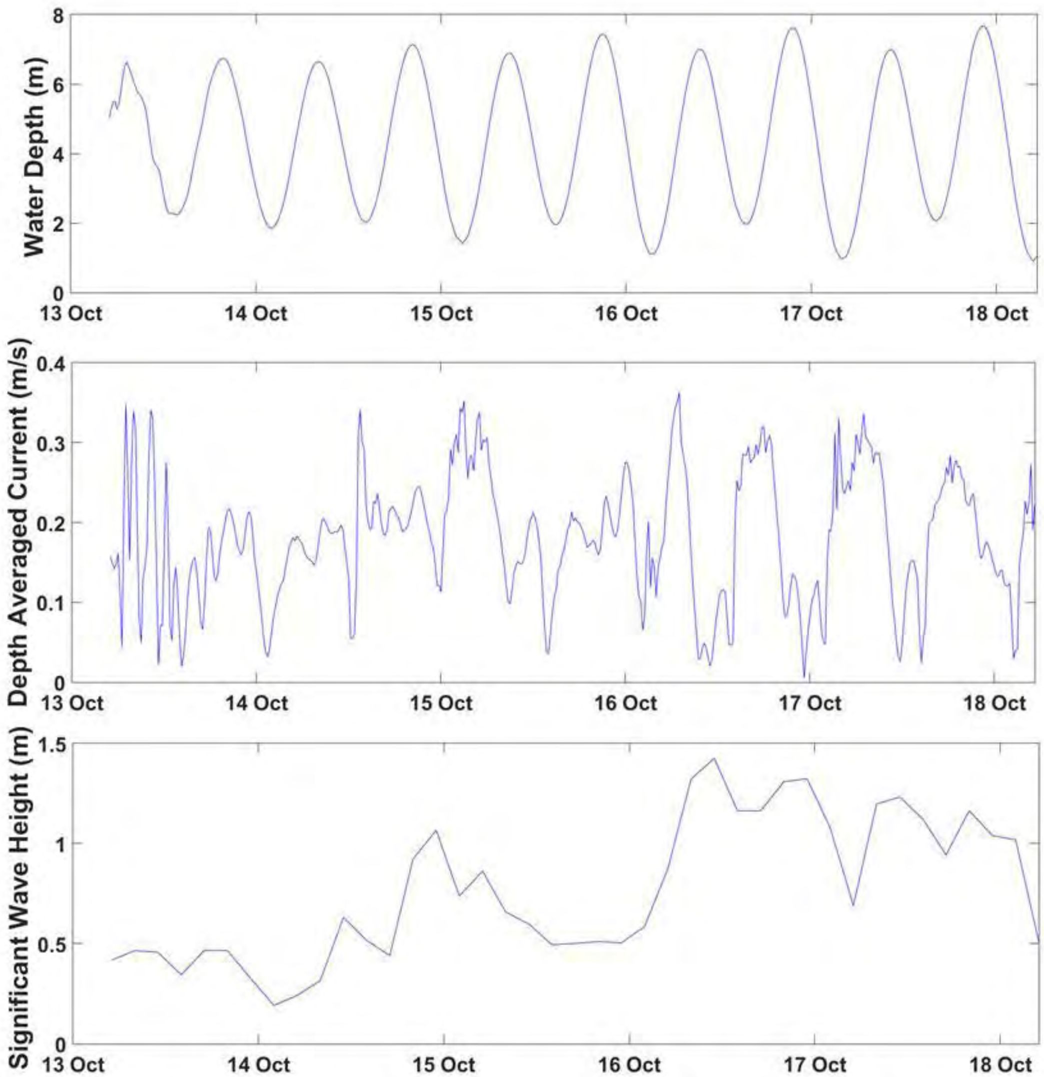


Figure H–84: Water level, depth averaged current, and significant wave height at observation point shown in Figure H–83 for 6 day period.

Figure H–85 to Figure H–90 show the significant wave heights, ebb currents, flood currents, total transport flux, net transport flux, and morphological changes, respectively, for the existing conditions (top) and proposed conditions (bottom).

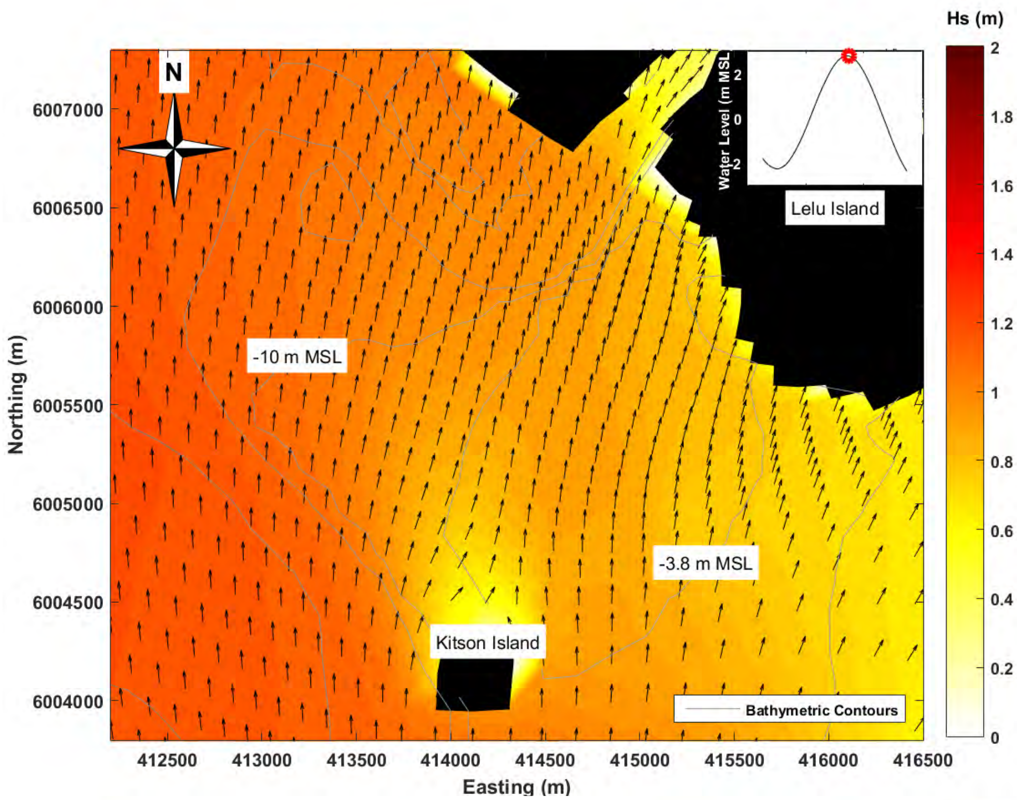
Figure H–85 shows the significant wave heights around Flora Bank at the peak of storm. The wave conditions are moderate and approaching the project area from the south during the storm. The wave height over Flora Bank is approximately 1.0 m. The marine structures only have a local influence on the wave height and wave direction.

Figure H–86 and Figure H–87 show snapshots of depth averaged ebb and flood currents at the peak of the storm, respectively. The magnitude of peak currents (ebb and flood) over

Flora Bank and Agnew Bank are approximately 0.25 m/s. The influence of marine structures on storm-induced currents is marginal.

Figure H–88 shows the total transport flux at the peak of the storm. Figure H–89 shows the net total transport flux computed throughout the 6 day simulation period.

Figure H–90 shows the morphological changes predicted around Flora Bank following the storm with and without structures. Results indicate that Flora Bank experiences minimal morphological changes during the storm.


Hs (m)
N
Northing (m)
Easting (m)
Water Level (m MSL)
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours

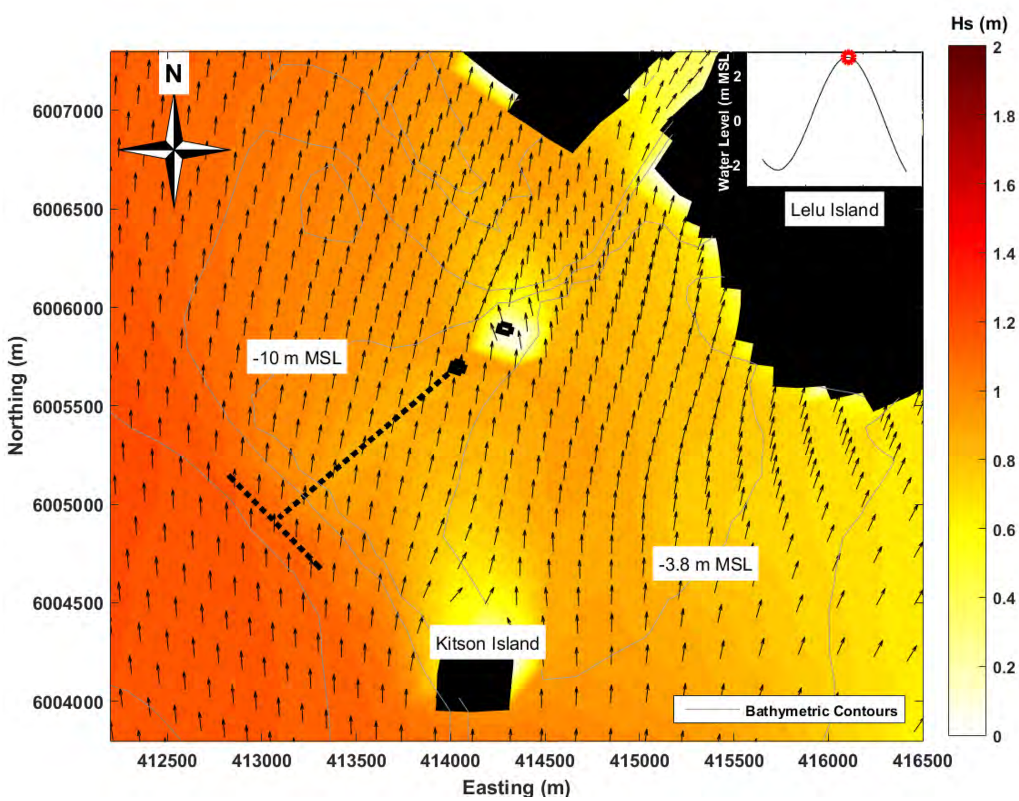
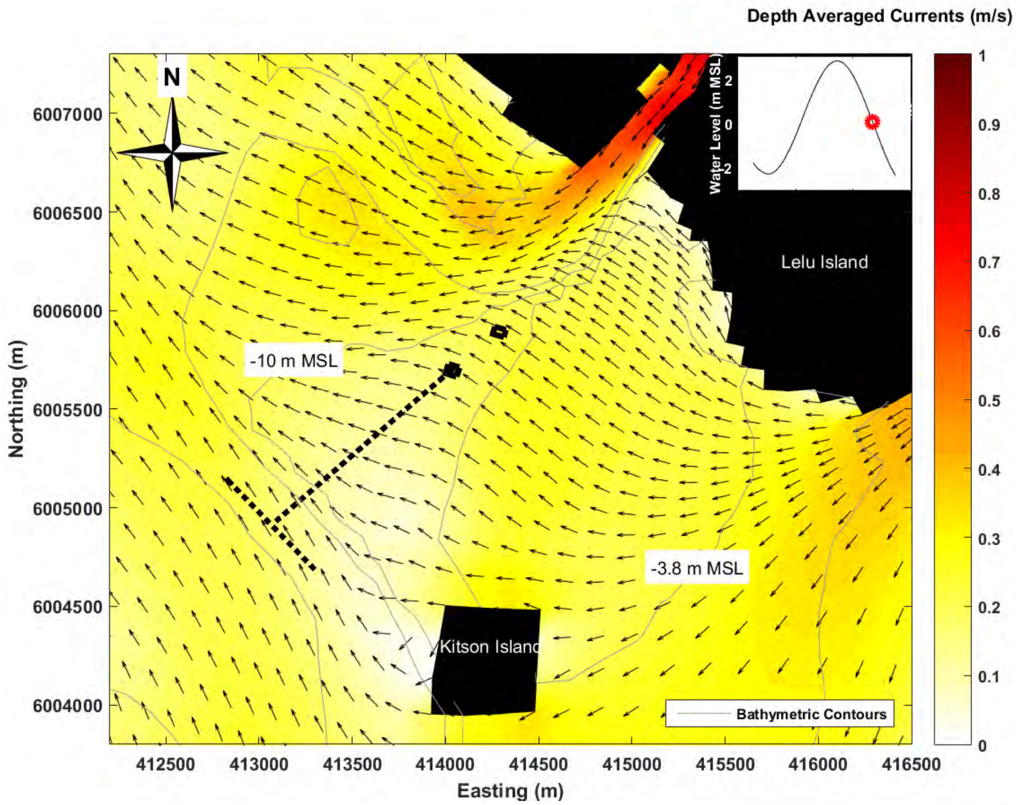

Hs (m)
N
Northing (m)
Easting (m)
Water Level (m MSL)
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours

Figure H–85: Significant Wave Height snapshots at time of mid-October storm for existing (top) and proposed (bottom) conditions.


Depth Averaged Currents (m/s)
N
Water Level (m MSL)
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
Easting (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500
413000
413500
414000
414500
415000
415500
416000
416500
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

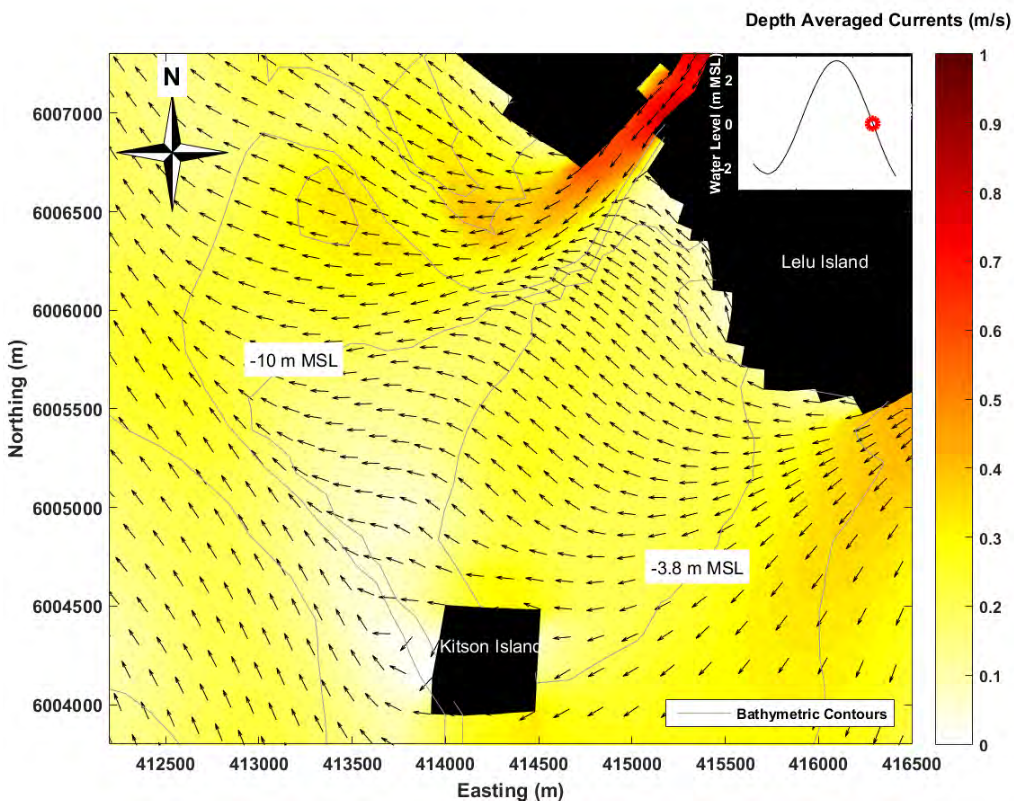
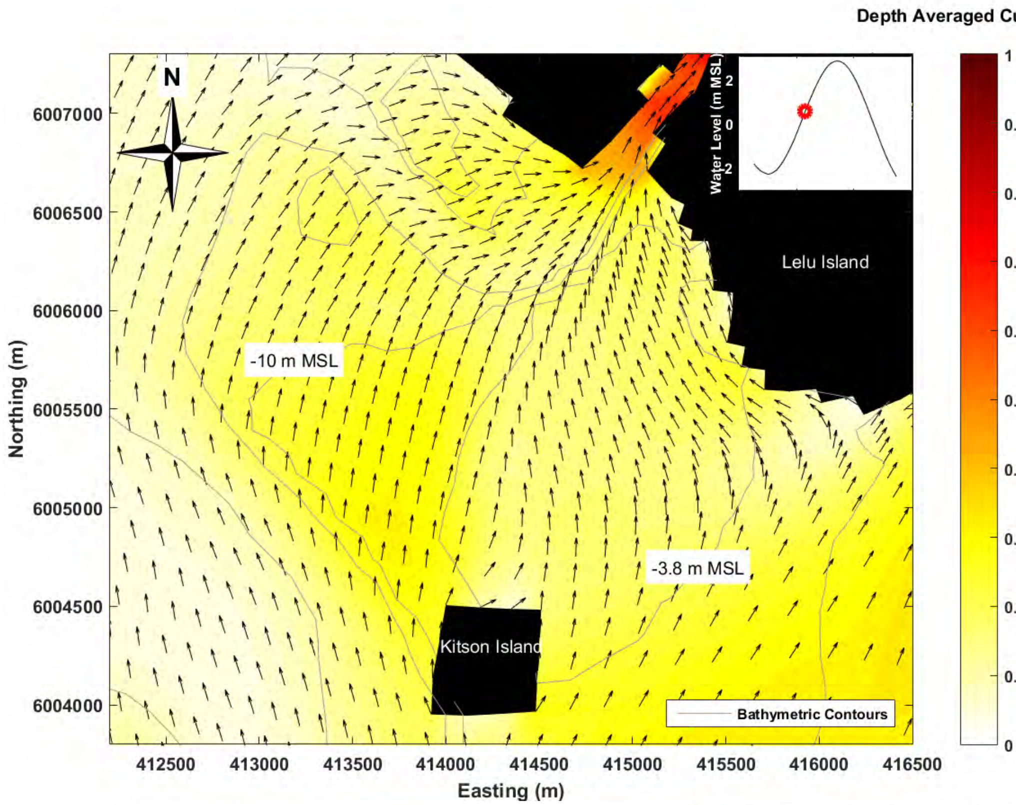

Depth Averaged Currents (m/s)
N
Water Level (m MSL)
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
Easting (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500
413000
413500
414000
414500
415000
415500
416000
416500
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure H–86: Ebb current snapshots at time of mid-October storm for existing (top) and proposed (bottom) conditions.


Depth Averaged Cu
N
Water Level (m MSL)
2
0
-2
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500
413000
413500
414000
414500
415000
415500
416000
416500
Easting (m)
1
0

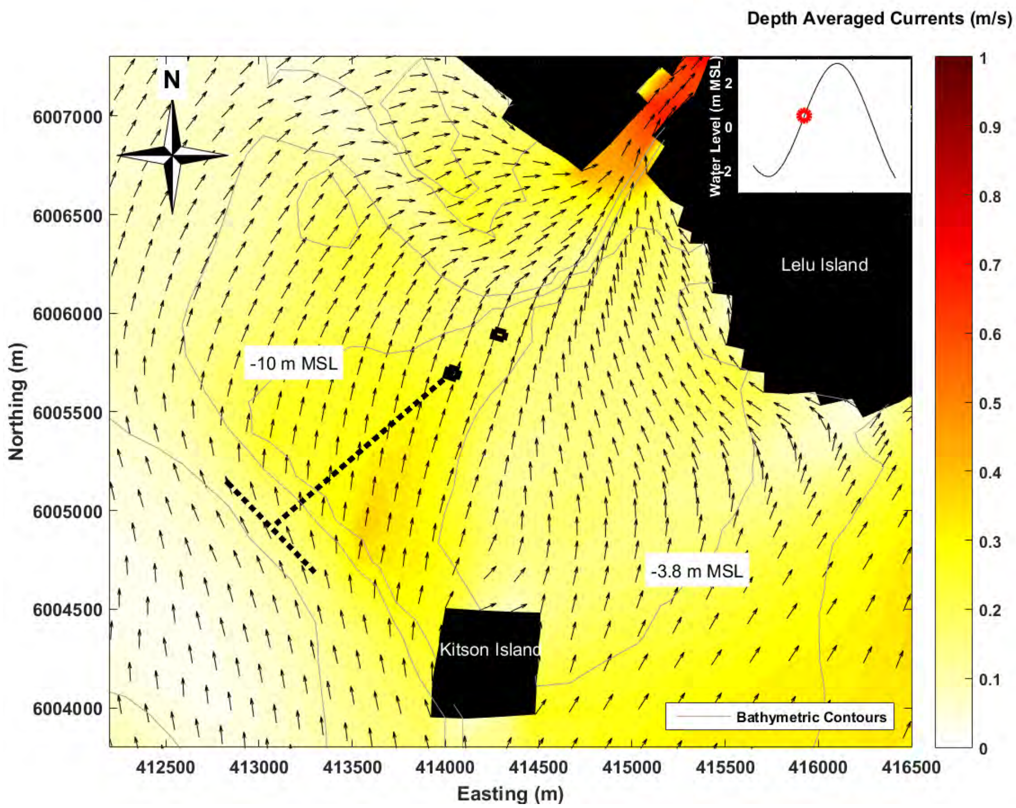
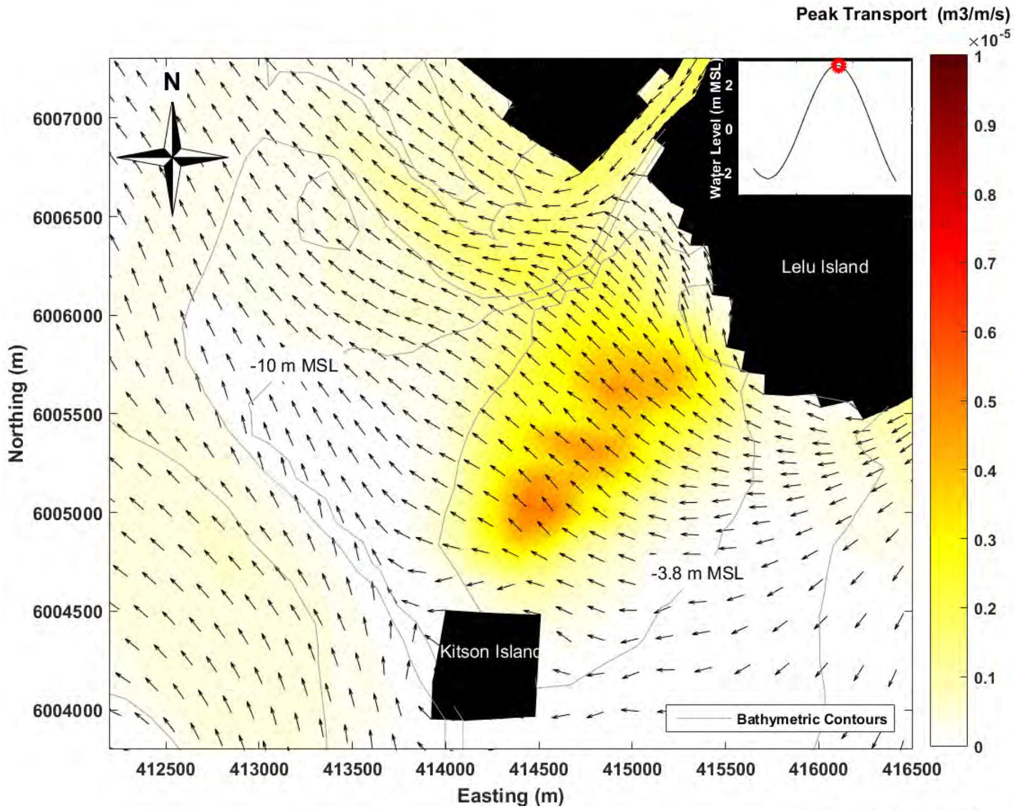
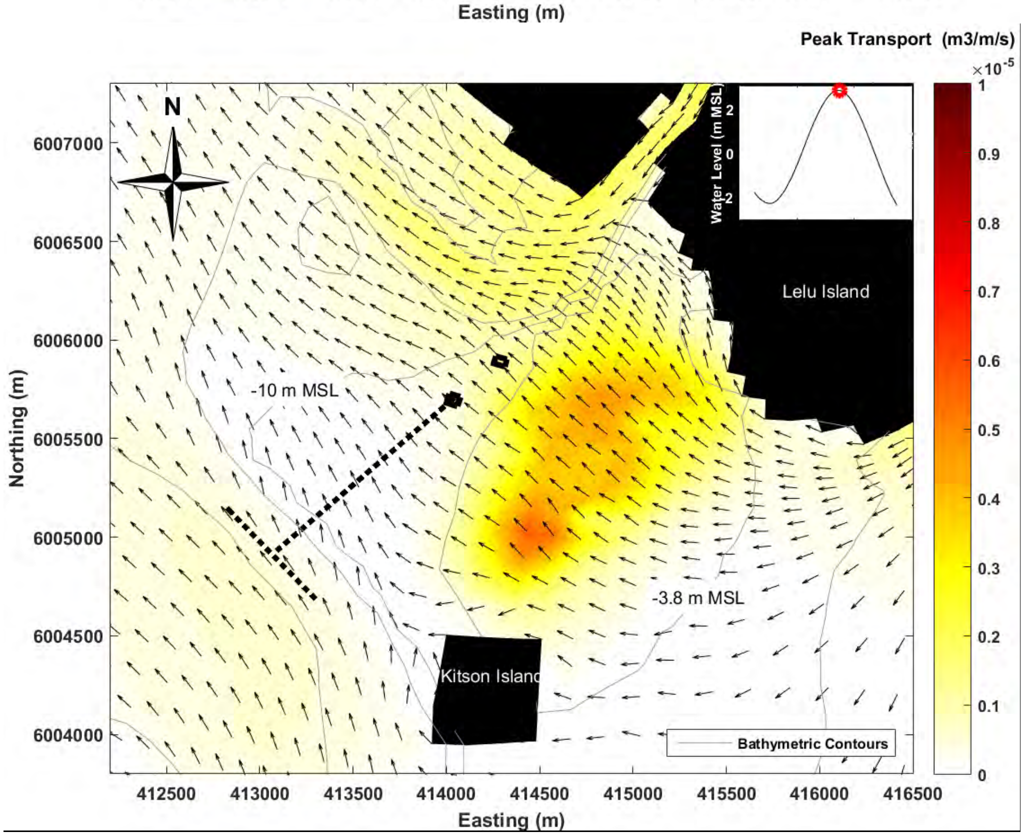

Depth Averaged Currents (m/s)
N
Water Level (m MSL)
2
0
-2
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500
413000
413500
414000
414500
415000
415500
416000
416500
Easting (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

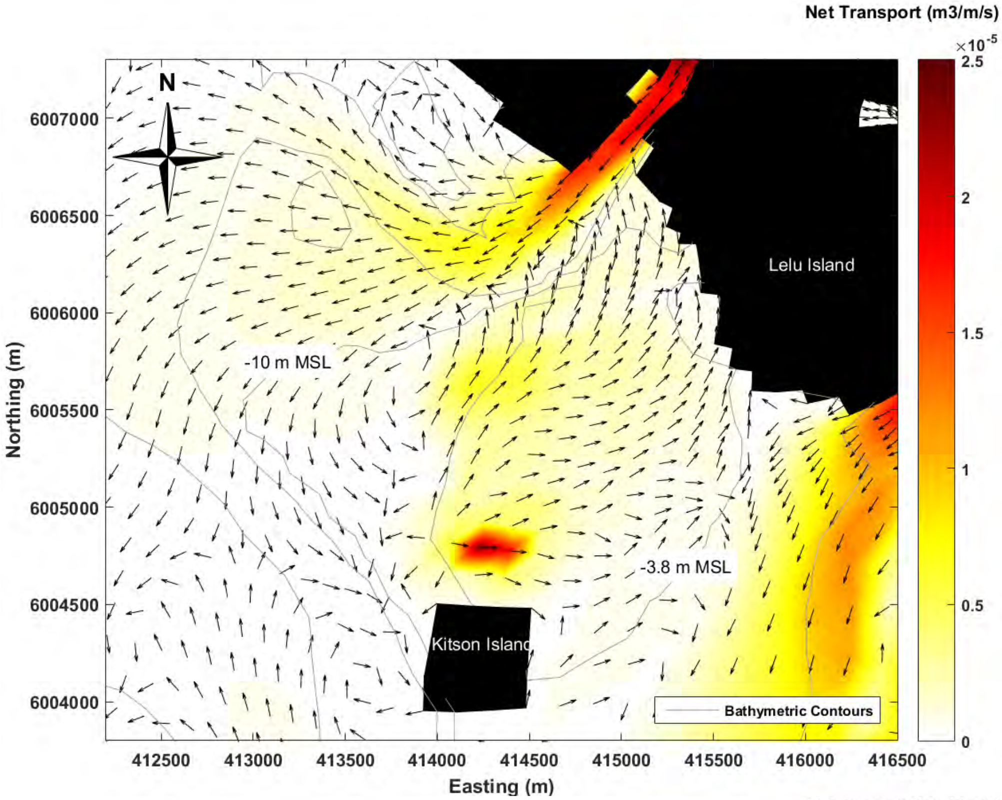
Figure H–87: Flood current snapshots at time of mid-October storm for existing (top) and proposed (bottom) conditions.

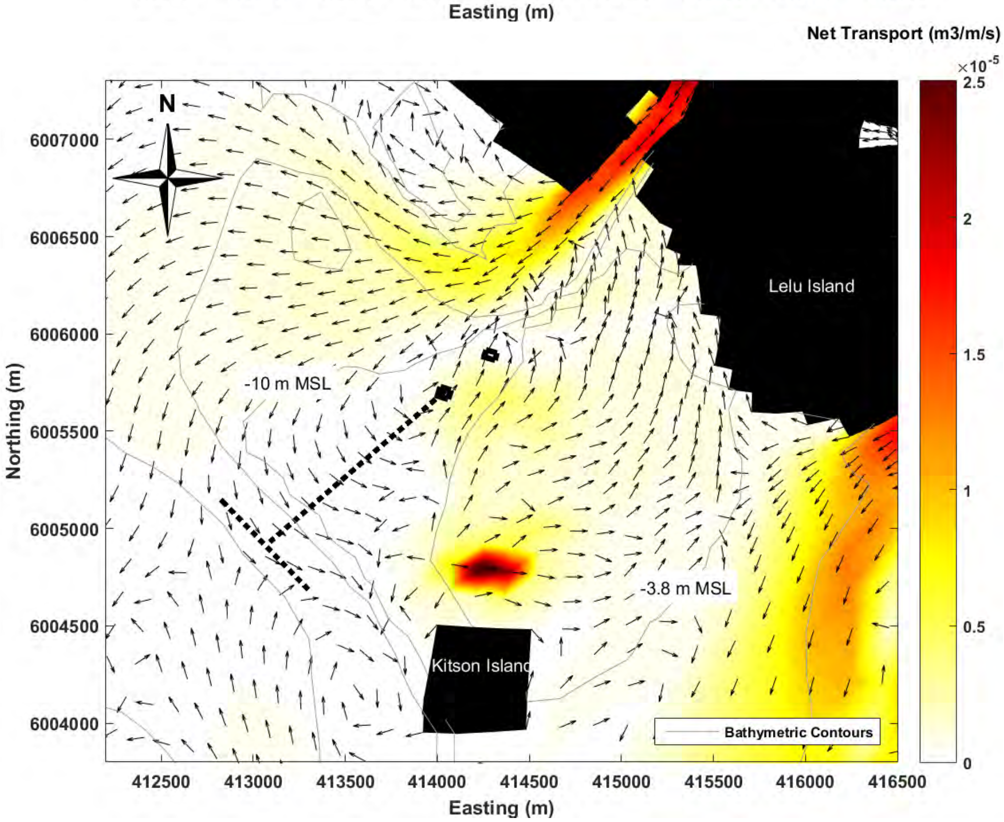




Safety • Quality • Sustainability • Innovation

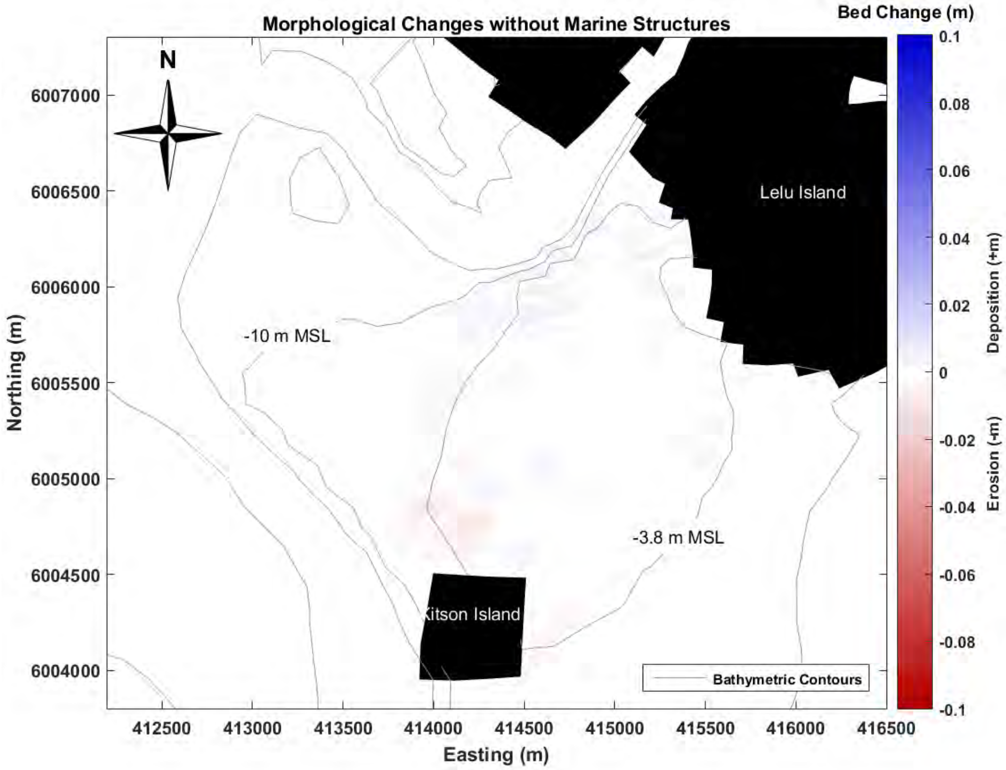
Figure H–88: Total transport flux snapshots at time of mid-October storm for existing (top) and proposed (bottom) conditions.





Safety • Quality • Sustainability • Innovation

Figure H–89: Net transport flux snapshots at time of mid-October storm for existing (top) and proposed (bottom) conditions.



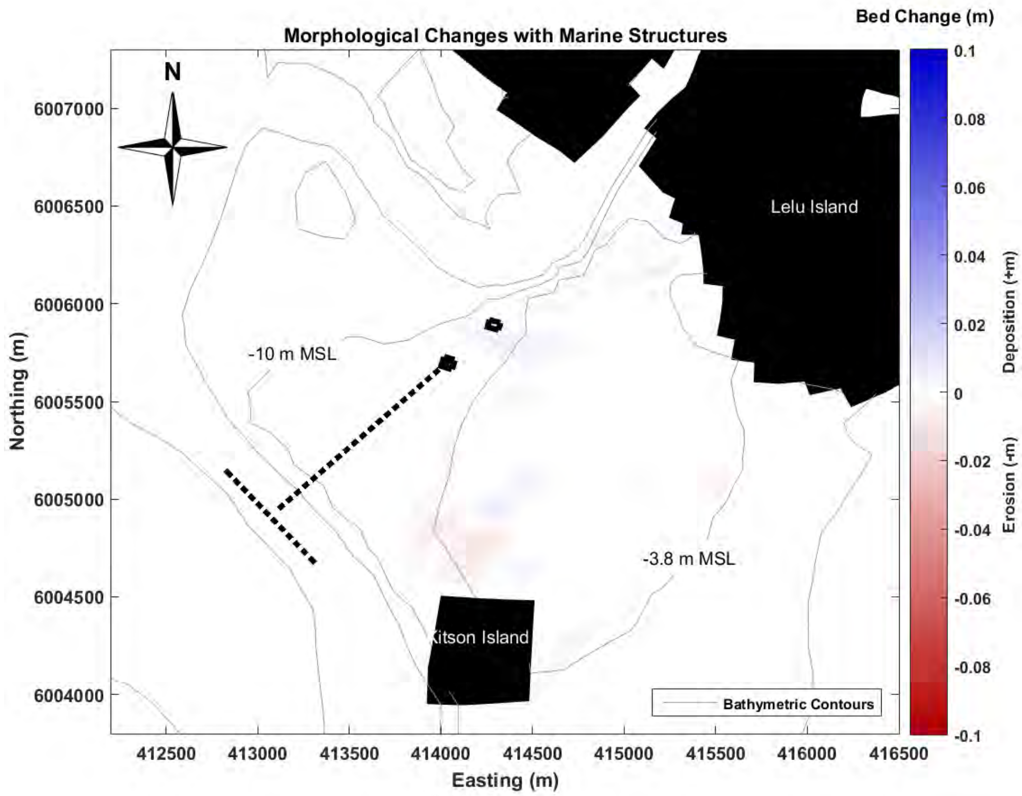


Figure H–90: Morphological changes during mid-October storm for existing (top) and proposed (bottom) conditions. NOTE: +/- 0.1 m color scale.

