Prioritizing Infrastructure and Ecosystem Risk from Coastal Processes in Mud Bay (PIER)

Final Report

MCIP15330

City of Surrey

February 14, 2020

1 Introduction

There are numerous ways in which future climate change is going to influence Canadian municipalities—City of Surrey has long recognized the need to explore the multifaceted climate change impacts and to proactively reduce the vulnerability of the community. As a result, the City has been engaging in comprehensive planning for forthcoming climate change; currently one of the main areas of focus is the coastal floodplain of the City and the adjacent lands. This project, Prioritizing Infrastructure and Ecosystem Risk from Coastal Processes in Mud Bay (PIER), represents the work dedicated to identifying and assessing vulnerabilities of the shoreline infrastructure and the natural environment to future impacts of sea level rise and other climate change impacts in Mud Bay, prioritizing high risk areas, and recommending actions to reduce the identified risks.

Predicted consequences of climate change in the Surrey coastal area include rising sea and groundwater levels, coastal squeeze, increased shoreline erosion, saltwater intrusion, higher levels and duration of floods, and increased risk of dyke breaching. Current coastal dykes are highly vulnerable: previous work estimated that for present conditions, the existing Colebrook Dyke (north side of Mud Bay) has a design return period of 22 years, whereas the sheltered area along Nicomekl is protected to above the 200 year design standard. As a result of sea level rise, these values will reduce over time with overtopping occurring annually (return period of less than a year) at all locations by 2070. With the purpose of further investigating and evaluating current and future impacts of predicted climate change on these areas, and identifying short- to long-term adaptation options, the Coastal Flood Adaptation Strategy (CFAS) was developed through a participatory, community-driven planning process.

CFAS is a higher-level plan that evaluated coastal flood impact the entire floodplain area of Surrey and assessed possible large-scale adaptation actions. However, additional detailed analysis of the historic and current state of the natural environment in the Mud Bay study area were needed in order to both better understand the risks of climate change effects on specific existing shoreline infrastructure (in particular, sea dykes), coastal natural habitats and species, offshore and nearshore conditions, and to inform area-wide adaptation. In order to address these knowledge gaps, the City has developed PIER based in part from stakeholder feedback received in the process of developing CFAS.

1.1 STUDY AREA

Mud Bay is part of Boundary Bay within the Fraser River Delta—estuarine habitats, such as salt marshes, found there provide important ecosystem services. Flood control is an example of a crucial regulating ecosystem service of floodplains, tidal marshes and estuaries, which provide act as natural storage reservoirs and limit the damage of storm surges and tidal waves by reducing the water’s speed and height. Such ecosystem functions supplement man-made flood control infrastructure and protect it from erosion and similar natural processes. Estuaries are, however, particularly vulnerable to climate change through processes such as coastal squeeze and shoreline erosion. Therefore, PIER also included gathering data on green infrastructure and environmental vulnerabilities and prioritizing areas for protection that will help the City develop future long-term adaptation strategies that maximize protection of both grey and green infrastructure. PIER was a standalone project with separate deliverables designed to address data gaps identified through CFAS and to improve long-term CFAS adaptation actions.

1.2 PRIORITIZING INFRASTRUCTURE AND ECOSYSTEM RISK FROM COASTAL PROCESSES IN MUD BAY (PIER)

Over its three phases, PIER investigated many aspects of the coastal environment and processes. While this final report includes several final summary deliverables, the deliverables produced in the first two phases also constitute a part of PIER as outlined below and will continue to be referred to in City's future work. Instead of combining all the deliverables of the three phases into one report, they were kept as three separate documents for ease of navigation.

1.3 PHASE 1

Phase 1 consisted of desktop literature analysis and mapping. 12 km of shorelines, riverbanks, and dykes were evaluated for the risk of erosion due to sea level rise and for potential future habitat disturbance; the obtained data was presented in a map form. A literature review of data relating to the intertidal habitats in Mud Bay was conducted. Shoreline inventory and mapping was verified with a field review. A coastal geomorphology study that explored the literature on historic and current sedimentary conditions of Mud Bay and their implications for flood adaptation strategies was conducted. Phase 1 report is available online.

1.4 PHASE 2

Phase 2 advanced the work accomplished in the previous phase. Continued estuary monitoring focused on water quality and elevation changes using surface elevation tables. Field surveys, mapping and experiments were used to evaluate nutrient loading on eelgrass beds. A workshop involving environmental experts was held to assess vulnerability and risks to coastal ecosystems and explore of potential mitigation approaches. A wave and wind monitoring plan was developed. Phase 2 report is available online.

1.5 PHASE 3

Phase 3 included final field monitoring, an evaluation of results from field assessments and monitoring, habitat mapping, hydrological analyses, development of recommendations for improved wave modelling, a summary document of environmental vulnerabilities, and an online story map for communication purposes.

This report summarizes the work finalized in Phase 3 and consists of the following chapters:

- **Chapter 1**: Summary of Environmental Reports
- **Chapter 2**: Mud Bay Monitoring Report
- **Chapter 3**: Mud Bay Nutrient Loading Effects on Eelgrass Bed Health
- **Chapter 4**: Summary of Wind Monitoring Component to Date
- **Chapter 5**: Green Infrastructure Recommendations – Reducing Wave Model Uncertainty
- **Chapter 6**: Coastal Flood Mitigation DEM Workshop
- **Chapter 7**: Conceptual Fish Passage for Serpentine River Sea Dam
- **Chapter 8**: Mud Bay – Ecosystem at Risk in Surrey, BC (online)

Chapter 1

Summary of Environmental Reports

Prioritizing Infrastructure and Environmental Risks from Coastal Processes in Mud Bay – Summary of Environmental Reports

City of Surrey,
Surrey, BC

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1.0 Introduction

Over the next 100 years, the effects of climate change, including sea level rise and increased precipitation, are predicted to cause widespread flooding of the Mud Bay area as well as the lowland floodplain areas associated with the Serpentine and the Nicomekl Rivers. The City of Surrey (City) recognizes the need to reduce climate vulnerability and mitigate the expected. In response to these changes, and their anticipated consequences, Surrey has developed a comprehensive Coastal Flood Adaptation Strategy (CFAS). This strategy focuses on both the current and future impacts of flooding within Surrey's coastal floodplain.

2.0 Environmental Studies Reviewed

As part of their Coastal Flood Adaptation Strategy, the City has undertaken a number of environmental studies to better understand current biophysical conditions in the study area and how they may be impacted by sea level rise. These studies were produced by numerous organizations and provide information on current conditions, potential impacts and options for mitigation. The following sections of the report is a summary of some of the key findings, options and opportunities for mitigation from these reports. The following reports have been completed as part of this planning process. A summary of each is provided in Appendix A.

1. City of Surrey: Coastal Flood Adaptation Strategy (CFAS) Draft Strategy
2. Diamond Head Consulting 2018: Surrey Flood Protection – Preliminary Habitat Impact Assessment Report
3. Diamond Head Consulting 2019: Prioritizing Infrastructure and Ecosystem Risk (PIER), Framework for Environmental Vulnerability
4. Associated Engineering: Final report 2018: Improving Coastal Flood Adaptation Approaches
5. Friends of Semiahmoo Bay Society 2018: City of Surrey Shoreline Assessment Mud Bay – Field Verification Report
6. Ducks Unlimited Canada 2018: Prioritizing Infrastructure and Ecosystem Risk from Coastal processes in Mud Bay - Estuary Monitoring Program
7. Friends of Semiahmoo Bay Society, Matthew Christensen & Dr. Sarah Joy Bitick, UBC; 2018: Preliminary Report on Mud Bay Nutrient Loading Effects on Eelgrass Bed health
8. Northwest Hydraulics 2015: Conceptual Fish Passage Gate for Nicomekl River Sea Dam
9. Friends of Semiahmoo Bay Society 2018: Mud Bay Eelgrass Mapping and Monitoring
10. Mud Bay: Ecosystem Services Potential for Coastal Flood Protection
11. Spartina Abundance Mud Bay 2017

3.0 Current Day Environmental Conditions

Surrey's low elevation floodplains are home to a variety of natural habitats that house a rich diversity of plants, wildlife, invertebrates and other organisms. A large area of Mud Bay is comprised of intertidal flats. These are generally sandy areas that are periodically exposed and dominated by non-vascular plants (eelgrass being the predominant species). The eelgrass plant communities provide important food and shelter for a high diversity of both marine and terrestrial species. As part of CFAS a detailed inventory of eelgrass was completed which provides a foundation for monitoring the impacts of sea level rise in the future. Experiments were also completed to better understand the impacts of nutrient loading on eelgrass health.

These intertidal areas are critical habitat for salmon, as well as spawning habitat for important foraging fish such as Pacific herring and surf smelts. These species are crucial components of the marine/intertidal food web. These intertidal areas are used extensively by adults and juvenile salmon for forage, cover from prey and to provide a zone for adaptation to the transition from salt to fresh water during migration.

The mud flats of Boundary Bay are well known as important areas where large migrating flocks stop, rest and feed to ensure they have enough energy for the rest of their migration. These mudflats are also very important wintering areas for waterfowl, shorebirds, and other resident birds.

Estuarine salt marshes exist through a relatively narrow elevation band between the mud flats and constructed dykes. These plant communities are very productive and support high levels of biodiversity as nutrients are continuously deposited and mixed by the action of tides and waves. Above the intertidal zone, a mix of disturbed habitats exists from a long history of agriculture and engineering to manage flooding.

The Serpentine and Nicomekl Rivers both drain into Mud Bay and support extensive salmon migrations. There is tidal influence on the lower reaches of these rivers which is regulated partly by the existing sea dams.

4.0 Predicting Environmental Impacts from Sea Level Rise

Over the next 100 years, the effects of climate change, including sea level rise and increased precipitation, are predicted to cause widespread flooding of the Mud Bay area as well as the lowland floodplain areas associated with the Serpentine and the Nicomekl Rivers. The rise of sea level is predicted to have significant influence on coastal ecosystems and the species populations that inhabit them. It was found through this planning process that it is difficult to predict with certainty what these impacts will be and to quantify them.

Assuming that the long-term management approach to sea level rise will be to realign diking to Highway 99 by the year 2100, the expected changes that are likely to have a significant effect on species and ecosystems in the Mud bay area include:

- The loss of estuarine marshes as sea levels rise up against existing dikes
- Less exposure time of mud flats and biofilm reducing foraging capacity for migrating birds
- Loss of existing eelgrass communities which provide critical habitat for a variety of marine life
- Changes in salinity in the lower reaches of the Serpentine and Nicomekl Rivers and Serpentine fen changing habitat for fish and amphibians
- Increased opportunities for the establishment and spread of invasive plants and animals

5.0 Prioritized Actions to Mitigate Impacts

Predicting the details of climate change and sea level rise over the next 100 years, and their influence on wildlife, their habitat and natural processes of ecosystems is complex. How we react and adapt to these changes will also have a major influence on the impacts to wildlife species and ecosystem dynamics. Over the next decade, a priority will be to complete studies and inventories to better understand the baseline environmental conditions that exist and to carry out experiments and pilot studies to determine the effectiveness of potential mitigation options.

5.1 Understand terrestrial and marine habitat

Additional understanding is required of the current environmental conditions in the Mud Bay area. This should include detailed ecotype mapping of terrestrial, marine and intertidal areas. Populations studies of wildlife that inhabit these areas should be completed regularly to track changes resulting from climate change and sea level rise. Recommended studies include:

1. Continue to monitor the health and location of eelgrass communities. Comprehensive mapping and analysis was completed as well as an assessment of nutrient loading on eelgrass health as part of this CFAS process. The health and location of these communities should be monitored periodically to track their migration in response to sea level rise. Recommended future monitoring includes annual foot based transects to assess eelgrass health. Boat based mapping is recommended every 5-10 years to verify eelgrass location and to help validate the use of remote sensing.
2. Monitor sediment transport in Mud Bay. A baseline study was completed by Ducks Unlimited Canada to measure the precise elevation of sediment at four monitoring stations. These should continue to be monitored and additional stations should be established to understand sediment transport throughout Mud Bay.
3. Complete detailed shoreline habitat mapping following BC Estuary Mapping System (1999). Some high-level mapping has been completed, however changes in plant communities are complex and a detailed understanding of them is important to plan future habitat restoration works.

4. Inventory and map all invasive plants and wildlife. The monitoring of Spartina has been ongoing along with trials for its treatment. This program should be expanded to include all invasive plants. The invasion of invasive animals is a recognized risk with changes in sea level and temperatures. Marine species are of particular concern. Inventories for species of concern should be completed by local biologists.

5.2 Experiment with enhancement and mitigation options

In anticipation of sea level rise and the plan to realign diking with Highway 99, experiments should be carried out to improve the habitat value outside of this area. Recommended studies include:

1. Carry out eel grass installation trials in areas that appear suitable. These areas should be identified as part of the eelgrass monitoring study. These experiments should be designed to test the habitat limits of different eelgrass species.
2. Design diking to enhance foreshore habitat. Eg. Green Shores and Living Dikes standards.
3. Install trial engineered structures designed to promote sediment accumulation. These should be coordinated with the sediment transport monitoring stations.

5.3 Monitor wildlife population levels

While tracking habitat types there needs to be an understanding of the population health of wildlife and how they are reacting to changes in their habitat. Some species are currently tracked in annual counts while others are poorly understood. Recommended studies include:

1. Compile findings from the annual bird count for Mud Bay and monitor species population changes.
2. Complete wildlife population monitoring for terrestrial species in addition to birds within the 100m of the shoreline around Mud Bay.
3. Carry out monitoring of fish presence and water quality through the lower Nicomekl and Serpentine to better understand how moving of the Dams and options for mitigation will impact fish habitat.

5.4 Acquire private lands

Acquire privately-owned lands as opportunities arise that will remain unprotected by the planned retreat and realignment to Hwy 99 by the year 2100. Built structures should be removed from these sites, invasive species mitigated, and all disturbed areas restored to a natural plant community. Incorporate wildlife habitat features when possible including woody debris, artificial wildlife trees and roosting sites. Encourage these areas to flood naturally when safe to do so to help them adapt to sea level rise.

Appendix 1 Summary of Environmental Reports

CFAS Draft Strategy
City of Surrey, 2019

The Draft Strategy plans for ocean and river flood hazards up until 2100, recognizing both short- and long-term hazards and risks. It identifies four key land areas of risk: agriculture and farming (which has economic implications); community and residential; environmental and recreation; transportation and infrastructure; and food security for Metro Vancouver. The Strategy is informed by three policy documents, the Sustainability Charter, Climate Adaptation Strategy and Community Climate Action Strategy. It informs five plans: Future Engineering Servicing Strategy; Future OCP updates; Future Design Standards; Future City and Neighborhood Plan updates; and Future Bylaw updates.

The Strategy focuses on three areas: Mud Bay, Crescent Beach and Semiahmoo Bay. It divides Mud Bay into seven sub-planning areas: Inter River West; Inter River East; Colebrook; Serpentine North; Nicomekl South; Nico Wynd Area; Mud Bay Foreshore. It shortlists 5 options to manage these 7 areas. The two options that are highlighted as being preferred include the realignment of Highway 99 and a managed retreat.