H1.3 Simulations of the Calmer Period (4 months)

This section provides additional morphology and TSS data for the annual calmer period (4 months).

To examine the data in Table 5-2 and Table 6-4 from the main report in more detail, statistics for erosion and deposition intervals for both existing and proposed conditions on Flora Bank have been included in Table H-10. The majority of morphological change on Flora Bank during this calmer period is within or close to the -0.05 m to 0.05 m range of elevation change.

Table H-10:Volume and Area Changes on Flora Bank for the 4 Month Summer Period (3-hr Coupling).

Safety • Quality • Sustainability • Innovation

	Area [m²]		Volumes [m³]		Absolute Volumes [m³]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.5 to -0.45	0	0	0	0	0	0
-0.45 to -0.4	0	0	0	0	0	0
-0.4 to -0.35	0	0	0	0	0	0
-0.35 to -0.3	0	0	0	0	0	0
-0.3 to -0.25	0	0	0	0	0	0
-0.25 to -0.2	0	0	0	0	0	0
-0.2 to -0.15	1740	0	0	0	0	0
-0.15 to -0.1	49160	8080	-1290	-20	1290	20
-0.1 to -0.05	98950	89560	-4600	-2590	4600	2590
-0.05 to 0	1207910	1328560	-18240	-14120	18240	14120
0 to 0.05	1835650	1792750	18560	14230	18560	14230
0.05 to 0.1	48290	28180	1200	430	1200	430
0.1 to 0.15	5420	0	30	0	30	0
0.15 to 0.2	0	0	0	0	0	0
0.2 to 0.25	0	0	0	0	0	0
0.25 to 0.3	0	0	0	0	0	0
0.3 to 0.35	0	0	0	0	0	0
0.35 to 0.4	0	0	0	0	0	0
0.4 to 0.45	0	0	0	0	0	0
0.45 to 0.5	0	0	0	0	0	0

Figure H–91 show the depth averaged TSS concentration over the 4 month summer period for both the existing and proposed conditions at four observations points over Flora Bank. The location of the observation points are displayed in Figure H-77 These time series illustrate that TSS concentrations are very similar for both existing and proposed conditions, however, because of the attenuating effect the proposed marine structures have on waves propagating toward Flora Bank this scenario appears to produce slightly lower TSS concentrations in general.

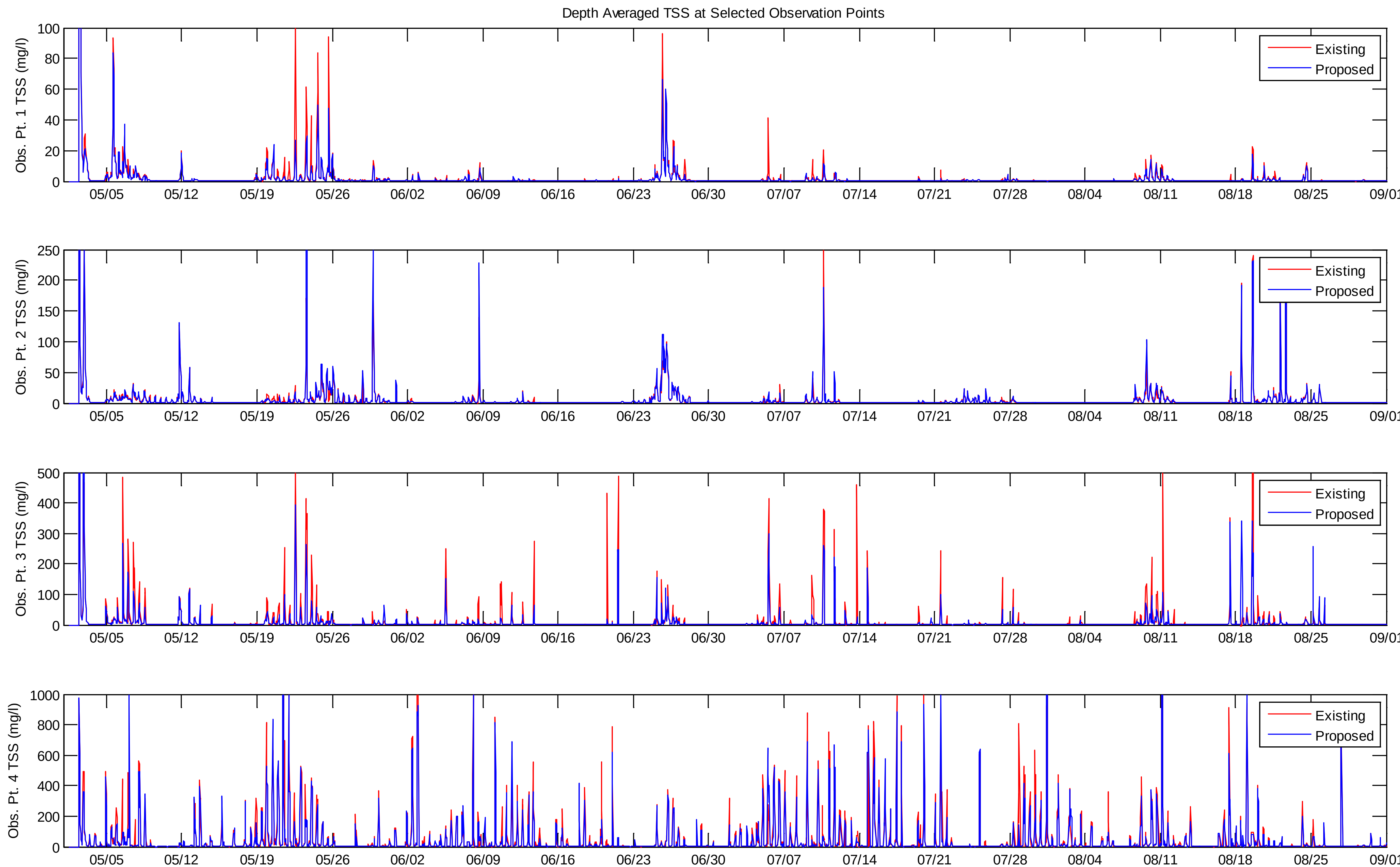


Figure H–91: Summer TSS time series (Note the different scale for each observation point).

Statistics on the above time series data were also analyzed to more quantitatively describe potential impacts of TSS changes. Table H-11 provides percentages of time over the 4 month summer period that either existing or proposed conditions generated TSS concentrations that were 5 mg/l or 25 mg/l greater than the other. This again illustrates that the existing conditions produce larger TSS concentrations more often than the proposed conditions. This table also highlights the larger difference in TSS concentrations that occur in locations with more wave energy such as the observation point just above Kitson Island.

Table H-11: 4 Month Calm Period Time Series Exceedance Statistics

4 month 3–hour coupling "summer" run	Percent of time Proposed TSS is 5 mg/l greater than Existing TSS	Percent of time Proposed TSS is 25 mg/l greater than Existing TSS	Percent of time Existing TSS is 5 mg/l greater than Proposed TSS	Percent of time Existing TSS is 25 mg/l greater than Proposed TSS
Obs. Point 1: East, near mid-trestle	0.1	0.0	1.7	0.3
Obs. Point 2: Eastern edge	1.6	0.4	1.3	0.2
Obs. Point 3: Northern central	1.5	0.5	8.5	3.9
Obs. Point 4: Above Kitson Island	7.0	3.5	19.9	9.0

Histograms showing the duration of events causing an increase in TSS over 5 mg/l and 25 mg/l were generated for each observation station and presented in Figure H–92 to Figure H–95. These histograms indicate that increases in TSS are typically not sustained for very long periods of time.

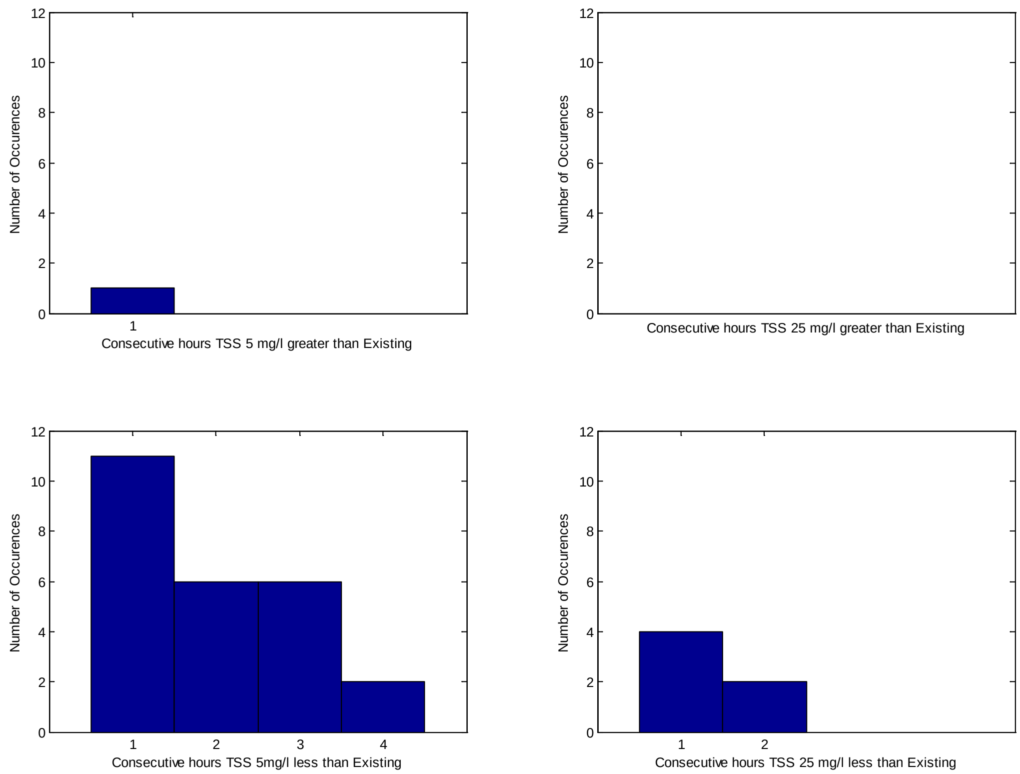


Figure H–92: Observation Point 1 Histogram

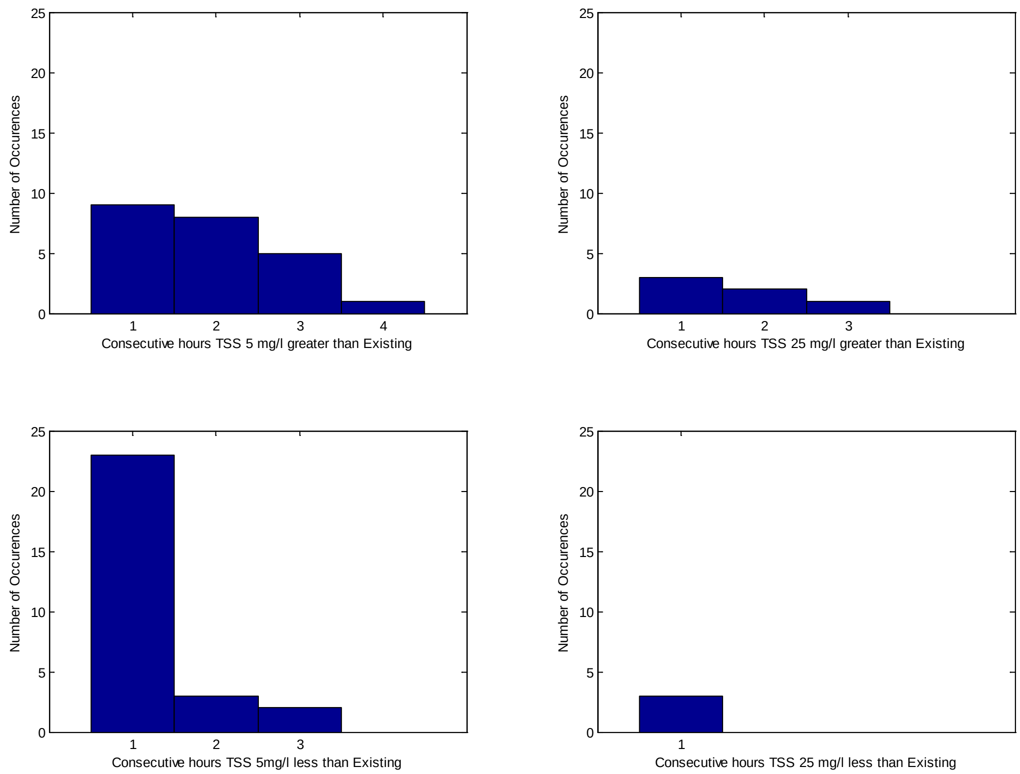


Figure H–93: Observation Point 2 Histogram

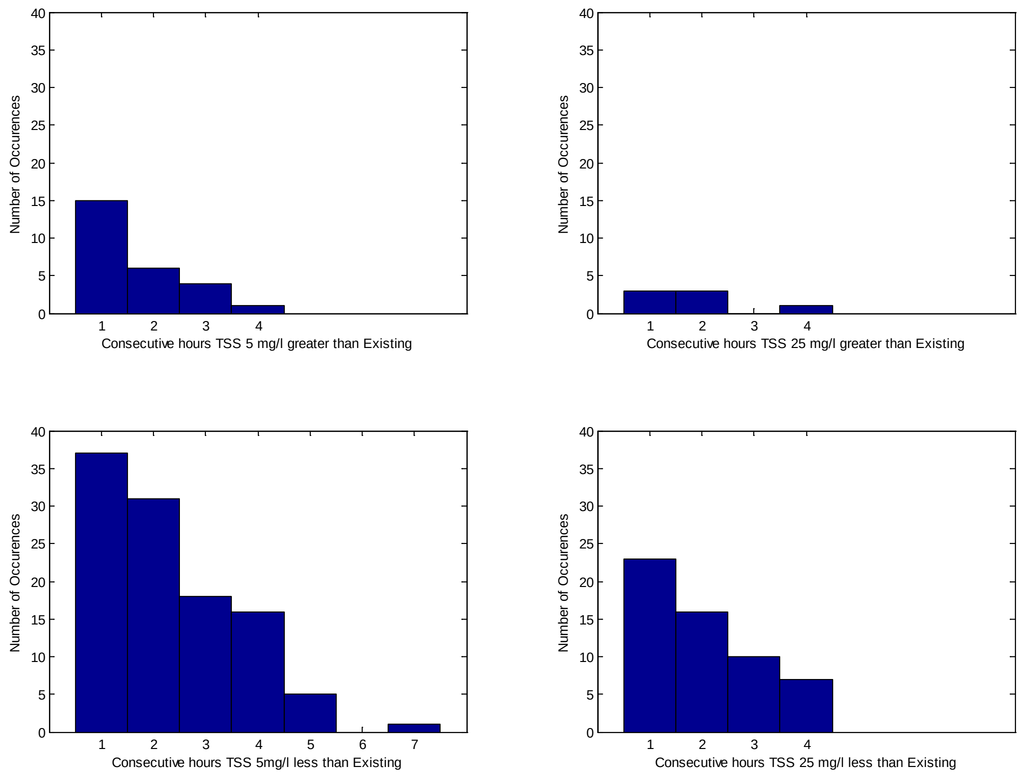


Figure H–94: Observation Point 3 Histogram

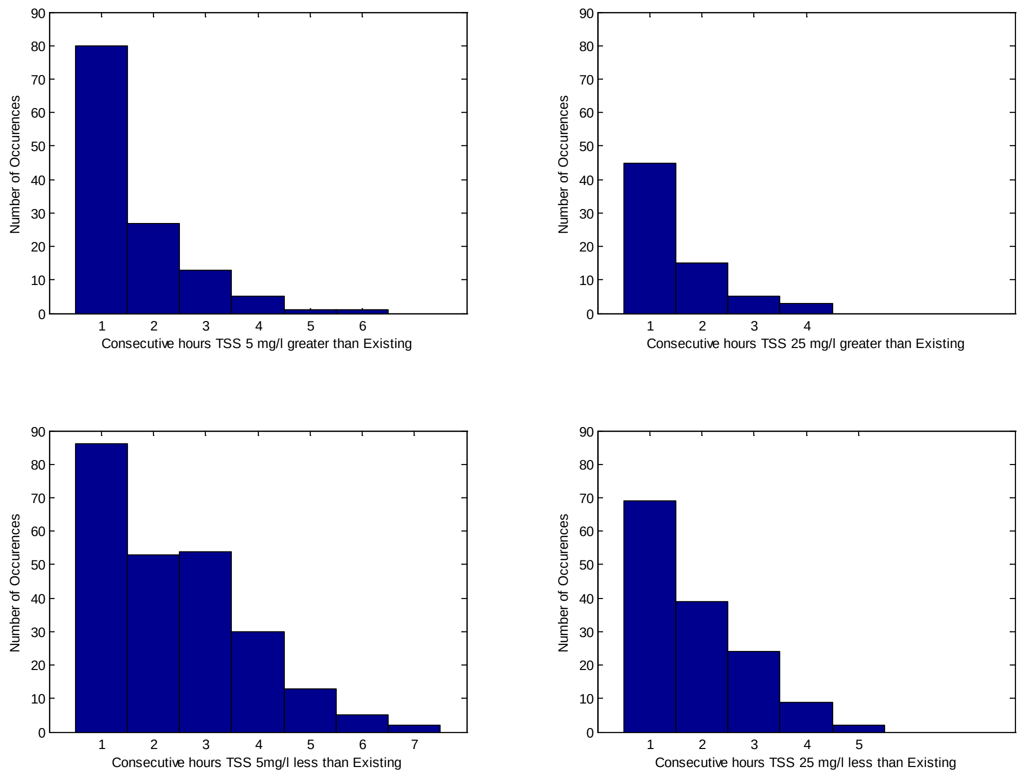


Figure H–95: Observation Point 4 Histogram

H1.4 Freshet Conditions

Additional results from the freshet simulation run from May 11, 2014 to June 8, 2014 are presented in this section. This simulation covers a time frame of the year with the highest volume of discharge from Skeena River and the least energetic wave conditions which causes minor morphological changes over Flora Bank. The main discussion of this simulation is included in Section 5.2 and Section 6.1.3 of the main report.

To examine the data in Table 6-2 (main report) in more detail, statistics for erosion and deposition intervals for both existing and proposed conditions on Flora Bank have been included in Table H-12 and Figure 6-16 (main report). These data show that the morphology changes during calmer periods (without high waves) are minimal.

Table H-12: Volume and Area Changes on Flora Bank for the 28-day Freshet Period

	Area [m²]		Volumes [m³]		Absolute Volumes [m³]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.5 to -0.45	0	0	0	0	0	0
-0.45 to -0.4	0	0	0	0	0	0
-0.4 to -0.35	0	0	0	0	0	0
-0.35 to -0.3	0	0	0	0	0	0
-0.3 to -0.25	0	0	0	0	0	0
-0.25 to -0.2	0	0	0	0	0	0
-0.2 to -0.15	0	0	0	0	0	0
-0.15 to -0.1	0	0	0	0	0	0
-0.1 to -0.05	0	0	0	0	0	0
-0.05 to 0	887750	841750	-650	-810	650	810
0 to 0.05	2357870	2405390	1490	1400	1490	1400
0.05 to 0.1	860	0	50	0	50	0
0.1 to 0.15	500	0	20	0	20	0
0.15 to 0.2	140	0	0	0	0	0
0.2 to 0.25	0	0	0	0	0	0
0.25 to 0.3	0	0	0	0	0	0
0.3 to 0.35	0	0	0	0	0	0
0.35 to 0.4	0	0	0	0	0	0
0.4 to 0.45	0	0	0	0	0	0
0.45 to 0.5	0	0	0	0	0	0

H1.5 Tide-Dominant Conditions

This section presents the results obtained during a 28-day period simulation using only the tides as the forcing condition. Winds, offshore waves, and river discharge were not included in this sensitivity test. The same simulation was conducted for the existing and proposed conditions to evaluate the impact of the marine structures on the purely tidal currents. The effects of the marine structures on the current velocity patterns, sediment transport and bed changes during tide-dominant conditions are presented in the following figures.

Instantaneous depth-averaged currents for existing and proposed conditions as well as the instantaneous difference during flood and ebb tides are presented in Figure H–96 and Figure H–97, respectively, where it shows that the depth-averaged currents are strong in Porpoise Channel, with velocities close to 1 m/s; however the currents on Flora Bank and Agnew Bank are below 0.4 m/s. The difference plots (bottom) indicate changes localized around the marine structures in the depth averaged current velocity during flood and ebb tides.

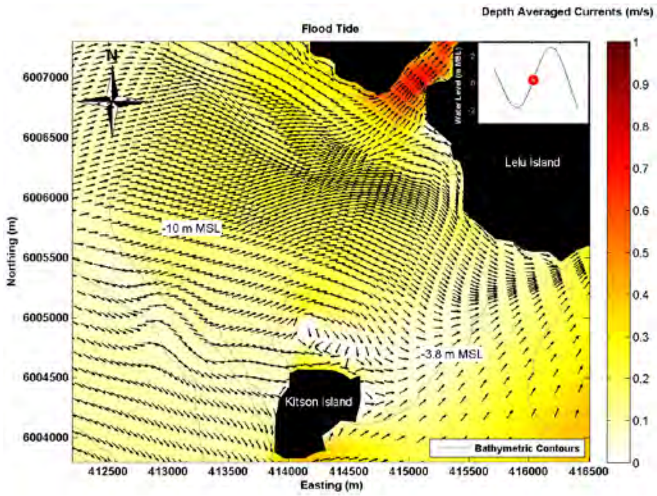
The net depth-averaged current velocity (Figure H–98) indicates that the ebb currents are slight more dominant than the flood currents and the net velocity is towards west-northwest on Flora Bank during tide-dominant periods. The net current change between the existing and proposed conditions during the 28 day of simulation demonstrates that the changes are localized around the trestle, SW Anchor Block and SW Tower.

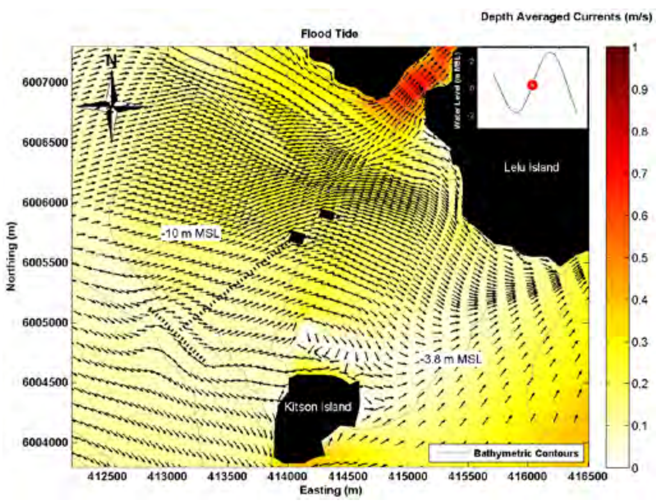
Figure H–99 shows the instantaneous sediment transport during the same flood and ebb tidal stages (presented before) for existing conditions, where the sediments are only mobile at the channels. Figure H–100 shows the instantaneous sediment transport during ebb and flood for the proposed conditions, where no significant differences are observed for the existing and proposed conditions.

The net sediment transport flux (Figure H–103) during the tide-dominant period, indicate that the tidal currents are not capable of transporting large amounts of sediments on Flora Bank. Even with the localized changes in current velocity, the changes in the net sediment transport flux are negligible during the tide-dominant period. The comparison between the net transport flux after 28-days of simulation (Figure H–103, bottom), shows negligible changes for the existing and proposed conditions.

Instantaneous TSS maps during the flood (top) and ebb (bottom) tides are presented in Figure H–102 and Figure H–103 respectively. In both cases, higher TSS concentrations are only observed in Porpoise Channel. The differences between TSS concentrations (Figure H–102 and Figure H–103) in the existing (top) and proposed (bottom) conditions are negligible, as the changes in TSS are only observed in the channels (during tide-dominant conditions) and the marine structures are not changing the flow in those areas.

The net sediment transport is very low over Flora Bank during currents driven only by the tides for existing and proposed conditions, causing minimum morphological changes on Flora Bank (Figure H–104). As the net sediment transport is very similar between existing and proposed conditions, the bed changes shown in Figure H–104 for the existing (top) and proposed (bottom) conditions are also very similar and no changes in the bed morphology are observed on Flora Bank.


Depth Averaged Currents (m/s)
Flood Tide
N
Lelu Island
Kitson Island
-10 m MSL
-3.8 m MSL
Bathymetric Contours
Northing (m)
Easting (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500 413000 413500 414000 414500 415000 415500 416000 416500
1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0


Depth Averaged Currents (m/s)
Flood Tide
N
Lelu Island
Kitson Island
-10 m MSL
-3.8 m MSL
Bathymetric Contours
Northing (m)
Easting (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500 413000 413500 414000 414500 415000 415500 416000 416500
1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0

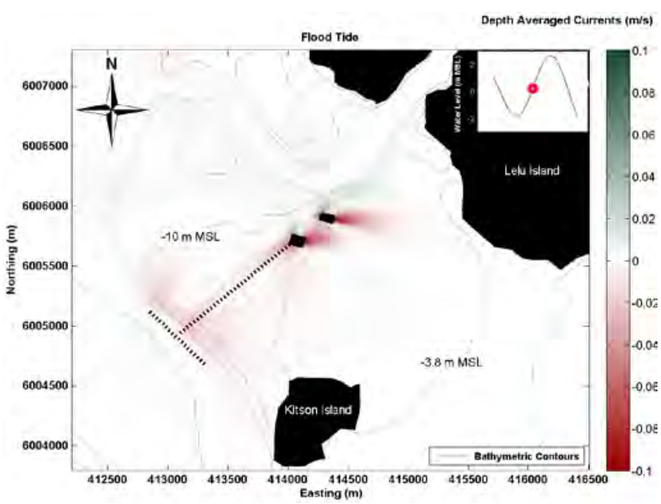
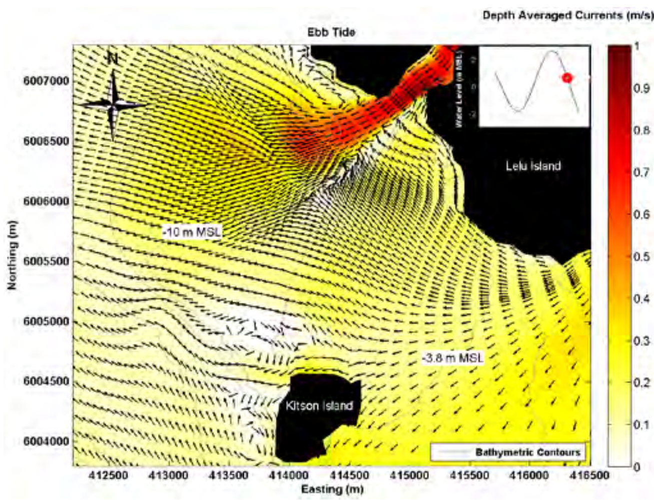
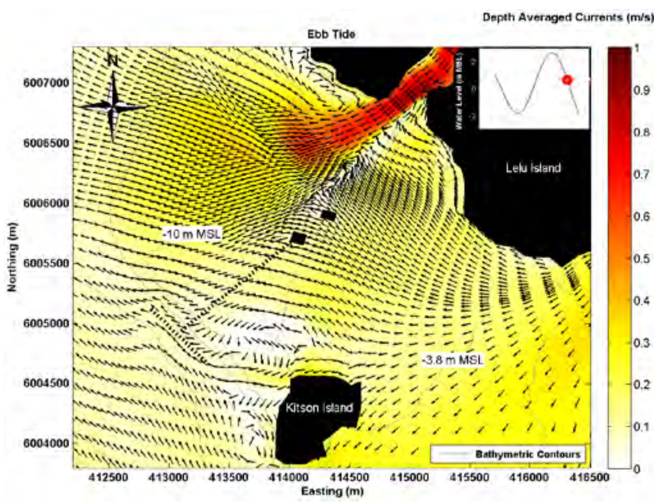

Depth Averaged Currents (m/s)
Flood Tide
N
Lelu Island
Kitson Island
-10 m MSL
-3.8 m MSL
Bathymetric Contours
Northing (m)
Easting (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500 413000 413500 414000 414500 415000 415500 416000 416500
0.1 0.08 0.06 0.04 0.02 0

Figure H–96: Depth averaged instantaneous flood current patterns during the tide-dominant condition for the existing (top) and proposed (middle) conditions, and the instantaneous difference (bottom).





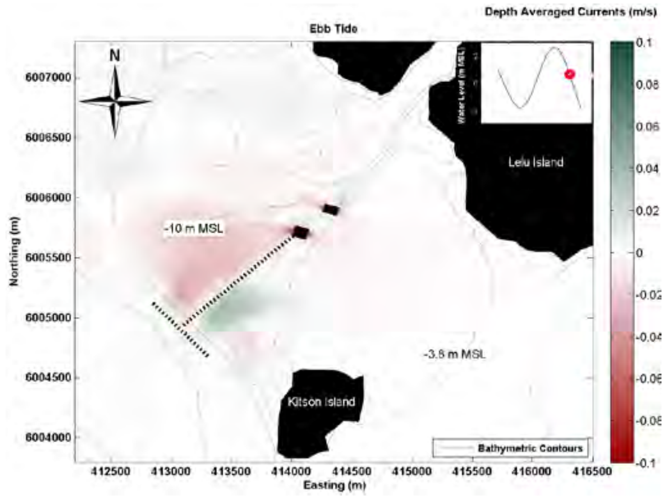
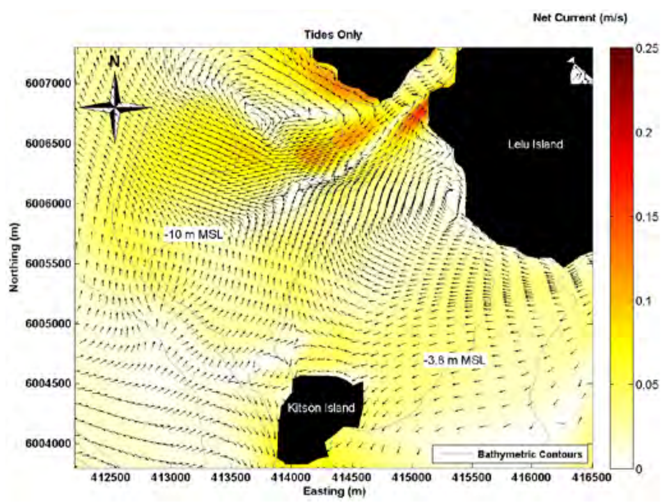


Figure H–97: Depth averaged instantaneous ebb current patterns during the tide-dominant condition for the existing (top) and proposed (middle) conditions, and the instantaneous difference (bottom).



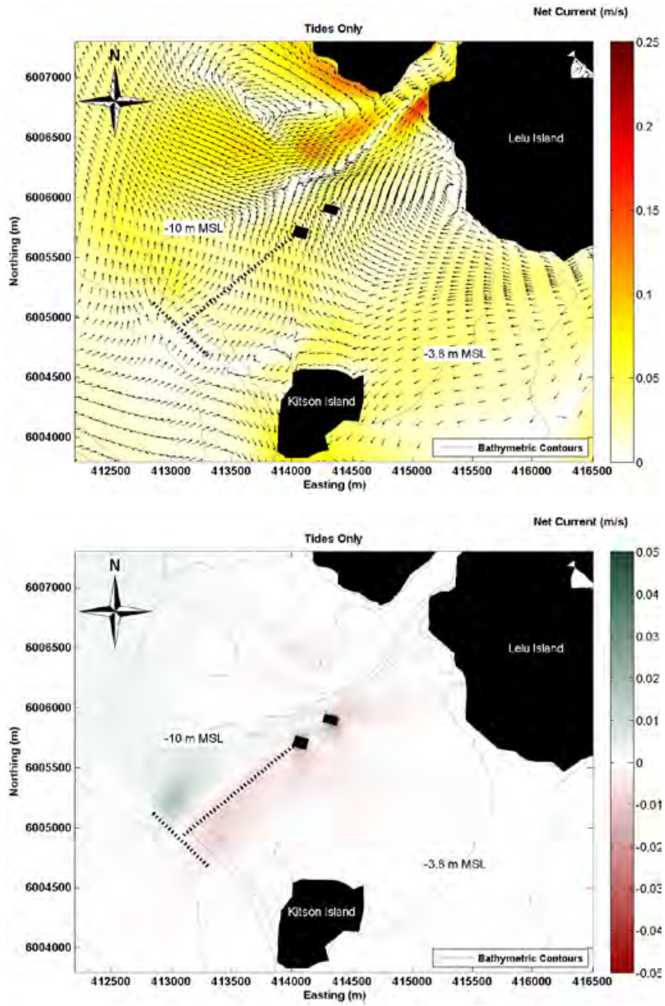
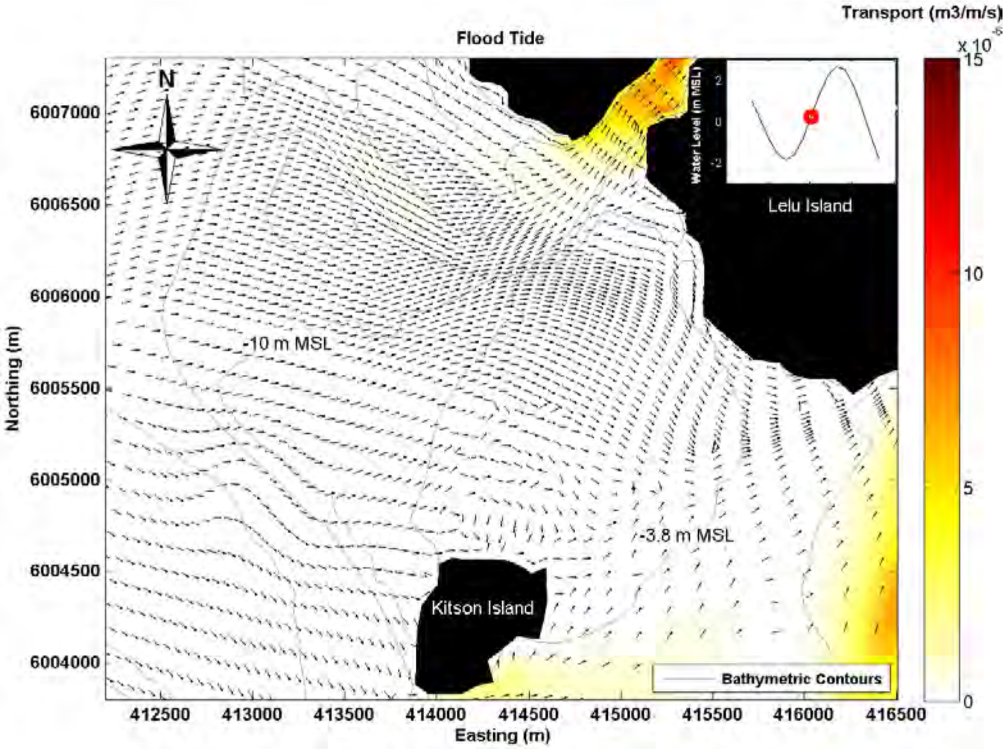


Figure H–98: Net depth averaged current patterns during 28 days of tide-dominant condition for the existing (top) and proposed (middle) conditions, and the net difference (bottom).


Transport (m3/m/s)
Flood Tide
x 10^-6
15
10
5
0
N
Water Level (m MSL)
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500
413000
413500
414000
414500
415000
415500
416000
416500
Easting (m)

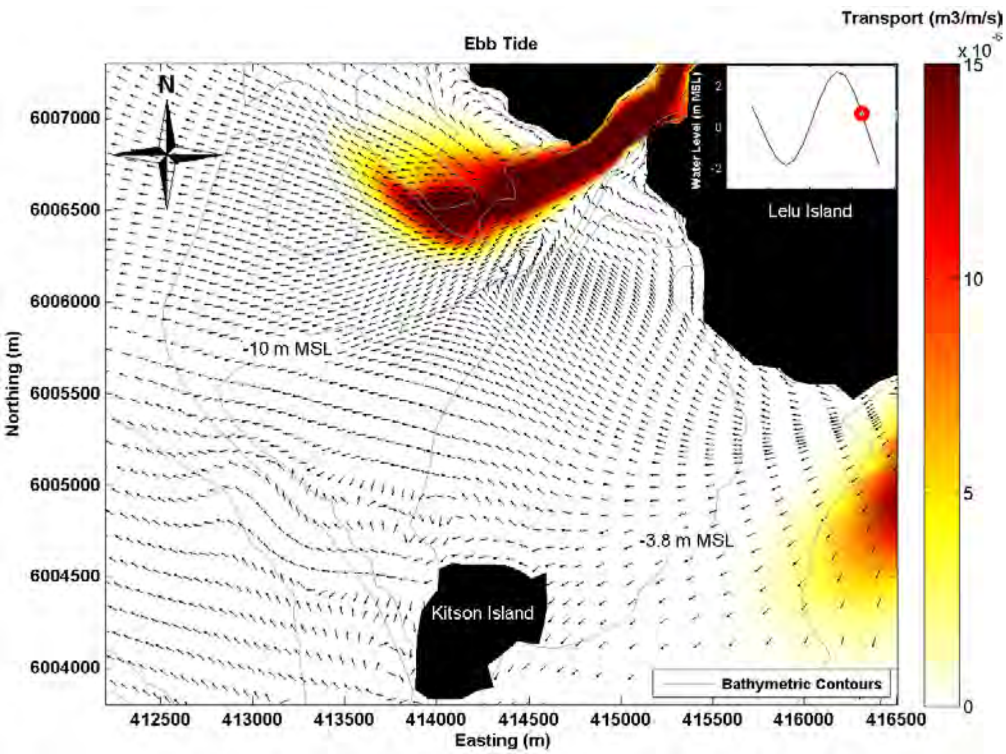

Transport (m3/m/s)
Ebb Tide
x 10^-6
15
10
5
0
N
Water Level (m MSL)
Lelu Island
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
6007000
6006500
6006000
6005500
6005000
6004500
6004000
412500
413000
413500
414000
414500
415000
415500
416000
416500
Easting (m)

Figure H–99: Instantaneous transport flux during flood (top) and ebb (bottom) for existing conditions during 28 days of tide-dominant conditions.