Surrey Flood Protection – Preliminary Habitat Impact Assessment Report
Diamond Head Consulting, 2018

This report was a high-level introduction to existing habitat types and ecological communities in the area of interest in the City of Surrey. It then proceeded to begin to address questions around how these habitats and communities are likely to respond to various sea level rise scenarios given existing knowledge. Given the different scenarios, the expected impacts range from loss of exposure time of the intertidal mud flats, loss of eelgrass and loss of estuarine marshes, to loss of urban and agricultural land and other terrestrial and freshwater aquatic impacts.

Prioritizing Infrastructure and Ecosystem Risk (PIER), Framework for Environmental Vulnerability
Diamond Head Consulting, 2019

As part of the CFAS Strategy, the City underwent an analysis for Prioritizing Infrastructure and Ecosystem Risk (PIER). As part of this process, Diamond Head undertook a risk assessment focusing on the shoreline and near shore environment. This analysis helped to clarify coastal ecosystem needs from an adaptation perspective for the Mud Bay and Crescent beach areas, and inform and prioritize actions the City can undertake to reduce ecosystem risk. The risk assessment identified the three largest areas of concern to include: Loss of mud flat exposure time, likely to most impact waterfowl and shorebirds; loss of eelgrass communities, likely to most impact waterfowl and marine fish; and loss of intertidal habitat, likely to most impact shorebirds, marine fish, and marine invertebrates.

City of Surrey Shoreline Assessment Mud Bay – Field Verification Report
Friends of Semiahmoo Bay Society, 2018

Three types of landscapes were assessed across the shoreline: Salt marshes, beaches and shorezones. Six plant species were found across the salt marshes; the beaches were found to contain gravel, which is essential for Forage fish species and cascading trophic relationships; the shorezone was divided into four zones (backshore, intertidal, shallow subtidal and deep subtidal). The key recommendations from this assessment was to implement feeder bluffs, protect the beaches due to their importance as spawning beaches for forage populations and trophic cascades, and use shorezone dataset to encourage shoreline assessment studies.

Prioritizing Infrastructure and Ecosystem Risk from Coastal processes in Mud Bay - Estuary Monitoring Program
Ducks Unlimited Canada, 2018

The Ducks Unlimited Canada Interim report found that salinity of river water was higher than 18.6 ppt in Mud Bay; that the temperature ranged between 13.5 and 30.5 degrees between July – August 2018; and that waterfowl and shorebirds were the most observed wildlife birds in the area. High frequency periods for waterfowls between September and March; high frequency periods for songbirds through spring and summer; high frequency periods for shorebirds are throughout fall, winter and spring; and high frequency periods for raptors are all season but summer and early fall.

Preliminary report on mud bay nutrient loading effects on eelgrass bed health
Matthew Christensen, Friends of Semiahmoo Bay Society; Dr. Sarah Joy Bitick, UBC, 2018

This report hypothesized that estuary productivity would change in response to climate change and related patterns of precipitation. Ocean temperature, salinity, and turbidity would also be affected by precipitation and nutrient-input from humans. The report found that Mud Bay Eelgrass had been affected by the nutrient overloads inputted by human activities, causing shoot density to lower substantially in Mud Bay than in Crescent Beach. Eelgrass bed structure and community composition had been altered by the nutrient loading, and was thought to be subject to further alteration under climate change conditions.

Conceptual Fish Passage Gate for Nicomekl River Sea Dam
Northwest Hydraulics, 2015

Hydraulic impacts were modelled for future system conditions with no dike overtopping except at spillways locations; all spillways were represented using design ultimate rather than existing geometry and elevations. Three water quality impact concerns were highlighted:

1) City liability from negatively impacting existing water license holders
2) Balancing Agricultural land use with fisheries habitat
3) Compliance with the B.C. Water Act/Water Sustainability Act

It is not possible to accurately model fish passage response to fish slot prior to installation, and therefore it is recommended to field monitor fish using the passage to determine the usefulness of gates. Other items that should be measured is water salinity and water extraction depth.

Mud Bay Eelgrass Mapping and Monitoring
Matthew Christensen, Friends of Semiahmoo Bay Society, 2018

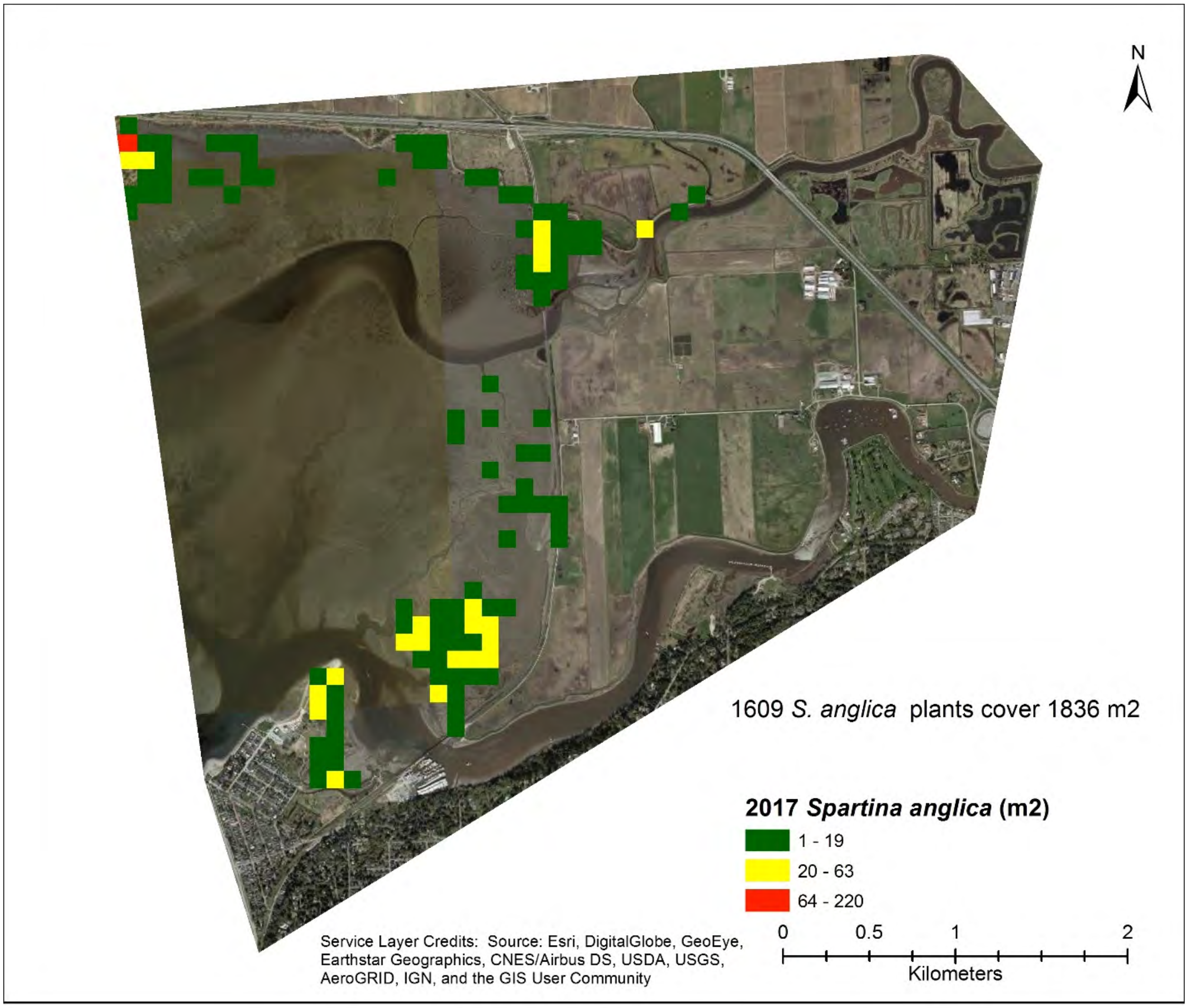
Eelgrass health is largely influenced by salinity, sediment type, current velocity, light availability, depth, temperature, pH, flushing and incident solar radiation. These environmental variables are not independent of each other. The vulnerability of eelgrass to sea level rise is difficult to determine due to the inter-related environmental variables that influence eelgrass. Increased average water levels may mean more sub-tidal habitat availability, however this may also mean increased sediment mixing and turbidity which would impact the newly available habitat's suitability. Follow up mapping should investigate data patches that were caused from lost field sheets or obstacles to mapping data. It is also recommended to investigate why certain areas do not have eelgrass when conditions appear suitable.

Mud Bay: Ecosystem Services Potential for Coastal Flood Protection
Ducks Unlimited Canada, 2018

The salt marshes in Mud Bay are resilient to sea level rise because they are capable of accreting sediment parallel to the expected sea level rise. Salt marshes protect the coast through three key means: wave attenuation; floodwater storage; shoreline stabilization. These are all strongly impacted by the amount, area and continuity of marsh vegetation; biomass productivity of above-ground and below-ground roots; and wetland presence accompanying marshlands for floodwater storage. 7 ecological components provide regulatory, productive and cultural ecosystem services (key points of which can be found in the appendix).

Spartina Abundance Mud Bay

Map shows spatial distribution and density of *Spartina anglica*.



Chapter 2

Mud Bay Monitoring Report

MUD BAY MONITORING REPORT

October 28, 2019

Submitted By:

Matt Christensen
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Background

The City of Surrey is implementing a participatory, community-driven planning approach to explore the impacts of climate change and sea level rise on Surrey's coastline. This initiative is known as the Coastal Flood Adaptation Strategy (CFAS) project. Surrey has partnered with Ducks Unlimited Canada (DUC) on a project titled "Prioritizing Infrastructure and Ecosystem Risk from Coastal Processes in Mud Bay" with funding from the Federation of Canadian Municipalities. As a part of this partnership project DUC is leading on Estuary Monitoring in Mud Bay which includes monitoring near-shore sediment and the collection of water quality, habitat and wildlife data. DUC has partnered with Smart Shores Inc. to develop and implement Unmanned Aerial Vehicle data collection to detect and quantify different habitat types in the study area.

Introduction

Mud Bay is situated within the City of Surrey and forms continuous tidal habitat with Boundary Bay to the west. Mud Bay is influenced by the Serpentine River in the north and the Nicomekl River in the south and is bounded by dykes at the landward side (Figure 1). Immediately adjacent land uses include agriculture, parks, residential areas, Highway 99, and a marina. The Serpentine Wildlife Management Area is located upstream along the south bank of the Serpentine River, immediately east of Highway 99. The City of Surrey has expressed interest in the Ecosystem Risk of Mud Bay in the face of Sea Level Rise. Surrey has partnered with DUC to try to answer this question.

Figure 1 Overview map of Mud Bay Study Area including rSET platform and datalogger locations

1. Estuary Monitoring

Methods

Surface Elevation Tables

To understand the physical processes that determine elevation change and the potential for sea level rise in estuary habitats, we require precise measurements of sediment elevation in these areas. The surface elevation table (SET) developed by scientists at the United States Geological Survey (USGS) provides accurate and precise measurements of sediment elevation of intertidal areas. The rod surface elevation table (rSET), is an improved version of the original SET.

Four rSET sampling stations were installed in Mud Bay based on recommendations by Northwest Hydraulic Consultants (NHC); one was installed at the north end of Mud Bay and three more were installed at the southern extent of the study area. These stations are location at roughly the same elevation. All four stations are anchored in the sediment using a shallow benchmark platform, which consists of four three-foot long, three -inch diameter sections of aluminum pipe driven vertically into the marsh, onto which we bolted an aluminum platform with a receiving collar for the rSET instrument itself. To avoid disturbing the sediment around the sampling station, we made a platform out of an aluminum plank mounted on two step stools on which staff can kneel or crouch while taking measurements.

After mounting the instrument on the platform, measurements were taken at the four positions (bearings). The same set of bearings, with respect to the platform, will be used to repeat the measurements in the future at each monitoring point location. The instrument arm is levelled, each pin is lowered to the sediment surface and the distance from the top of the arm to the top of the pin is recorded. The mean of all 36 measurements (9 pins X 4 bearings) at a station is determined. Further details on installation and measurement can be found here: https://www.pwrc.usgs.gov/set/SET/rod.html.

Marker horizons were also placed to help distinguish between shallow subsidence and sediment accretion. Without them differences in surface elevation are assumed to be due to sediment accretion.

Figure 2 Marker horizon at MB2 placed in May 2018

Water

Monitoring water conditions can provide information on the degree of water circulation and tidal flushing throughout a site, which can directly affect vegetation and wildlife species using the area. The dataloggers collect water levels, water temperature and water salinity. The loggers were installed within a PVC pipe that was driven into the sediment. An RTK GPS was used to record the elevation of the top of the pipe, and a tape measure was used to record the length of the cord used to hang the device from the top of the pipe to give the datum referenced elevation of the dataloggers. The loggers provide continuous data (collected every 10 min) on water levels, temperature and salinity in Mud Bay. Dataloggers are deployed at monitoring points MB1, MB3 and MB4 as shown in Figure 1.

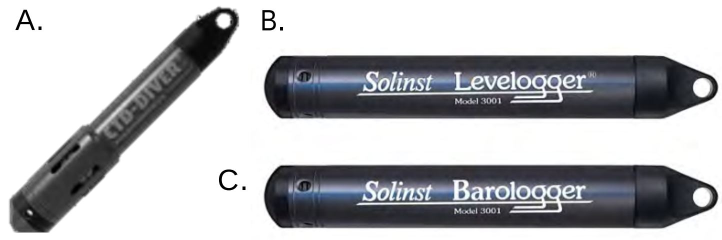


Figure 3 Installed datalogger models A. Van Essen CTD-Diver, B. Solinst Levelogger Model 3001 and C. Solinst Barologger Model 3001

Level

The dataloggers measure pressure to determine water level. Corresponding barometric (air) pressure is subtracted from the pressure recorded by the datalogger in the well. The difference in pressure returns the amount of water above the sensor. The height of the water with respect to a vertical datum is then presented based on the elevation of the cap of the datalogger, less the length of the cable.

Salinity

Specific conductivity (mS/cm) was recorded by the dataloggers at 10-minute intervals. The salinity is then calculated based on the temperature and specific conductivity readings. CTD-Diver dataloggers have to different thresholds for specific conductivity, up to 30 mS/cm and up to 120 mS/cm.

Temperature

Temperature (˚C) was recorded by the dataloggers at 10-minute intervals.

Wildlife

Birds

Bird species and observation records for Mud Bay are available through eBird, a citizen science-based database. eBird data documents bird distribution, abundance, habitat use, and trends through checklist data collected within a simple, scientific framework. Birders enter when, where, and how they went birding, and then fill out a checklist of all the birds seen and heard during the outing. The eBird Reference Dataset (ERD) is updated once annually includes observational and checklist data, is zero-filled, and associated with a suite of landscape variables (Sullivan et al., 2009). The eBird Observation Dataset (EOD) is updated annually and made available through the Global Biodiversity Information Facility (GBIF.org, 2018). The EOD contains basic occurrence data including species, date, and location. Additional metadata associated with these observations, including sampling event data (such as effort), are not included in the EOD.

Habitat

Vegetation community types and extent was measured using Un-manned Aerial Vehicles (UAV) flights and photogrammetry. This is explained in more detail in Section 2 - Remote Sensing of Near-shore Vegetation by UAV flights. Additionally, a historical literature was conducted for a species list and supplemented by field observations.