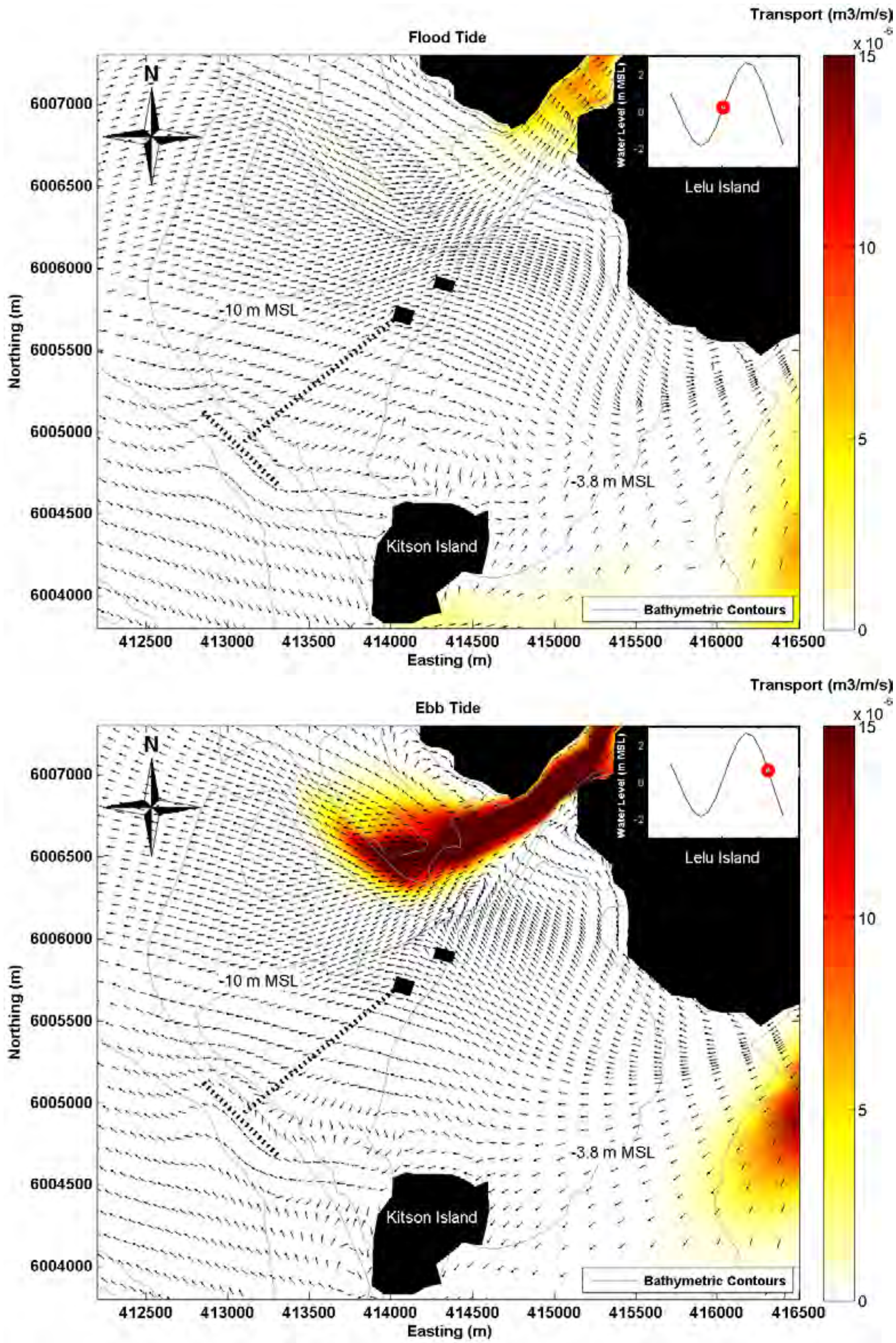
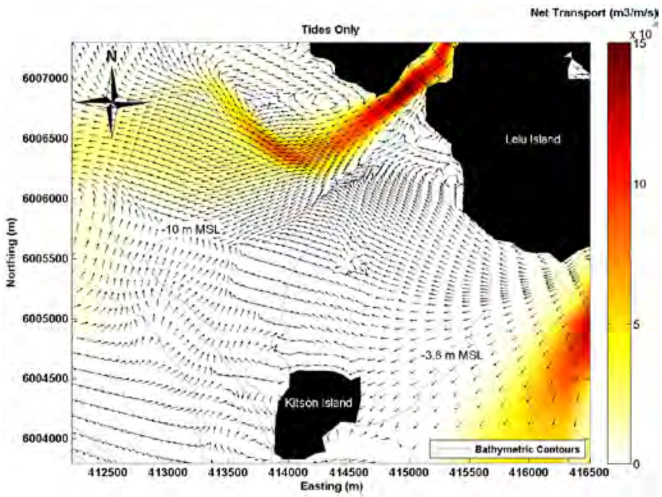
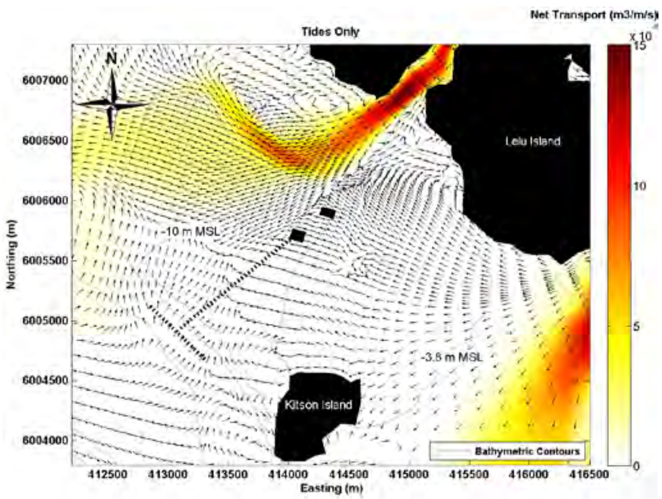


Figure H–100: Instantaneous transport flux during flood (top) and ebb (bottom) for the proposed conditions during 28 days of tide-dominant conditions.





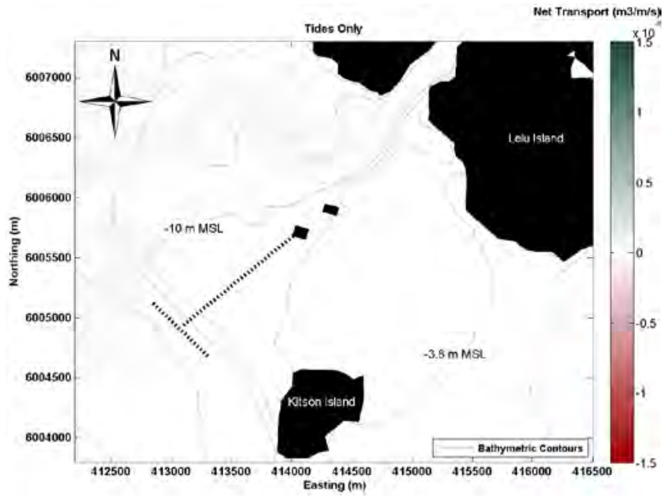
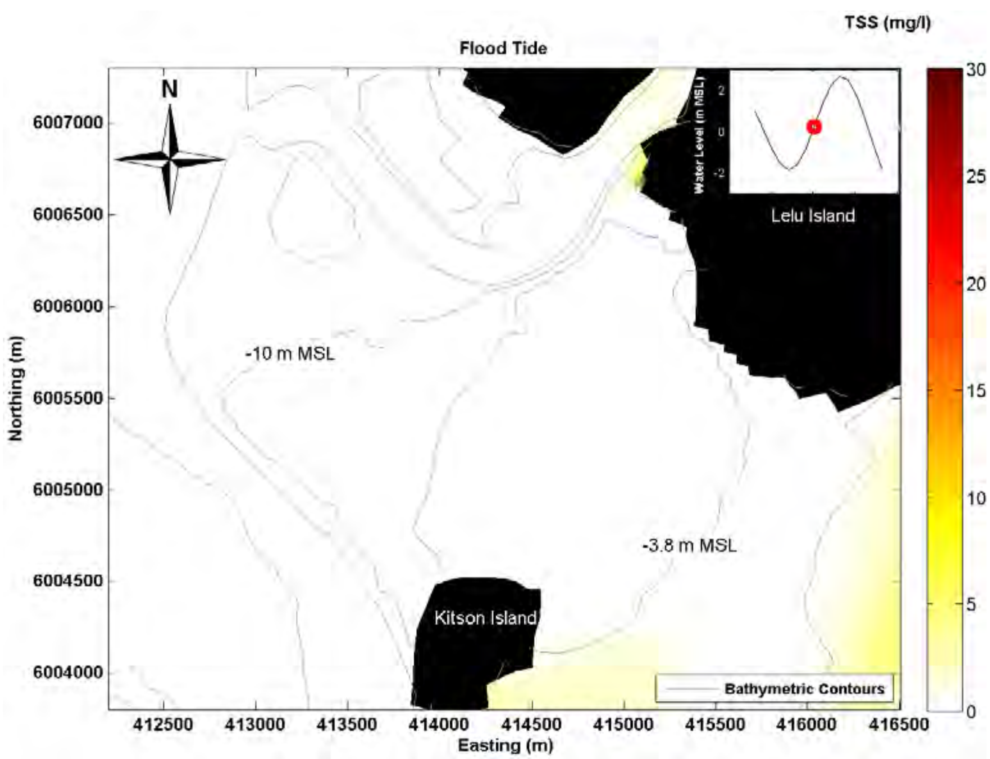


Figure H–101: Net transport flux during 28 days of tide-dominant condition for the existing (top) and proposed (middle) conditions, and the net difference (bottom).



Safety ● Quality ● Sustainability ● Innovation

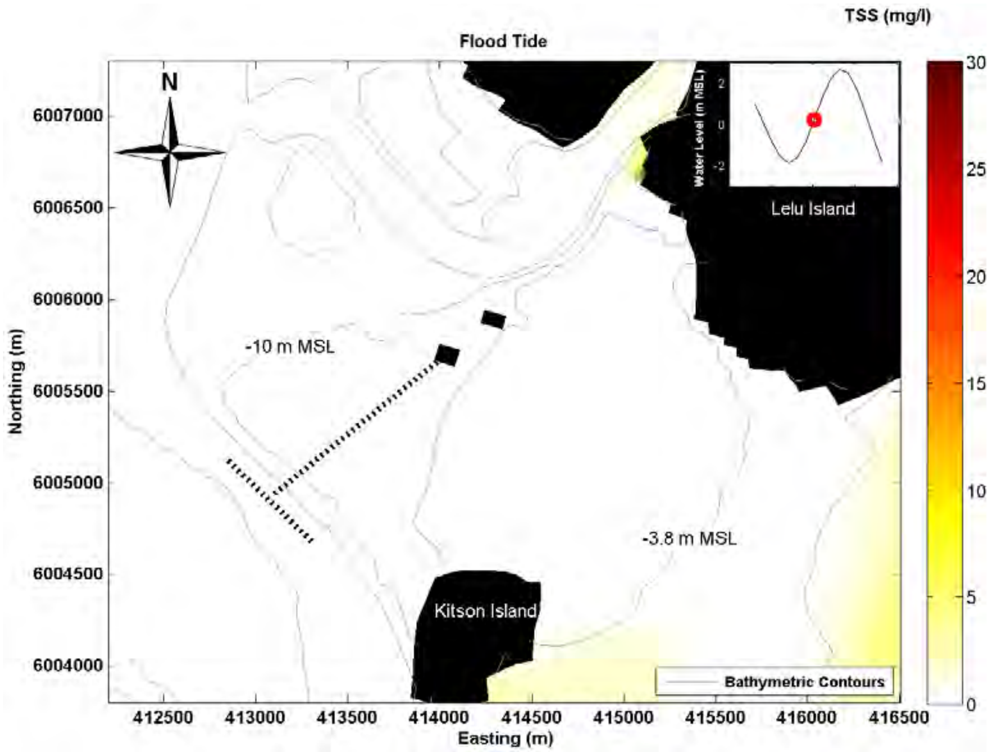
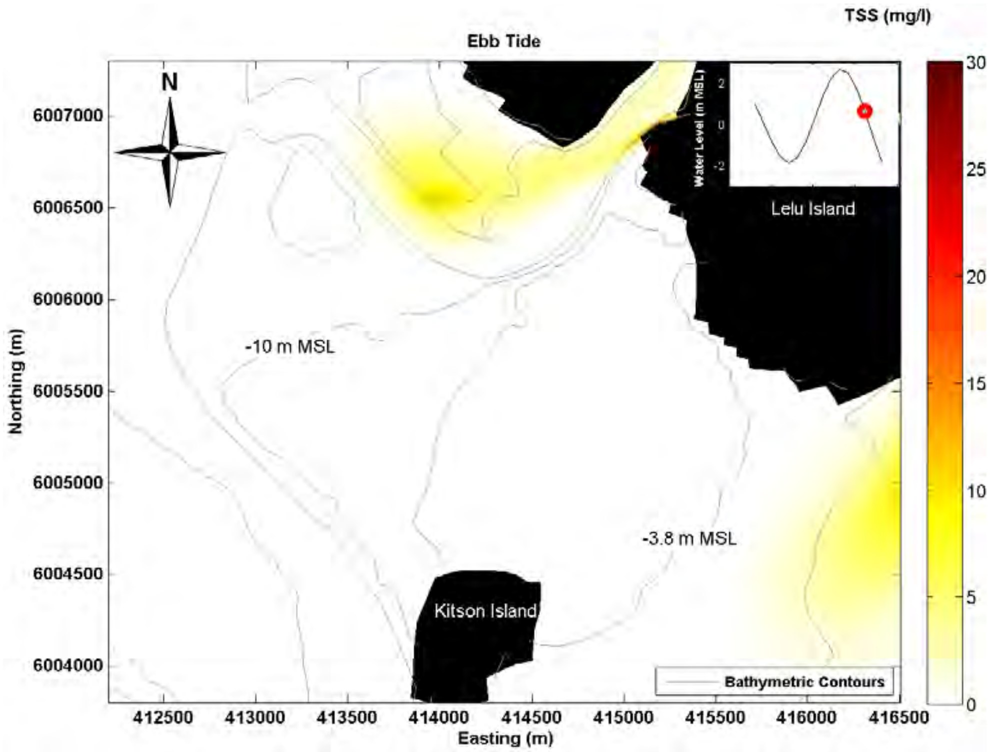


Figure H–102: Instantaneous TSS concentration during flood for existing (top) and proposed (bottom) conditions during 28 days of tide-dominant conditions.


TSS (mg/l)
Ebb Tide
N
Lelu Island
Water Level (m MSL)
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
Easting (m)

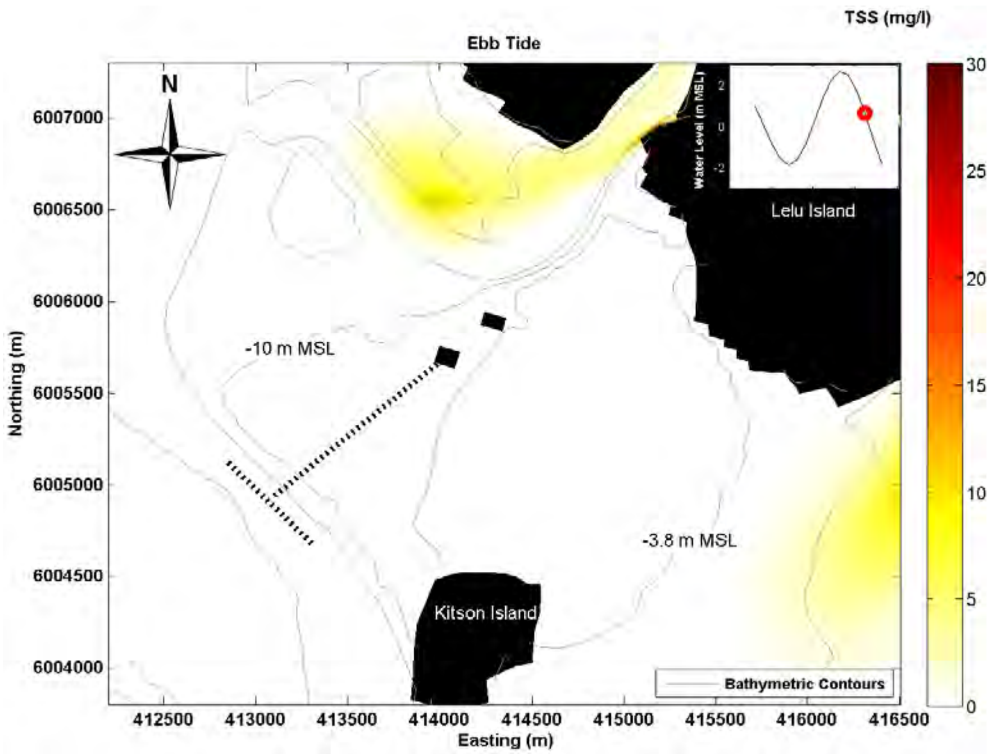
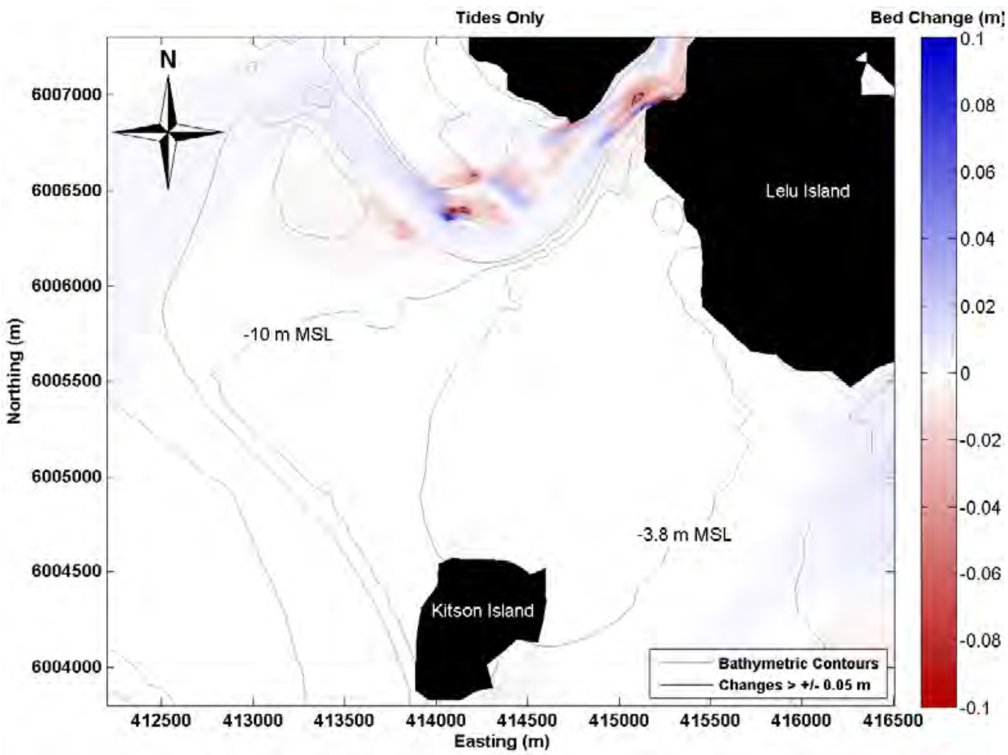

TSS (mg/l)
Ebb Tide
N
Lelu Island
Water Level (m MSL)
-10 m MSL
-3.8 m MSL
Kitson Island
Bathymetric Contours
Northing (m)
Easting (m)

Figure H–103: Instantaneous TSS concentration during ebb for existing (top) and proposed (bottom) conditions during 28 days of tide-dominant conditions.



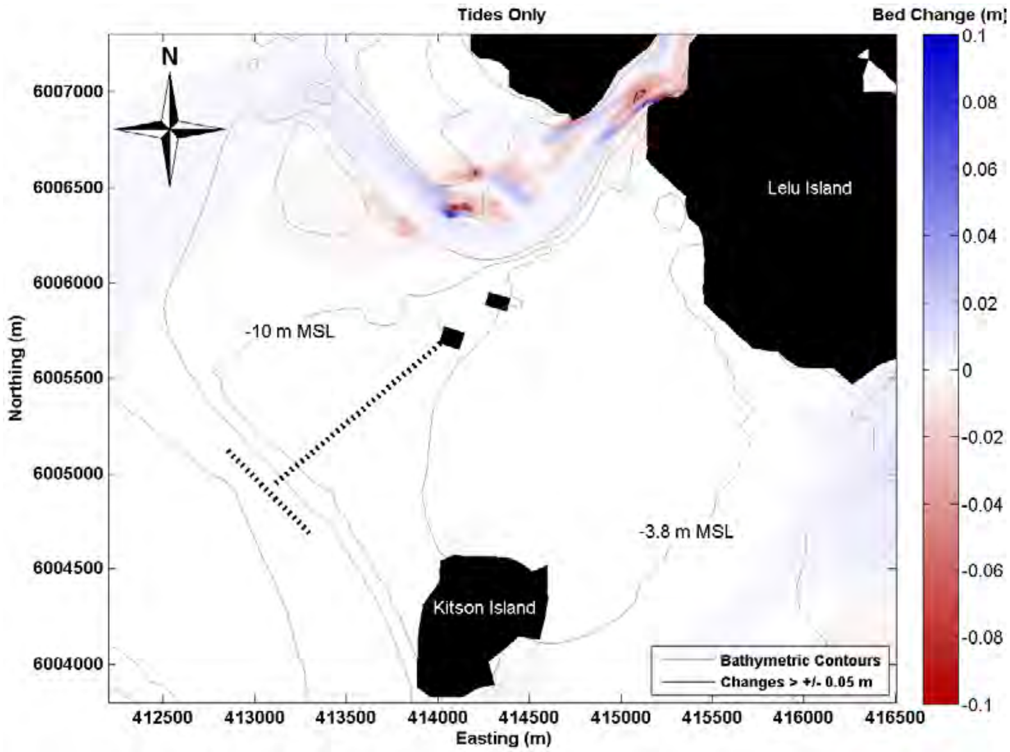


Figure H–104: Morphological changes during 28 days of tide-dominant conditions for the existing (top) and proposed (bottom) conditions. NOTE: +/- 0.1 m color scale.

The morphological change statistics for existing and proposed conditions (without and with marine structures, respectively) for the 28 day tides-only simulation are shown in Table H-13.This table lists the erosion, deposition, and net volumetric change as well as the corresponding footprint area and average elevation change. The resulting erosion, deposition and net average elevations of 0.00 m show that Flora Bank experiences almost no morphological changes in both existing and proposed conditions.

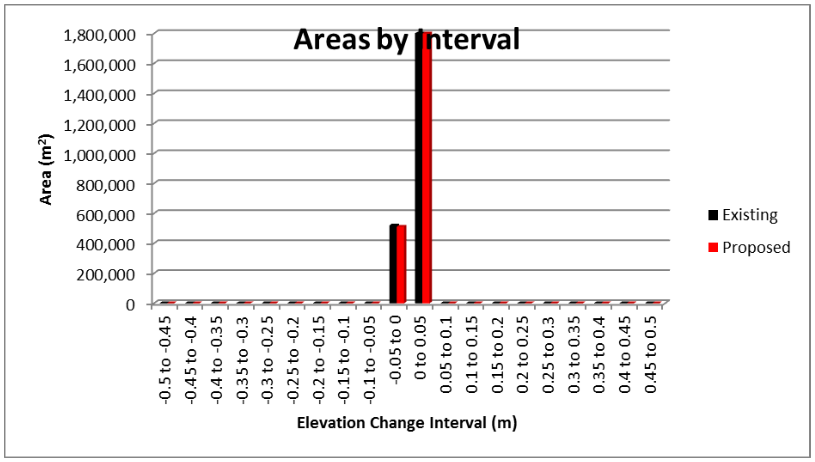
Table H-13: Flora Bank Volumetric Changes in 28 day Tides-Only Period.

Simulation Length [days]	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
28	**Without**	-290	560	270	0	0	0.00	0.00	0.00
	With	-480	570	90	1,490	0	0.00	0.00	0.00

To examine the data in Table H-13 in more detail, statistics for erosion and deposition in 0.05 m intervals for both existing and proposed conditions on Flora Bank have been included in Table H-14 and Figure H–105. These figures show that the existing and proposed conditions follow the same trend in volume and area, although the proposed conditions are slightly attenuated by the marine structures.

Table H-14: Volume and Area Changes on Flora Bank for in 28 day Tides-Only Period

	Area [m²]		Volumes [m³]		Absolute Volumes [m³]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.5 to -0.45	0	0	0	0	0	0
-0.45 to -0.4	0	0	0	0	0	0
-0.4 to -0.35	0	0	0	0	0	0
-0.35 to -0.3	0	0	0	0	0	0
-0.3 to -0.25	0	0	0	0	0	0
-0.25 to -0.2	0	0	0	0	0	0
-0.2 to -0.15	0	140	0	0	0	0
-0.15 to -0.1	0	500	0	-20	0	20
-0.1 to -0.05	0	860	0	-50	0	50
-0.05 to 0	519,360	511,030	-290	-410	290	410
0 to 0.05	2,727,760	2,734,590	560	570	560	570
0.05 to 0.1	0	0	0	0	0	0
0.1 to 0.15	0	0	0	0	0	0
0.15 to 0.2	0	0	0	0	0	0
0.2 to 0.25	0	0	0	0	0	0
0.25 to 0.3	0	0	0	0	0	0
0.3 to 0.35	0	0	0	0	0	0
0.35 to 0.4	0	0	0	0	0	0
0.4 to 0.45	0	0	0	0	0	0
0.45 to 0.5	0	0	0	0	0	0



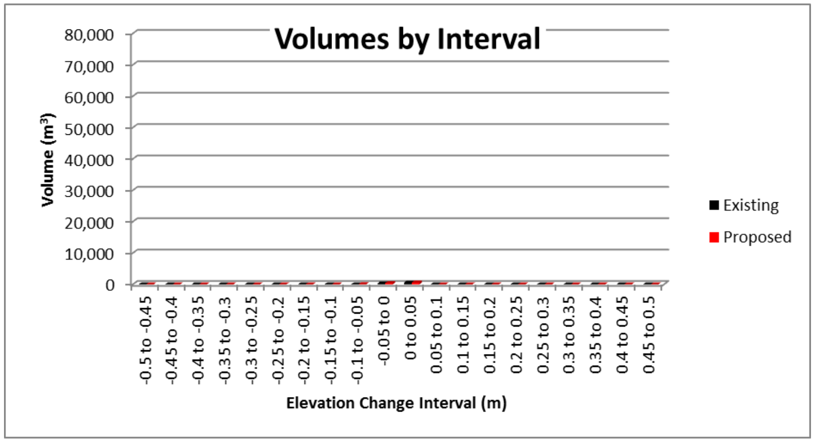


Figure H–105: Area Changes (top) and Absolute Volume Changes (bottom) on Flora Bank for the 28 day Tides-Only Period.

H1.6 Long-term Simulations

This section presents additional quantitative results for the long-term simulations, specifically for the 1 year time series of stormy period with 1–hour wave-flow coupling, 1 year time series with 3–hour wave-flow coupling (September 2012 to September 2013), and 1 year time series with 3–hour wave-flow coupling (May 2012 to May 2013). Statistics on the erosion volume, deposition volume, net volume change, area with erosion/deposition greater than 0.05 m, and net elevation have been tabulated for both existing and proposed conditions in each simulation. An explanation of how these values were computed is listed in Section H1.1.2. Figures displaying the bed elevation changes for existing and proposed conditions are provided for the two 1 year simulations as they are not in the main report.

H1.6.1 1 year Time Series of Stormy Period with 1–hour Wave-Flow Coupling

Additional results from the 1 year 1-hr coupling simulation run from September 1, 2012 to September 1, 2013 are presented here. This simulation covers a time frame of the year with the most energetic wave conditions which causes the vast majority of morphological changes over Flora Bank. The main discussion of this simulation is included in Section 5.3.4.4 and Section 6.1.4.3 of the main report.

To examine the data in Table 6-5 (main report) in more detail, statistics for erosion and deposition intervals for both existing and proposed conditions on Flora Bank have been included in Table H-15. These figures show that the existing and proposed conditions follow the same trend in volume and area, although the proposed conditions are slightly attenuated by the marine structures.

Table H-15: Volume and Area Changes on Flora Bank for Long-term, 1 year, 1-hr coupling.

	Area [m^2]		Volumes [m^3]		Absolute Volumes [m^3]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.6 to -0.55	2310	690	-40	-10	40	10
-0.55 to -0.5	6890	3780	-270	-120	270	120
-0.5 to -0.45	9720	7080	-700	-390	700	390
-0.45 to -0.4	10890	10190	-1210	-820	1210	820
-0.4 to -0.35	12050	11940	-1790	-1380	1790	1380
-0.35 to -0.3	13550	13530	-2420	-2010	2420	2010
-0.3 to -0.25	15990	16220	-3160	-2750	3160	2750
-0.25 to -0.2	49680	27040	-4500	-3680	4500	3680
-0.2 to -0.15	92820	73030	-8300	-6230	8300	6230
-0.15 to -0.1	151090	101940	-13860	-10570	13860	10570
-0.1 to -0.05	305930	222910	-25860	-17510	25860	17510
-0.05 to 0	877690	1130710	-50480	-48630	50480	48630
0 to 0.05	1069930	1149660	55150	47030	55150	47030
0.05 to 0.1	401000	291250	19910	15260	19910	15260
0.1 to 0.15	162810	133710	6500	5540	6500	5540
0.15 to 0.2	47660	43150	1790	1360	1790	1360
0.2 to 0.25	14090	10290	460	160	460	160
0.25 to 0.3	3020	0	30	0	30	0
0.3 to 0.35	0	0	0	0	0	0
0.35 to 0.4	0	0	0	0	0	0
0.4 to 0.45	0	0	0	0	0	0
0.45 to 0.5	0	0	0	0	0	0
0.5 to 0.55	0	0	0	0	0	0

H1.6.2 1 Year Time Series with 3–hour Wave-Flow Coupling (September 2012 to September 2013)

In addition to the 1 year simulation with 1–hour Wave-Flow coupling, a 12 month time series simulation was conducted using 3–hour Wave-Flow Coupling. This simulation was performed beginning September 1, 2012 for 12 months. This simulation included a complete range of coastal processes including the stormy periods with high winds and waves but naturally lower river flows, and the summer period with naturally less stormy periods and higher river flows. This simulation was performed using less frequent coupling between the wave and flow models (3–hour coupling) for higher efficiency.

Figure H–106 shows bed elevation changes predicted by the end of the 12 month simulation beginning September 1, 2012. In general, erosion areas and depositional areas are similar to results from other simulations, but changes are greater in magnitude.

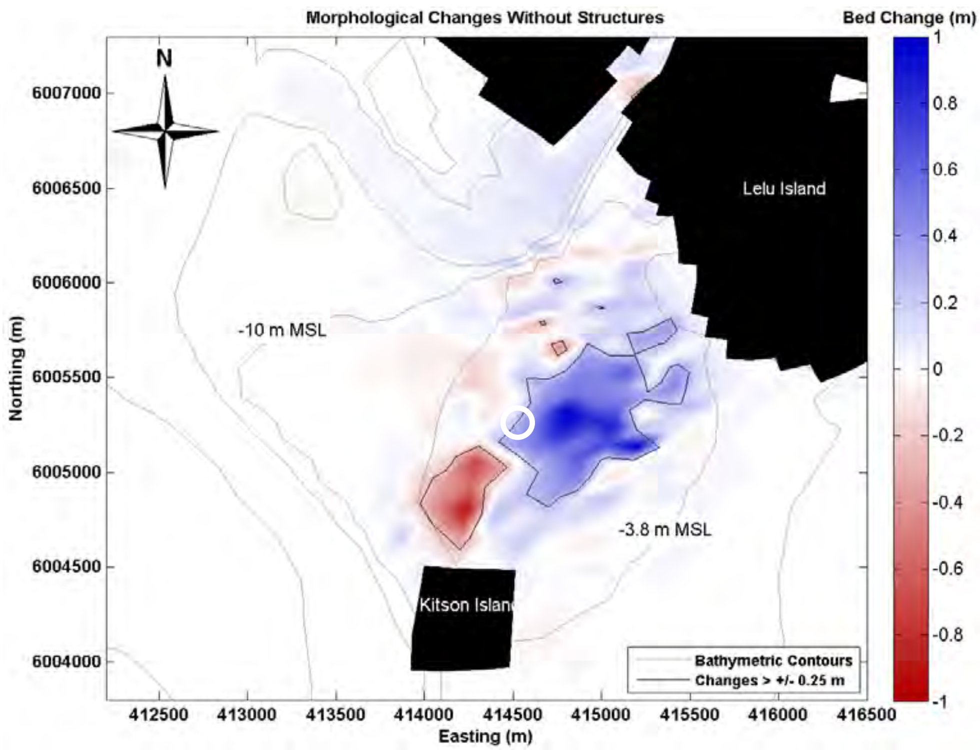


Figure H–106: Morphological changes predicted during 12 month time series simulation beginning September 1, 2012, with 3–hour coupling between wave and flow models.

The 3–hour coupling process has introduced some bed change artifacts that might not be noticeable if background bed elevation changes were not very small. More detailed analysis was performed to investigate the larger changes found with the larger coupling interval. Figure H–107 shows time histories of depth, velocity, erosion/deposition, and wave parameters at the location of the white circle shown in Figure H–106 (depositional area). Using this high-resolution output and direction comparison of results for 1–hour and 3–hour coupling, large and unrealistic velocity spikes are observed in the 3–hour coupling results which directly cause relatively large and rapid bed changes (sedimentation at this location) of roughly 0.3 m, whereas the results with the more resolved 1–hour coupling show negligible bed changes.

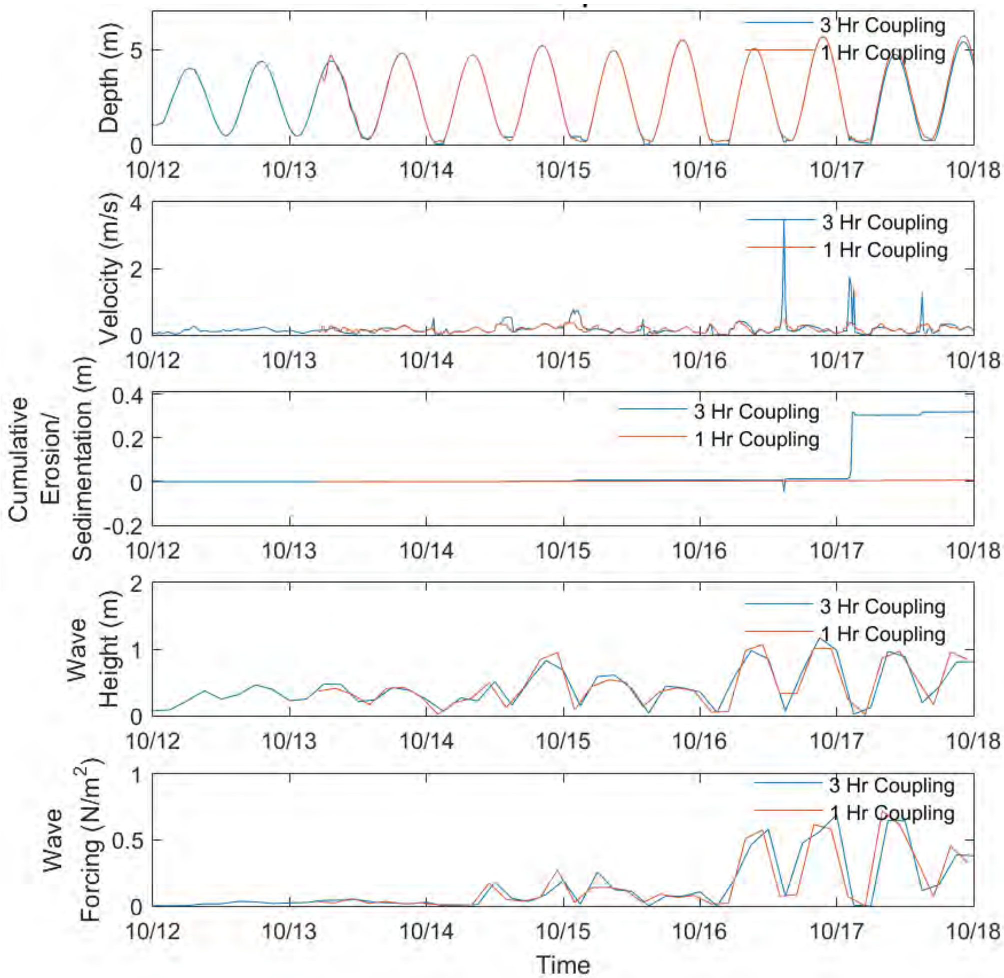


Figure H–107: Time histories of depth, velocity, erosion/deposition and wave parameters during 6 day period from October 12, 2012 to October 18, 2012, for both 1-hour and 3-hour coupling of the wave and flow models.