Results and Discussion

Surface Elevation Tables

Measurements were taken in January 2018, April 2019 and October 2019. The next measurement recordings for the rSET platforms will be in January 2020. The platforms were surveyed using a Spectra SP80 GNSS rover with network connection in July 2018, April 2019 and October 2019. Marker horizons were installed in May 2018. Platform measurements can be found in shown in Appendix I.

Analysis

rSET

Elevations recorded and presented are relative to the SET base. Marsh surface elevations were averaged by bearing (n = 9 pins) and averaged to each SET (n = 4 bearings) for all dates measured. Elevation change rates for each SET location were attempted to be determined using a linear regression over time. Due to variability in measurements at each SET base and the relatively short sampling period, a linear regression model could not be fitted to estimate elevation changes rates. Continued data collection on an annual to bi-annual frequency will improve the data set and likelihood of being able to fit a model confidently to determine elevation change rates. Figure 4 shows the range of average measurements for each rSET platform for each sampling period. In general platforms MB1 and MB3 show an increase in mean elevation over time, however this is not significant. From the first sampling period to the last MB2 shows a declining mean elevation and MB4 appears to maintain its elevation in relation to the rSET platform. At the site level there is some evidence to support accretion of sediments in the Mud Bay salt marshes with a mean elevation relative to the rSET platform increasing with each sampling interval. This is further supported by the marker horizons placed at three of the four rSET platforms.

Given the variability in measurements reported it is recommende that monitoring continue to increase the size of the data set temporally. Additionally, now that some baseline data has been collected, a power analysis should be completed to determine the sample size (number of platforms) required to be able to develop an sediment budget model that is sufficiently confident. RTK surveying in the future should emphasize longer recording intervals for each point, especially platform heights and should include post processing to improve the accuracy of the data collected as well as report out on confidence of the data.

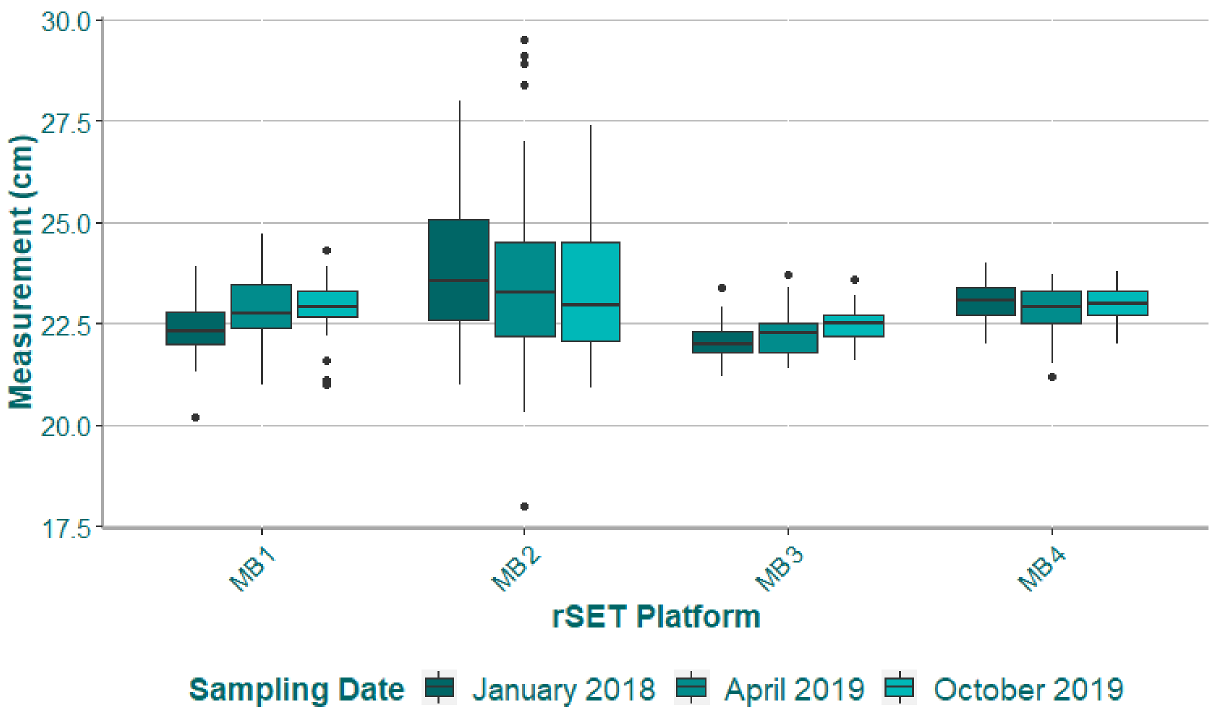


Figure 4 Directional elevation averages for each rSET platform. Elevations are relative to rSET platform.

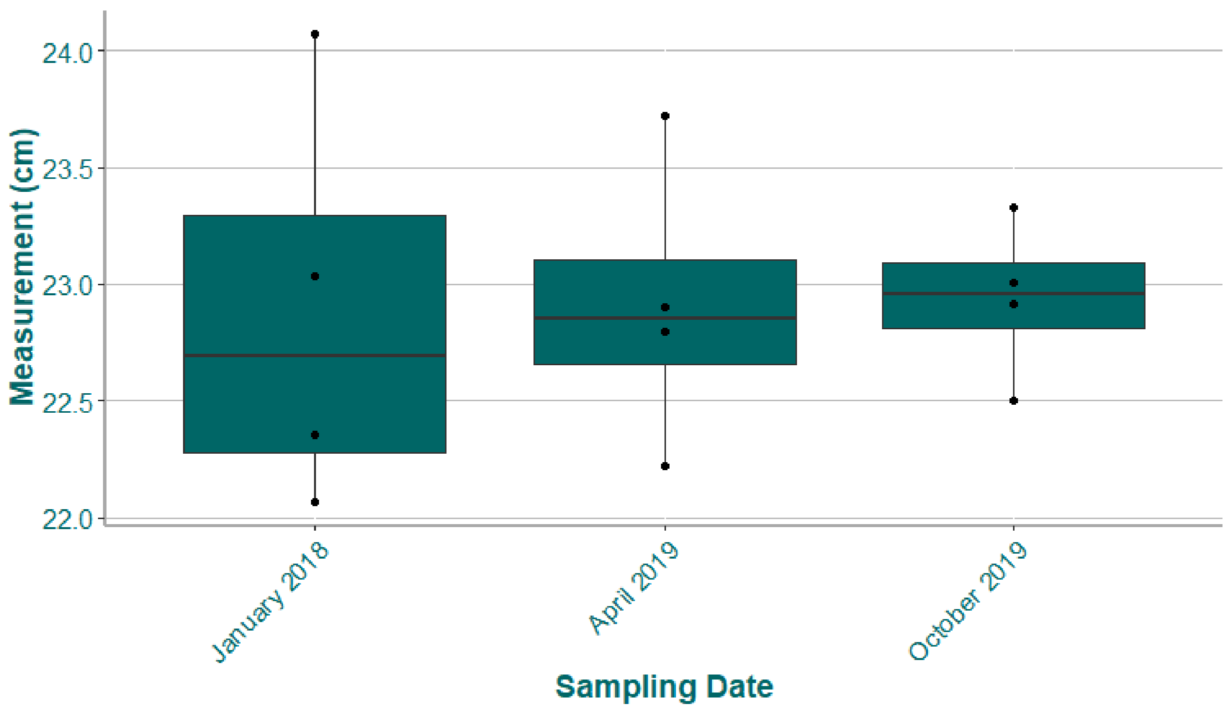


Figure 5 Elevation averages for each sampling interval. Elevations are relative to rSET platform

Marker Horizons

Four marker horizons were placed at each rSET platform in a square formation surrounding the platform. MB4 had an additional marker horizon placed in the mud for qualitative assessment compared to marsh surface. A PVC constructed sediment corer was uses to extract cores of marsh. The vertical distance between the marsh surface and the top of the marker horizon was measured using Vernier calipers (+/-0.1 mm). For each of the four horizons at each rSET platform one measurement was taken of each core and for one sampling period. Each of the marker horizons for each rSET platform had a little less than 1 mm of sediment accretion on top of the marker horizon. The only exception was that the Mud marker horizon appeared to have ~1.5 mm of sediment accretion. Repeated future sampling will allow for using linear regressions of changing depths over time. Marker horizon elevations were recorded at three time periods (August 2018, April 2019, and October 2019). Due to technical difficulties the points collected were not able to be post-processed and their vertical precision can not be reported. All marker horizon elevation data including calculated change between sampling intervals is reported in Appendix II – Marker Horizon Elevations

Figure 6. Marker horizon measurement being taken using vernier calipers. Marker horizon is the pink band below what is currently being measured between the caliper's external jaws.

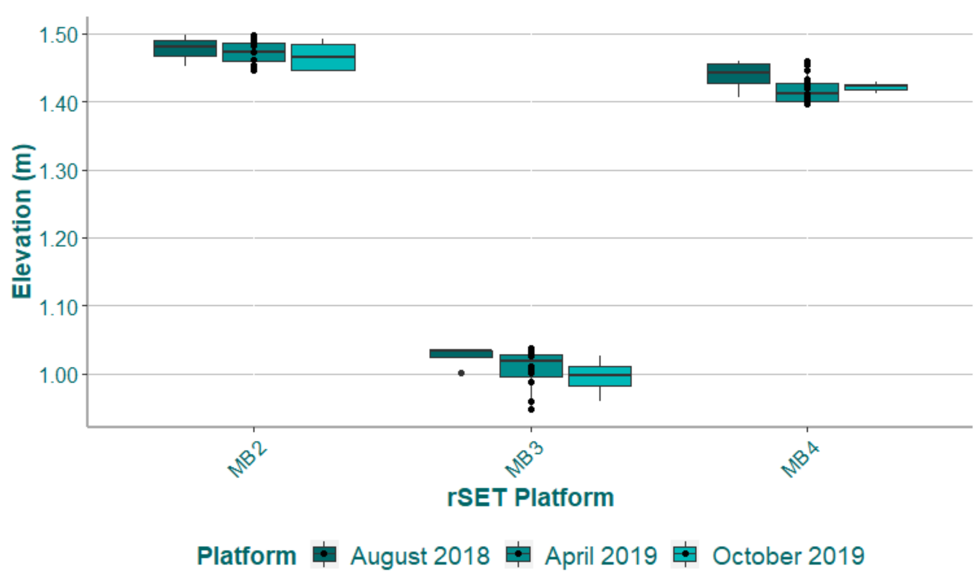


Figure 7 Marker Horizon elevations for three sampling periods at each platform

Figure 8 Map of RTK elevation transect surveys

Table 1 RTK Transect names, lengths and descriptions

Transect Name	Length (m)	Description
MBT1	70.0	Mud Bay Park
MBT2	90.6	Perpendicular to Nicomekl Tressel
MBT3	49.4	Mud to marsh bench at Nicomekl mouth
MBT4	123.3	Mud at Nicomekl mouth
MBT5	45.3	Mud at Nicomekl mouth
MBT6	38.5	Marsh bench to MB4 platform
MBT7	131.8	Marsh bench edge along ditch parallel to train tracks
MBT8	18.9	Ditch Profile
MBT9	518.7	MB2 to MB3, mostly mud
MBT10	215.1	MB2 marsh parallel to train tracks

Water

Dataloggers were installed in Mud Bay from February 2018. Only data collected between May 2018 and October 2019 has been used in this analysis. Data collected during February 2018 and May 2018 used a different type of datalogger and had issues with sedimentation obstructing the sensor. To avoid visibility (and theft) in the future as well as issues with sedimentation, PVC pipes should be installed to ground level and the sensor mounted to the cap at the top. The next step will be to determine the inundation periods of each habitat type using the habitat data from the UAV, water level data and site elevation data.

Analysis

Harmonic analysis of water level data from the CTD-Divers was used to determine four major harmonic constituents (M2, S2, K1, & O1) and predict Mean Lower Low Water (MLLW), Mean Higher Low Water (MHLW), Mean Sea Level (MSL), Mean Lower High Water (MLHW) and Mean Higher High Water (MHHW). TideHarmonics (Stephenson, A. G., 2016) was used to complete this analysis.

	Water Level (cm) CGVD28 GVRD				
	MLLW	MHLW	MSL	MLHW	MHHW
MB1	70.7	82.9	87.6	92.3	104.5
MB3	14.1	48.1	53.3	58.4	92.4
MB4	14.1	48.1	53.3	58.4	92.4

Salinity

The range of salinity between May 2018 and October 2019 was 18 to 28 ppt with most readings occurring between 15 to 26 ppt. The weekly mean salinity calculated and plotted over time as shown in Figure 9. Figure 9 shows two distinct events 1) 2018-08-27 and 2) 2019-04-02. Start of datalogging until 2018-08-27 had maxed out the setting on the conductivity sensor to determine salinity. Once the sensor setting was adjusted, salinity spiked to reflect actual levels that were outside of the threshold of the previous setting. On 2019-04-02 the datalogger data was downloaded and the sensors were re-installed at new heights. Mud continually seeped into the PVC pipes throughout data collection. On 2019-04-02 salinity dropped at MB4 and MB1, it is possible that these sensors need re-calibrated.

Temperature

Temperature readings were summarized to weekly means and plotted over time. Average weekly sea temperature gradually declines from mid to late August until March with January and February have the coolest average weekly sea temperature. Residual sea water in the PVC pipe that the loggers were mounted to may have influenced weekly mean temperatures. Either time periods without inundation could be removed from the analysis or the averaging interval could be smaller (ie. < 1 week) to better track sea water temperature.