As a comparison to demonstrate these coupling effects, Figure H–108 shows bed elevation changes predicted by the end of the 3 month stormy simulation starting September 1, 2012 using 1-hour coupling between the wave and flow models (top), and 3-hour coupling (bottom). In general erosional areas and depositional areas are similar, however, the changes predicted with 3-hour coupling are greater in magnitude and are partially a result of numerical artifacts.

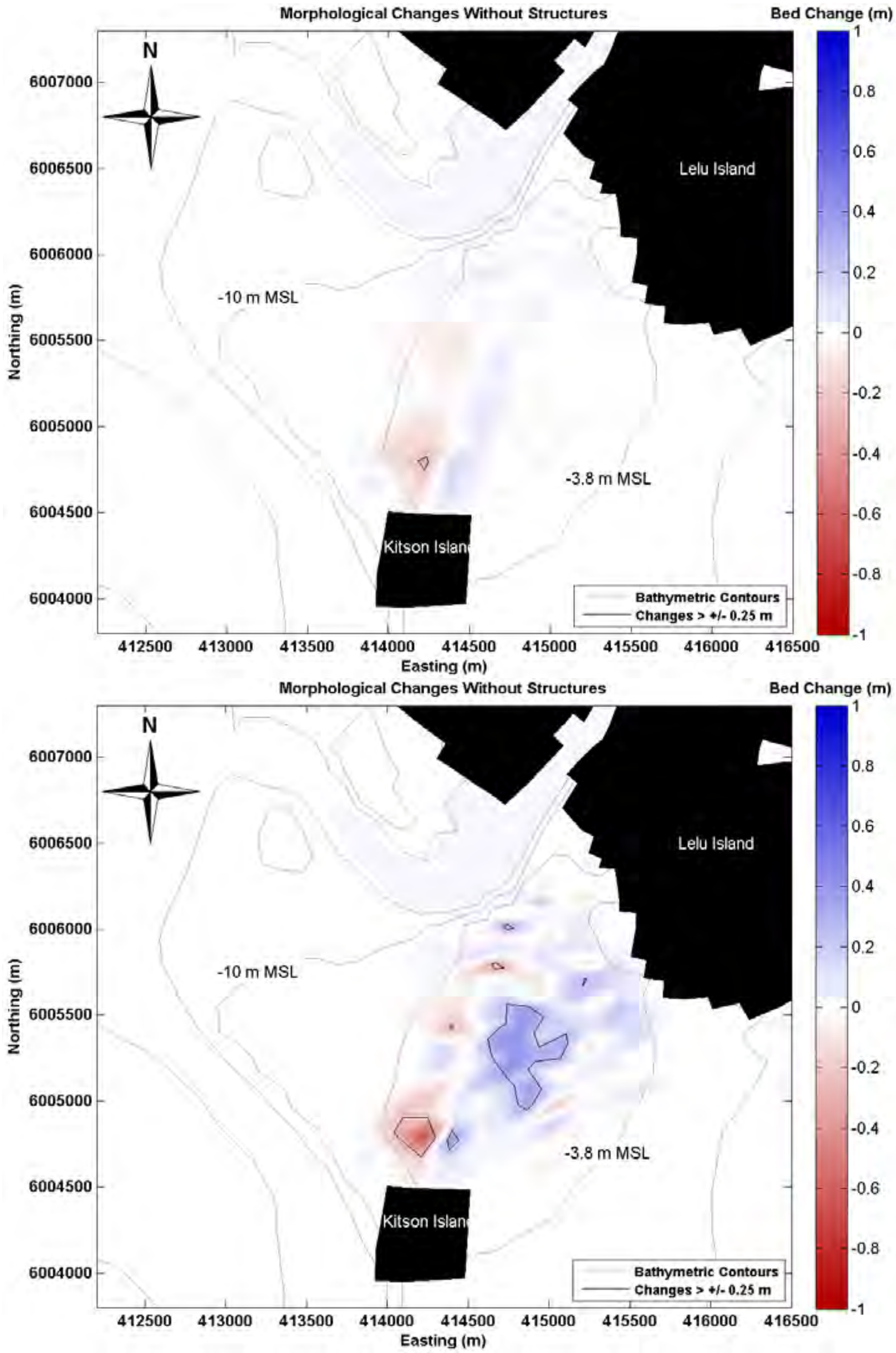


Figure H–108: Morphological changes predicted during 3 month time series simulations beginning September 1, 2012 for 1-hour wave-flow coupling (top) and 3-hour coupling (bottom).

Figure H–109 shows bed elevation changes predicted by the end of the 12 month simulation beginning September 1, 2012 without the marine structures (top), and with the marine structures (bottom). In general, the patterns of changes are similar to results from other simulations, but bed elevation changes are greater in magnitude. Although changes are clearly exaggerated for this and all of the stormy period simulations that used 3-hour coupling, there is a measure of consistency in the bed changes in terms of the erosion and deposition locations and general magnitudes. The effect of the marine structures, as in all other simulations, is to modestly dampen the predicted levels of erosion and deposition.

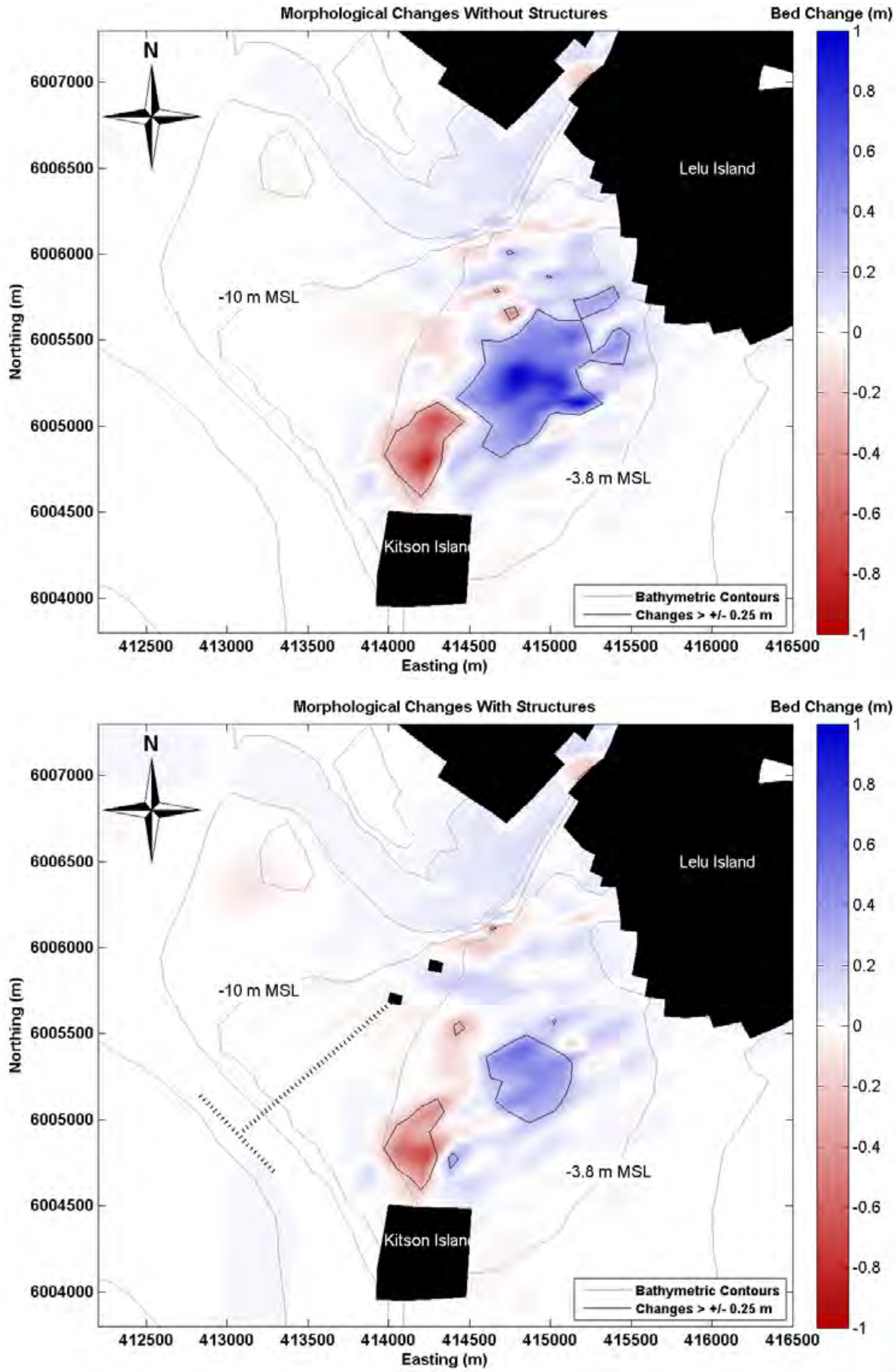


Figure H–109: Morphological changes predicted during 12 month time series simulation beginning September 1, 2012 with 3-hour coupling between wave and flow models, without marine structures (top) and with marine structures (bottom). Note that Figure H–108 is for 3 months while Figure H–109 is for 12 months.

Although some bed elevation changes are clearly exaggerated for 3-hour coupling simulations, the bed changes occur in similar locations with a similar pattern. Figure H–110 displays the morphological changes after 12 months after filtering of the numerical artifacts.

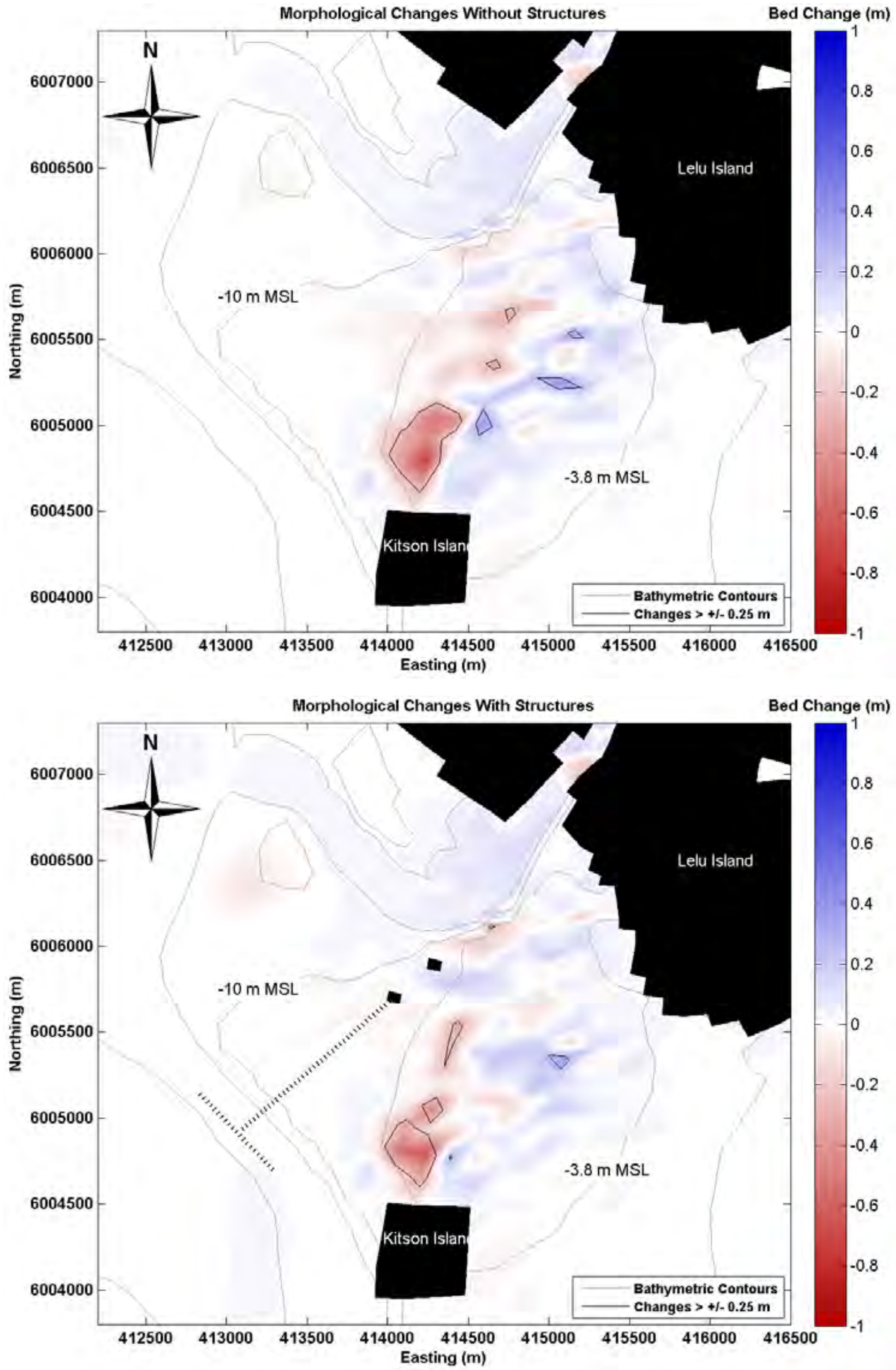


Figure H–110: Morphological changes predicted during 12 month time series simulation beginning September 1, 2012 with 3-hour coupling between wave and flow models with numerical artifacts filtered, without marine structures (top) and with marine structures (bottom).

Bed change results were analyzed to determine the trends in erosion and deposition patterns, volumes, and net changes on Flora Bank over the 12 month period from September 1, 2012 to August 31, 2013. These results have been filtered to remove the numerical artifacts and are presented in Table H-16.

Table H-16: Volumes of Change During a 12 month Period (September 2012-2013).

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
Sept	**Without**	-127,620	101,270	-26,350	681,780	768,790	-0.04	0.03	-0.01
	With	-106,800	97,730	-9,070	540,200	724,340	-0.03	0.03	0.00

To examine the data in Table H-16 in more detail, statistics for erosion and deposition in 0.05 m intervals for both existing and proposed conditions on Flora Bank have been included in Table H-17 and Figure H–111. These figures show that the existing and proposed conditions follow the same trend in volume and area, although the proposed conditions are slightly attenuated by the marine structures.

Table H-17: Volume and Area Changes on Flora Bank for Long-term, 12 month, 3-hr coupling.

	Area [m²]		Volumes [m³]		Absolute Volumes [m³]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.75 to -0.7	140	0	0	0	0	0
-0.7 to -0.65	1560	90	-40	0	40	0
-0.65 to -0.6	3300	2570	-160	-50	160	50
-0.6 to -0.55	5040	6090	-370	-270	370	270
-0.55 to -0.5	7060	8800	-670	-650	670	650
-0.5 to -0.45	13920	9740	-1170	-1120	1170	1120
-0.45 to -0.4	18640	11590	-2010	-1640	2010	1640
-0.4 to -0.35	20380	14720	-2990	-2300	2990	2300
-0.35 to -0.3	25340	18620	-4110	-3120	4110	3120
-0.3 to -0.25	35360	32090	-5610	-4330	5610	4330
-0.25 to -0.2	53610	49000	-7760	-6390	7760	6390
-0.2 to -0.15	78440	68330	-11090	-9280	11090	9280
-0.15 to -0.1	122050	105260	-15850	-13530	15850	13530
-0.1 to -0.05	296930	213380	-25590	-20980	25590	20980
-0.05 to 0	849840	873890	-50210	-43150	50210	43150
0 to 0.05	946710	1108600	57580	59550	57580	59550
0.05 to 0.1	454760	426330	26490	23980	26490	23980
0.1 to 0.15	198160	179120	9530	9920	9530	9920
0.15 to 0.2	58730	92820	4080	3320	4080	3320
0.2 to 0.25	26950	18520	2120	720	2120	720
0.25 to 0.3	17290	5820	1050	210	1050	210
0.3 to 0.35	9900	1720	370	30	370	30
0.35 to 0.4	3000	0	50	0	50	0

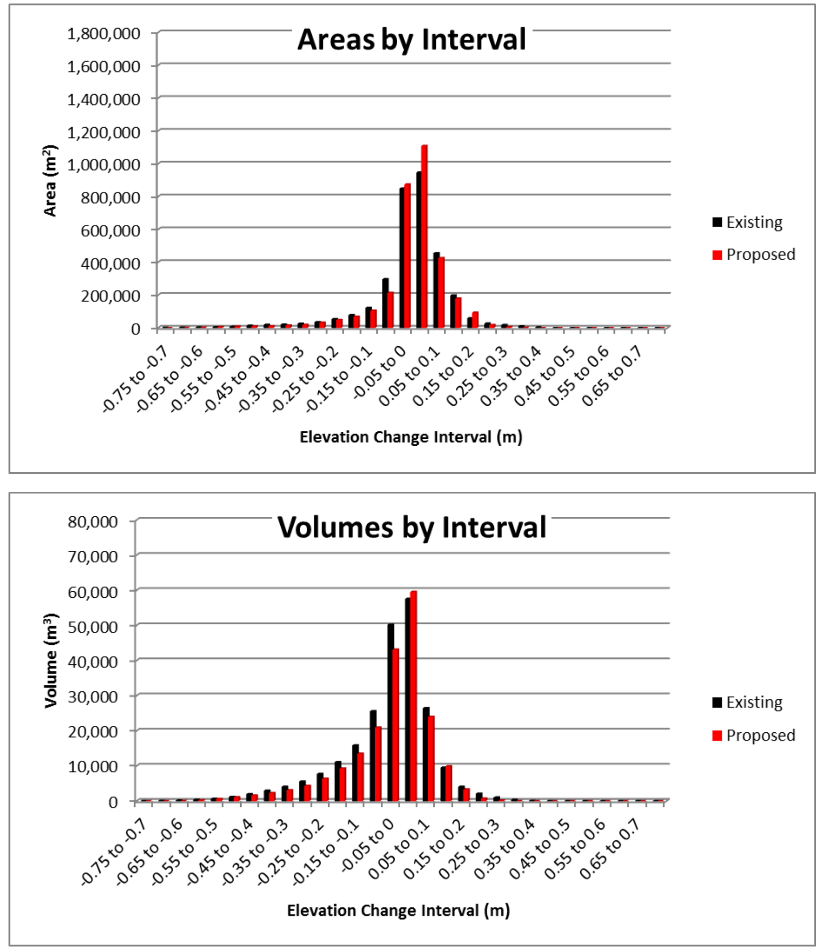


Figure H–111: Area Changes (top) and Absolute Volume Changes (bottom) on Flora Bank for Long-term, 12 month, 3-hr coupling Starting in September 2012

H1.6.3 1 Year Time Series with 3-hour Wave-Flow Coupling (May 2013 to May 2014)

Another 3–hour coupling simulation was completed which ran continuously for a 12 month period from May 1, 2013 to April 30, 2014. The morphology change for the existing and proposed conditions are shown in Figure H–112.

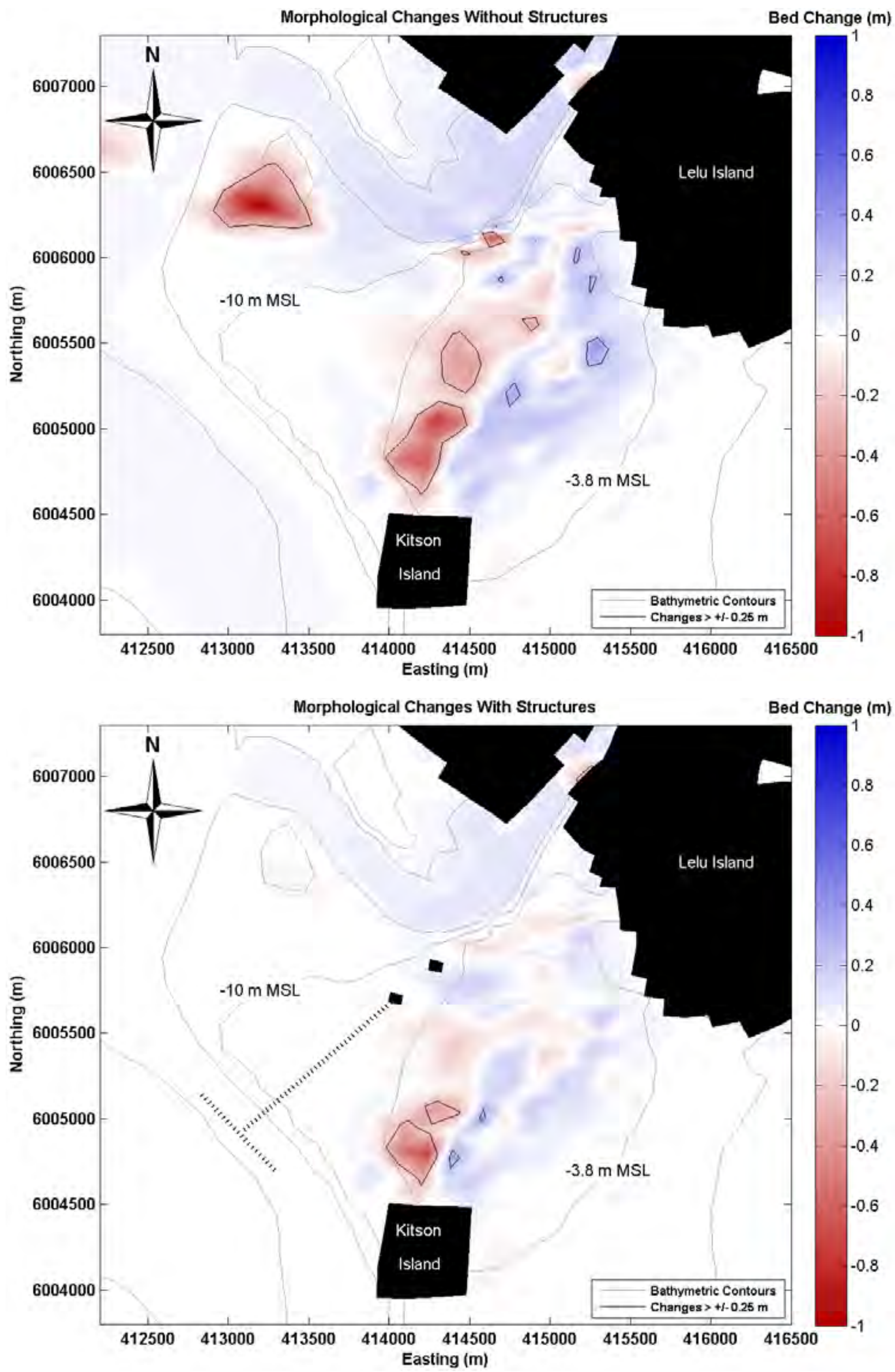


Figure H–112: Morphological changes predicted during 12 month time series simulation beginning May 1, 2013 with 3-hour coupling between wave and flow models with numerical artifacts filtered, without marine structures (top) and with marine structures (bottom).

Table H-18 shows erosion and deposition volumes over Flora Bank over a 12 month period, from May 2013 to May 2014. These results have also been filtered to remove the numerical artifacts. The table also shows erosion and deposition volumes for a continuous the12 month simulation. Net average elevation changes are calculated as an average value over all of Flora Bank.

Overall, as indicated previously, material tends to move around on Flora Bank, but changes caused by the marine structures over the scale of Flora Bank (in terms of average thickness) are relatively small. This is consistent with all sets of simulations.

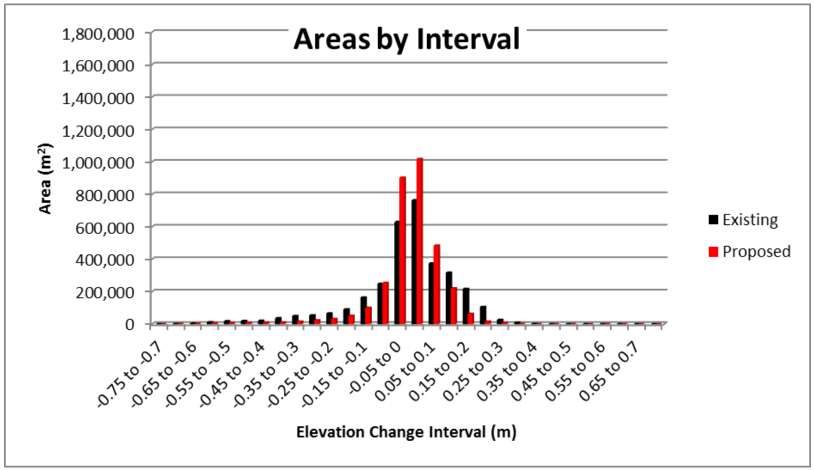
Table H-18: Volumes of Change During a 12 month Period (May 2013-2014)

Simulation Start Month	Presence of Marine Structures	Erosion Volume [m^3]	Deposition Volume [m^3]	Net Volume [m^3]	Erosion Area [m^2]	Deposition Area [m^2]	Erosion Average Elevation Change [m]	Deposition Average Elevation Change [m]	Net Average Elevation Change [m]
May	**Without**	-164,880	153,670	-11,210	795,120	1,057,280	-0.05	0.05	0.00
	With	-97,810	98,670	860	528,980	796,150	-0.03	0.03	0.00

A similar morphologic pattern observed in the 1 year simulation from September 2012 to September 2013 was repeated in the May to May simulation, also showing that Flora Bank is a stable environment, where most changes in area and volume are notice between -0.05 m and 0.05 m (Table H-19).The histograms (Figure H–113) show that the marine structures decrease the energy in the project area and decrease erosion and deposition magnitudes,

Table H-19: Volume and Area Changes on Flora Bank for Long-term, 12 month, 3-hr coupling.

	Area [m^2]		Volumes [m^3]		Absolute Volumes [m^3]	
Interval [m]	Existing	Proposed	Existing	Proposed	Existing	Proposed
-0.75 to -0.7	300	30	0	0	0	0
-0.7 to -0.65	1880	1360	-60	-30	60	30
-0.65 to -0.6	4400	3420	-200	-150	200	150
-0.6 to -0.55	11820	5480	-590	-370	590	370
-0.55 to -0.5	18700	7480	-1370	-690	1370	690
-0.5 to -0.45	20610	8740	-2370	-1100	2370	1100
-0.45 to -0.4	21830	9780	-3430	-1570	3430	1570
-0.4 to -0.35	37520	11300	-4670	-2080	4670	2080
-0.35 to -0.3	50530	16330	-7130	-2760	7130	2760
-0.3 to -0.25	54480	23980	-9690	-3760	9690	3760
-0.25 to -0.2	66580	32550	-12710	-5170	12710	5170
-0.2 to -0.15	92180	52610	-16550	-7230	16550	7230
-0.15 to -0.1	165130	100680	-22880	-10800	22880	10800
-0.1 to -0.05	249180	255280	-32970	-19000	32970	19000
-0.05 to 0	630310	903640	-50270	-43110	50270	43110
0 to 0.05	764410	1018330	67020	59430	67020	59430
0.05 to 0.1	375740	484780	43170	26270	43170	26270
0.1 to 0.15	318170	221620	25620	9490	25620	9490
0.15 to 0.2	218150	64270	12520	2400	12520	2400
0.2 to 0.25	107040	16010	3960	830	3960	830
0.25 to 0.3	26990	8050	1070	240	1070	240
0.3 to 0.35	9180	1420	290	20	290	20
0.35 to 0.4	2020	0	30	0	30	0



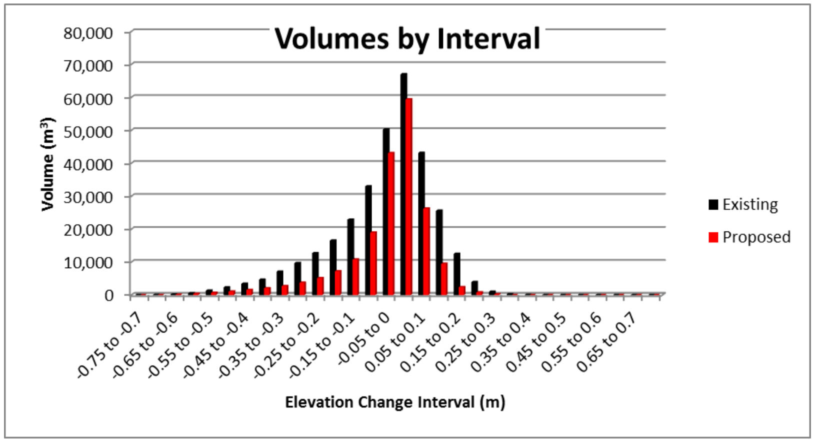


Figure H–113: Area Changes (top) and Absolute Volume Changes (bottom) on Flora Bank for Long-term, 12 month, 3-hr coupling Starting in May.

Safety • Quality • Sustainability • Innovation

Appendix I: Long-Term Time Series Modelling Summary

I1. Long-Term Time Series Modelling Summary

This appendix documents the iterative effort of refining model inputs in order to improve stability and decrease run times of the long-term simulations presented in this report. These modifications were made based on a standard of recommended practices and by analyzing diagnostic files and output of several tentative simulations.

I1.1 May 5 Model refinement

The original grid and setup are based on the simulations conducted to prepare the May 5 report (Hatch, 2015). The following refinements/modifications were made to the grid and inputs of the model setup presented in the May 5 report:

- The "Hotstart" file in the Delft3D-WAVE (SWAN) model was deactivated to prevent small, insignificant blips in the wave model results from growing larger and corrupting the model results over time.
- Initial simulations were run with 5 vertical layers. A 10 vertical layer hydrodynamic setup (sediment transport) was generated and run for 1 year to determine initial salinity conditions for all long-term morphology runs.
- Initial attempts at parallelizing Delft3D setups to decrease run times failed. Trial and error testing revealed issues with writing output "print" files for parallel runs. These files are redundant and are not necessary for model analysis so the option to write "print" files was turned off for all subsequent simulations. Optimal parallel setting gained a speed up of ~50% over serial runs. Speed tests on different machines varied significantly depending on specific hardware but generally required about 40 days of computational time per year of model time.
- Attempts to run parallel simulations incorporating pier trestles as porous plates failed. The failures were caused by Delft3D limitations of running simulations with skewed structures (in one grid cell), when running Delft3D simulations in parallel. The porous plate was instead incorporated into the model as a staircase shape which followed grid cells as close to its real position as possible.
- In an attempt to further speed up model run times and facilitate quicker debugging additional testing of 1-hour vs 3-hours wave coupling was performed. No significant differences in wave validation or flow results were observed over a week period so 3-hour coupling was considered acceptable and used for subsequent simulations until issues with the wave-flow coupling interval became evident. Later on, it was observed that some unrealistic current velocities occurred using 3-hours coupling during wetting/drying processes on Flora Bank when the water column was very small. These high velocities caused some exaggerated morphologic changes in these shallow areas.

The following modifications to the original model setup were made in an iterative process in an attempt to increase model stability.

- Smaller time steps were used in an attempt to increase stability
- An increased spin-up time for hydrodynamics and delay period for morphological changes were used in an attempt to smoothly transition from initial conditions
- "Hotstarting" the model before the time it previously crashed with a reduced time step
- Using different starting dates
- Improving individual grid cell orthogonalities was improved
- Smoothing the transition between individual grid cell size transition where possible
- Improving individual grid cell aspect ratio where possible
- Bathymetry in localized problem areas was smoothed
- Background horizontal eddy viscosity was increased to 10 m^2/s in to increase model stability (A comparison to originally used values revealed hydrodynamic results which were nearly identical)
- Variable vertical (sigma) layer widths along the grid were tested in an attempt to increase stability
- Using MORFAC = 1 vs MORFAC = 5
- Not incorporating morphological updates into SWAN from the hydrodynamic module
- Not using hydrodynamic current velocities in SWAN (relatively minor effect of currents on waves was ignored, however, wave induced forces impacting currents were still included)

The statuses of simulations which are variations of the May 5 model setup are listed in Table I-1 (yellow highlighted simulations are still running or completed).

Table I-1: Status of Simulations Varied off the May 5 Model

Vertical Layers	Condition	Starting Date	Other	Last Output Date	Status
10 layers equal	Existing	9/1/2012		9/27/2012	Crashed
10 layers equal	Proposed	9/1/2012		10/20/2012	Crashed
10 layers variable	Existing	9/1/2012	MORFAC = 5	10/20/2012	Crashed
10 layers variable	Proposed	9/1/2012	MORFAC = 5	10/20/2012	Crashed
10 layers equal	Existing	1/1/2013		1/12/2013	Crashed
10 layers equal	Proposed	1/1/2013		1/12/2013	Crashed
10 layers equal	Existing	5/1/2013		7/20/2013	Crashed
10 layers equal	Proposed	5/1/2013		9/2/2013	Crashed
10 layers equal	Existing	9/1/2012	MORFAC = 5	10/20/2012	Crashed
10 layers equal	Proposed	9/1/2012	MORFAC = 5	10/20/2012	Crashed
10 layers equal	Existing	9/1/2012	No Waves	5/1/2013	Finished
10 layers equal	Proposed	9/1/2012	No Waves	5/1/2013	Finished
10 layers equal	Existing	3/1/2013		3/30/2013	Crashed
10 layers equal	Proposed	3/1/2013		3/10/2013	Crashed

Because of stability issues encountered when running the May 5 model setup over long time periods, a modified setup grid was generated by making moderate changes to the original grid in order to improve grid properties. This setup used the same grid for both flow and wave. In general model stability increased and run times were longer but many of these simulations eventually crashed. In addition, the following refinements/changes were further made to the modified grid setup in an iterative process.

- Not using hydrodynamic current velocities in SWAN (relatively minor effect of currents on waves was ignored, however, wave induced forces impacting currents were still included).
- Initially attempted lowering the boundary reflection parameter alpha from the values used in the original grid. Subsequently increased boundary reflection parameter alpha to original values.
- Smoothed out the relatively coarse gridded wind data set in an attempt to eliminate instabilities which may have been generated by large wind speed gradients due to the resolution of the wind data.
- Adjusting the number of vertical layers to 5 layers (disregarded as didn't improve stability)
- Using dry cells to better incorporate a handful of smaller far field islands instead of using positive land elevation bathymetry values.

It is believed that the total of the modifications up to this point eliminated the instabilities which were causing the long-term simulations to crash. This modified setup is described in further detail in Appendix B. Once instabilities were eliminated it became possible to analyze longer time periods and it became evident that there were occasional numerical spikes (non-physical) in current velocities which were causing exaggerated changes in bed elevation. Sensitivity tests were performed adjusting the following parameters to determine the cause of these spikes was the flow-wave coupling interval during wetting/drying processes in the shallow water over Flora Bank.

- Adjusting the minimum water depth threshold
- Using 1-hour instead of 3-hour wave-flow coupling

The status of simulations which are variants of the modified grid setup are shown in Table I-2 (yellow highlighted simulations are still running or have completed).

Table I-2: Status of Simulations with the Modified Grid

Vertical Layers	Condition	Starting Date	Other	Last Output Date	Status
10 layers equal	Existing	9/1/2012	Modified Grid	12/15/2012	Crashed
10 layers equal	Proposed	9/1/2012	Modified Grid	12/15/2012	Crashed
10 layers equal	Existing	9/1/2012	Modified Grid, MORFAC = 5	12/15/2012	Crashed
10 layers equal	Proposed	9/1/2012	Modified Grid, MORFAC = 5	12/15/2012	Crashed
10 layers variable	Existing	9/1/2012	Modified Grid, MORFAC = 5	12/11/2012	Crashed
10 layers variable	Proposed	9/1/2012	Modified Grid, MORFAC = 5	10/15/2012	Crashed
10 layers variable	Existing	9/1/2012	Modified Grid, MORFAC = 1	10/4/2012	Crashed
10 layers variable	Proposed	9/1/2012	Modified Grid, MORFAC = 1	10/2/2012	Crashed
10 layers equal	Existing	3/1/2013	Modified Grid MORFAC = 1	4/26/2013	Crashed
10 layers equal	Proposed	3/1/2013	Modified Grid MORFAC = 1	4/29/2013	Crashed
5 layers equal	Existing	9/1/2012	Original Grid, MORFAC = 1	26/2/2013	Crashed
5 layers equal	Proposed	9/1/2012	Original Grid, MORFAC = 1	20/2/2013	Crashed
10 layers equal	Existing	9/1/2012	Modified Grid, MORFAC = 1,Alpha Increase, Smooth winds, 3-hr coupling	9/1/2013	Finished
10 layers equal	Proposed	9/1/2012	Modified Grid, MORFAC = 1,Alpha Increase, Smooth winds, 3-hr coupling	9/1/2013	Finished
10 layers equal	Existing	5/1/2013	Modified Grid, MORFAC = 1,Alpha Increased, Smooth winds, 3-hr coupling	5/1/2014	Finished
10 layers equal	Proposed	5/1/2013	Modified Grid, MORFAC = 1,Alpha Increase , Smooth winds, 3-hr coupling	5/1/2014	Finished
10 layers equal	Existing	1/1/2013	Modified Grid, MORFAC = 1,Alpha Increase , Smooth winds, 3-hr coupling	6/14/2013	Stopped to free up comp. space
10 layers equal	Proposed	1/1/2013	Modified Grid, MORFAC = 1,Alpha Increase, Smooth winds, 3-hr coupling	9/23/2013	Stopped to free up comp. space
10 layers equal	Existing	9/1/2012	Modified Grid, MORFAC = 1,Alpha Increase, Smooth winds,1-hr coupling	9/1/2013	Finished
10 layers equal	Proposed	9/1/2012	Modified Grid, MORFAC = 1,Alpha Increase, winds, 1-hr coupling	9/1/2013	Finished

I1.2 Alternate setup

An alternate setup, which was not based on the May 5 setup, was also generated and tested. A number of modifications which increased stability for the other simulations were incorporated into this alternate setup:

- Locating the open-water boundary conditions further from the project site, specifically across the Dixon Entrance near the northern end of Queen Charlotte Island and across the Hecate Strait between Sandspit and Bonilla Island.
- Maintaining a high degree of orthogonality between the longshore and cross-shore grid lines (> 87.4°).
- Where possible, keeping transitions in cell spacing within 25% between adjacent rows of grid cells.
- Using simpler boundary conditions on the open-water boundaries based on the astronomical tides (WebTide Version 0.7.1) at either end of each boundary.
- Aligning the grid lines to the proposed structure's centreline in the immediate project area.
- Using a higher eddy diffusivity equal to 10 m^2/s in the horizontal directions.
- De-activating the "Hotstart" file in the Delft3D-WAVE (SWAN) model.
- This setup generally eliminated instabilities originating near the boundaries.

The alternative setup was still subject to model instabilities developing in the interior of the grid, although not near the immediate project area. These tended to occur in shallow water areas near shorelines when the simulated waves were high, suggesting that they occurred to due wave breaking at long, narrow grid cells. To increase model stability, the following modifications were made in an iterative process:

- Reducing the time step from 30 to 15 s.
- Deleting grid cells in the far-field areas with elevations of -10 m MSL or shallower. This brought wave heights down to observed levels and eliminated most, but not all, instabilities originating in the interior of the grid.
- Using an increased spin-up time for hydrodynamics and delay period for morphology
- "Hotstarting" the model before the time it previously crashed with a reduced time step.
- Not using hydrodynamic current velocities in SWAN (current's effects on waves ignored, however, wave induced forces impacting currents are still included)

- Smoothed out the relatively course gridded wind data set in an attempt to eliminate instabilities which may have been generated by large wind speed gradients due to the resolution of the wind data.

The status of simulations which are variants of the alternative model setup are in Table I-3 (yellow highlighted simulations are still running).

Table I-3: Status of Simulations with the Alternate Grid

Vertical layers	Condition	Starting Date	Other	Last Output Date	Status
10 layers equal	Existing	9/1/2012	Alternate Grid	15/10/2012	Crashed
10 layers equal	Proposed	9/1/2012	Alternate Grid	17/10/2012	Crashed

The model stability and results using this approach were considered less efficient than the simulations described above, therefore this approach was disregarded.

I1.3 Deltares Nested Setup

An attempt was made to run a simulation with a coarse outer domain and higher resolution nested inner domain. A simulation for the outer domain was successfully run for a month in order to obtain boundary conditions for the inner nested domain, however, it was determined that the time step necessary to run a stable inner nested domain was far too small to make this option a practical alternative.

I1.4 Summary

The model setups above remain stable if they are not coupled with Delft3D-WAVE (SWAN). The instabilities that cause the model to crash occur when coupling the two models (flow and waves) regardless of wave coupling interval. However, the instabilities were reduced and the model completed the long-term simulations (1 year).

The non-physical (numerical) unrealistic velocities appear to be caused by using a larger wave coupling interval that exaggerates the current speeds during wetting/drying processes on the shallow bathymetries of Flora Bank. The velocity spikes reduced significantly when the waves and currents were coupled every 1 hour.

I1.5 References

Hatch (2015). “3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation”. H345670-0000-12-124-0012, Rev. 0, May 5, 2015.

Appendix J:
High-Resolution Modelling

J1. High-Resolution Modelling

High-resolution modelling was performed using a separate coastal processes modelling system, MORPHO, to more accurately define the hydrodynamic, transport and morphological impact of the larger marine structures. The coastal conditions at the location of the SW Tower and SW Anchor Block were simulated in the Delft3D regional model and used as boundary conditions for the MORPHO model.

J1.1 Coupling of Nested and Regional Hydrodynamic Models

These conditions were reproduced in the MORPHO model through one-way coupling with water levels and current velocity components at the outer boundary. Numerous MORPHO modelling domains were evaluated and the domain with the best coupling performance was selected. Three simulations are presented:

- 28 day freshet simulation, which includes mild wave and wind-induced current activity, as well as Skeena River discharge
- 28 day tides-only simulation, which includes tidal forcing and tidal currents, but no winds, waves or Skeena River flows
- 11 day storm simulation for 50-year conditions from 270 degrees

Figure J-1 shows a comparison of the original Delft3D current velocity, current direction and water levels during a portion of the 28 day freshet simulation, and a comparison with those values extracted in the MORPHO nested model simulation for existing conditions (no marine structures). Time histories were extracted at a location between the SW Tower and SW Anchor Block. The nested MORPHO model reproduces current direction and water levels very well, and slightly over-predicts the peak current speeds. Given the complexity of coupling two very different hydrodynamic tools, the coupling is considered to be sufficient.

Figure J-2 shows coupling for the 28 day tides-only simulation, which is performed on the same domain and during the same time period as the 28 day freshet simulation, but without winds, waves or Skeena River flows. Currents are lower during this period and the coupling between the Delft3D and MORPHO models is good. In general the MORPHO model has slightly higher peak current speeds which will contribute to conservative results regarding potential impacts of the marine structures.

For storm simulations, the complexity of the wave-generated currents at the location of the SW Tower and SW Anchor Block prevented the type of coupling that was used for existing conditions simulations. Therefore, a more localized domain was setup for each of the two marine structures. Time histories of currents and water levels at each structure location in the Delft3D model were used constant around the boundary to force each domain, so that the structures encounter the same hydrodynamics that they would have in the larger Delft3D modelling domain. Since the modelling domains are smaller and more idealized, the coupling is very good as shown in Figure J-3.

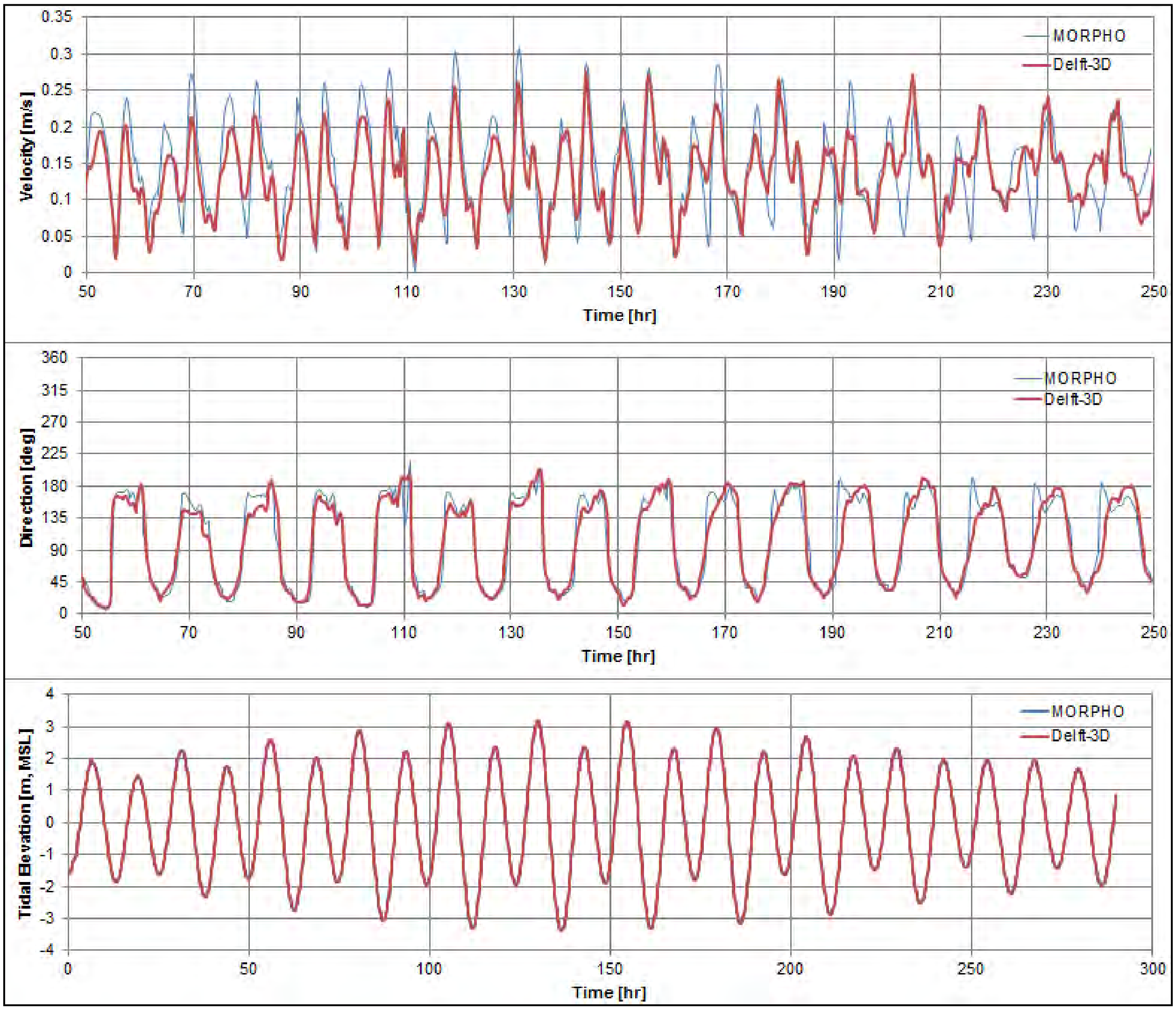


Figure J-1: Comparison of current speed, current direction and water level (bottom) between nested MORPHO model and regional Delft3D model during the 28 day freshet simulation.

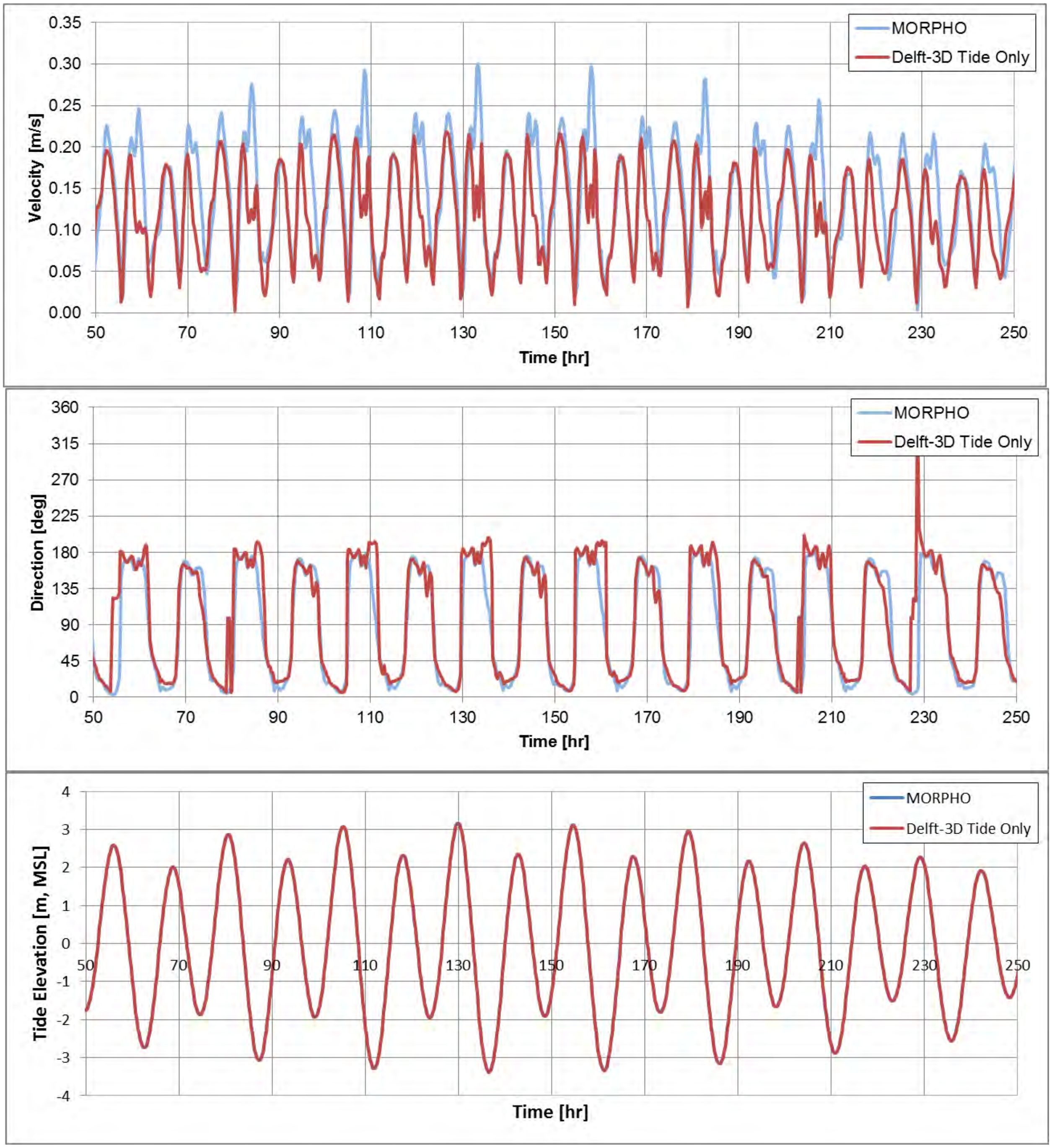


Figure J-2: Comparison of current speed, current direction and water level (bottom) between nested MORPHO model and regional Delft3D model during the 28 day tides-only simulation.

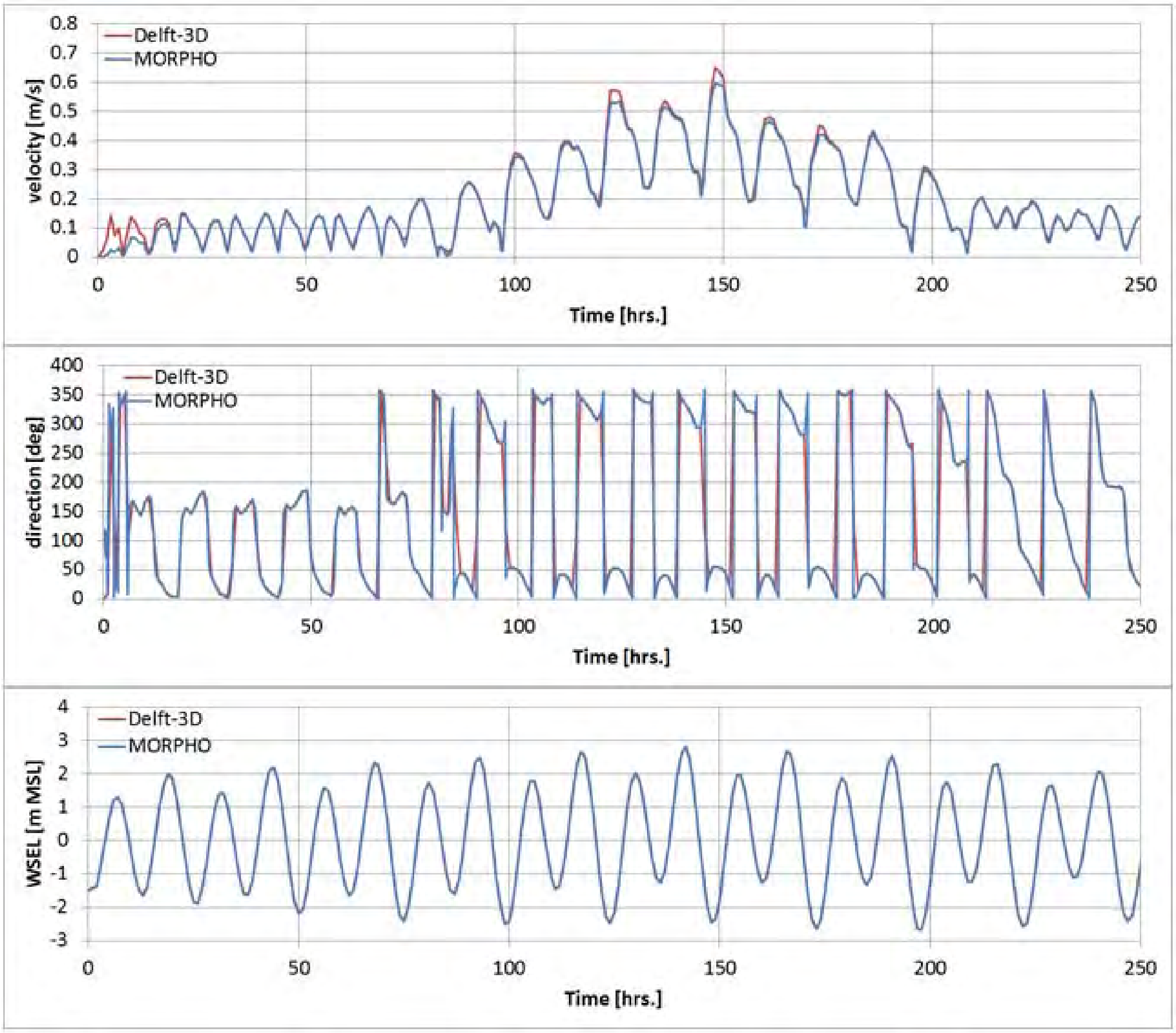


Figure J-3: Comparison of current speed, current direction and water level (bottom) between nested MORPHO model and regional Delft3D model during the 50-year storm simulation.

J1.2 Sediment Transport Model Description

Sediment transport modelling was performed using an array of equilibrium transport formulations, of which Engelund-Hansen total load transport formulation (Engelund et al, 1967) provided realistic distributions of erosion and deposition, and the largest amounts of scour and deposition of all other available transport formulations in the MORPHO model. This transport formulation is very commonly used, and is an option within the Delft3D model, and the default transport formulation within the Mike3 system (Danish Hydraulics Institute). The model was run using dynamic/interactive coupling between hydrodynamics and transport/erosion. The SW Anchor Block domain included 0.14 mm median grain size sand,

and the SW Tower domain included 0.3 mm median grain size sand. Simulations were performed without morphological acceleration (MORFAC = 1).

J1.3 Tides-Only Sediment Transport Modelling Results

Sediment transport modelling results shown in the main body of the report include those for 28 day freshet conditions as well as for a 50-year storm from 270 degrees True North. Additional simulations were performed upon suggestion from federal experts that would include forcing from only tidal currents. Figure J-4 displays the maximum velocities for existing conditions (top) and with the proposed structures (bottom) for the tides-only simulation. Figure J-5 shows erosion and deposition patterns caused by the marine structures for the SW Anchor Block (top) and the SW Tower (bottom) over a 1 year period, extrapolated linearly from results of 28 day tides-only simulation. The scour and deposition patterns are reduced in magnitude relative to the freshet simulation which contained higher velocities.

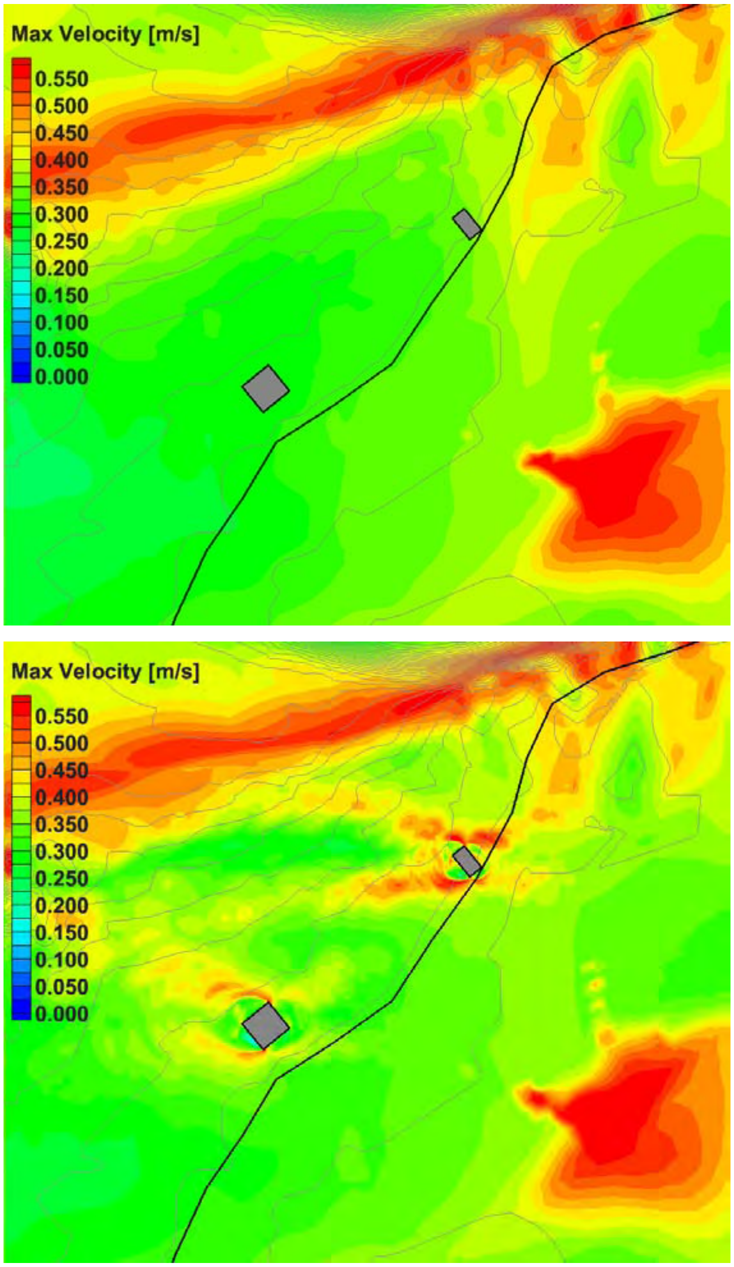


Figure J-4: Maximum velocities for existing conditions (top) and with the structures (bottom) for tides-only simulation

J1.4 Sediment Transport Modelling Results without Scour Protection

Sediment transport modelling results shown in the main body of the report include the proposed scour protection systems. Additional simulations were also performed without scour protection to provide more intuitive representations of potential scour. Figure J-6 shows erosion and deposition patterns caused by the marine structures for the SW Tower (0.3 mm sediments) with scour protection (top) and without scour protection (bottom) during the 50-year storm from 270 degrees True North. With the scour protection system installed, the maximum scour during the 11 day simulation was 0.6 m, which was spread fairly consistently over a 3 m wide area. Without scour protection, the peak scour is more localized at the south corner of the structure and was approximately 4 m, with average scour within 3 m of the corner of roughly 2.3 m.

Figure J-7 shows erosion and deposition patterns caused by the marine structures for the SW Anchor Block (0.14 mm sediments) with scour protection (top) and without scour protection (bottom) during the 50-year storm from 270 degrees True North. With the scour protection system installed, the maximum scour during the 11 day simulation was 0.2 m, which was spread fairly consistently over several meters. Without scour protection, the peak scour is highly localized with a maximum at the south corner of the structure and was approximately 4.4 m, with average scour within 3 m of the corner of roughly 2.4 m.

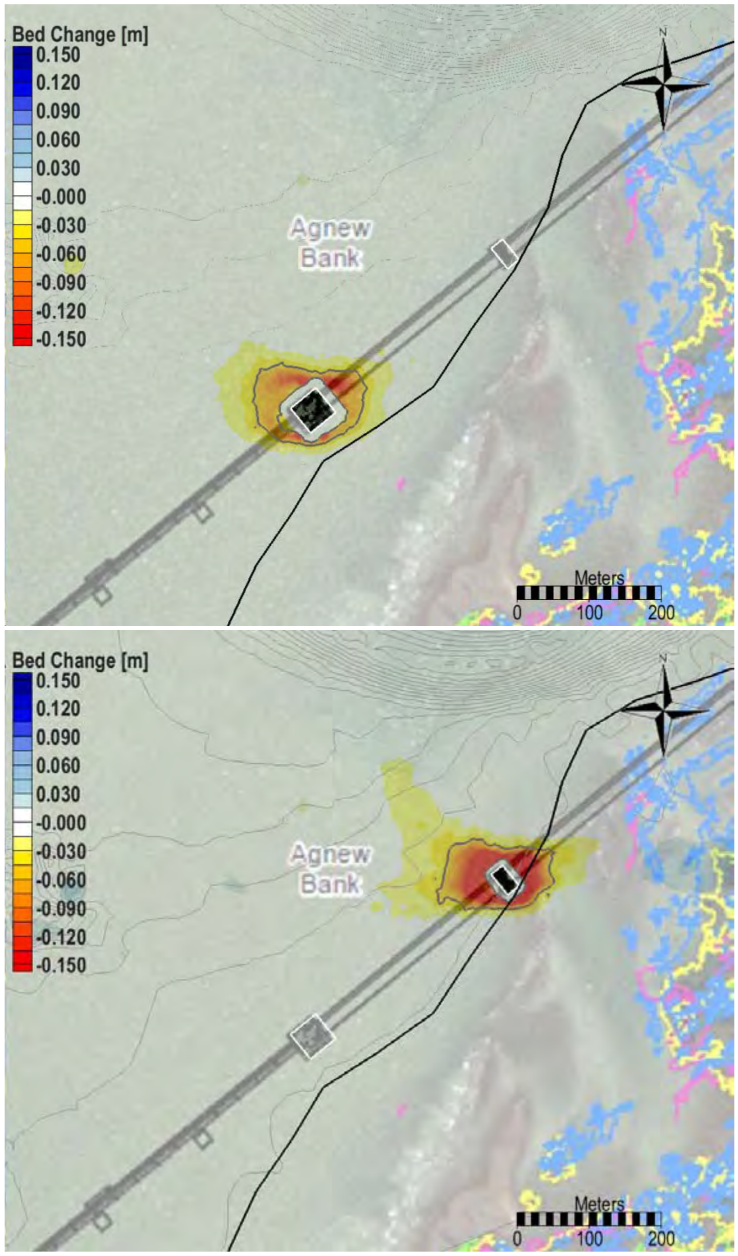


Figure J-5: Erosion and deposition patterns caused by the marine structures for the SW Anchor Block (top) and the SW Tower (bottom) over a 1 year period, extrapolated linearly from results of 28 day tides-only simulation. Dark lines indicate changes in excess of 5 cm/year.

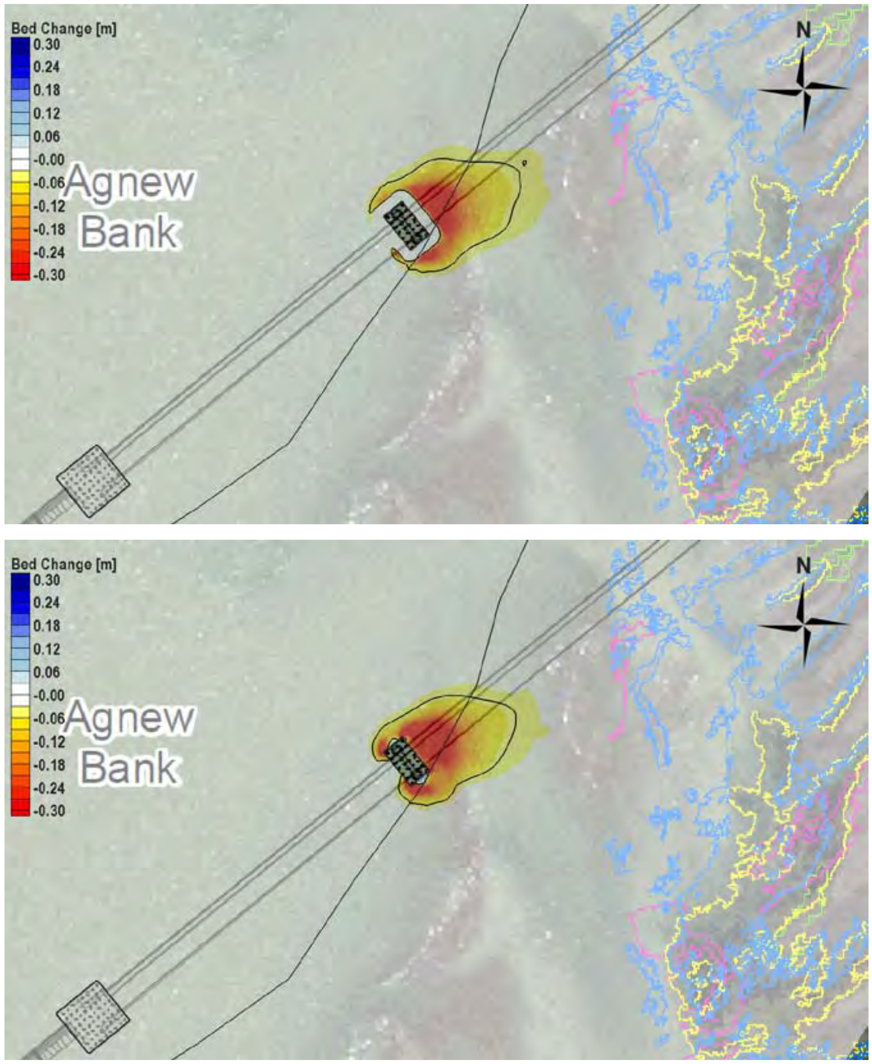


Figure J-6: Erosion and deposition patterns caused by the marine structures for the SW Tower (0.3 mm sediments) with scour protection (top) and without scour protection (bottom) during the 11 day storm simulation. Dark lines indicate changes in excess of 5 cm.

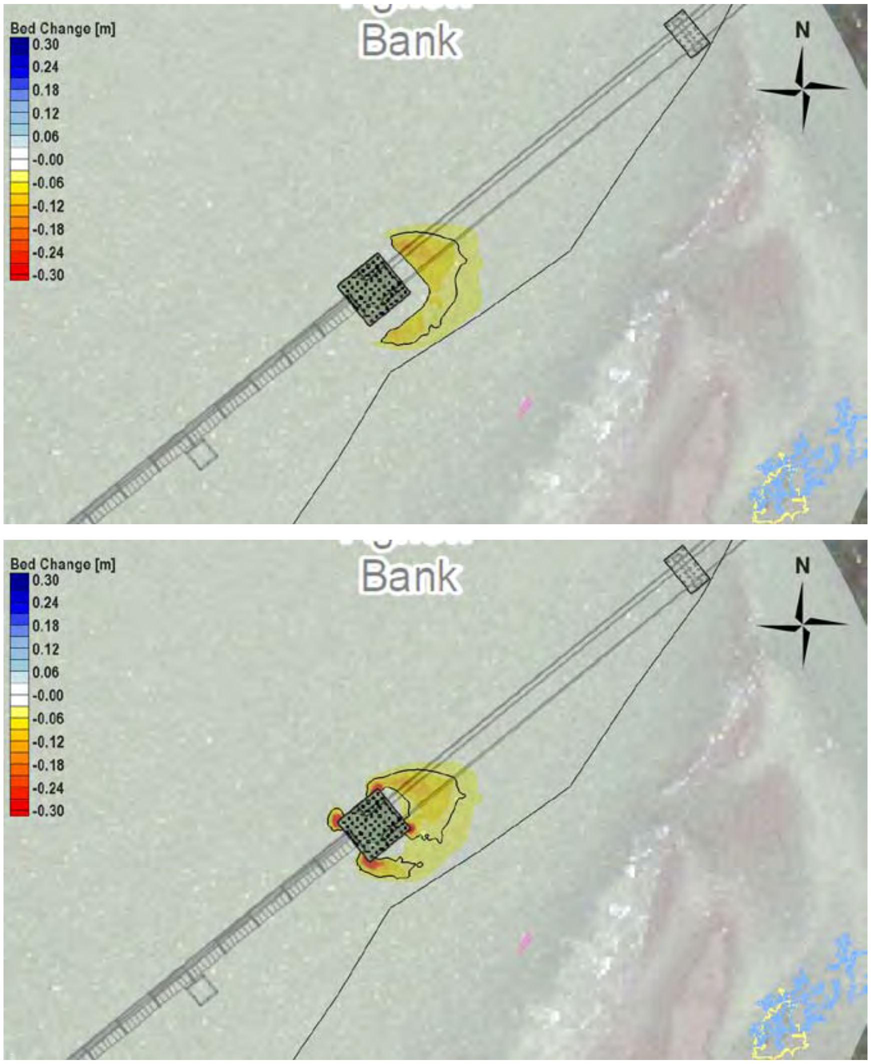


Figure J-7: Erosion and deposition patterns caused by the marine structures for the SW Anchor Block (0.14 mm sediments) with scour protection (top) and without scour protection (bottom) during the 11 day storm simulation. Dark lines indicate changes in excess of 5 cm.

J1.5 Sediment Grain Size Sensitivity Analysis

Sediment transport modelling was performed for the SW Tower with sediment grain sizes to demonstrate the relative changes in scour patterns that could result as a function of different sediment size assumptions. The sediment sizes tested in the modelling included 0.177 mm, 0.25 mm, 0.3 mm (the reported mean grain diameter at this location), and 0.5 mm. Figure J-8 shows erosion and deposition patterns caused by the marine structures for the SW Tower during the 11 day, 50-year storm from 270 degrees True North.

Results indicate that the overall scour pattern, in particular the location of the 5 cm scour line, is relatively independent of sediment grain size for this range of sand sizes. The sediments have different levels of mobility, erosion rate when mobilized, and fall velocities. The results lend confidence to the modelling in that assumptions regarding sediment sizes used for the simulations do not have a significant effect on the sediment transport and erosion/deposition results.

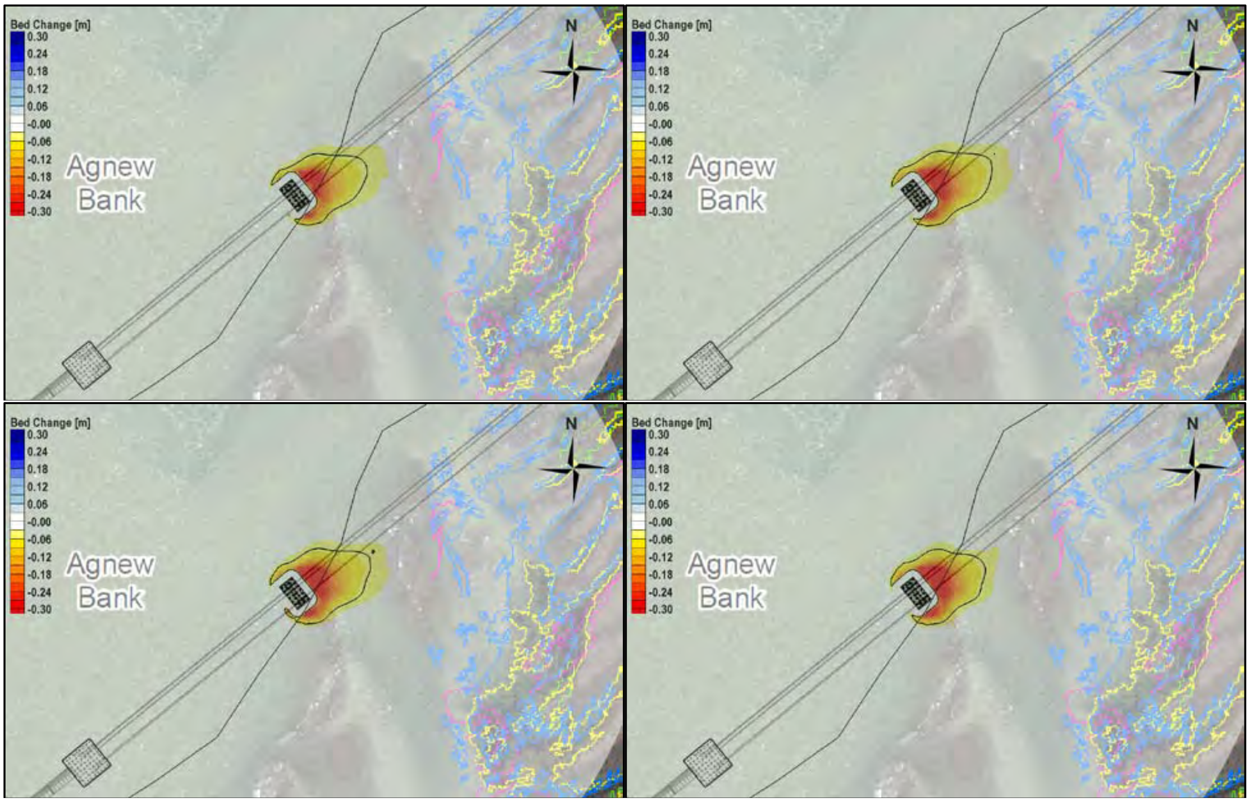


Figure J-8: Erosion and deposition patterns caused by the SW Tower with scour protection for a range of sediment grain sizes, including 0.177 mm (top left), 0.25 mm (top right), 0.3 mm (bottom left) and 0.5 mm (bottom right).