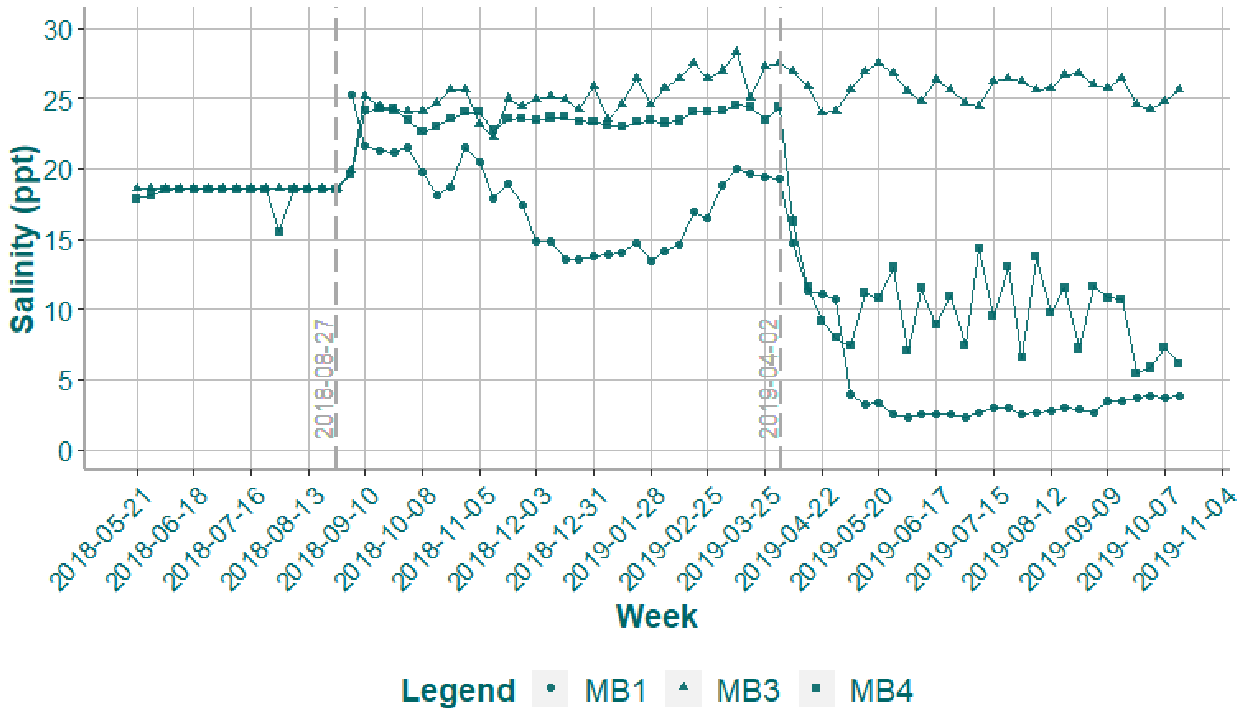


Figure 9 Mean weekly salinity at three datalogger locations in Mud Bay

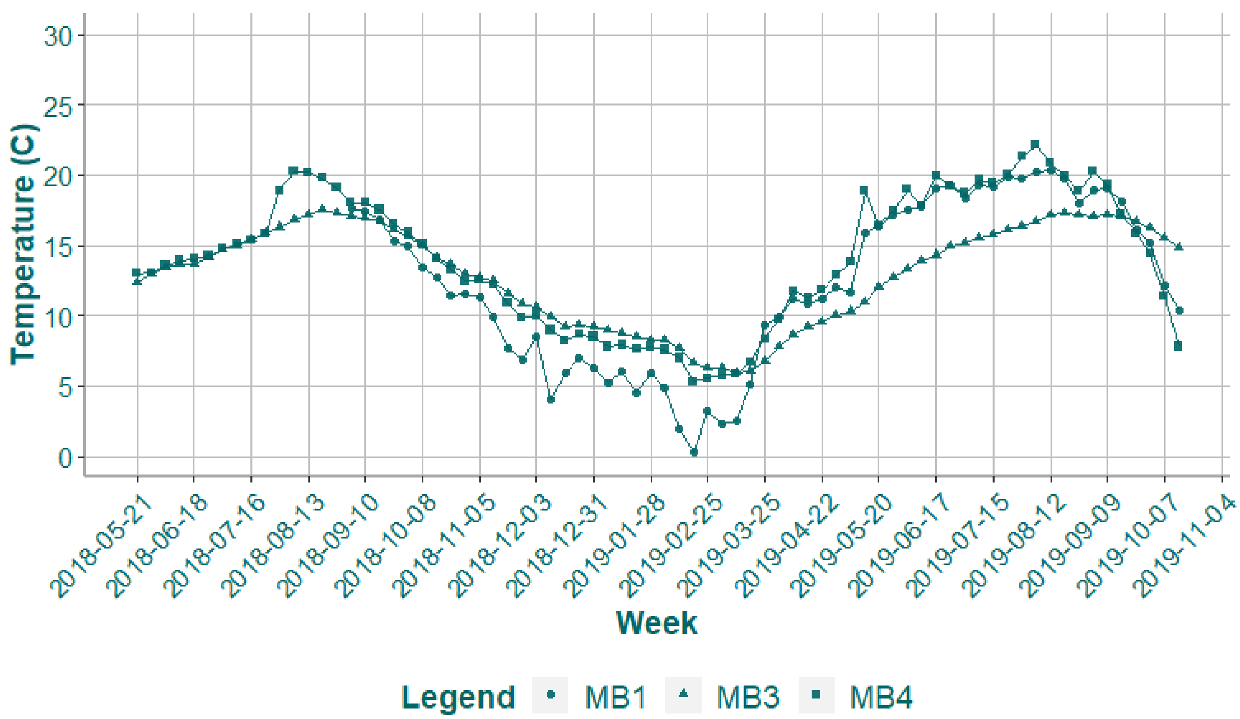


Figure 10 Mean weekly temperature at three datalogger locations in Mud Bay

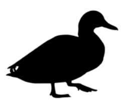
Birds

The EOD was used to create a bubble chart to show the relative number of observations of each type of bird in Mud Bay between 2013 and 2018(Figure 12). Waterfowl and shorebirds were the most observed types with waterfowl out ranking shorebirds. Mud Bay is within the Fraser River Delta, home to Canada's largest wintering waterfowl population. As a result, the number of waterfowl observations likely outranks the number of shorebird observations due to the residency time in the bay. Shorebirds may pass through in greater number but for shorter residency times. A map was also created to show the relative number of observations of each species using the study area; the locations of the bubbles are averages of the observation locations and not a reflection of the area of Mud Bay the species is frequently observed (Figure 13). The next steps will be to explore abundance using the ERD database.

Figure 11 Great Blue Heron fannini subspecies (Ardea herodias fannini) picture foreground, with American wigeon (Mareca americana) shown dabbling in the background

Bird species frequencies downloaded from eBird and grouped into guilds as shown in Table 2. Five representative species were selected for each guild and plotted by season and/or month. Song bird frequency is the greatest in late spring to early summer (May, June and July). Waterfowl are most frequent in winter months as with raptors.

Table 2 Bird guilds and five selected representative species for each

 Songbirds	American Goldfinch American Robin Barn Swallow Violet Green Swallow White crowned sparrow	 Shorebirds	Greater Yellowlegs Killdeer Western Sandpiper Western Grebe Whimbrel
 Waterfowl	Mallard Northern Pintail Green-winged teal American Wigeon Snowgoose	 Raptors	Bald Eagle Northern Harrier Red-tailed hawk Peregrin Falcon Rough legged hawk

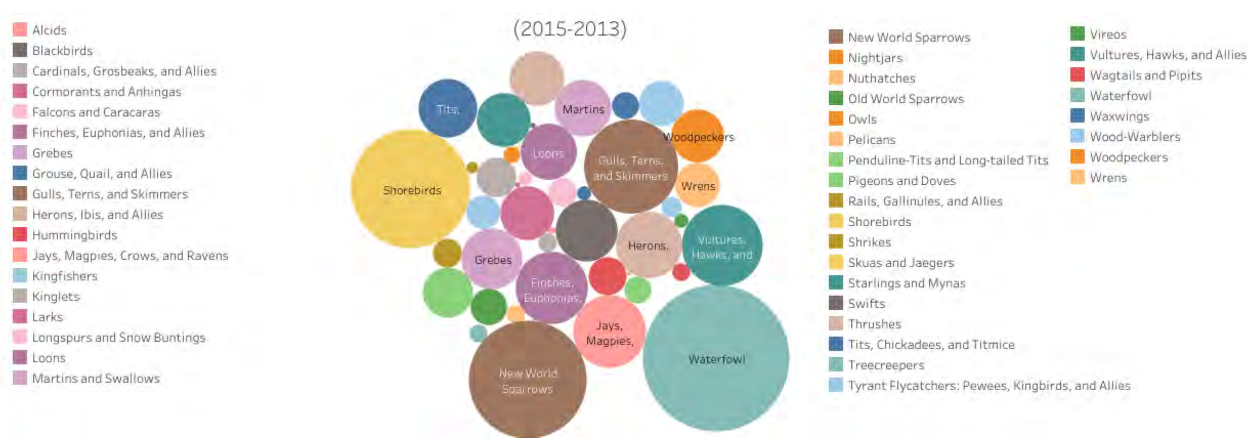


Figure 12 Bubble graph showing the number of observations of each bird type in Mud Bay, Surrey, BC

Throughout migration season, Boundary Bay and Mud Bay host most of the world's western sandpiper population (individuals number up to 500,000 birds daily and provide key foraging areas for 10% of the global *pacifica* subspecies of dunlin (*Calidris alpine*), and 3% of the world's black-bellied plovers (*Pluvialis squatarola*) during migration (Schaefer 2004, BirdLife International 2018). These abundant shorebirds provide an important prey source for raptors such as Peregrine falcons (*Falco peregrinus*), Merlins (*Falco columbarius*), and Northern Harriers (*Circus cyaneus*) (Dekker and Ydenberg 2004, Pomeroy 2006). Migrating and overwintering waterfowl also forage in the Bays in large numbers. In fall and early winter, daily waterfowl counts often reach 100,000, including up to 2% of the global American Wigeon population and 1% of the North

American Northern pintail population, as well as high numbers of mallard, green-winged teal, snow geese, and trumpeter swans (BirdLife International 2018). Other dabblers, including green winged teal and northern pintail, feed primarily on small crustaceans, snails, and bivalves (Baldwin and Lovvorn 1992, 1994). Boundary Bay rookeries encompass 6% of the breeding population of the endangered great blue heron fannini subspecies (BirdLife International 2018).

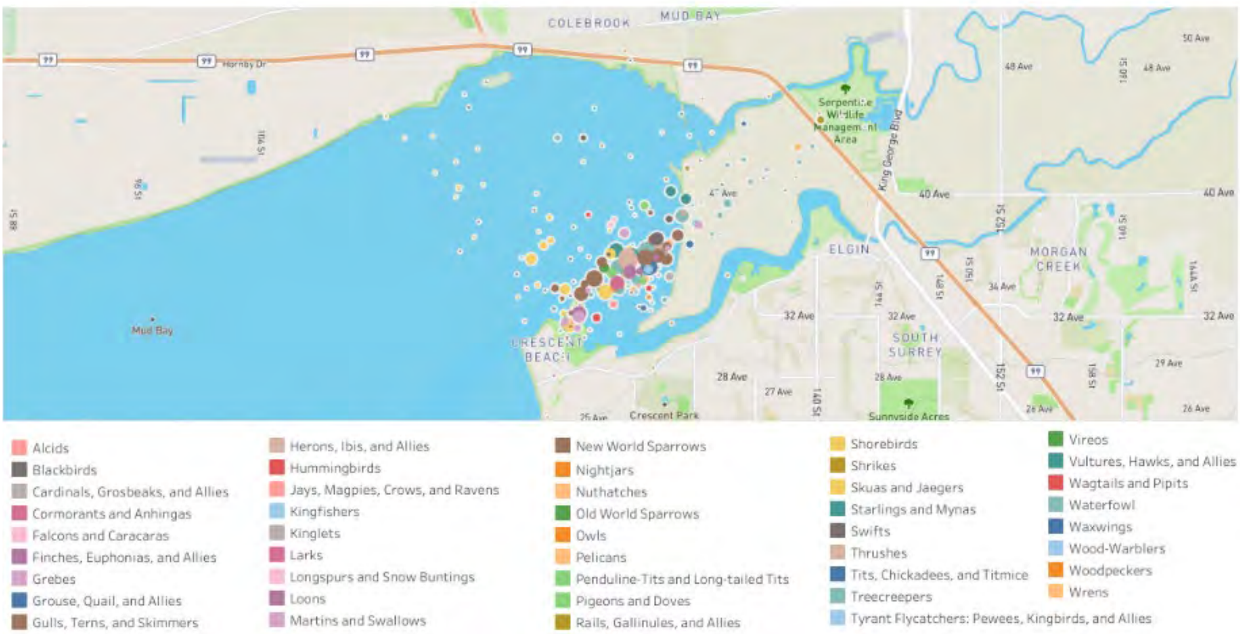


Figure 13 Map of the relative number of observations of each bird type in observed in Mud Bay, Surrey (2013-2018)

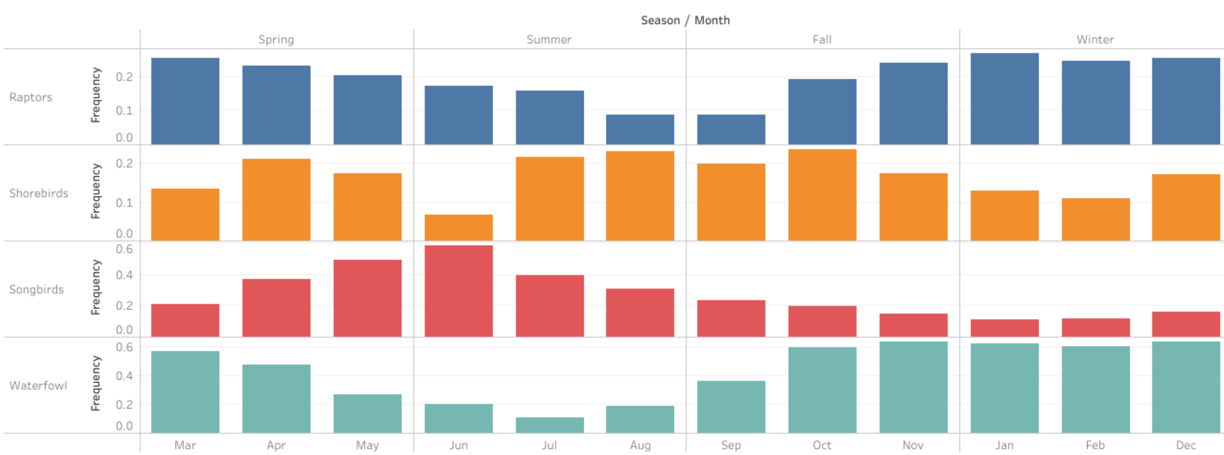


Figure 14 Frequency of bird guilds observed by season/month (consisting of 5 representative species for each) for Mud Bay, Surrey (2013-2018)

Habitat

Kellerhals and Murray 1969 describes the salt marsh fringing Mud Bay as dense and up to 15 cm in height, with perpendicular extent from the dike as low as "a few tens of feet". This description appears consistent with the current extent of salt marsh in Mud Bay (Figure 16). North and Teversham (KPA Engineering LTD 1994) mapped the distribution of vegetation in Boundary/Mud Bay using surveyor notebooks from 1859 – 1890. Notes from that time describe salt marsh, consisting of species such as glasswort (*Sarcocornia virginica*), sea arrowgrass (*Triglochin maritimum*) and seashore salt grass (*Distichlis spicata*). As of 1983, these vegetation types were still present in Boundary Bay, though to a much lesser extent that in the late 1800's as a result of diking (North and Teversham 1983). A number of subsequent vegetation surveys in Boundary Bay, including one at the eastern edge of Boundary Bay at Mud Bay in 1982, yielded a very similar plant list (Parsons 1975, Sheppard 1981, Porter 1982, Clague et al. 1998). Prior to diking, the Serpentine and Nicomekl floodplains were most likely occupied by high-marsh species such as tufted hairgrass (*Deschampsia caespitosa*), transitioning gradually to shrubs, and then wet coniferous forest at higher elevations (*North and Teversham 1983*). Saltmeadow rush (*Juncus gerardii*) dominates much of the high salt marsh in Mud Bay today. Other species observed throughout the duration of this project includes common orache (*Atriplex patula*), Canadian sandspurry (*Spergularia canadensis*), Puget Sound gumweed (*Grindelia integrifolia*) and invasive english cordgrass (*Spartina anglica*).

Section 2. Remote Sensing of Near-shore Vegetation by UAV flights details the methods and accuracy used to classify different habitat types in Mud Bay. Classified sections of the point cloud were exported as shapefiles.