J1.6 Equilibrium Scour Around Rip-Rap Protection

The large marine structures are representative of isolated structures such as bridge piers because these structures are small relative to the large, homogeneous flow fields in which they are sitting, and the bottom slope at the structures is flatter than 100H:1V. Extensive empirical equations for **equilibrium scour depth** and **equilibrium scour extents** have been developed for riverine and coastal applications. All research fundamentally shows that **equilibrium exists**, and is reached for a complete range of coastal conditions and structure types.

Many laboratory studies (Escarameia & May, 1999) have been performed to better understand the effect of major factors (e.g. water depth, pier shape, sediment size, reversal of flow direction) upon **equilibrium scour depth** and evolution of the scour depth over time prior to reaching **equilibrium**.

Many publications demonstrate that individual or groups of structures cause localized bed changes but those bed changes reach an equilibrium state. The equilibrium state is shown in many of the publications, such as Das et al (2014).

The scour patterns vary based on structure shape as has been demonstrated in this report; however they all do reach a state of **equilibrium**. Numerous entities have published formulations to determine **equilibrium scour**, for the purposes of design. This means that it is a well-known fact that scour will not continue at the same rate forever, but will slow to a relative halt when the sediment around the structure is too deep to be mobilized.

In addition, the following references provide formulations which describe "**equilibrium**" scour depth and extents, which were determined using laboratory studies:

- Sheppard et al (2010)
- Arneson et al (2012)
- Nordila et al (2014)
- Escarameia & May (1999)

Escarameia & May (1999) found that **equilibrium scour depths**, measured in tidal conditions in the laboratory, were always much less than those found for unidirectional conditions. The combined findings above as well as the characteristics of the project site and marine structures (SW Tower and SW Anchor Block) strongly imply that the rate of scour will be slow, that equilibrium depths around the structures will be reached, and that the equilibrium scour depth will be relatively small in comparison to predictions made using empirical formulations because of the shallow water at the project site.

Figure J-9 below shows scour trends over time for live-bed scour (situations where sediments are mobile approaching the structure) and for clear-water scour (situations where flows approaching the structure are mostly below threshold of movement in the absence of the structure). Most of the time, the SW Tower and SW Anchor Block are located in areas of limited mobility and hence clear-water scour would better apply. The Dutch Scour Manual (Hoffmans, 1997) indicates that under live-bed hydraulic conditions scour reaches equilibrium depth more rapidly than the equivalent clear-water case, which is consistent with current U.S. guidance (Richardson, 2001).

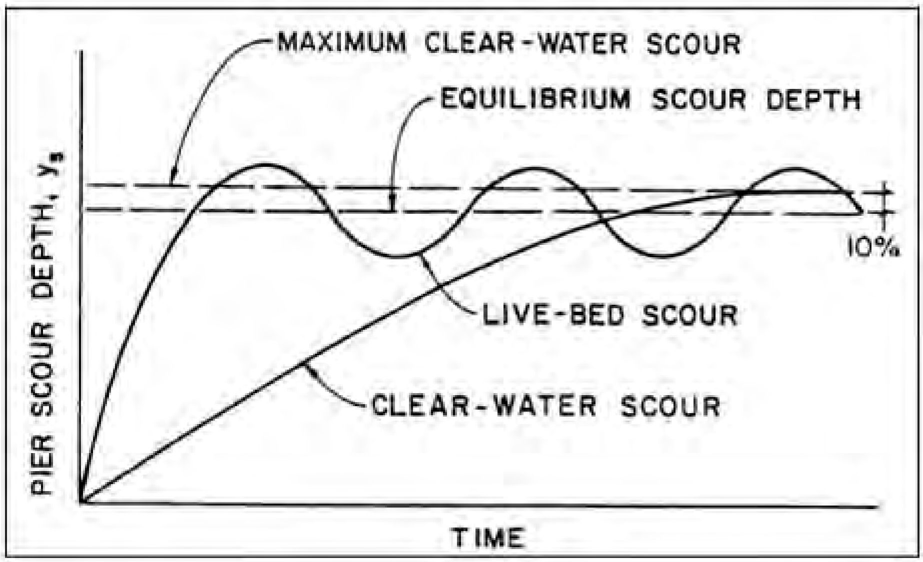


Figure J-9: Pier scour depth in a sand-bed stream as a function of time on an arithmetic axis (source: Richardson, 2001)

Time scales during which scour reaches equilibrium vary significantly. One important factor is the fraction of time where bottom velocities at the structure are above threshold. At the SW Tower and SW Anchor block, in particular in the areas surrounding the scour protection (i.e. some distances form the actual structures), scouring does not continually occur. Given the relatively low scour rates observed in the modelling, with scouring only occurring for short durations during peak flows, it is anticipated that equilibrium depths around the edges of the riprap scour protection are likely to be reached in time periods ranging from several months to a few years.

Installation of rip-rap around the marine structures is proposed at the time of construction (Hatch, 2014). This will effectively eliminate scour directly up against the structures, but scour will occur to a lesser degree farther away from the structure. While scour will occur around the outer edges of the scour protection (rip-rap), a state of equilibrium scour will be reached surrounding the scour protection as well.

Literature references extensively state that rip-rap is the most effective way to reduce and even prevent scour of the seabed over structures. Chen et al. (2012) concluded from physical modelling that scour protection with different rock gradations was the most effective in preventing scour for sea-crossing bridge foundations. USACE recommends that quarry stone aprons be used to protect marine structures such as Bridge Piers and Gravity Based Structures from scour.

Thickness of the scour protections shall be designed to:

- Mitigate edge scour by applying falling apron principle;
- Prevent winnowing of sand out from between the scour protection material, and;
- Allow natural horizontal movements of individual rocks without locally reducing the scour protection layer.

Scour countermeasures will have to be more effective on the corners of block because scour will be more concentrated in these regions as demonstrated by Sumer & Fredsøe (2002) and Bos et al. (2002). To reduce edge scour at the scour protection a gradual transition from the scour protection armour to the unprotected sea bed should be made. This will typically be accomplished by extending the underlayer out from under the armour layer to form a protective flexible apron of the scour protection.

J1.7 References

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., & Clopper, P. E. (2012).Evaluating scour at bridges (No. FHWA-HIF-12-003).

Engelund, F. and Hansen, E. (1967) A monograph on sediment transport in alluvial streams: Teknisk Vorlag, Copenhagen, Denmark, 62 p.

Bos, K.J., Chen, Z., Verheij, H.J., Onderwater, M., Visser, M. (2002) : Local Scour and Protection of F3 offshore GBS platform, Proceedings of the 21th International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway

Chen, H., Yang, R., Kuo, P. and Hwung, H., 2012. Physical Modeling Study on Scour and Scour Countermeasure for Sea-Crossing Bridge Piers. Bridge Pier Scour Assessment - Proc., 33rd International Conference Coastal Engineering, Santander, Spain, 15 p.

Das, S., Das, R., & Mazumdar, A. (2014). Variations in clear water scour geometry at piers of different effective widths. Turkish Journal of Engineering and Environmental Sciences, 38(1), 97-111.

Escarameia, M., & May, R. W. P. (1999). Scour around structures in tidal flows.

Guo, Junke, et al. Pier scour in clear-water conditions with non-uniform bed materials. No. FHWA-HRT-12-022. 2012.

Harris, J., Whitehouse, R. J. S., & Benson, T. (2010). The time evolution of scour around offshore structures. ICE-Maritime Engineering, 163(1), 3-17.

Hatch, 2014. Pacific Northwest LNG Lelu Island LNG Terminal. Marine Structures Scour (H345670-12-124-0008). Appendix G.17, Report issued Dec. 11, 2014.

Hoffmans, G.J.C.M. and H.J. Verheij, 1997, "Scour Manual," A.A. Balkema: Rotterdam, Brookfield.

Lagasse, P F, Clopper, P E, Zevenbergen, L W and Girard, L G. 2007. ―Countermeasures to protect bridge piers from scour‖. Washington, DC: Transportation Research Board of the National Academies (NCHRP Report 593).

Melville, Bruce W., and Yee-Meng Chiew. "Time scale for local scour at bridge piers." Journal of Hydraulic Engineering 125.1 (1999): 59-65.

Nordila, A., Ali, T. M., Faisal, A., & Badrunnisa, Y. (2014, January). Local Scour at Wide Bridge Piers. In International Journal of Engineering Research and Technology (Vol. 3, No. 1 (January-2014)). ESRSA Publications.

Richardson, E.V. and Davis, S.R., 2001. Evaluating Scour At Bridges Fourth Edition. U.S. Department of Transportation. FHW NHI 01-001 HEC-18.

Sumer, B.M., and J. Fredsøe. 1997. Scour at the Round Head of a Rubble-mound Breakwater. Coastal Engineering 29, Elsevier, pp. 231-262

Sumer, B.M., and J. Fredsøe. 2002. The Mechanics of Scour in the Marine Environment, World Scientific, Singapore.

USACE 2006. Coastal Engineering Manual, 2006. Section VI-5-6 Scour and Scour Protection. Scour at Piles, VI-5-238.

Appendix K:
Sediment Mobility and Transport

K1. Sediment Mobility and Transport

This appendix outlines the sediment threshold and sediment movement analyses for the bottom sediments around the marine structures and on Flora Bank.

K1.1 Sediment Mobility Analysis

Nine points around the marine structures (SW Anchor Block and SW Tower) and over Flora Bank were selected for this analysis as shown in Figure K–1 and Table K-1

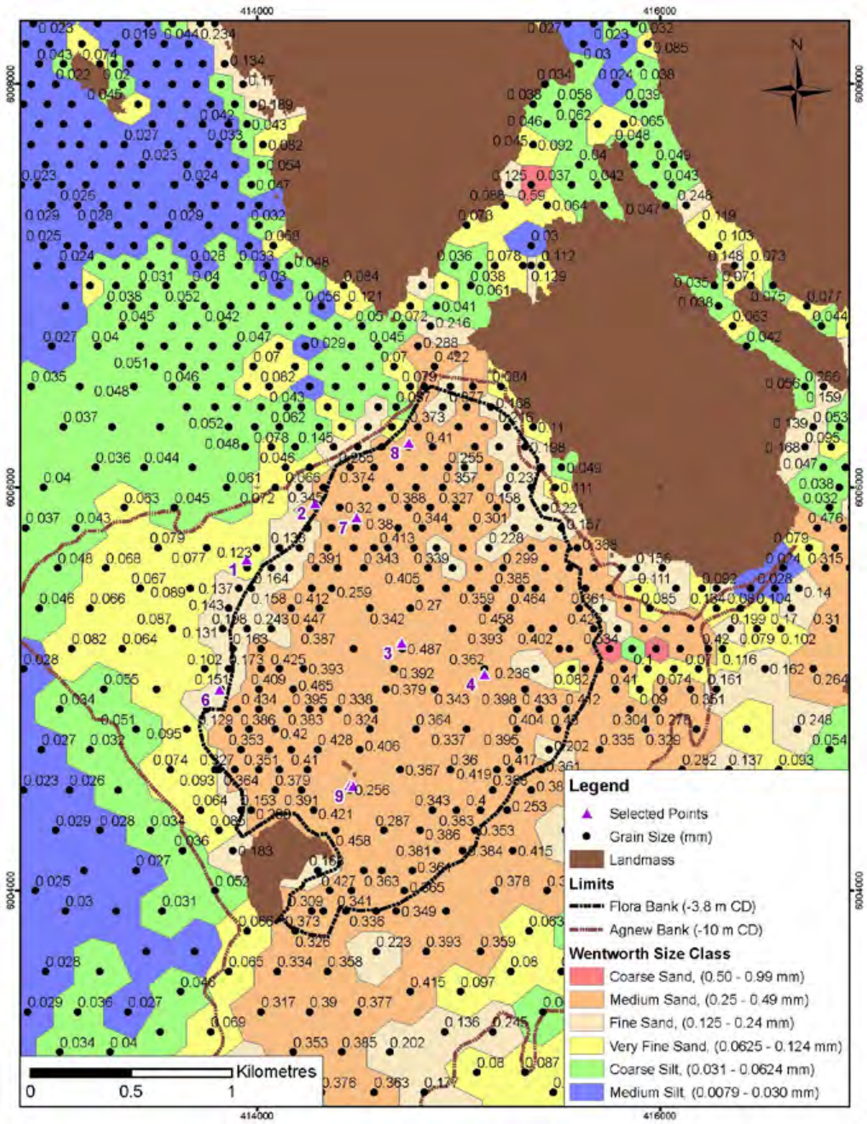
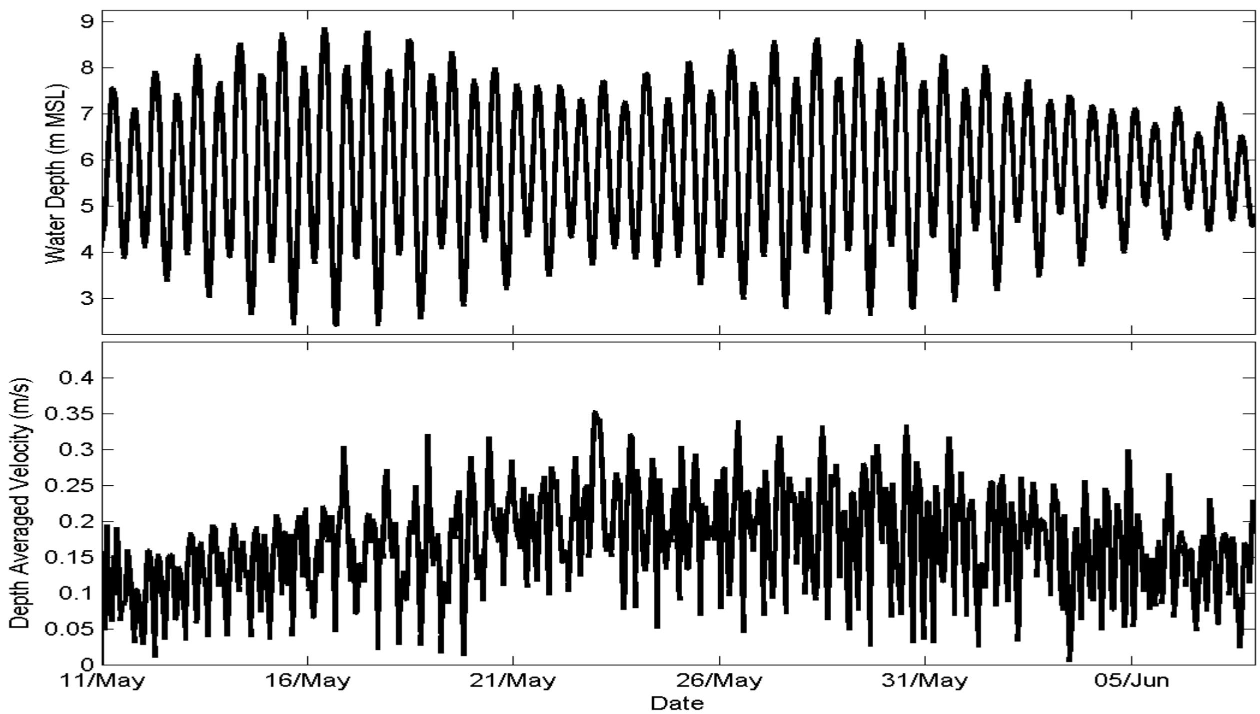


Figure K–1: Selected Points for Sediment Movement (Modified from SedTrend, 2015)

Table K-1: Seabed Characteristics at the Nine Selected Points

Point	Location Description	Median Diameter, D_{50} (mm)	Peak Magnitude of Depth Averaged Velocity, V (m/s)	Easting (m)	Northing (m)
1	Near SW Anchor Block	0.12	0.353	413946	6005643
2	Near SW Tower	0.31	0.3	414286	6005921
3	Center of Flora Bank	0.49	0.377	414716	6005229
4	East of Point 3	0.36	0.349	415126	6005074
5	Near Kitson Island	0.26	0.392	414458	6004525
6	Southwest limit of Flora Bank	0.15	0.427	413811	6004996
7	Near SW Anchor Block inside Flora Bank	0.21	0.281	414493	6005849
8	Near SW Tower inside Flora Bank	0.41	0.314	414750	6006221
9	Near middle of Bridge Span	0.33	0.331	414475	6004518

The hydrodynamic conditions considered were obtained from the Delft3D model results for typical flow conditions during the 28 day freshet simulation for the year 2014. This simulation modelled typical tidal flow conditions, as shown in the time-series plots of water levels and flow velocities for Point 1 to Point 9 in Figure K–2 and Figure K–3, as well as Figure K–4 to Figure K–10.



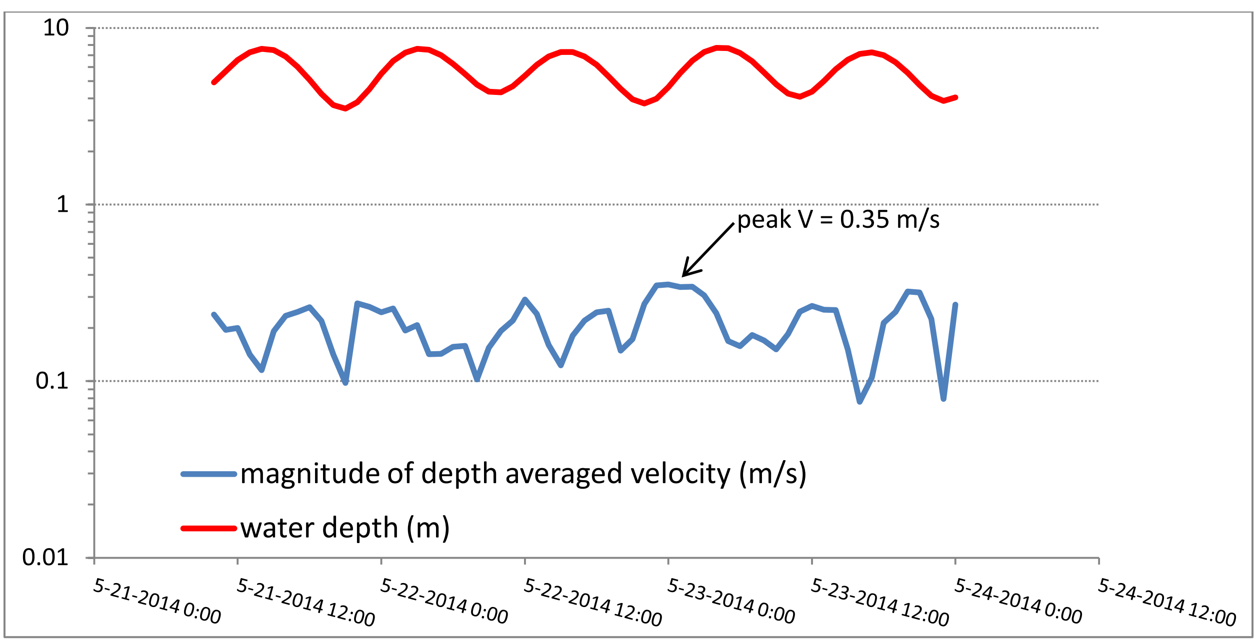
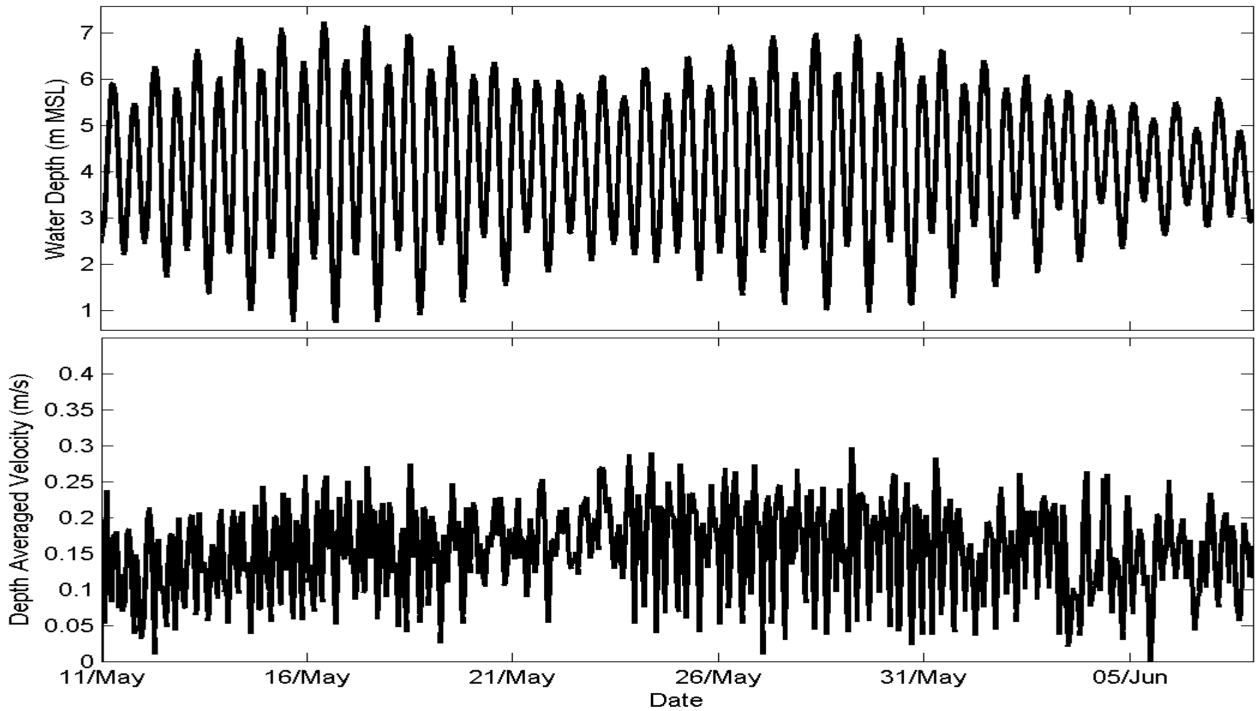


Figure K–2: Simulated time-series at Point 1 (and zoomed plot near peak velocity) — SW Anchor Block (Freshet 2014)



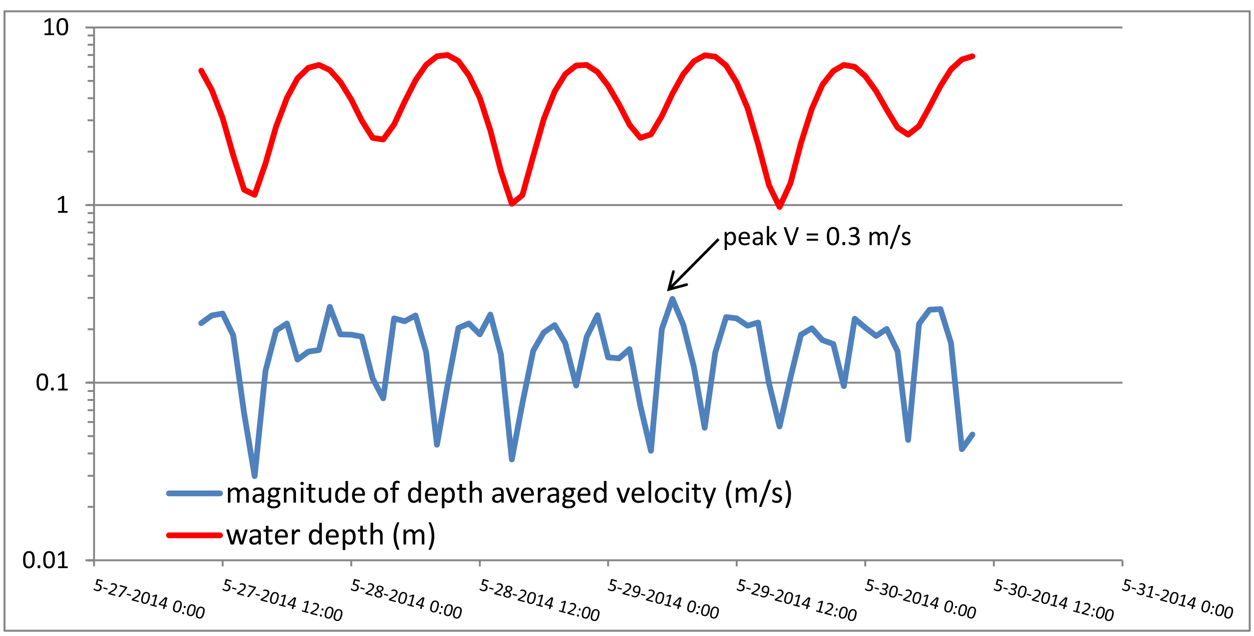


Figure K–3: Simulated time-series at Point 2 (and zoomed plot near peak velocity) – SW Tower (Freshet 2014)

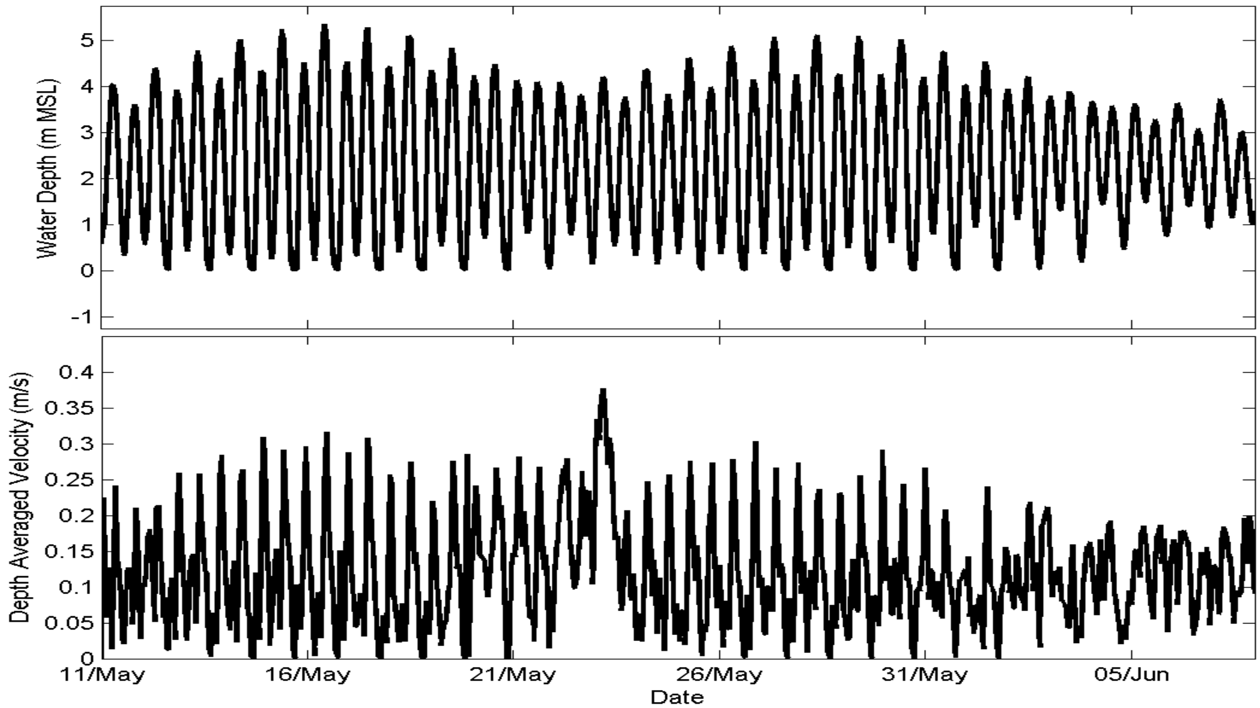


Figure K–4: Simulated time-series at Point 3 – SW Tower (Freshet 2014)

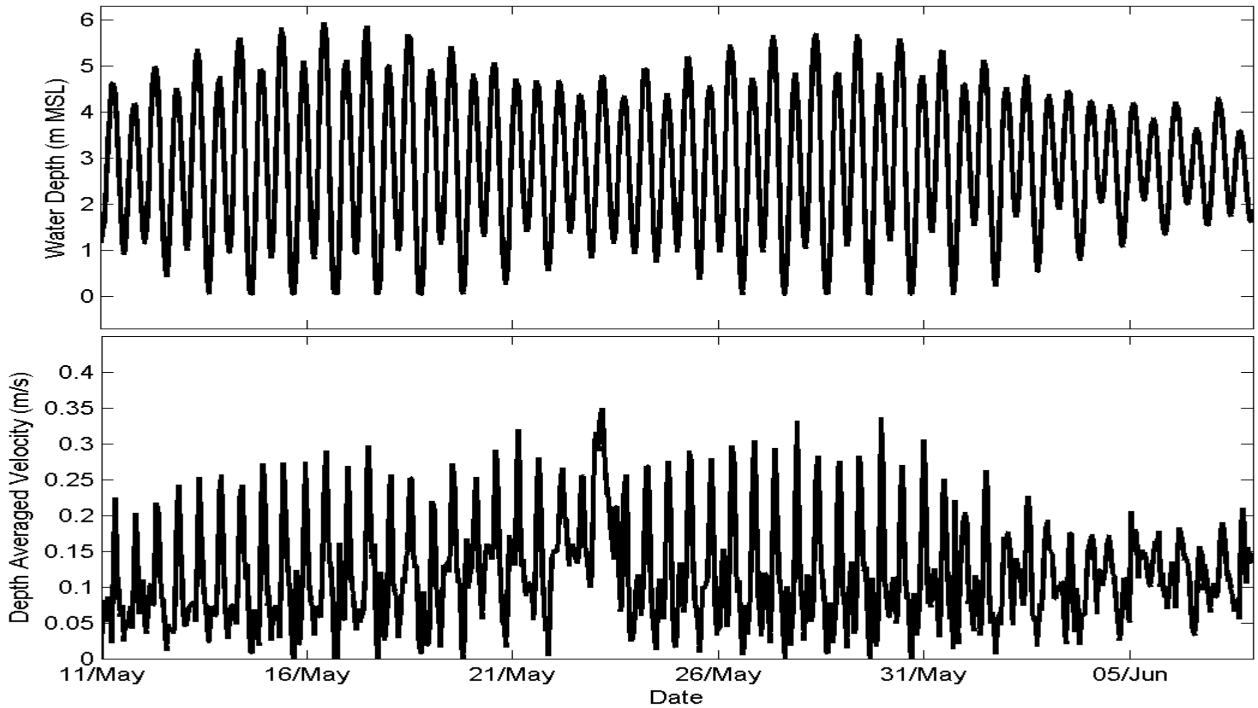


Figure K–5: Simulated time-series at Point 4 - SW Tower (Freshet 2014)

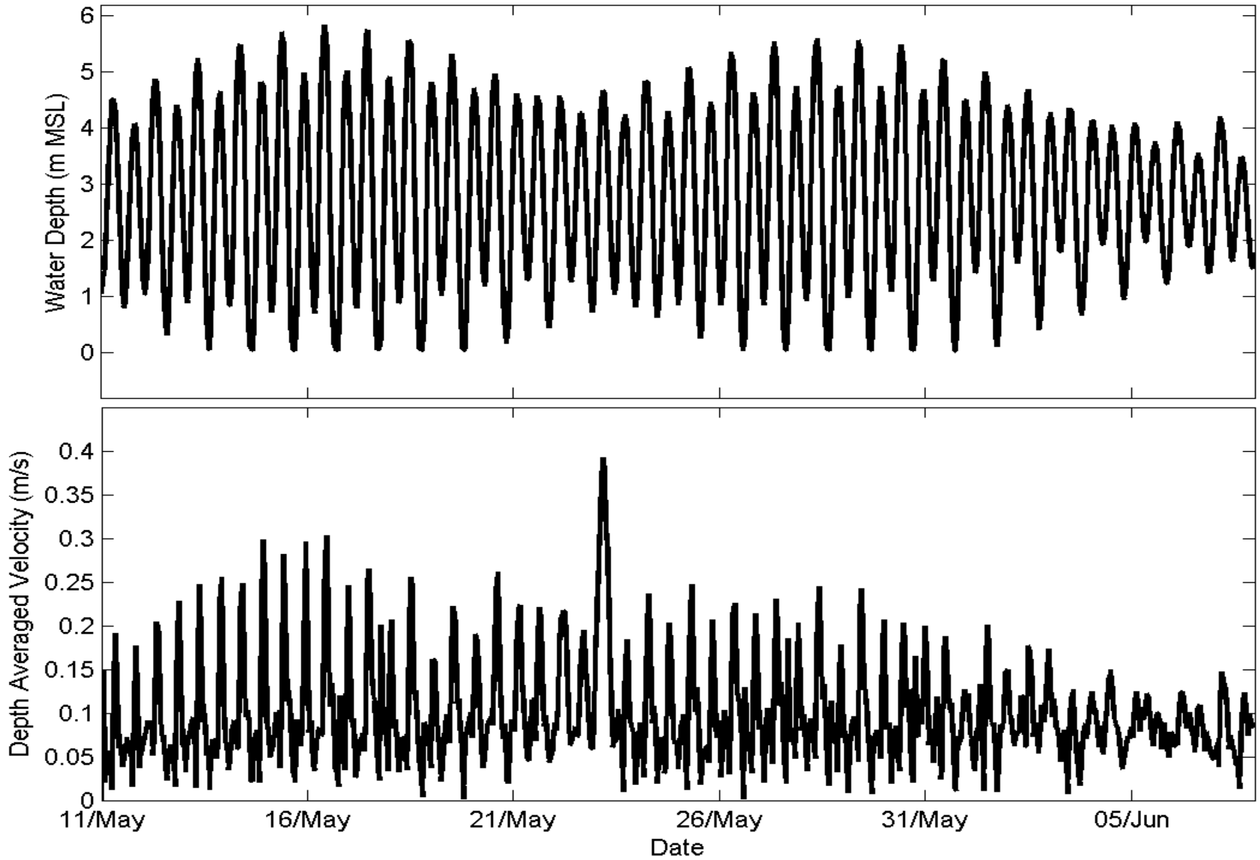


Figure K–6: Simulated time-series at Point 5 - SW Tower (Freshet 2014)

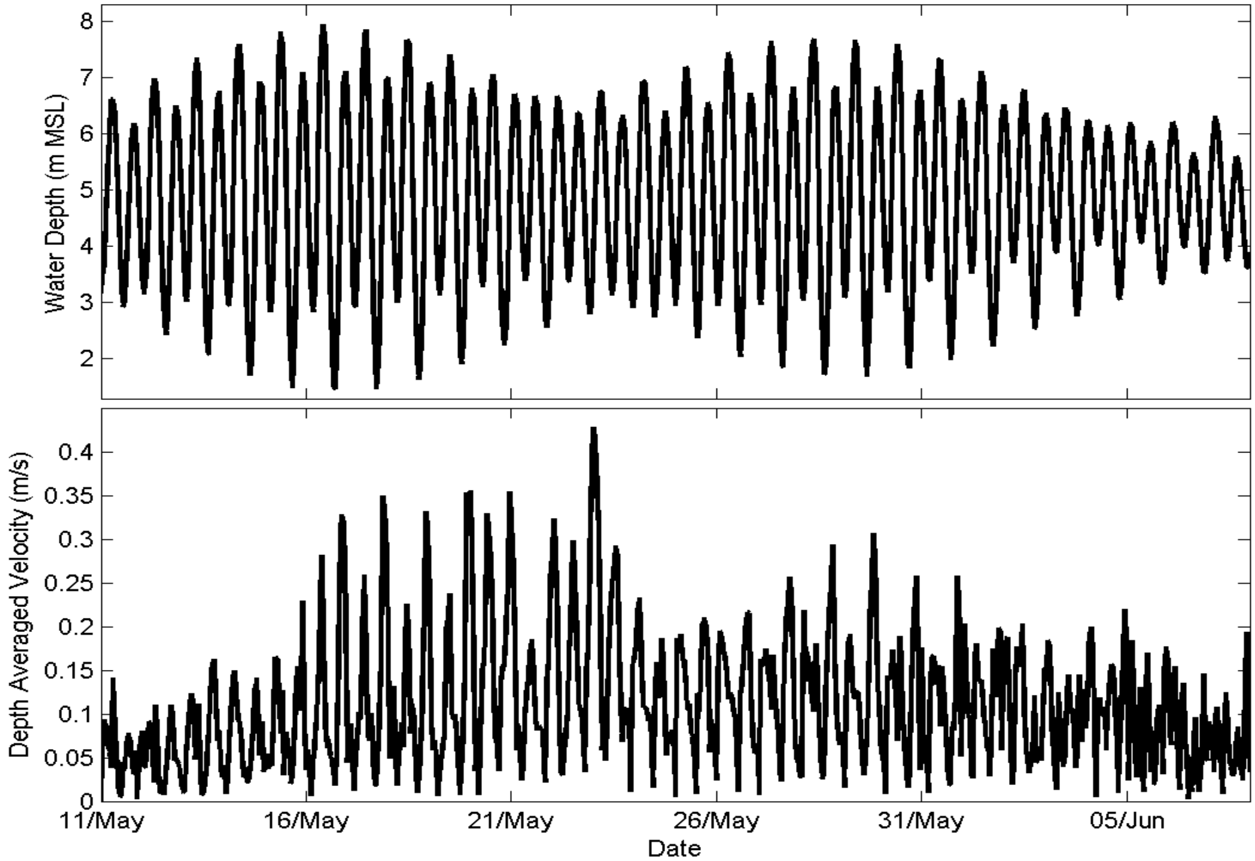


Figure K–7: Simulated time-series at Point 6 - SW Tower (Freshet 2014)