While mud is the most abundant habitat type in Mud Bay, it is important not to discount mud habitat's role in estuaries. Mud hosts biofilm which is a mixture of organic matter, algae, microbes and meiofauna present as a thin layer on mud and sand-flats and represents a guild of important primary producers throughout the Fraser Estuary (Otte and Levings 1975, Moss et al. 2006, Jardine et al. 2015). Within the Fraser Estuary, Mud Bay has the highest concentration of biofilm per area (Jardine et al. 2015). Biofilm appears to be an important food source for migrating Western Sandpipers and managing habitat to maintain biofilm may be important for maintaining shorebird populations (Jardine et al. 2015). Biofilm can also be a valuable indicator of estuarine ecosystem health, since it represents a diverse suite of microorganisms which help to mediate many important biogeochemical processes (e.g. nutrient cycling; Moss et al. 2006).

All of Mud Bay was not classified and of the area classified further refinement is still required to improve the accuracy of the classification. If a classification was completed for remainder of the Mud Bay study area, we would see a dramatic increase in the total mud habitat area. Salt marsh extent would also increase, particularly for the northern most shore adjacent to highway 99. Iterative classification of three seasons of collected data will improve confidence in the classified areas.

Figure 15 Habitat classes used for UAV Image Classification

Table 3 Habitat types classified and their total area.

	Habitat Types Classified	Area (ha)*
Mud & Other Classifications	Mud	412.6
	Mud Algae	2.7
	Other Vegetation	5.3
Salt Marshes	Juncus gerardii dominant	13.9
	Distichlis spicata dominant	10.8
	Salicornia dominant	3.6
	*The entire extent of the study area was not classified.	

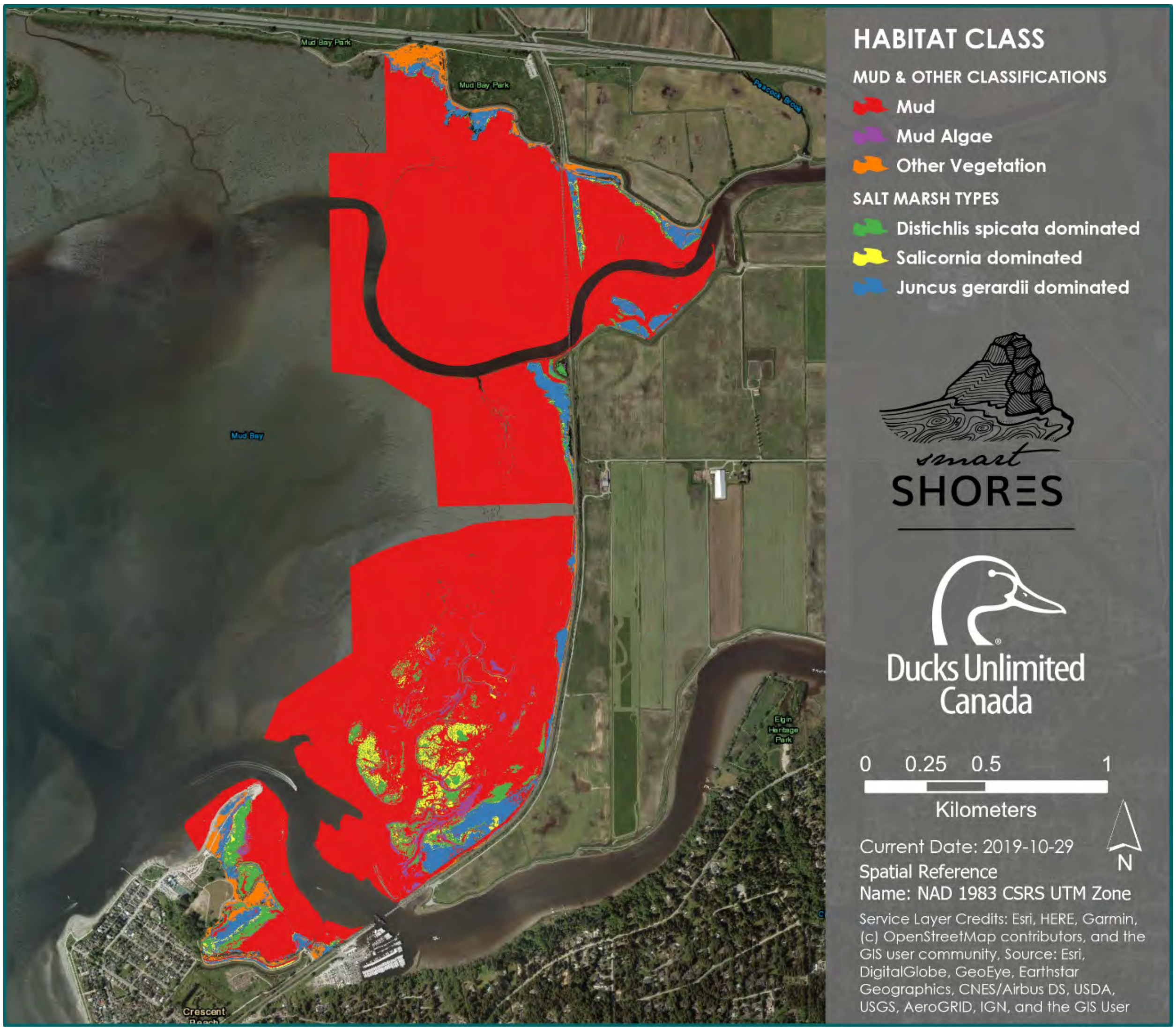


Figure 16 Mud Bay habitats classified by dominant species or cover

2. Remote Sensing of Near-shore Vegetation by UAV flights

This section describes the process of collecting and interpreting spatial data using a drone and translating this into actionable insights for environmental managers using photogrammetry and machine learning.

Drones provide an opportunity for fast, high-precision and cost-effective data collection. They are becoming common for industrial applications such cut/fill volume assessments in mining, progress tracking in construction, and remote infrastructure inspection for utilities companies. There is a clear case for drones in these industries where rapid remote site assessments save money and reduce risk to personnel. Adoption in the environmental fields has been slower. This is because substantial personnel hours are required to translate high volume, high precision data into actionable insights for environmental managers.

In contrast to industrial applications, the use of drones in environmental management requires a more nuanced analysis of landscape scenes, often over a larger spatial scale. High-resolution point clouds, elevation models and orthophotos must be interpreted to suit the needs of each project and the nuances of each site. This is prohibitively time consuming.

In this report, we present an approach for addressing this problem - automated classification surface cover and vegetation in the intertidal zone. This approach takes a large scene, in this case the 600-hectare Mud Bay ecosystem, breaks it down into hundreds of millions of data points, labels each point in a way that is meaningful to the needs of a specific environmental manager, and generates out-of-the-box actionable deliverables.

Methods

We collected data for Mud Bay by flying a drone mounted with a camera in overlapping transects, collecting images from nadir (top-down). We also measured RTK GPS ground points throughout the site. Data were collected in October 2018 and April, June and August 2019. These months were selected so that vegetation could be captured at different phases of growth (and senescence). The purpose of this time-series dataset was to showcase the ecosystem across seasons and to provide a broad range of data for training a machine-learning algorithm to identify relevant vegetation classes.

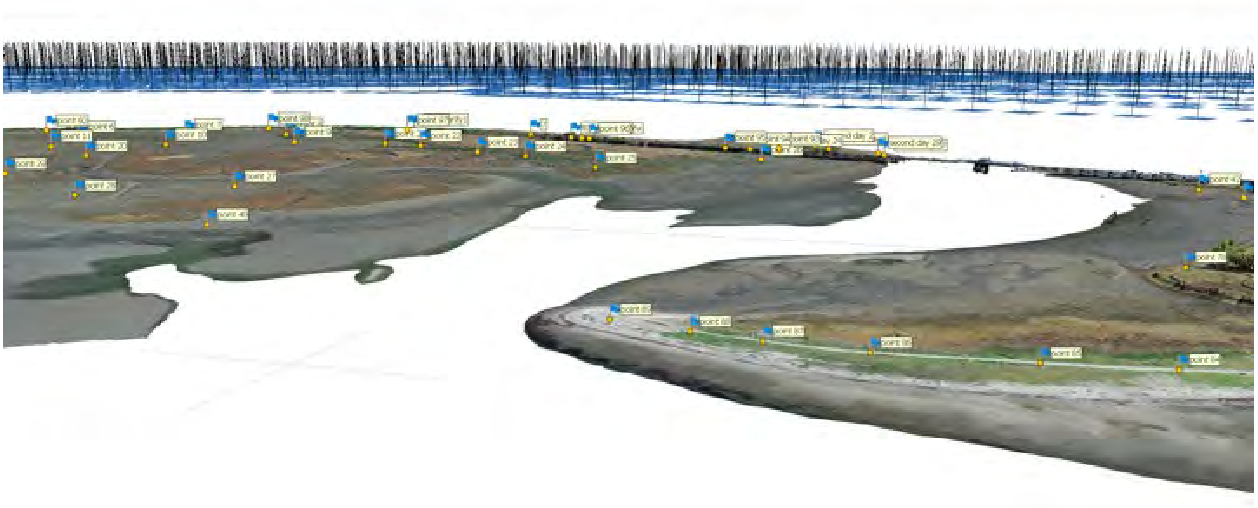


Figure 17 Photogrammetry is used to create a detailed 3D model of Mud Bay

In Figure 17 blue squares at the top of the image represent the position of a drone each time a photo was taken. The markers represent GPS tie points and the landscape is a colourized 3D point cloud (with water removed) of the mouth of the Nicomekl River in October 2018.

Each point in a point cloud represents a point in space that was reconstructed using the process of photogrammetry and calibrated using known ground control points. Photogrammetry is the science of taking measurements from photographs. Each pixel in over 18,000 overlapping photos was identified and matched with adjacent photos to create tie points among stereoscopic image pairs. These tie points formed the basis for a point cloud. This point cloud's geographic coordinates were initially based on the camera positions as measured by the drone's onboard GPS. The point cloud was then calibrated using a combination of RTK GPS data collected at sub-2cm vertical precision with a Trimble R10 rover and a City of Surrey DEM produced from LiDAR data collected in 2018. LiDAR was used for estimating the elevation of areas of soft mud far from shore. All data were referenced to NAD83 UTM 10N (EPSG:: 3157) and vertical elevations were referenced to the HT2 geoid model.

Each point in the point clouds produced for this project contains spatial coordinates (X, Y, Z) and RGB (red, green, blue) colour codes that include hue, saturation and intensity. When viewed in GIS or other compatible software the point cloud appears as a 3D model of a survey area.

Figure 18 Screenshot of a point cloud, facing NW from behind the Nicomekl rail bridge

We produced point clouds for each data collection session with an average density of 70 points per square metre. The number of points per m^2 can be increased to over 300 if required. However, such resolution is computationally expensive and would not be practical for this project (identifying site-level elevation and vegetation distribution).

The point cloud was used to generate Digital Elevation Models with an average precision of 5cm vertical and 3cm horizontal, and an average resolution of 12cm. Digital Elevation Models are created by converting the point clouds to raster files with a contiguous surface. Like the point cloud, the resolution of the DEM can be increased with further processing.

Orthomosaics were then created by projecting orthorectified images onto the DEM. The average resolution of orthomosaics for this project is 3cm. An orthomosiac of this resolution allows for fine-scale features to be observed and provides additional environmental monitoring opportunities. For example, 107 seals were visible (Figure 20) near the mouth of the Serpentine River and photographed with enough detail to measure the proportions of each seal. Of these data, the point cloud was used to automate the identification of vegetation within the site. This process is described below.

Figure 19 Colourized Nicomeckl Digital Elevation Model (DEM) for October 2018 overlain on a satellite image

Figure 20 Orthomosaic of the Serpentine River Mouth

Automated Identification and Classification of Salt Marsh Vegetation

This section describes the approach used to develop a point-cloud based, automated vegetation classifier built specifically for Mud Bay, and discusses the results. The goal of this exercise was to automate the identification of the predominant vegetation species in the Mud Bay intertidal zone at a spatial resolution of 12 cm by training a machine learning algorithm to identify these. This classifier uses high-resolution images collected by a visible light (RGB) camera mounted to a drone (UAV) and processed using a technique called photogrammetry (described in the previous section).

The predominant species in Mud Bay are *Juncus gerardii*, *Salicornia*, *Distichlis spicata* and a variety of species making up a class we labeled *mud algae*. Mud dominates the intertidal zone, with mixed vegetation along the shoreline. These six classes were used for labeling the scene after water was removed.

The result provides proof-of-concept that an automatic classifier based on visible light photogrammetric data can reliably identify the characteristic features of different plant types and can be used to automate the spatial assessment and inventory of salt marsh flora in the area over the long-term, at high resolution and at a low cost relative to LiDAR and/or in-person field surveys.

Methodology

Vegetation in the intertidal zone surrounding the mouth of the Nicomekl River was used to build and test the machine learning system. This site was selected because it has a higher proportion of vegetation cover compared to the area surrounding the mouth of the Serpentine River or Crescent Beach and would thus provide a more robust training site. Once the machine learning system was built and tested, it was applied to the area surrounding the mouth of the Serpentine River.

This section describes the process of building and testing the machine learning system at the Nicomekl River mouth. Given that the intertidal area surrounding the Serpentine River contains the same vegetation as the Nicomekl intertidal zone, we assume that the classifier will perform with the same accuracy in this area.

Raw Data

A point cloud of the intertidal region at the mouth of the Nicomekl River in Mud Bay was produced by using photogrammetry and a GPS ground survey to translate high-resolution drone images into a 3D landscape model (see previous section for details). The point cloud consists of nearly 90 million data points of which roughly 16 million corresponded to vegetation and 74 million to mud, roads, and other landmarks. These points are evenly distributed over the survey area with a density of 60 points per square meter. Each point in the point cloud contains information about the longitude, latitude, and elevation of the point, as well as the red, green, and blue (RGB) colour intensity and hue. Each point is accurate to 2cm (horizontal) and 5cm (vertical).

Each point in the scene was identified as either vegetation, mud, water or stone using an automated classification tool developed by Smart Shores. This tool is accurate to >95% at a spatial resolution of 12cm. The vegetation points were extracted from the point cloud and were used to train and validate the automated vegetation classifier.

Building an Automated Vegetation Classifier for the Mud Bay Intertidal Zone

Salt marsh vegetation was delineated into vegetation polygons (shapefiles) representing the predominant vegetation species in Mud Bay. This was accomplished through a combination of on-the-ground visual inspection and manual review of a high-resolution (3cm) orthomosaic. The shapefiles representing each class were split into training and validation polygons. Training polygons were used to “teach” the machine learning system how to identify the specific characteristics of each species. Salt marsh vegetation was labeled as one major class (salt marsh) with sub-classes for each dominant species (*Juncus gerardii*, *Salicornia*, *Distichlis spicata*). *Mud algae* was labeled as a single major class.

In areas where vegetation was mixed (transitional zones) shapefiles were labelled to reflect only the most prevalent sub-class. For example, a transitional zone that is dominated by *Distichlis spicata* with only some *Salicornia* was relabelled to *Distichlis Spicata*. This focus on the most prevalent sub-class in transitional vegetation zones will reduce the accuracy of the classifier because it will combine two species into one class. Each class remains dominated by one species so this effect should be minimal, but this methodological constraint must be noted. In future, a more precise training dataset that was labelled 100% correctly could be used to enhance the accuracy of the classifier.

Feature Engineering

Elevation and colour were selected as the features that would inform the machine learning algorithm. Elevation naturally plays a critical role as vegetation bands correspond tightly to salt water inundation, with more salt tolerant plants occupying lower elevations. Colour is also integral to differentiate further the nuances between different plants. In this study, colour was transformed into data describing the hue, saturation and value color coordinate system (HSV) for each of the red, green and blue colour bands. In this colour representation, hue describes the colour tone (green, magenta, cyan, red, etc.), saturation indicates the colour intensity, and the HSV value is used as a measure of the overall brightness of the color. Rigorous evidence that these features (elevation and colour) describe the differences between the vegetation classes sufficiently well are displayed below in Figure 21, Figure 22, and Figure 23.

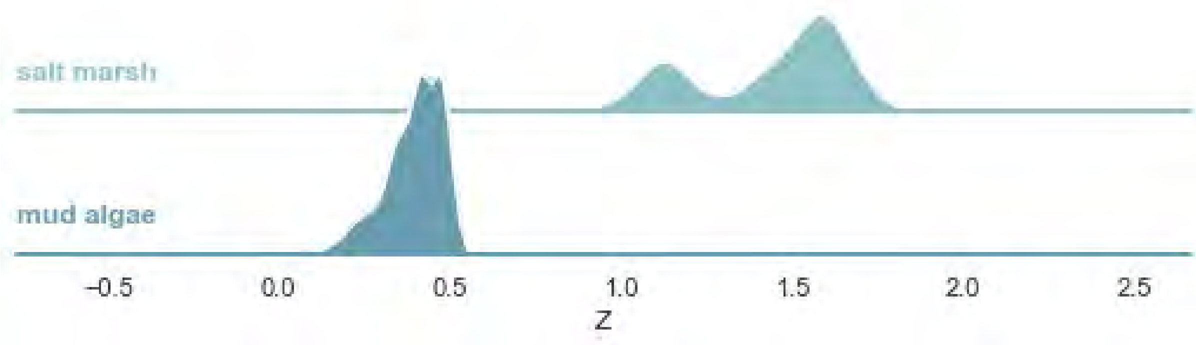


Figure 21 Algae and salt marsh by elevation

The abundance of the major vegetation classes is plotted against the elevation variable, z. While mud algae are exclusively found in low elevations between 0 and 0.5 m, salt marsh in Mud Bay has an elevation range of 0.8-2m.

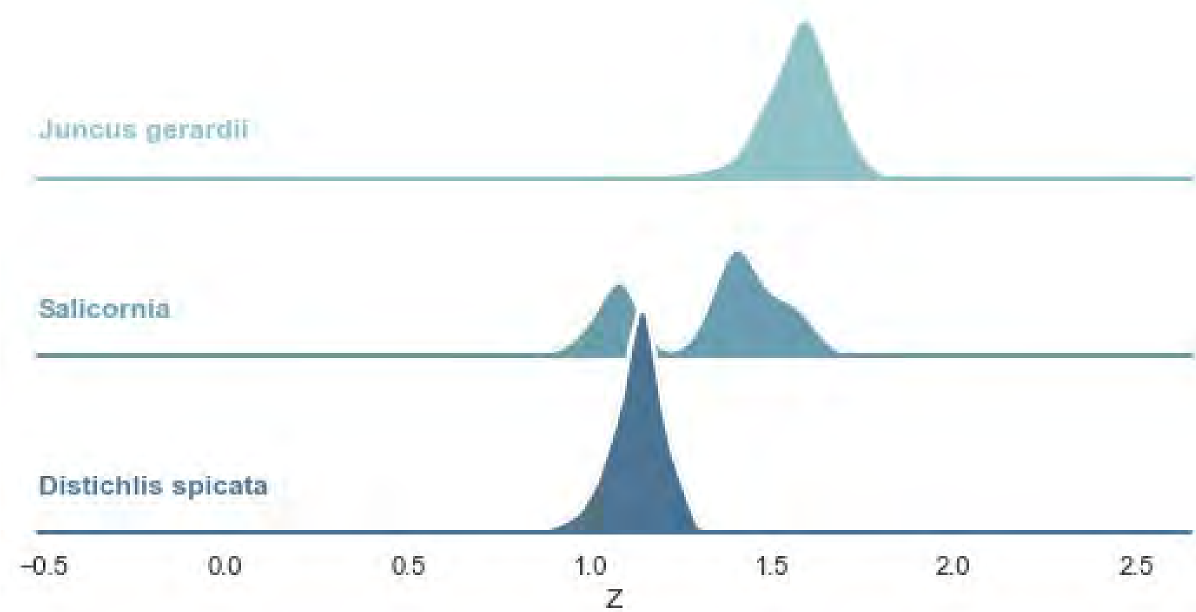


Figure 22 The abundance of salt marsh vegetation by elevation

This figure describes the vegetation composition of the salt marsh as a function of elevation. Both Salicornia and *Distichlis spicata* grow in an elevation bad between 0.8-1.4m. The upper range between 1.4 and 1.8 m is shared between Salicornia and *Juncus gerardii*.

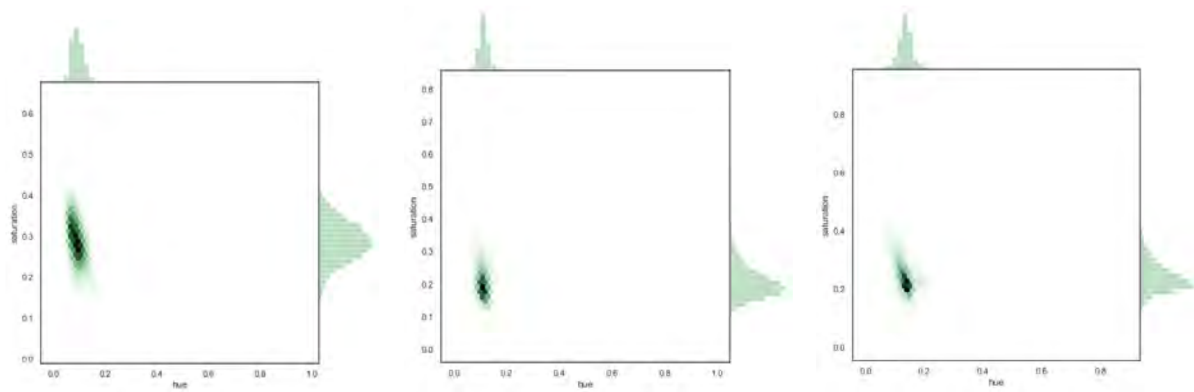


Figure 23 Colour parameters for salt marsh vegetation. Salicornia (left) Juncus gerardii (centre), and Distichlis spicata (right) compared by hue (x-axis) and saturation (y-axis). Both Juncus gerardii and Distichlis spicata share similar hue and saturation distributions. In contrast, Salicornia show a much higher saturation.

Machine learning and evaluation metrics

A random forest classifier was used with a maximum depth of 5 and 100 independent estimators. The implementation of the open source package sklearn was used with a random state of 0 for reproducibility. The classification results were evaluated based on the statistical metrics accuracy, precision, recall, and f1-score.

The most important among these metrics is **accuracy,** which we defined as the ratio of correctly labeled points to the total number of points assigned to a given class by the classifier. That is, the accuracy score (a percentage) indicates the likelihood that a randomly chosen point is correctly labelled.

Precision describes how many of the points assigned to each class were assigned correctly. For example, it describes how many of the points identified as *Salicornia* are indeed *Salicornia.* This measure shows the frequency of false positives, or Type 1 error, present in a given class.

Recall describes how many of the total points of a given class within a scene are assigned to the correct class. For example, of all the *Salicornia* in the scene, how much of this was assigned to the *Salicornia* class and how much was assigned elsewhere. This measure shows the frequency of false negatives, or Type 2 error.

These results are summarized in the **f1-score** and are used to measure the reliability of the classifier. For all three metrics, values close to 0 reflect a poor performance while proximity to 1 highlight exceptional predictions.

Results

The first step in our assessment of the classifier's performance was to assess the results of the training phase. That is, this step answers the question "how well does the classifier perform when looking only at the areas it has already seen during training?" The classifier performed well when analyzing the training data, with an average accuracy of 88%. Salicornia has the tendency of being mistaken with the other salt marsh plants. It is important to note the perfect prediction for mud algae in interpreting these results.

This is due to a phenomenon called overfitting that occurs when the training data is either too narrow or the model to become too complex. Further refinement of the training data could help solve this problem.

Table 1: Performance of the shoreline vegetation classification on the training set.

	precision	recall	f1-score	# points
Distichlis spicata	0.91	0.96	0.93	213772
Juncus gerardii	0.89	0.94	0.92	602932
Salicornia	0.75	0.56	0.64	172579
Mud algae	1.00	1.00	1.00	28015
Accuracy			0.88	1017298
Macro avg	0.89	0.87	0.87	1017298
Weighted avg	0.88	0.88	0.88	1017298

The next step involved testing the accuracy of the classifier on data it had not seen before. This involved an analysis of the remaining points surrounding the Nicomekl River mouth that had been manually defined, ground-truthed and digitized (validation points). This test is a measure of the accuracy of the automated classifier for use going forward.

The performance of the vegetation classification is good across the species classes with an average accuracy of 92%. It is important to note that this overall average is raised by the exceptional accuracy with which the classifier identified *juncus gerardii* (99%) and the large number of points in this class (75% of all vegetation in the validation dataset). A closer look reveals that *Salicornia*, *Distichlis spicata* and *mud algae* were reasonably well differentiated (81%, 67% and 70% accuracy, respectively) but had a much weaker performance than *Juncus gerardii*. This is likely the result of two problems; 1) there were not enough points in the scene for *Salicornia*, *Distichlis spicata* and *mud algae* to train a robust classifier, and, 2) transitional zones containing multiple species, but labelled as one, reduced the accuracy of the training dataset. Both these problems can be resolved by re-training the classifier on more and better labeled data.

Table 4 Performance of the vegetation classification on the validation set.

	precision	recall	f1-score	# points
Distichlis spicata	0.51	0.97	0.67	74855
Juncus gerardii	0.99	0.98	0.99	768622
Salicornia	0.93	0.71	0.81	98779
Mud algae	1.00	0.54	0.70	79396
Accuracy			0.92	1021652
Macro avg	0.86	0.80	0.79	1021652
Weighted avg	0.95	0.92	0.92	1021652

Table 5 Recall scores for each species, showing where errors occurred

Ground-Truthed Species	Species Predicted by the Classifier							
	Distichlis spicata		Juncus gerardii		Salicornia		Mud algae	
	# of points	% of total	# of points	% of total	# of points	% of total	# of points	% of total
Distichlis spicata	72,890	97.37%	73	0.10%	1885	2.52%	7	0.00000935%
Juncus gerardii	10548	1.37%	754,800	98.20%	3274	0.43%	0	0%
Salicornia	23125	23.41%	5163	5.23%	70,491	71.36%	0	0%
Mud algae	36686	46.21%	0	0.00%	0	0.00%	42,710	0.54%

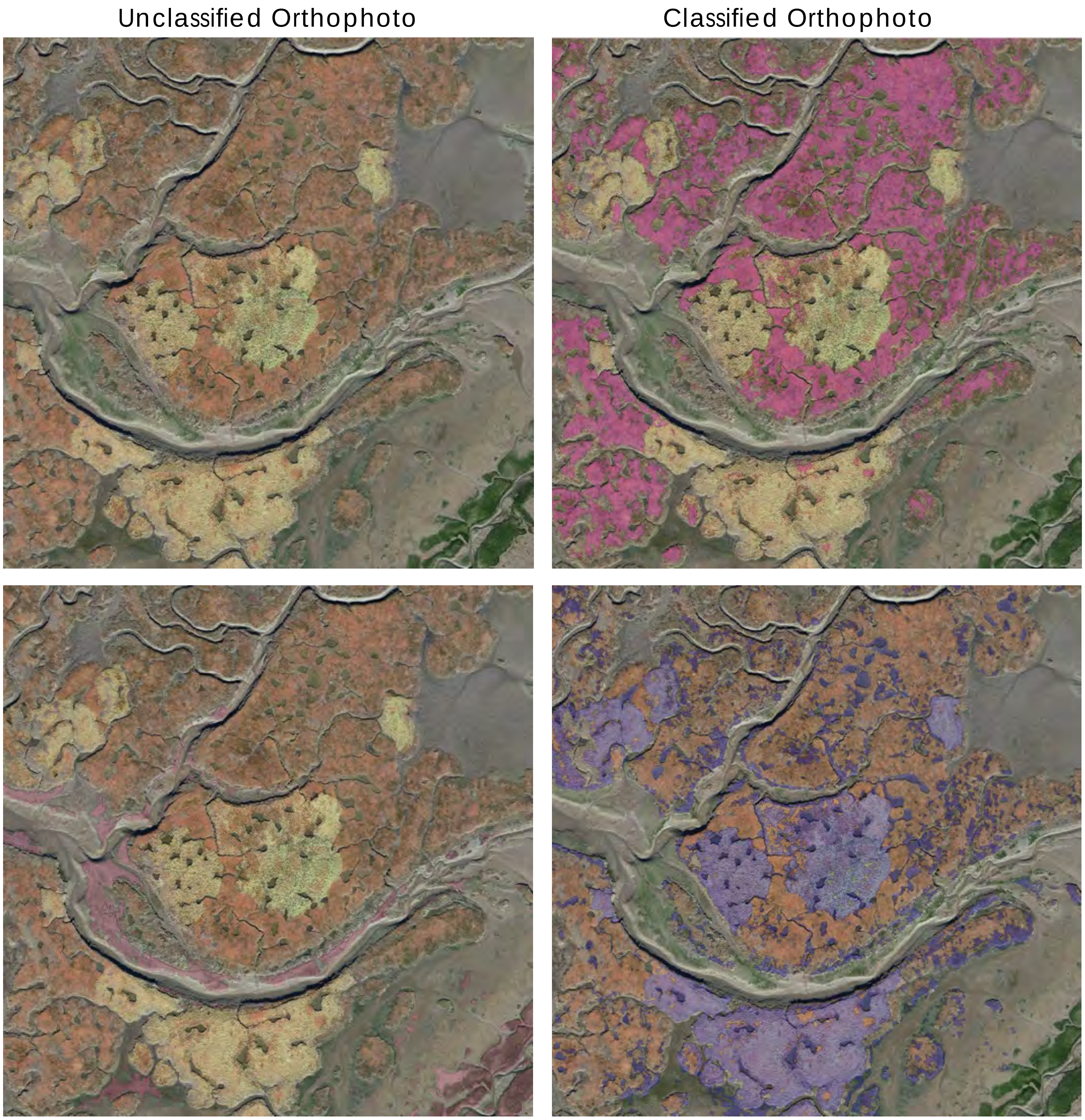


Figure 24 Sample screenshots of vegetation polygons overlaid on an orthophoto. Classified salicornia dominated salt marsh polygon shown in red (Top Right). Classified D. spicata dominant salt marsh shown in purple (Bottom Right)

Discussion

These results have shown that automatic vegetation classification can be a powerful tool for ecosystem management. The spatial resolution of the classifier is high enough to identify small isolated patches of vegetation and to differentiate small tidal pools from vegetation within the salt marsh. The vegetation edge, measured to 12cm resolution, is a powerful tool for assessing marsh recession.