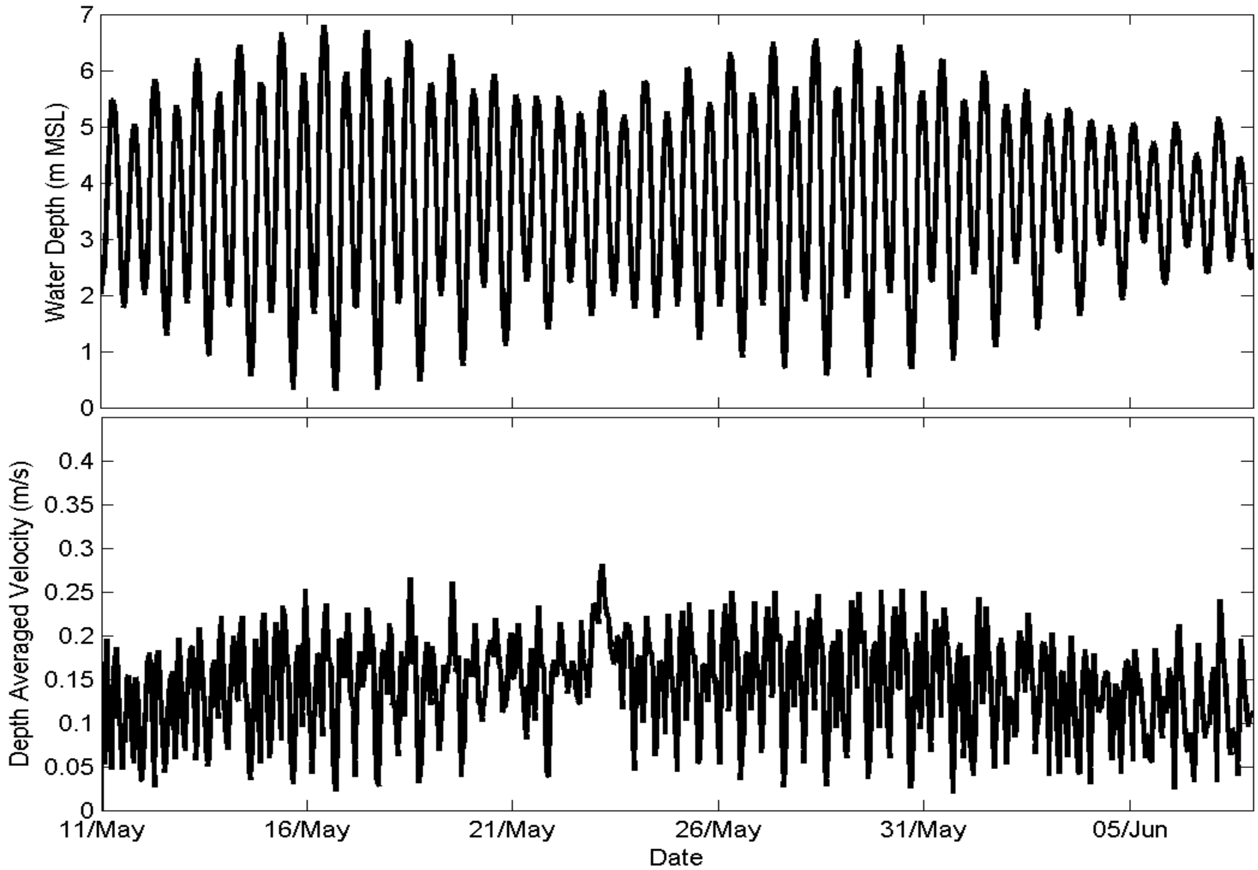


Figure K–8: Simulated time-series at Point 7 - SW Tower (Freshet 2014)

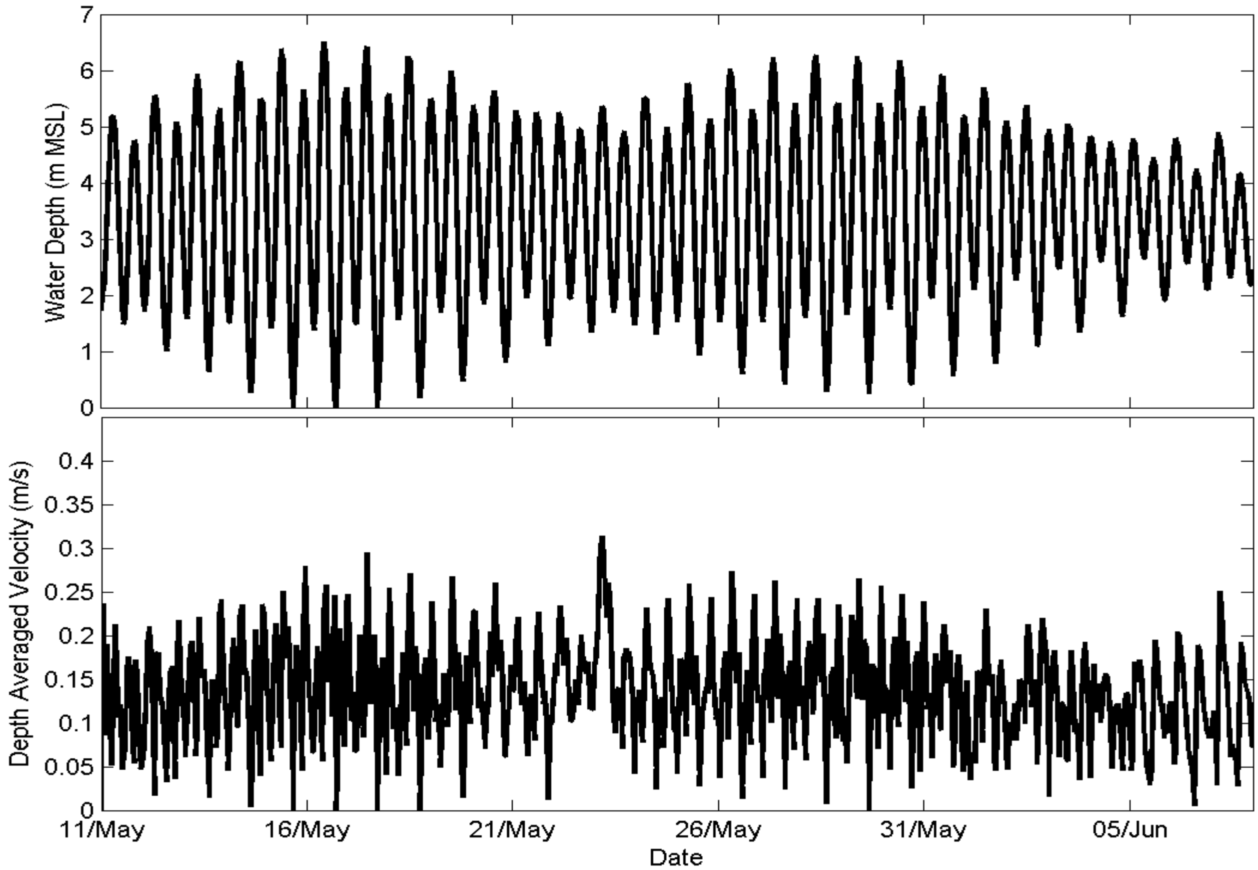


Figure K–9: Simulated time-series at Point 8 - SW Tower (Freshet 2014)

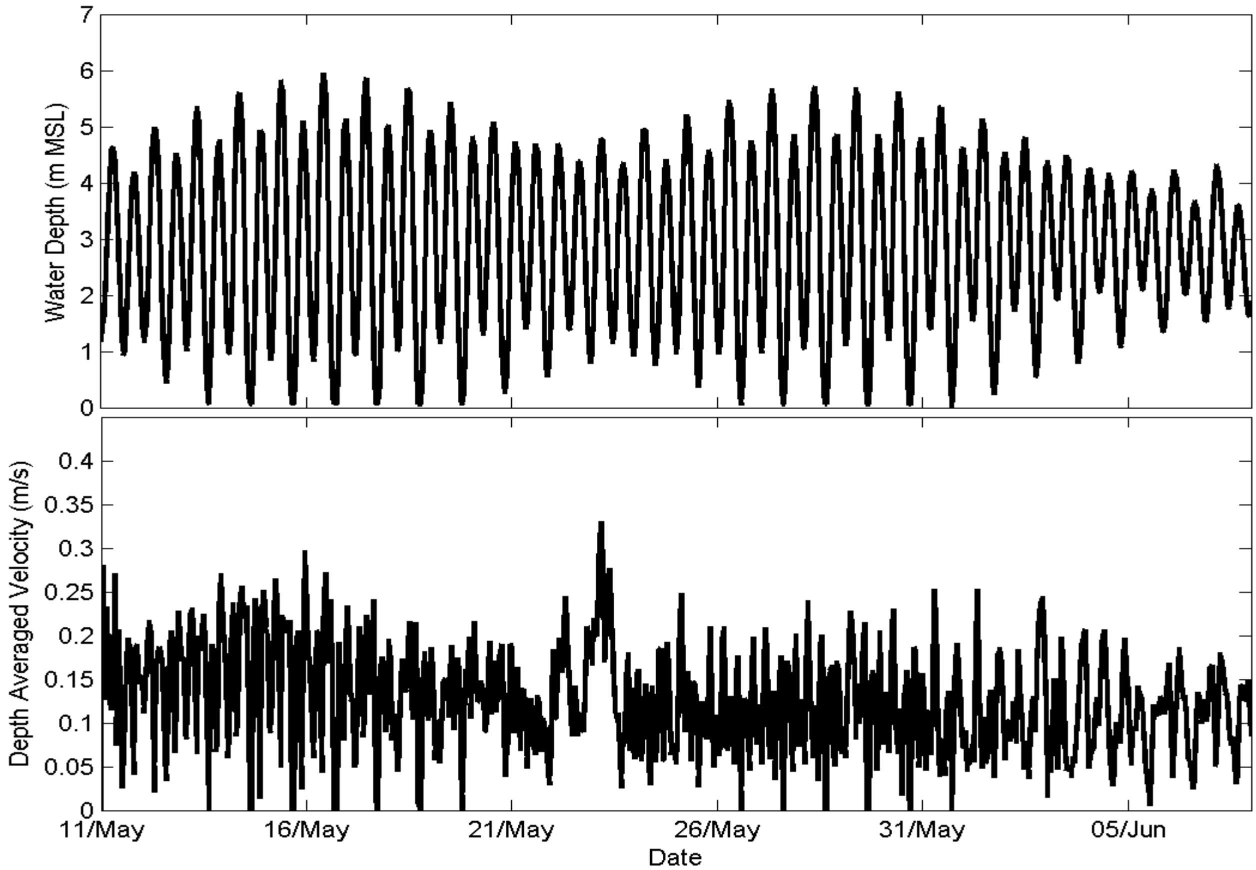


Figure K–10: Simulated time-series at Point 9 - Middle of Bridge Span (Freshet 2014)

K1.2 Shields Method

The threshold of sediment movement was analyzed using the Shields method (Yalin, 1977; Yalin, 1992, CEM, 2003). Figure K–11 and Figure K–12 show, respectively, the Modified Shields Diagram and the typical movements of a sediment particle.

Sediments may be transported as either bed load or suspended load, under the action of tidal currents. Bed load is the movement of particles along the seabed by either rolling, sliding, or saltating. Sediments that move by suspended load are in suspension.

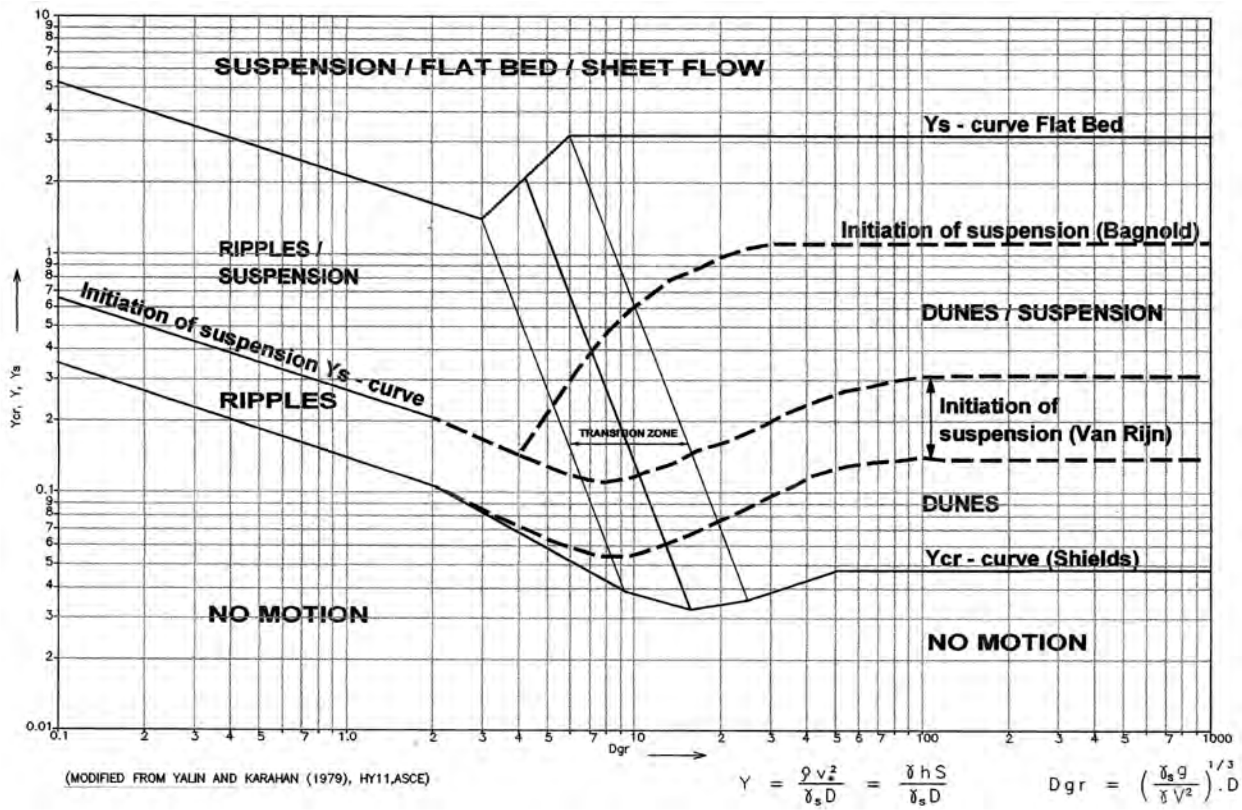


Figure K–11: Modified Shields Diagram (Modified from Yalin and Karahan, 1979)

Figure K–11 is known as the Modified Shields Diagram (Yalin, 1977, Yalin and Karahan, 1979, Yalin, 1992, CEM, 2003). The function Y_{cr} is the critical sediment mobility number and D_{gr} is a dimensionless grain size number, a characteristic parameter of the bottom sediments.

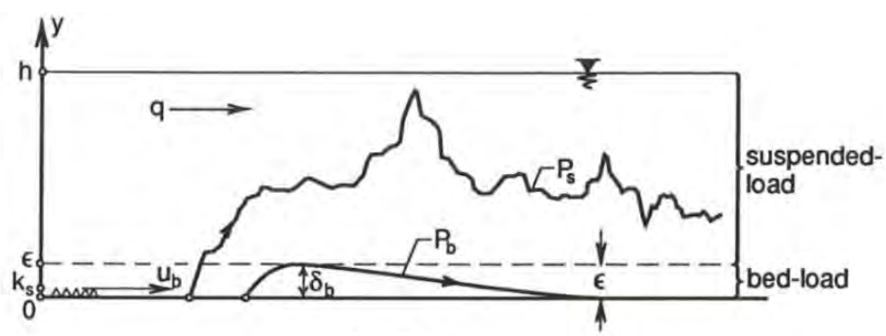


Figure K–12: Sediment Movement due to Currents (Yalin, 1992)

The threshold of sediment movement using the Shields method assumes cohesionless material (sands), where the movement of grains occurs for values of bottom shear stresses greater than a critical value defined by the Shields function: $Y_{cr} = f(D_{gr})$ where:

$$D_{gr} = \left(\frac{\gamma_s}{\gamma}\frac{D^3 g}{\nu^2}\right)^{1/3}$$

and

$$Y_{cr} = \frac{\rho v_{*cr}^2}{\gamma_s D}$$

In the above Equations, D is the median grain diameter, γ is the specific weight of water, ρ is the water density, g is the acceleration due to gravity and v is the kinematic viscosity of water. The subscript cr corresponds to critical values; v* is the shear velocity, and is given by:

$$v_* = \sqrt{\tau_o / \rho}$$

where τ_0 is the bottom shear stress. The parameter γ_s is the specific weight of a grain in water, defined as:

$$\gamma_s = (\rho_s - \rho)g$$

For a particular sediment location and depth, if the mobility number (*Y*-values) fall below the critical function, $Y_{cr} = f(D_{gr})$ then potentially no motion occurs at this location.

K1.2.1 Mobility of Selected Points Near Flora Bank

An expression of critical flow velocity was considered in the threshold analysis based on the equations presented above. Assuming sand material as bottom sediments, logarithm velocity distribution with depth, and constant bottom friction, an expression for critical shear stress was developed which may be expressed in terms of critical flow velocity (V_{cr}) as follows:

$$V_{cr} = 0.353\ D^{0.22}$$

where V_{cr} is in m/s and D in mm.

The critical flow velocity equation was plotted in Figure K–13, together with the peak flow velocities for all nine points during the typical flows of the Freshet 2014. It may be seen that peak flow velocities are in general higher than the critical velocities for all points, included the ones located outside Flora Bank perimeter where sediments are finer.

For the points located near the marine structures but inside Flora Bank, the peak velocities are similar in magnitude to the critical velocities. Looking at Point 2, Point 3 and Point 4, which are located across Flora Bank, the peak velocities are smaller than 1.2 times the critical velocities, which signifies threshold of motion with relatively small movement. The same happens at the points near the marine structures but within Flora Bank, Point 7, Point 8 and Point 9, which show peak velocities well within 1.2 times critical velocities as well, demonstrating (at most) only initiation of motion of bottom sediments at those locations.

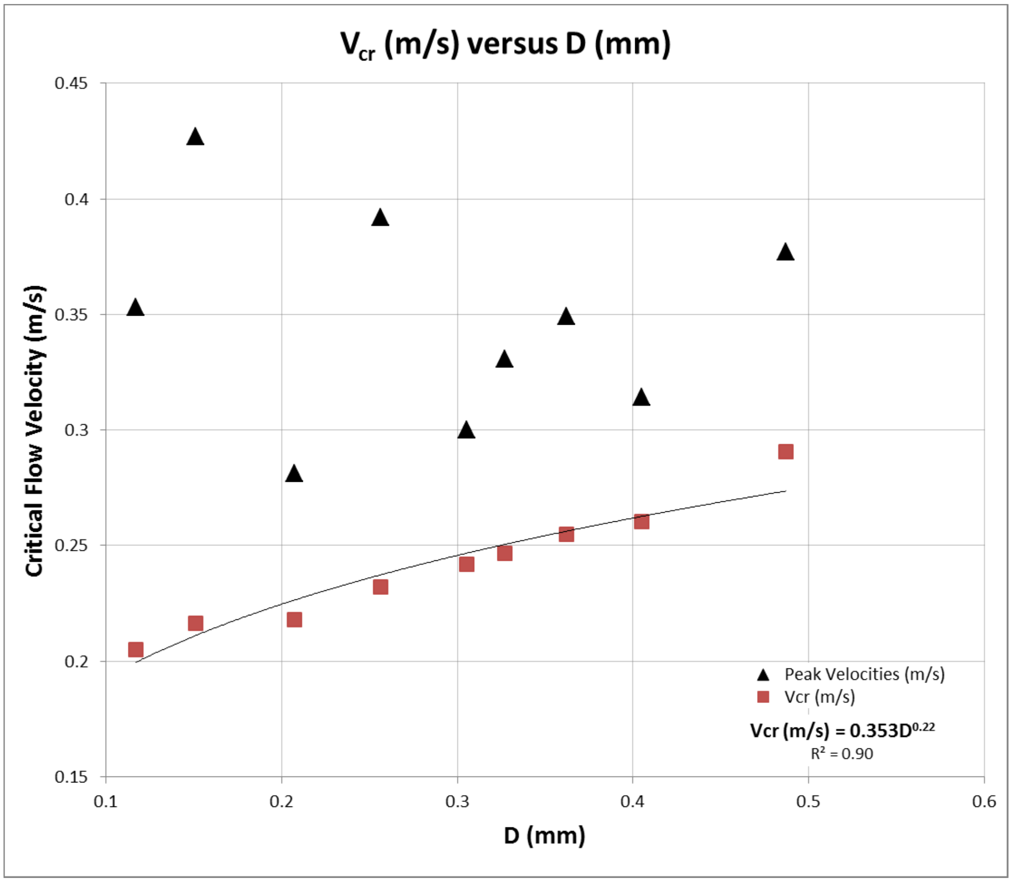


Figure K–13. Critical Flow Velocities at Selected Points near Flora Bank

K1.3 Point 1: SW Anchor Block

Bed sediments at Point 1, near the SW Anchor Block, are fine sands with a D_{50} of 0.12 mm. Figure K–14 (zoomed from time-series presented in Figure K–2) shows the time-series of flows and critical velocities near Point 1.

The critical flow velocity at Point 1 is 0.22 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.010 m/s.

At Point 1 sediment transport may occur over approximately 5 hours, on a rising tide and water levels (flood), with near a peak velocity (V) of 0.28 m/s to 0.35 m/s. During movement the sediments are transported as bed load, resulting in the formation of ripples.

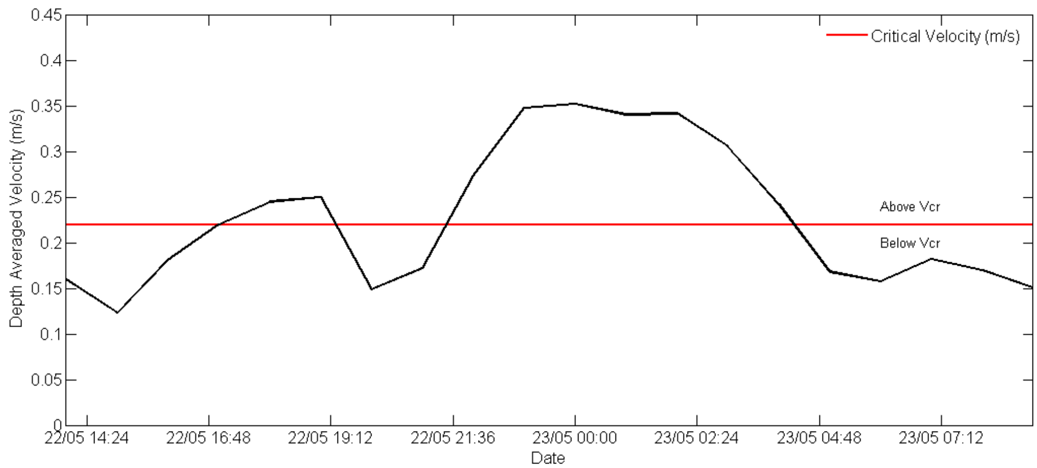


Figure K–14: Bed sediment critical velocity and flow at Point 1 (D = 0.12 mm)

K1.4 Point 2: SW Tower

Bed sediments at Point 2, near the SW Tower, are medium sands with a D_{50} of 0.31 mm. Figure K–15 (zoomed from time-series presented in Figure K–4)shows the time-series of flows and critical velocities near Point 2.

The critical flow velocity at Point 2 is 0.27 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.012 m/s.

At Point 2, potential sediment transport occurs only during peak velocity (for less than 1 hour), on a rising tide (flood) with a depth (h) of 4 m and peak velocity (V) of 0.3 m/s. During this small duration of time, the sediments begin to move and may be transported as bed load.

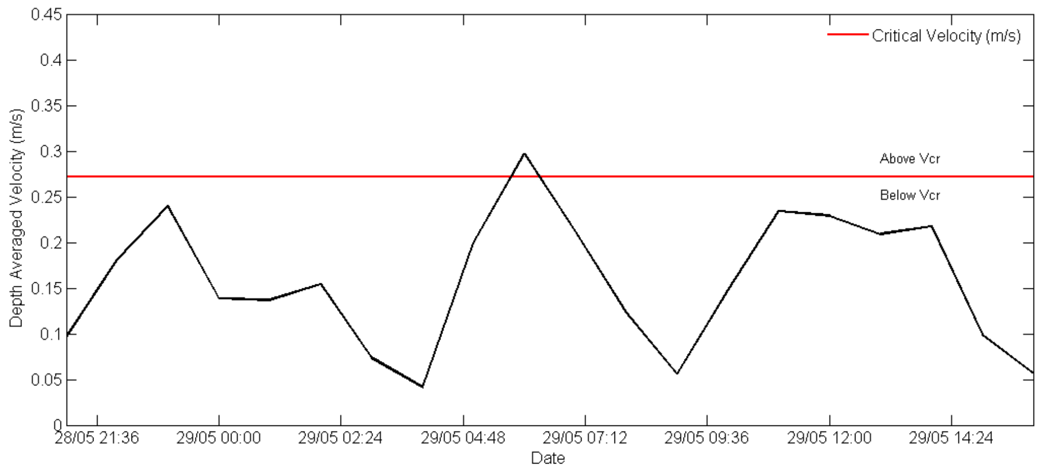


Figure K–15: Bed sediment critical velocity and flow at Point 2 (D = 0.31 mm)

K1.5 Point 3: Flora Bank

Bed sediments at Point 3, near the center of Flora Bank, are coarse sands with a D_{50} of 0.49 mm. Figure K–16 (zoomed from time-series presented in Figure K–4) shows the time-series of flows and critical velocities near Point 3.

The critical flow velocity at Point 3 is 0.30 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.014 m/s.

At Point 3 sediment transport occurs during the rising tide and beginning of ebb for about 3 h. During this time velocities are above 0.30 m/s and with depth (h) values about 3.8 m to 4.2 m. During movement the sediments are transported as bed load, with potential initiation of dunes.

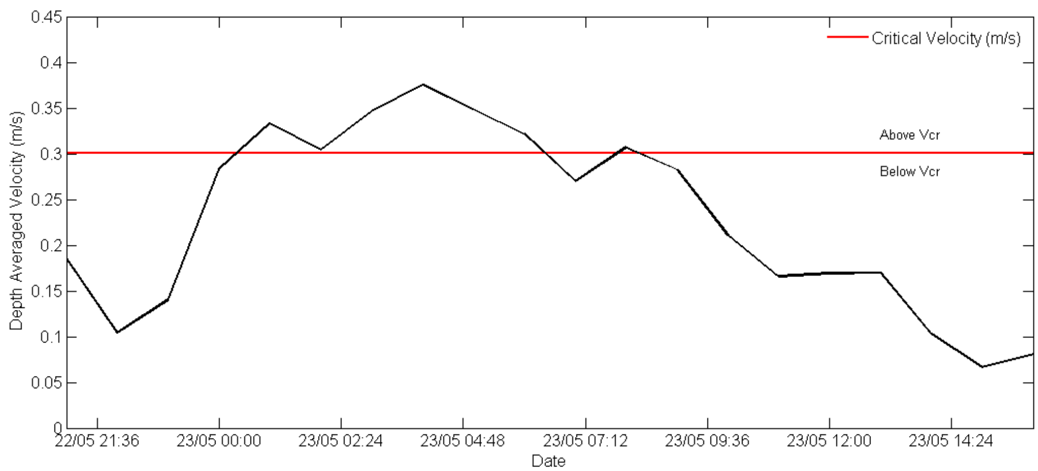


Figure K–16: Bed sediment critical velocity and flow at Point 3 (D = 0.49 mm)

K1.6 Point 4: Flora Bank

Bed sediments at Point 4, to the east of the center of Flora Bank, are coarse sands with a D_{50} of 0.36 mm. Figure K–17 (zoomed from time-series presented in **Figure K–6**) shows the time-series of flows and critical velocities near Point 4.

The critical flow velocity at Point 4 is 0.28 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.013 m/s.

Point 4 demonstrates the same behaviour as Point 3, with sediment transport occurring during the rising tide for about 3 hours. At this time velocities are above 0.28 m/s with depth (h) increasing from 3.6 m to about 5 m. During movement the sediments are transported as bed load, with potential initiation of dunes.

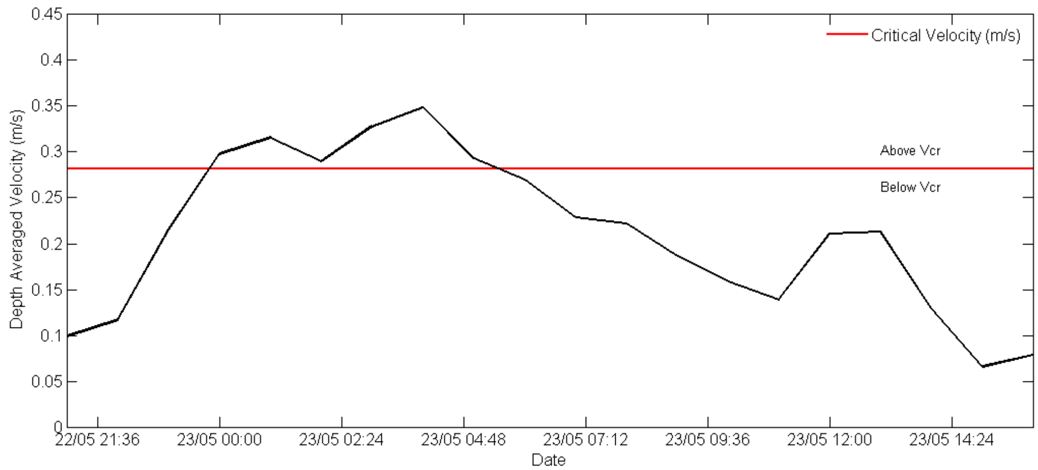


Figure K–17: Bed sediment critical velocity and flow at Point 4 (D = 0.36 mm)

Safety ● Quality ● Sustainability ● Innovation

K1.7 Point 5: Flora Bank

Bed sediments at Point 5, to the north of Kitson Island, are medium sands with a D_{50} of 0.26 mm. Figure K–18 (zoomed from time-series presented in **Figure K–6**) shows the time-series of flows and critical velocities near Point 5.

The critical flow velocity at Point 5 is 0.26 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.012 m/s.

At Point 5 sediment transport occurs during the high water levels, at rising tide and beginning of ebb for about 4 hours. At this time velocities are above 0.26 m/s and with depths (h) of 3.5 m to 4.7 m. During movement the sediments are transported as bed load, with initiation of dunes and potential initiation of suspension.

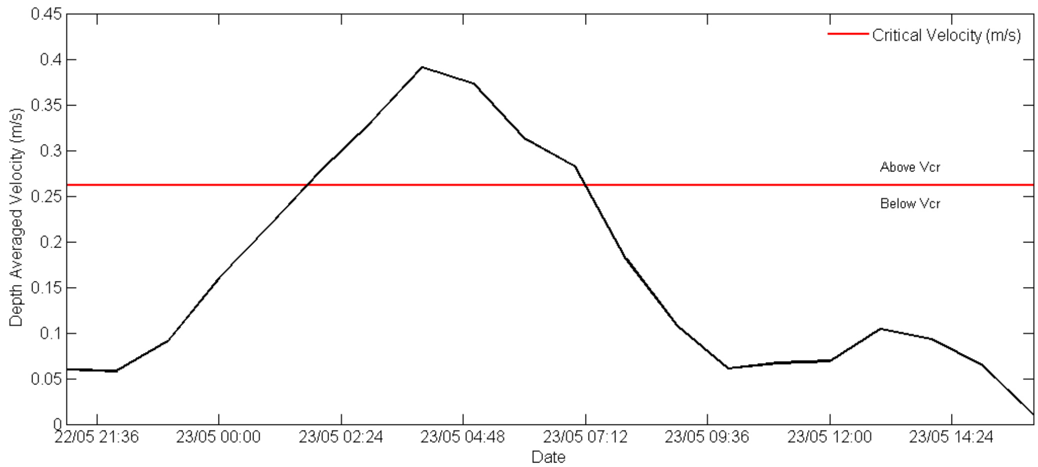


Figure K–18: Bed sediment critical velocity and flow at Point 5 (D = 0.26 mm)

K1.8 Point 6: Southwest Limit of Flora Bank

Bed sediments at Point 6, the point at the southwest edge of Flora Bank, are fine sands with a D_{50} of 0.15 mm. Figure K–19 (zoomed from time-series presented in **Figure K–7**) shows the time-series of flows and critical velocities near Point 6.

The critical flow velocity at Point 6 is 0.23 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.011 m/s.

Sediment transport at Point 6 occurs during a rising tide (flood) for about 6 hours when velocities are above 0.23 m/s with depths (h) increasing from 3 m to about 6 m. During movement the sediments are transported as bed load, with the formation of ripples and dunes and initiation of suspension.

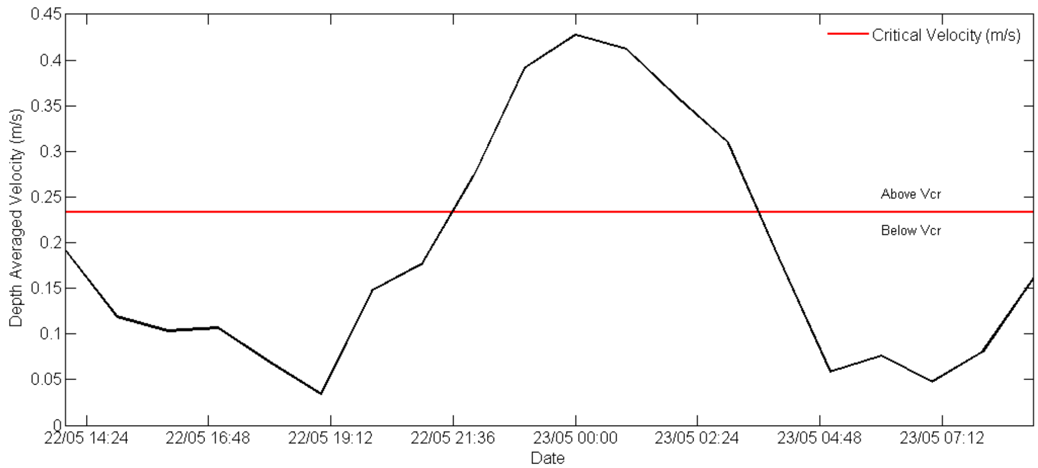


Figure K–19: Bed sediment critical velocity and flow at Point 6 (D = 0.15 mm)

K1.9 Point 7: Near SW Anchor Block, Inside Flora Bank

Bed sediments at Point 7, the point near the SW Anchor Block and inside Flora Bank, are fine sands with a D_{50} of 0.21 mm. Figure K–20 (zoomed from time-series presented in **Figure K–8**) shows the time-series of flows and critical velocities near Point 7.

Critical flow velocity at Point 7 is 0.25 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.011 m/s.

At Point 7 potential sediment transport occurs only during peak velocity (for less than 1 hour), on a rising tide (flood). This occurs with a depth (h) of 5.5 m and peak velocity (V) of 0.28 m/s. During this small duration of time the sediments begin to move and may be transported as bed load.

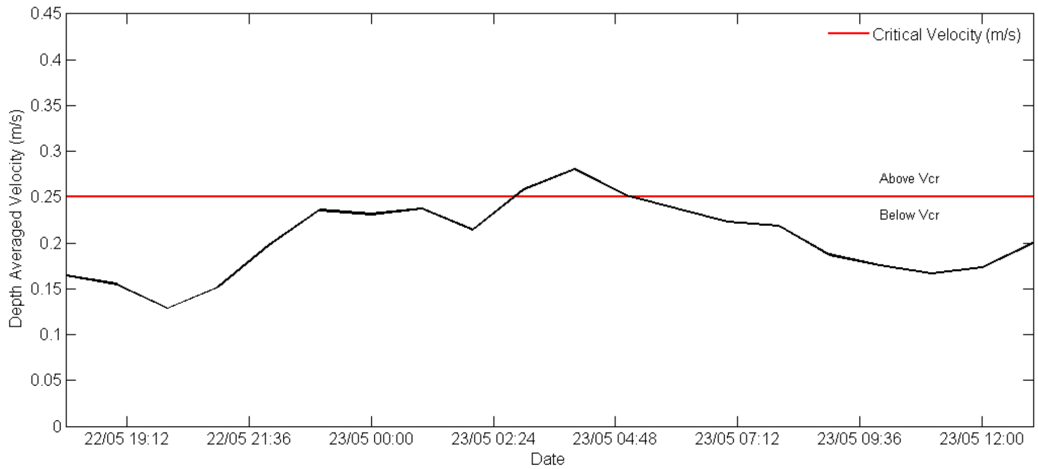


Figure K–20: Bed sediment critical velocity and flow at Point 7 (D = 0.21 mm)

K1.10 Point 8: Near SW Tower, Inside Flora Bank

Bed sediments at Point 8, the point near the SW Tower and inside Flora Bank, are medium sands with a D_{50} of 0.41 mm. Figure K–21 (zoomed from time-series presented in **Figure K–9**) shows the time-series of flows and critical velocities near Point 8.

The critical flow velocity at Point 8 is 0.29 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.013 m/s.

At Point 8 potential sediment transport occurs only during peak velocity (for less than 1 hour), on a rising tide (flood). This occurs with a depth (h) of 5.4 m and peak velocity (V) of 0.31 m/s. During this small duration of time the sediments begin to move and may be transported as bed load.

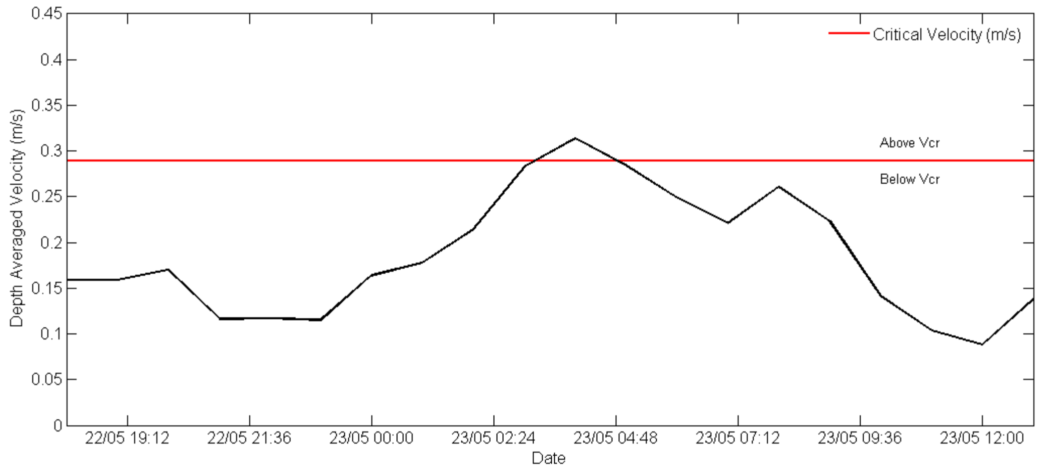


Figure K–21: Bed sediment critical velocity and flow at Point 8 (D = 0.41 mm)

K1.11 Point 9: Near the Middle of Bridge Span, Inside Flora Bank

Bed sediments at Point 9, the point near the SW Tower and inside Flora Bank, are medium sands with D_{50} of 0.33 mm. Figure K–22 (zoomed from time-series presented in **Figure K–10**) shows the time-series of flows and critical velocities near Point 9.

The critical flow velocity at Point 9 is 0.28 m/s. Flow velocities above this value will cause sediment motion. The critical bed shear velocity (v_*) values are constant at 0.012 m/s.

At Point 9 potential sediment transport occurs only during peak velocity (for less than 1 hour), on a rising tide (flood). This occurs with a depth (h) of 4.8 m and a peak velocity (V) of 0.33 m/s. During this small duration of time the sediments begin to move and may be transported as bed load.

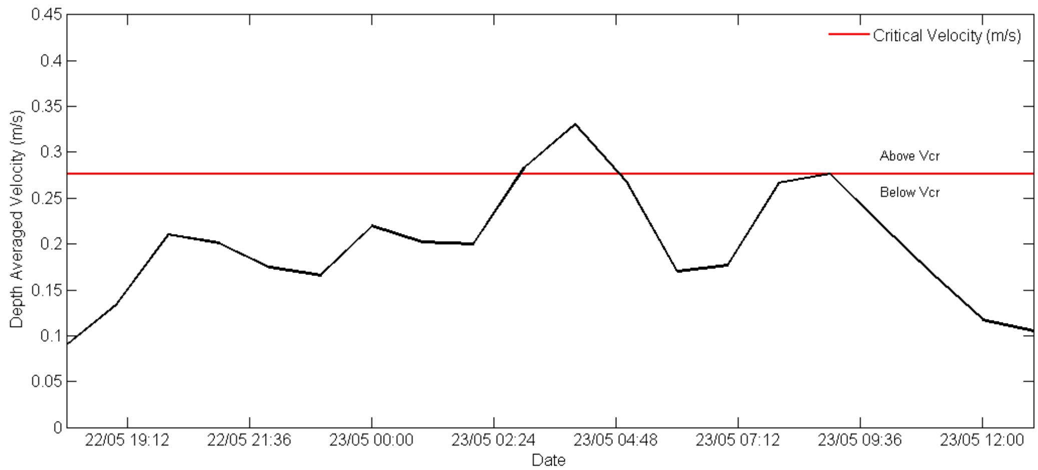


Figure K–22: Bed sediment critical velocity and flow at Point 9 (D = 0.33 mm)

K1.12 Shields Method: Results and Discussion

Sediment mobility on Flora Bank was analyzed by means of a Shields sediment movement and threshold analysis. Bottom material around the SW Anchor Block and SW Tower, as well as over the area of Flora Bank, were investigated during typical flow conditions at large tides.

All previous time-series figures as well as Figure K–23 show that for every typical median grain size over Flora Bank (medium to coarse sands varying from 0.3 mm to 0.7 mm) there may be an interval of tidal flows where sediment is mobilized, however, primarily by currents as their transport parameters (Y) fall below the threshold curve for waves. This is expected during typical tidal flow conditions, as was the hydrodynamic simulated during the freshet 2014, when the wave heights were very small.

It was found that sediments are potentially in motion only during a few hours near the peak magnitudes of the tidal flow currents and do not travel far from their original location.

Table K-2 shows the percent of time (considering the 28 days of simulation) where sediment is in motion. Figure K–14 to Figure K–22 focus on specific times when the current velocities exeeced the different threshold limits at each point.

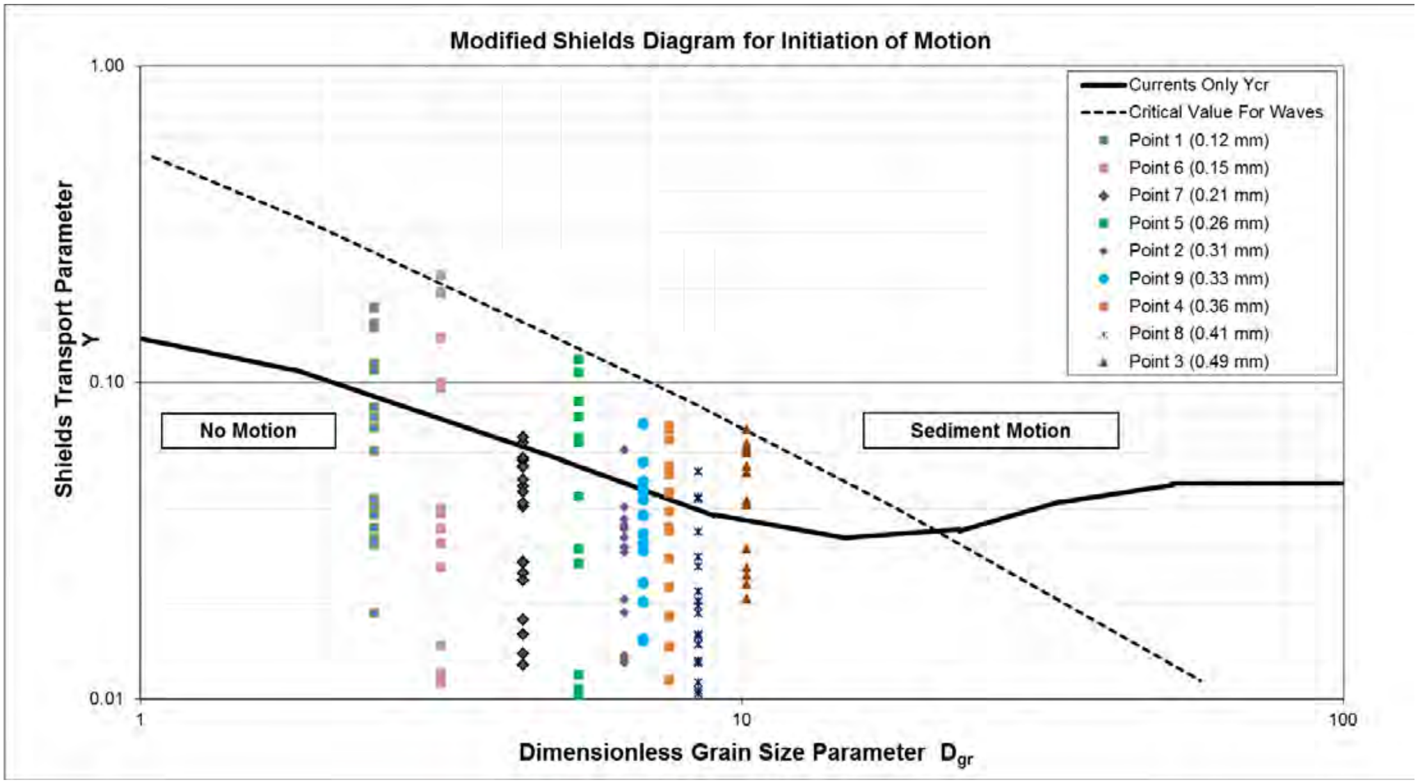


Figure K–23: Shields Diagram for Sediment Mobility

Table K-2: Percentage of time above threshold of Sediment Motion during the 28 days of the Freshet 2014 simulation

Percentage of Time (%) above Threshold								
Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9
21.8	1.0	1.6	2.8	1.6	7.1	1.6	0.3	0.7

Sediment particle excursions near the SW Anchor Block (Point 1) and near the SW Tower (Point 2) are generally small. The opposing flood and ebb flow directions may cause the sediments to move around their original location but tend to have small net transport rates and travel distances.

Sediment particle excursions for all other points over Flora Bank are expected to be small, leading to the conclusion that sediment particles mobilized by tidal flow under typical conditions do not move very far from the pick-up point. Also, the presence of eelgrass contributes preventing localized sediment movement around them, causing localized mound accumulations and decreasing sediment transport.

The sediment movement and threshold analysis supports the understanding that Flora Bank is stable, while the small scale surface features over Flora Bank are in dynamic equilibrium.

K1.13 Threshold Predictions with Structures

The threshold for erosion is investigated near the location of the bridge structures, in Point 1 and Point 2 (Figure K–1), using hydrodynamics time-series from the high-resolution model (MORPHO). Initially, Delft3D model currents were compared with MORPHO currents to define if the presence of the large structures contribute to increase the local hydrodynamics.

Figure K–24 and Figure K–25 show comparisons of current magnitude results from both models at the SW Anchor Block Point 1. Delft3D currents at the SW Anchor Block have higher magnitudes than high-resolution model currents for 70% of the time. Figure K–25 shows that high-resolution model current magnitudes are lower than 0.3 m/s.

Figure K–26 and Figure K–27 show comparisons of current magnitude results from both models at the SW Tower Point 2. At the SW Tower, Delft3D currents are higher than high-resolution model currents for 65% of the time. At this site (SW Tower Point 2), the maximum current magnitude is slightly higher for the high-resolution model results, about 0.3 m/s, when compared with Delft3D maximum currents of 0.30 m/s (Figure K–27).

As current magnitude results from both models are similar, bed sediment critical velocity and flow conditions presented in Figure K–14 (Point 1) and Figure K–15 (Point 2) are also similar. It is concluded that sediment threshold conditions near the location of large structures (Point 1 and Point 2) are valid for both model results.

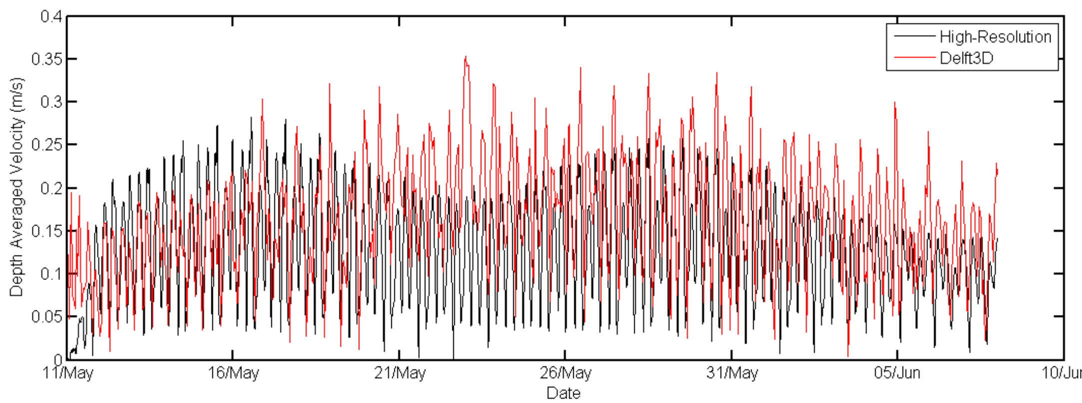


Figure K–24: Time-series comparison of Delft3D and MORPHO current magnitudes at the SW Anchor Block (Point 1)

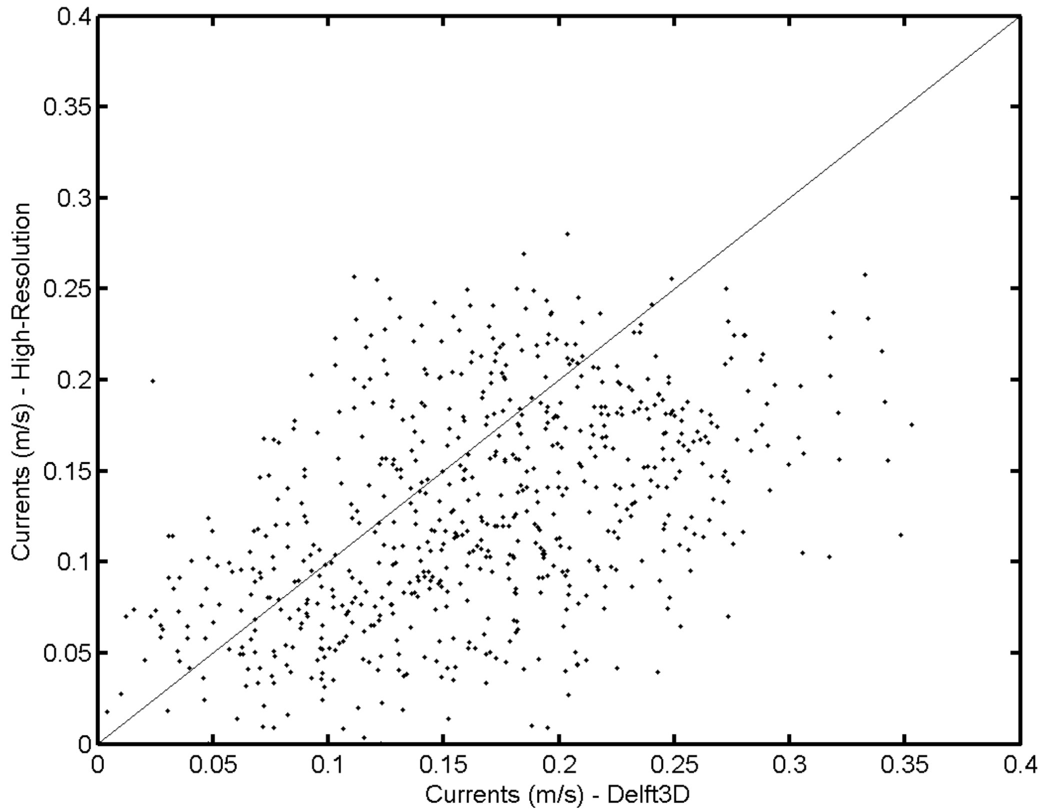


Figure K–25: Delft3D and MORPHO current magnitudes at the SW Anchor Block (Point 1)

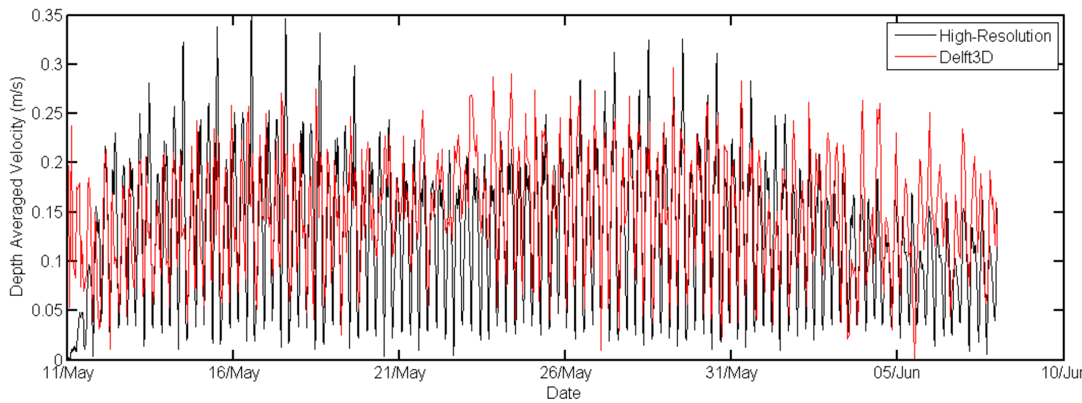


Figure K–26: time-series comparison of Delft3D and MORPHO current magnitudes at the SW Tower (Point 2)

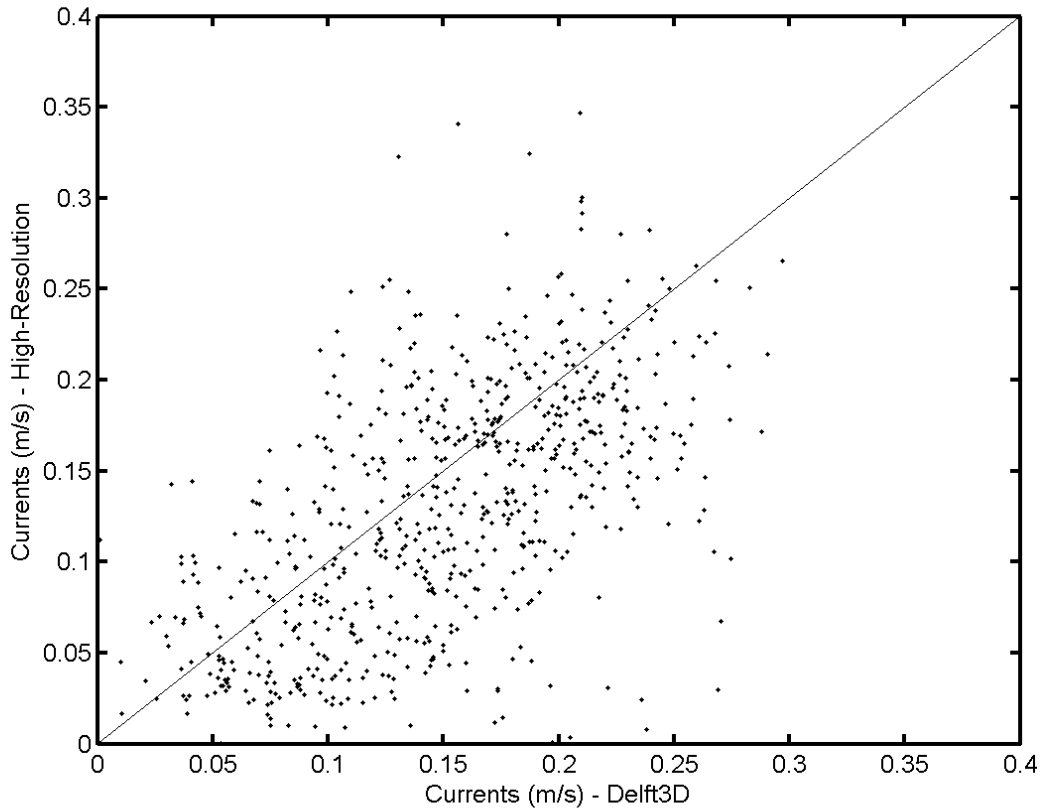


Figure K–27: Delft3D and MORPHO current magnitudes at the SW Anchor Block (Point 1)

K1.14 References

CEM (2003). "Coastal Engineering Manual". USACE.

SedTrend Analysis Ltd. (2015). "Final Report A Sediment Trend Analysis (STA) of Prince Rupert Harbour and its Surrounding Waters".

Yalin, M.S. (1977). "Mechanics of Sediment Transport". 2^{nd} Ed., Pergamon Press.

Yalin, M.S. (1992). "River Mechanics". Pergamon Press.

Yalin, M.S., and Karahan, E. (1979). "Inception of Sediment Transport". ASCE, Journal Hyd. Div., Vol. 105, HY 11.

Appendix L:
Scour Protection Details

L1. Scour Protection Details

The following section provides a summary of the " direct impact" footprint of the proposed marine structures arising from the preliminary scour protection details developed under previous efforts (Hatch 2014b).

L1.1 Scour Protection Details

Potential scour along the bridge and trestle foundations were determined using available technical literature and adjusted to the site conditions along the marine terminal jetty structures. Scour mitigation measures, specifically using riprap to protect from scour, was also evaluated. With the use of scour protection around the marine structures foundations no significant adverse effects from scour are expected.

For the purposes of preliminary design, the proposed scour protection for trestle and berth structures and adjacent to the SW Tower and SW Anchor Block structures is assumed to consist of riprap quarry stone between 0.16 m and 0.57 m in size (10-500 kg) with a thickness of 0.8 m.

The overall area of direct impacts may be summarized in Table L-1 as follows.

Table L-1: Area of Direct Impacts

Location / Element	Structure Footprint (m^2)	Scour Protection Footprint (m^2)	Total Footprint (m^2)
Marine Trestle	210	3,790	4,000
Marine Berth	190	3,455	3,645
SW Anchor Block	1,980	3,810	5,790
SW Tower	735	1,690	2,425
Berth Complex	5,645		5,645
Total Footprint:			21,505

The following figures demonstrate the preliminary scour protection arrangement for the marine structures, and illustrate the area used to calculate the direct impacts of the marine structures.

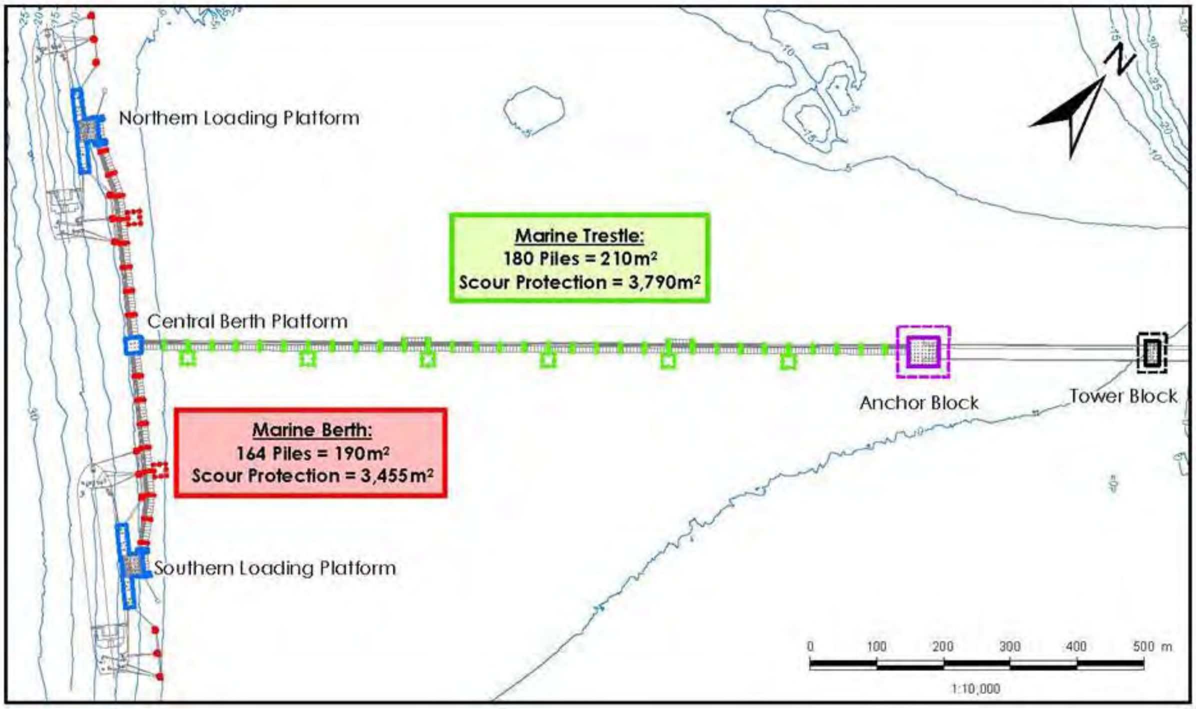


Figure L–1: Overview of Marine Structures Direct Impacts

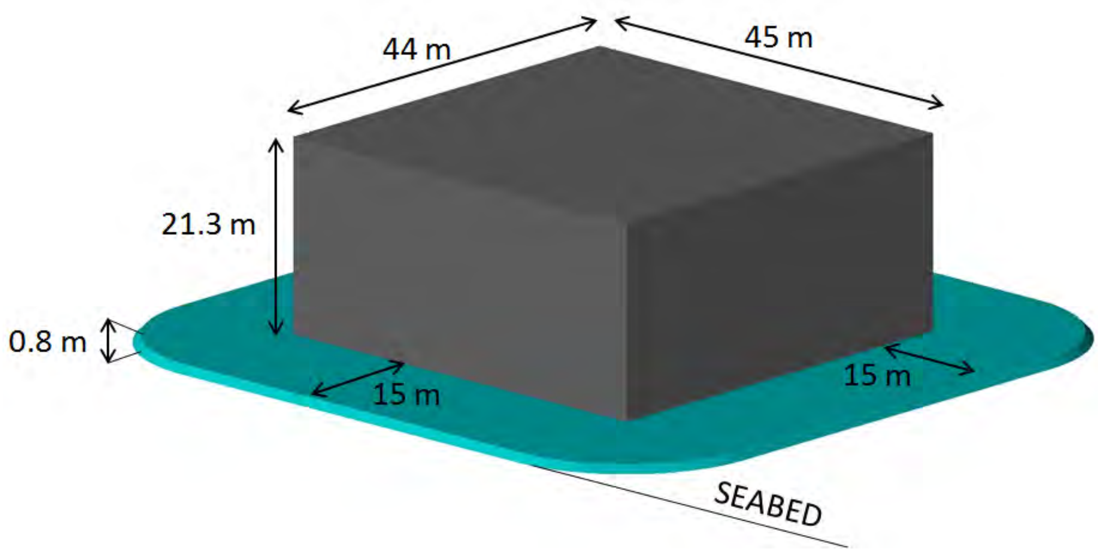


Figure L–2: 3D Rendering SW Anchor Block Scour Protection

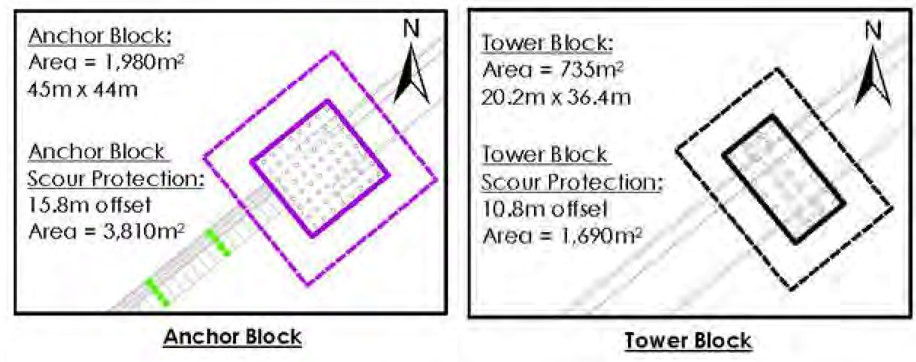


Figure L–3: Direct Impacts of SW Anchor Block (left) and SW Tower (right)

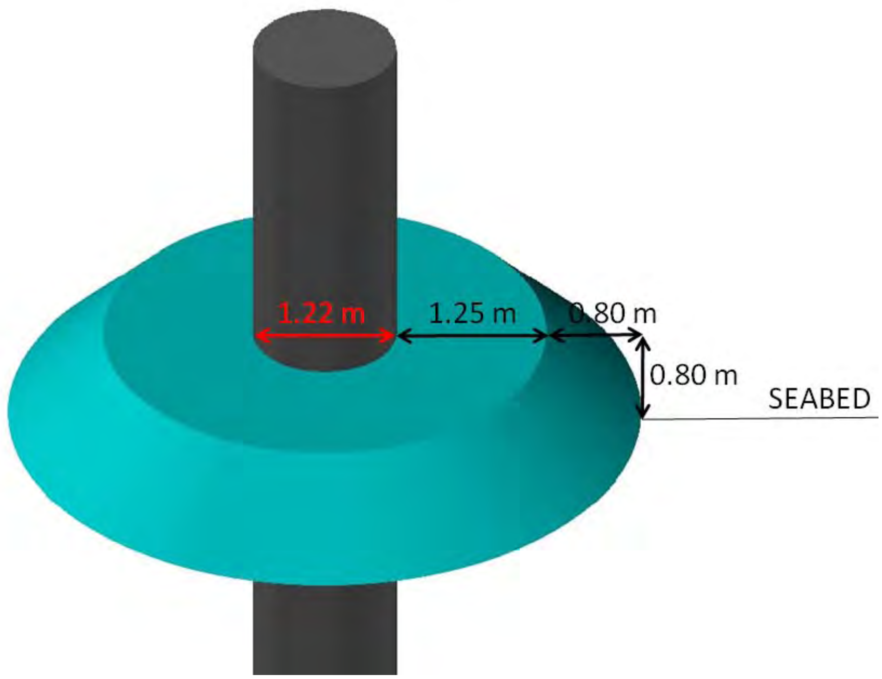


Figure L–4: 3D Rendering Single Pile Scour Protection

Figure L–5: Direct Impacts of the Expansion Loops

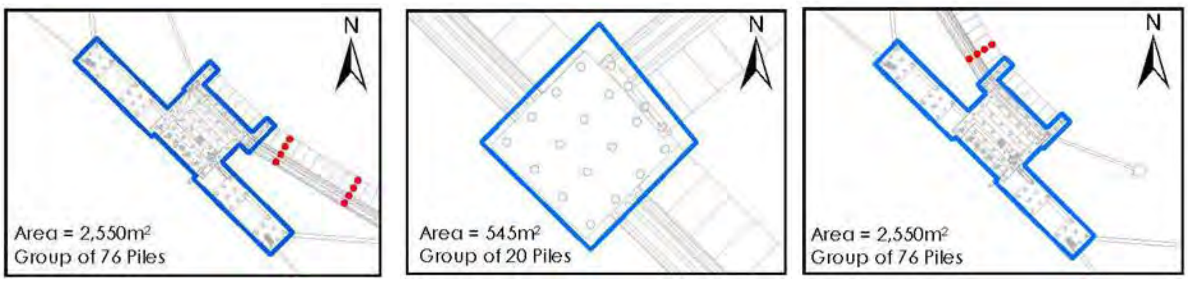


Figure L–6: Direct Impacts of the Berth Complex

Appendix M:
Summary of Animation Products

M1. Summary of Animation Products

The following section provides a summary of the animated products produced to further illustrate the coastal processes in the project area. The simulations are provided along with the report on the FTP site.

M1.1 Currents

M1.1.1 Tides-Only Simulations

28-day simulations without wind or wave forcing (tides-only) were conducted using the MORPHO model in the vicinity of the SW Anchor Block and Tower. The following animations of the currents are included:

- **M-1_Currents-Tides Only-Peak Ebb-Anchor Block and Tower.avi.** This animation shows 5.0 hours of tides-only (no winds, waves or river flows) simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding processes during a typical **ebb** current. Both the SW Tower and SW Anchor Block are included in the animation.
- **M-2_Currents-Tides Only-Peak Flood-Anchor Block and Tower.avi**. This animation shows 5.0 hours of tides-only (no winds, waves or river flows) simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding processes during a typical **flood** current. Both the SW Tower and SW Anchor Block are included in the animation.
- **M-3_Currents-Tides Only-Anchor Block and Tower-Long Duration.avi**. This animation shows 4.0 days of tides-only (no winds, waves or river flows) simulation results with less frequent output (15-minute frames) to demonstrate longer-term current patterns and changes in directions between typical ebb and flood currents. Both the SW Tower and SW Anchor Block are included in the animation.

M1.1.2 50-Year Return Period Storm Simulations

50-year storm simulations, which are described further in Appendix G, were conducted using the MORPHO model in the vicinity of the SW Anchor Block and SW Tower. The following animations of the currents are included:

- **M-4_Currents-50Yr Storm-Tower.avi**. This animation shows 6.0 hours of 50-year storm simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding processes during stronger flows including both peak flood currents and wave-induced currents. Only the SW Tower is included in the animation.
- **M-5_Currents-50Yr Storm-Anchor Block.avi.** This animation shows 6.0 hours of 50-year storm simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding processes during stronger flows including both peak flood currents and wave-induced currents. Only the SW Anchor Block is included in the animation.

- **M-6_Currents-50Yr Storm-Tower-Long Duration.avi**. This animation shows approximately 4.2 days of 50-year storm simulation results with less frequent output (15-minute frames) to demonstrate longer-term current patterns and changes in directions. Both the SW Tower and SW Anchor Block are included in the animation.

M1.2 Total Suspended Solids

M1.2.1 Tides-Only Simulations

28-day simulations without wind or wave forcing (tides-only) were conducted using the MORPHO model in the vicinity of the SW Anchor Block and Tower, and results included predictions of Total Suspended Solids (TSS) variations. The following simulations with TSS results are included:

- **M-7_TSS-Tides Only-Peak Ebb-Anchor Block.avi**. This TSS animation shows 5.0 hours of tides-only (no winds, waves or river flows) simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding and TSS transport processes during a typical **ebb** current. Only the SW Anchor Block is included in the animation.
- **M-8_TSS-Tides Only-Peak Ebb-Tower.avi**. This TSS animation shows 5.0 hours of tides-only (no winds, waves or river flows) simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding and TSS transport processes during a typical **ebb** current. Only the SW Tower is included in the animation.
- **M-9_TSS-Tides Only-Peak Flood-Anchor Block.avi**. This TSS animation shows 5.0 hours of tides-only (no winds, waves or river flows) simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding and TSS transport processes during a typical **flood** current. Only the SW Anchor Block is included in the animation.
- **M-10_TSS-Tides Only-Peak Flood-Tower.avi**. This TSS animation shows 5.0 hours of tides-only (no winds, waves or river flows) simulation results with high-frequency output (30-second frames) to demonstrate vortex shedding and TSS transport processes during a typical **flood** current. Only the SW Tower is included in the animation.
- **M-11_TSS-Tides Only-No Marine Structures.avi**. This TSS animation, which does NOT include the marine structures, shows 4.0 hours of tides-only (no winds, waves or river flows) simulation results with high-frequency output (30-second frames) to demonstrate TSS transport processes that occur during a typical ebb current, and drying of Flora Bank, in the absence of the marine structures.
- **M-12_TSS-Tides Only-Tower.avi**. This TSS animation is identical to M11 except that it includes the SW Tower. The intent of the animation is to demonstrate how TSS increases occur around the SW Tower in comparison with M11 above.
- **M-13_Merge of M-11 and M-12.avi**. This TSS animation is simply M11 and M12 merged side-by-side for visual comparison.

M1.2.2 50-Year Return Period Storm Simulations

Simulations during the 50-year storm, which is described further in Appendix G, were conducted using the MORPHO model in the vicinity of the SW Anchor Block and Tower. A simulation of the TSS with a cylindrical layout of the SW Tower was also conducted for comparison. The following animations of TSS are included:

- **M-14_TSS-50Yr Storm-Tower.avi**. This TSS animation shows 6.0 hours of storm simulation results at the peak of the 50-year storm during flood currents, with high-frequency output (30-second frames) to demonstrate vortex shedding and TSS transport processes. Only the SW Tower is included in the animation.
- **M-15_TSS-50Yr Storm-Anchor Block.avi**. This TSS animation shows 6.0 hours of storm simulation results at the peak of the 50-year storm during flood currents, with high-frequency output (30-second frames) to demonstrate vortex shedding and TSS transport processes. Only the SW Anchor Block is included in the animation.
- **M-16_TSS-50Yr Storm-Cylinder Tower.avi**. This TSS animation shows 6.0 hours of storm simulation results at the peak of the 50-year storm during flood currents, with high-frequency output (30-second frames) to demonstrate vortex shedding and TSS transport processes. Only a cylinder-shaped version of the SW Tower is included in the animation.

Suite 1000, 1066 West Hastings Street
Vancouver, British Columbia, Canada V6E 3X2
Tel Tel: +1 (604) 689 5767 ◆ Fax Fax: +1 (604) 689 3918