Through machine learning, changes in the shoreline vegetation can be sustainably monitored over decades, and at fine spatial scales (in this case, 12cm resolution). The high overall prediction accuracy of 92% is a promising sign that the classifier can pick up on ecological patterns and draw precise conclusions. It is also encouraging that this accuracy can be further improved with a larger training dataset and more accurate training data labels.

The dataset used to build this classifier was collected in October, when vegetation was senescent. Further exploration of the classifier's performance across seasons may yet yield better results.

The results also suggest that the two suggestive features, elevation and color, can already provide a stable foundation to base predictions upon. For the three salt marsh species, the differences in these features were enough to label these effectively and suggests that there is value for high-spatial resolution data in vegetation classification in intertidal areas.

Some technical challenges naturally arise when considering expanding this classifier to other species. These may occur where different plants look similar from afar or compete within the same elevation range. Then, elevation and color might not be sufficiently distinct, and a classifier may be prone to mislabeling. Hence, flora with shared lineage and similar phenology are inherently challenging to assess. A potential solution to this limitation may be advanced feature engineering. The integration of the near-infrared color channel and the introduction of spatial variation all may help to further separate vegetation from data derived from aerial images.

Based on the current methodology, substantial improvements can be expected from a diversification of the training samples. An increased number of spatial patches per class and different survey areas can provide a more reliable internal representation of the underlying ecological patterns. In addition, more temporal diversity (seasonality) can support the development of a classification algorithm that is resilient to seasonal changes in vegetation appearance. The combined result would be in both cases a robust, resilient and externally valid classifier.

The application of drone-based photogrammetry and machine learning systems have demonstrated that it is possible to track fine-scale changes within the intertidal zone at an unprecedented scale and resolution.

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Appendix I – rSET Measurements

Name	Direction	Bearing	M1	M2	M3	M4	M5	M6	M7	M8	M9	Recording Date
MB1	D5	170	22.1	21.8	22	22.3	22.9	23.9	23	23.9	23.9	01-26-2018
MB1	D3	293	23.2	22.1	22.1	21.6	21.8	22.4	22.3	22.8	22.3	01-26-2018
MB1	D1	2	22	21.6	22.2	22.8	22.1	21.9	21.3	20.2	20.2	01-26-2018
MB1	D7	93	22.2	22.3	22.7	23.4	22.7	22.2	22.7	23	22.8	01-26-2018
MB2	D3	295	*25.6*	24.7	23.4	22.8	21.8	22.2	23.5	24	23.5	02-15-2018
MB2	D1	205	23.6	22.2	21.6	23.1	23.7	23.5	22.5	21	24.5	02-15-2018
MB2	D7	115	22.6	22.7	22.6	23.1	24.6	26.2	25.8	23.9	22.3	02-15-2018
MB2	D5	190	27.8	27	27.5	27	27.6	28	24.9	24.4	21.4	02-15-2018
MB3	D3	156	22.3	22.5	22.3	22.3	21.6	21.6	21.3	21.2	21.5	02-15-2018
MB3	D7	20	22.6	22.8	21.8	22.4	22.2	22.2	21.9	22.1	22	02-15-2018
MB3	D1	250	22.9	22.6	22	22.2	22	22	21.9	22	21.9	02-15-2018
MB3	D5	77	22.1	23.4	22.3	21.9	21.6	21.3	22	21.8	21.8	02-15-2018
MB4	D7	263	23.4	23.4	23.8	23	22.4	22.2	23.3	23.4	23.7	02-15-2018
MB4	D3	97	24	23.7	23.6	23.6	23.6	23.1	22.9	23.2	23	02-15-2018
MB4	D5	5	22.4	22.4	22.7	22.7	22.9	23.2	23.1	23	22.6	02-15-2018
MB4	D1	164	23.1	23.1	22.9	22.9	22.5	22	23.1	22.4	23	02-15-2018
MB1	D5	170	22.6	22.3	22.4	22.4	22.7	22.8	22.7	23.3	23.9	04-02-2019
MB1	D3	293	24.3	23.9	23.2	23.1	23.6	24.3	23.9	24.7	23.9	04-02-2019
MB1	D1	2	22.9	22.7	23.6	23.4	22.4	22.2	21.6	21.3	21	04-02-2019
MB1	D7	93	22.9	22.5	22	22.6	22.5	22.5	23	23	22.4	04-02-2019
MB2	D3	295	22.5	22.3	22	23.3	24.3	25.8	24	23.3	22.1	04-02-2019
MB2	D1	205	23.5	21.6	21.3	22.1	23.2	23.5	22.8	18	20.3	04-02-2019
MB2	D7	115	23.1	24	22.5	22.2	20.9	21.7	22.8	23.3	23	04-02-2019
MB2	D5	190	29.1	28.4	29.5	27	27	28.9	25.6	24.8	24.4	04-02-2019
MB3	D3	156	22.4	22.1	22.4	22.7	21.9	21.6	21.5	21.4	21.6	04-02-2019
MB3	D7	20	22.6	22.8	22.2	22.7	22.4	22.4	22.5	22.6	22.5	04-02-2019
MB3	D1	250	22.3	23.7	22.2	22.2	21.8	21.7	21.8	22	21.8	04-02-2019
MB3	D5	77	22.3	23.4	22.6	22.5	21.7	21.4	21.9	21.9	22.4	04-02-2019
MB4	D7	263	22.6	22.6	22.7	22.5	22	22.3	22.5	22.9	22.9	04-02-2019
MB4	D3	97	23.7	23.4	23.3	23.5	23.5	23.4	23.5	23.5	23.2	04-02-2019
MB4	D5	5	23.1	23.2	23.7	23.7	23.1	23.1	23.2	23.2	22.6	04-02-2019
MB4	D1	164	22.6	22.5	22.6	22.4	21.6	21.2	21.7	21.5	21.7	04-02-2019
MB4	D7	263	23.4	23.6	23.6	23.7	23.2	22.8	23.4	23.6	23.3	10-07-2019
MB4	D3	97	23.7	23.3	23.1	23.3	23.2	23	23	23.2	22.9	10-07-2019
MB4	D5	5	22.6	22.7	22.6	22.3	22.4	22.6	22.6	22.7	22.7	10-07-2019
MB4	D1	164	22.9	23.3	23.8	23.2	22.9	22.7	22.8	22	22.2	10-07-2019
MB3	D3	156	23.1	23	22.8	23.2	22.9	22.4	22.5	22.1	22	10-07-2019
MB3	D7	20	22.7	22.9	22.4	22.7	22.6	22.5	22.8	22.7	22.3	10-07-2019
MB3	D1	250	22.6	23.6	22.7	22.6	22	21.9	21.9	22.1	21.8	10-07-2019
MB3	D5	77	22.5	23.6	22.7	22.2	21.8	21.6	22.4	22.2	22.3	10-07-2019
MB1	D5	170	22.8	23	22.5	23.1	22.9	22.8	22.7	23.2	23.7	10-07-2019
MB1	D3	293	22.7	23.2	23.6	23.9	22.6	22.4	21.6	21	21.1	10-07-2019
MB1	D1	2	24.3	23.3	22.9	22.7	23.2	23.6	23.5	23.8	23.2	10-07-2019
MB1	D7	93	22.6	22.7	22.2	22.9	23.2	22.7	23.4	23.3	22.6	10-07-2019
MB2	D3	295	25.4	24.9	22.5	22.1	21.1	21.8	23.2	23.4	23.3	10-11-2019
MB2	D1	205	23.4	21.8	23.6	27.3	27.4	26.5	24.5	24.5	24	10-11-2019
MB2	D7	115	22.9	22.3	22.1	23	25	26.1	24.5	23.8	22.3	10-11-2019
MB2	D5	190	22.8	21.9	21.4	21.7	22.8	22.6	21.9	20.9	21.2	10-11-2019

Appendix II – Marker Horizon Elevations (m)

All values reported in recorded using HTMVBC00_Abb geoid model and reported in CGVD28 vertical reference datum.

	Period 1	Period 2	Period 3			
	30-Aug-18	02-Apr-19	10-Oct-19	Period 1 - Period 2	Period 2 - Period 3	Period 1 -Period 3
MB3-MH1	1.033	1.012	0.989	-0.021	-0.023	-0.044
MB3-MH2	1.036	1.038	1.026	0.002	-0.012	-0.01
MB3-MH3	1.034	1.026	1.007	-0.008	-0.019	-0.027
MB3-MH4	1.001	0.949	0.96	-0.052	0.011	-0.041
MB2-MH1	1.488	1.454	1.447	-0.034	-0.007	-0.041
MB2-MH2	1.472	1.492	1.492	0.02	0	0.02
MB2-MH3	1.497	1.485	1.482	-0.012	-0.003	-0.015
MB2-MH4	1.452	1.462	1.446	0.01	-0.016	-0.006
MB4-MH1	1.453	1.445	1.428	-0.008	-0.017	-0.025
MB4-MH2	1.406	1.402	1.412	-0.004	0.01	0.006
MB4-MH3	1.459	1.396	1.425	-0.063	0.029	-0.034
MB4-MH4	1.433	1.42	1.42	-0.013	0	-0.013

Appendix III – Mud Bay Transects

All values reported in recorded using HTMVBC00_Abb geoid model and reported in CGVD28 vertical reference datum.

OBJECTID	Northing	Easting	Elevation	Transect_Name	Description	Notes
1	5434153.572	509731.551	1.411	MBT6	Marsh bench to MB4 platform	
2	5434154.266	509730.28	0.433	MBT6	Marsh bench to MB4 platform	
3	5434038.722	509695.867	0.311	MBT2	Perpendicular to Nicomekl Tressel	Mudflat
4	5434047.63	509691.023	0.281	MBT2	Perpendicular to Nicomekl Tressel	Mudflat
5	5434055.301	509686.24	0.321	MBT2	Perpendicular to Nicomekl Tressel	Mudflat
6	5434062.022	509684.297	0.415	MBT2	Perpendicular to Nicomekl Tressel	Mudflat
7	5434070.095	509680.082	0.432	MBT2	Perpendicular to Nicomekl Tressel	Mudflat
8	5434090.847	509671.439	0.457	MBT2	Perpendicular to Nicomekl Tressel	Mudflat
9	5434104.166	509663.618	0.486	MBT2	Perpendicular to Nicomekl Tressel	Mudflat
10	5434114.625	509657.894	0.409	MBT3	Mud to marsh bench at Nicomekl mouth	Mudflat
11	5434115.859	509659.969	0.473	MBT3	Mud to marsh bench at Nicomekl mouth	Mudflat with Salicornia
12	5434122.098	509667.325	0.585	MBT3	Mud to marsh bench at Nicomekl mouth	Mudflat with Salicornia
13	5434130.257	509675.305	0.591	MBT3	Mud to marsh bench at Nicomekl mouth	Mudflat with Salicornia
14	5434137.915	509682.026	0.564	MBT3	Mud to marsh bench at Nicomekl mouth	Mudflat with Salicornia
15	5434140.72	509683.659	0.491	MBT3	Mud to marsh bench at Nicomekl mouth	Mudflat
16	5434149.079	509692.984	0.456	MBT3	Mud to marsh bench at Nicomekl mouth	Mudflat
17	5434485.568	509771.202	0.999	MBT9	MB2 to MB3, mostly mud	Marsh
18	5434489.001	509776.754	0.99	MBT9	MB2 to MB3, mostly mud	Marsh
19	5434492.459	509783.693	0.906	MBT9	MB2 to MB3, mostly mud	Marsh
20	5434496.489	509791.701	0.937	MBT9	MB2 to MB3, mostly mud	Marsh
21	5434499.71	509798.748	1.029	MBT9	MB2 to MB3, mostly mud	Marsh
22	5434504.173	509808.083	1.062	MBT9	MB2 to MB3, mostly mud	Marsh
23	5434507.991	509816.721	0.948	MBT9	MB2 to MB3, mostly mud	Marsh
24	5434513.997	509825.259	0.858	MBT9	MB2 to MB3, mostly mud	Marsh
25	5434517.948	509829.443	0.114	MBT9	MB2 to MB3, mostly mud	Tidal Channel
26	5434519.734	509830.901	-0.041	MBT9	MB2 to MB3, mostly mud	Tidal Channel
27	5434522.758	509832.022	0.178	MBT9	MB2 to MB3, mostly mud	Tidal Channel
28	5434524.198	509833.589	-0.003	MBT9	MB2 to MB3, mostly mud	Tidal Channel
29	5434529.917	509837.001	0.004	MBT9	MB2 to MB3, mostly mud	Tidal Channel
30	5434539.121	509845.746	0.04	MBT9	MB2 to MB3, mostly mud	Tidal Channel
31	5434555.877	509864.268	0.93	MBT9	MB2 to MB3, mostly mud	Marsh
32	5434568.788	509876.493	0.947	MBT9	MB2 to MB3, mostly mud	Marsh
33	5434582.357	509889.732	1.009	MBT9	MB2 to MB3, mostly mud	Marsh
34	5434598.248	509906.816	0.46	MBT9	MB2 to MB3, mostly mud	Mudflat
35	5434604.682	509915.012	0.672	MBT9	MB2 to MB3, mostly mud	Mudflat
36	5434633.904	509970.846	0.762	MBT9	MB2 to MB3, mostly mud	
37	5434658.162	509996.583	0.619	MBT9	MB2 to MB3, mostly mud	Soft Mud
38	5434670.811	510009.686	0.614	MBT9	MB2 to MB3, mostly mud	Soft Mud
39	5434680.703	510016.558	0.615	MBT9	MB2 to MB3, mostly mud	
40	5434692.937	510027.766	0.62	MBT9	MB2 to MB3, mostly mud	Soft Mud
41	5434718.617	510050.386	0.567	MBT9	MB2 to MB3, mostly mud	Soft Mud
42	5434747.581	510086.296	0.477	MBT9	MB2 to MB3, mostly mud	Soft Mud
43	5434803.061	510173.888	0.657	MBT9	MB2 to MB3, mostly mud	Soft Mud
44	5434854.737	510256.911	1.317	MBT10	MB2 marsh parallel to tracks	Marsh
45	5434801.345	510250.673	1.361	MBT10	MB2 marsh parallel to tracks	Marsh
46	5434730.456	510234.339	1.272	MBT10	MB2 marsh parallel to tracks	Marsh
47	5434692.525	510226.072	1.433	MBT10	MB2 marsh parallel to tracks	Marsh
48	5434643.03	510220.368	1.372	MBT10	MB2 marsh parallel to tracks	Marsh
49	5434170.779	509879.822	1.304	MBT7	Marsh bench edge along ditch parallel to train tracks	Marsh
50	5434164.822	509870.37	1.318	MBT7	Marsh bench edge along ditch parallel to train tracks	Marsh
51	5434143.184	509835.71	1.311	MBT7	Marsh bench edge along ditch parallel to train tracks	Marsh
52	5434123.363	509808.951	1.325	MBT7	Marsh bench edge along ditch parallel to train tracks	Marsh
53	5434103.788	509780.073	1.334	MBT7	Marsh bench edge along ditch parallel to train tracks	Marsh
54	5434096.434	509771.155	1.307	MBT7	Marsh bench edge along ditch parallel to train tracks	Marsh
55	5434126.222	509816.441	0.513	MBT8	Ditch Profile	Tidal Channel
56	5434124.605	509818.178	0.134	MBT8	Ditch Profile	Tidal Channel
57	5434122.518	509819.635	-0.048	MBT8	Ditch Profile	Tidal Channel
58	5434120.654	509821.043	-0.161	MBT8	Ditch Profile	Tidal Channel
59	5434119.38	509822.82	-0.082	MBT8	Ditch Profile	Tidal Channel
60	5434117.538	509825.826	0.056	MBT8	Ditch Profile	Tidal Channel
61	5434117.13	509831.708	0.522	MBT8	Ditch Profile	Tidal Channel
62	5437359.479	509712.127	0.802	MBT1	Mud Bay Park	Mud
63	5437363.746	509712.787	0.833	MBT1	Mud Bay Park	Mud
64	5437367.491	509714.214	0.811	MBT1	Mud Bay Park	Salt Marsh Edge
65	5437371.494	509715.62	0.853	MBT1	Mud Bay Park	Salt Marsh
66	5437375.98	509717.161	1.091	MBT1	Mud Bay Park	Salt Marsh
67	5437380.618	509718.588	1.214	MBT1	Mud Bay Park	Salt Marsh
68	5437384.762	509720.656	1.28	MBT1	Mud Bay Park	Salt Marsh
69	5437389.29	509722.611	1.337	MBT1	Mud Bay Park	Salt Marsh
70	5437394.253	509723.866	1.322	MBT1	Mud Bay Park	Salt Marsh
71	5437398.825	509725.572	1.3	MBT1	Mud Bay Park	Salt Marsh
72	5437403.433	509727.808	1.317	MBT1	Mud Bay Park	Salt Marsh

73	5437408.698	509729.853	1.528	MBT1	Mud Bay Park	Salt Marsh
74	5437413.358	509731.771	1.71	MBT1	Mud Bay Park	Salt Marsh
75	5437416.942	509734.373	1.857	MBT1	Mud Bay Park	Salt Marsh
76	5437420.877	509737.158	2.247	MBT1	Mud Bay Park	Salt Marsh
77	5437423.677	509738.799	2.299	MBT1	Mud Bay Park	Salt Marsh
78	5434164.143	509697.049	1.209	MBT6	Marsh bench to MB4 platform	HIGH MARSH
79	5434162.704	509702.55	1.222	MBT6	Marsh bench to MB4 platform	HIGH MARSH
80	5434162.056	509710.655	1.334	MBT6	Marsh bench to MB4 platform	HIGH MARSH
81	5434159.348	509719.414	1.365	MBT6	Marsh bench to MB4 platform	HIGH MARSH
82	5434156.332	509726.391	1.406	MBT6	Marsh bench to MB4 platform	HIGH MARSH
83	5434202.778	509695.719	0.35	MBT4	Mud at Nicomekl mouth	
84	5434206.485	509697.261	0.348	MBT4	Mud at Nicomekl mouth	
85	5434211.039	509698.899	0.356	MBT4	Mud at Nicomekl mouth	
86	5434215.821	509700.279	0.381	MBT4	Mud at Nicomekl mouth	
87	5434220.19	509702.021	0.369	MBT4	Mud at Nicomekl mouth	
88	5434224.648	509704.386	0.399	MBT4	Mud at Nicomekl mouth	
89	5434229.144	509707.718	0.415	MBT4	Mud at Nicomekl mouth	
90	5434233.713	509712.449	0.374	MBT4	Mud at Nicomekl mouth	
91	5434238.53	509716.685	0.443	MBT4	Mud at Nicomekl mouth	
92	5434243.807	509722.611	0.476	MBT4	Mud at Nicomekl mouth	
93	5434246.806	509727.084	0.515	MBT4	Mud at Nicomekl mouth	
94	5434250.053	509731.605	0.541	MBT4	Mud at Nicomekl mouth	
95	5434254.093	509737.965	0.537	MBT4	Mud at Nicomekl mouth	
96	5434258.238	509745.352	0.541	MBT4	Mud at Nicomekl mouth	
97	5434262.711	509752.521	0.588	MBT4	Mud at Nicomekl mouth	
98	5434266.681	509760.18	0.712	MBT4	Mud at Nicomekl mouth	
99	5434270.464	509765.2	0.575	MBT4	Mud at Nicomekl mouth	
100	5434273.567	509769.902	0.558	MBT4	Mud at Nicomekl mouth	
101	5434276.787	509774.784	0.563	MBT4	Mud at Nicomekl mouth	
102	5434281.14	509780.23	0.503	MBT4	Mud at Nicomekl mouth	
103	5434284.299	509783.375	0.381	MBT4	Mud at Nicomekl mouth	
104	5434253.728	509794.782	0.715	MBT5	Mud at Nicomekl mouth	
105	5434255.636	509799.212	0.66	MBT5	Mud at Nicomekl mouth	
106	5434259.275	509805.433	0.618	MBT5	Mud at Nicomekl mouth	
107	5434261.487	509809.551	0.603	MBT5	Mud at Nicomekl mouth	
108	5434265.045	509815.244	0.634	MBT5	Mud at Nicomekl mouth	
109	5434267.524	509819.864	0.624	MBT5	Mud at Nicomekl mouth	
110	5434270.946	509825.06	0.6	MBT5	Mud at Nicomekl mouth	
111	5434272.98	509829.502	0.601	MBT5	Mud at Nicomekl mouth	
112	5434275.253	509834.585	0.572	MBT5	Mud at Nicomekl mouth	

Appendix IV - Point Cloud Classes for mouth of Nicomekl River

J. gerardii dominated salt marsh

Mud algae

Mud

Other vegetation

Salicornia dominated salt marsh

D. spicata dominated salt marsh

Chapter 3

Mud Bay Nutrient Loading Effects on Eelgrass Bed Health

Mud Bay Nutrient Loading Effects on Eelgrass Bed Health

Prepared On:
September 30th, 2019

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LIBER ERO FELLOWSHIP PROGRAM PROGRAMME POSTDOCTORAL

Friends of Semiahmoo Bay Society

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This work could not have been undertaken without the support and leadership of local community members and subject matter experts. UBC post-doctoral fellow Dr. Sarah Joy Bittick and her team of researchers including, Felipe Amadeo, Katie Tjaden-McClement, Clare Atkinson, Andreanna Schultz, and Carmen Wu, diligently collected and processed eelgrass samples. Matt Christensen provided regional expertise and contributed to all aspects of the project's execution. Dr. Mary O'Connor provided expert guidance and resourcing through her Lab at UBC to have researchers and citizen scientists collaborate. Semiahmoo Secondary International Baccalaureate® (IB) students, assisted with initial sample processing. Many other undergrads and volunteers participated in several aspects of the project. The City of Surrey was instrumental in supporting this project as a part of its' Coastal Flood Adaptation Strategy. The City's continual support of Friends of Semiahmoo Bay Society has enabled countless opportunities for community environmental education and engagement in project activities.

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CONTENTS

EXECUTIVE SUMMARY

Between April 2018 and September 2019 FOSBS and UBC carried out eelgrass monitoring and a nutrient loading experiment to fill known data gaps on biodiversity within eelgrass beds in Boundary Bay. In part, this project will inform the City of Surrey's Coastal Flood Adaptation Strategy by informing ecosystem risk prioritization in Mud Bay. The productivity of estuaries, such as Mud Bay, will change in response to climate change related patterns of precipitation; precipitation driven runoff may alter ocean temperature, salinity, turbidity, and inputs of terrestrially-derived nutrients washed into the ocean (Harley et al 2006, Scavia et al. 2002).

To identify impacts of nutrient loading on eelgrass beds, an indicator species for estuarine habitat, a field experiment was conducted by UBC researchers and Friends of Semiahmoo Bay Society between April 2018 and September 2019. Nutrient treatments were applied to eelgrass beds and monitored for changes to eelgrass bed structure (physical and biological community). The objectives of this experiment are to: a) Set a baseline ecosystem status of Mud Bay eelgrass beds including measures of water quality, primary producer abundance, eelgrass density, macroalgal biomass, and sediment characteristics, b) Determine whether the eelgrass ecosystems in Mud Bay and Crescent Beach are experiencing negative impacts nutrient pollution, and c) Catalyze and inform a discussion on a conservation planning/management framework for climate adaptation in Mud Bay and Boundary Bay.

Field sampling has been completed and sample processing and analysis is still underway. Mud Bay eelgrass beds are suspected to already be subject to reduced flushing from being in an enclosed bay and potentially subject to higher nutrient loading from the Serpentine and Nicomekl Rivers. Mud Bay eelgrass beds have a lower shoot density (shoots/m2) than Crescent Beach eelgrass beds. As well, Crescent Beach eelgrass bed shoot density decreased when nutrients were applied, whereas Mud Bay bed densities remained unaffected by nutrient addition. Mud Bay may already be subject to nutrient loading at a scale where the field experiment concentration applied did not have an effect. Mud Bay has more epifauna diversity but a lower abundance compared to Crescent Beach. Nutrient enriched plots significantly altered percent change in epiphyte loading at Mud Bay between June and August 2018. Increased nutrient loading in Mud Bay and Boundary Bay as a potential result of climate change might alter eelgrass bed structure and community composition, thereby affecting the productivity of the estuary. Further analysis of other sampling parameters will help inform whether a shift in eelgrass beds from nutrient loading is certain and may indicate what types of changes to expect.

STUDY BACKGROUND

As the transition zone between freshwater and marine environments, estuaries are particularly vulnerable to climate change and sea level rise. Estuarine habitats, particularly salt marshes and eelgrass beds provide significant ecosystem services such as nutrient cycling, water filtration, fish habitat and carbon sequestration (Beck et al. 2001; Campbell 2015; Orth et al. 2006). Unfortunately, these habitats have undergone precipitous declines worldwide (Campbell 2015 Crooks et al. 2011).

Figure 1 Map of Boundary Bay with pins at the two study locations. 1) Mud Bay (46.066840, -122.890244) and 2) Crescent Beach (46.044783, -122.894224) eelgrass beds.

Climate change and sea level rise adaptation requires assessment and planning for both infrastructure and ecosystems components. The City of Surrey is leading a project funded by the Federation of Canadian Municipalities to prioritize infrastructure and ecosystem risk in Mud Bay. The City has partnered with Ducks Unlimited Canada (DUC), Friends of Semiahmoo Bay Society (FOSBS), and ecologists at University of British Columbia (UBC), each of which has expertise in the ecological components of Mud Bay. Between April 2018 and September 2019 FOSBS and UBC carried out eelgrass monitoring and experiments to fill known data gaps on biodiversity within eelgrass beds in Boundary Bay as it related to water quality and pollution. Estuarine productivity will change in response to climate change related patterns of precipitation; precipitation driven runoff may alter ocean temperature, salinity, turbidity, and inputs of terrestrially-derived nutrients washed into the ocean (Harley et al 2006, Scavia et al. 2002). The eastern portion of Mud Bay is part of Boundary Bay within the Fraser River Delta, an estuary designated as a wetland of international importance under the Ramsar Convention. The project area is also part of the Boundary Bay Wildlife Management Area (WMA), which provides an important stopover on the extensive Pacific Flyway migration route. There are no comparable sites along the Pacific Coast between California and Alaska. The value and importance of Boundary Bay is also recognized internationally as an Important Bird Area by Bird Life

International, and a site of hemispheric importance by the Western Hemisphere Shorebird Reserve Network.

Considering the renowned importance of the project area and the critical role of eelgrass in estuarine ecosystems, there has been little research on eelgrass in Boundary Bay/Mud Bay. Eelgrass (*Zostera spp.)* provides essential habitat to juvenile salmon, macroalgal and invertebrate resources, and provide the surface area for over 400 species of epiphytic algae, which form the basis of the food web for juvenile salmon and other fish (Phillips 1984). Zostera beds in British Columbia are disproportionately important compared to other habitats because they are "salmon highways" and home to over 80% of commercially important fish and shellfish species (Durance 2012; Wright et al. 2014). In addition, eelgrass helps to stabilize coastlines and buffers coastal communities like those adjacent to Mud Bay from effects of climate change such as increased storm energy and erosion. These habitats may be degraded by a suite of human pressures, including nutrient enrichment from the Nicomekl and Serpentine rivers that are surrounded by agricultural lands and have several drainage ditch outflows that feed into them. However, linking habitat degradation to specific human pressures and corresponding impact to focal species is not simple. A framework of research, monitoring and direct communication with local communities is recommended to inform climate change and sea level rise adaptation planning. Here we use a bottom-up ecological approach, with the goal of linking predictors of Zostera bed health, with a focus on nutrient loading, to impacts on trophic structure and support.

Objectives

- *Set a baseline ecosystem status of Mud Bay eelgrass beds including measures of water quality, primary producer abundance, eelgrass density, macroalgal biomass, and sediment characteristics;*
- *Determine whether the eelgrass ecosystems in Mud Bay and Crescent Beach are experiencing negative impacts of nutrient pollution;*
- *Catalyze and inform a discussion on a conservation planning/management framework for climate adaptation in Mud Bay and Boundary Bay.*

METHODS

Increased macroalgal abundance in seagrass systems can indicate a shift to nutrient-enriched systems. As the macroalgae grows and photosynthesizes, it also respires and ultimately senesces. As the macroalgae increases and then senesces, light to seagrass and epiphytes is attenuated. This can ultimately result in a system dominated by detrital material and sediment with a microalgae film. In this experiment invertebrate samples were collected to detect change in invertebrate community abundance and diversity in response to nutrient enrichment.

Sites

All surveys and experiments occurred in two eelgrass beds in Boundary Bay (Figure 1). The first is in Mud Bay at the outflow of the Nicomekl and Serpentine rivers, predicted to be subject to high disturbance and nutrient load. For comparison an eelgrass beds in Crescent Beach was also selected for monitoring and experimental methods because it is predicted to be a high flow site with lower nutrient loads and potentially less impacted eelgrass beds than Mud Bay.

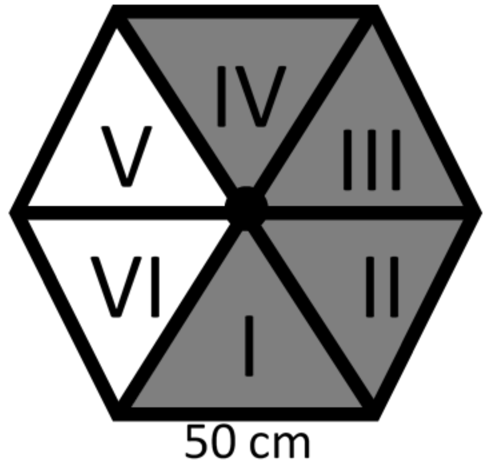

Figure 2 Plot schematic and sampling schedule. June 2018 (I), July 2018 (II), August 2018 (II), September 2018 (IV), Not Completed (V) & (VI). Shaded segments indicate that they were completed.

Experimental design

32 plots were set up across two sites. Nutrient treatments (300-gram bundles of slow release Scott's Osmocote fertilizer) were applied to 8 experimental plots at both Mud Bay and Crescent Beach, for a total of 16 experimental "+N" plots. Plot were staked with 1 piece of rebar in center, down approximately 1.5 m into the sediment. Each plot was sampled 4 times over the course of the experiment using a 50 cm equilateral triangle oriented by compass bearing. Each site had 8 additional ambient plots as "controls", with no nutrient addition. Osmocote or other slow release fertilizer is often used in ecological research to simulate the effect of nutrient enrichment (eutrophication) from human impacts because it releases incremental amounts over time and is localized to within 1 meter before the effect dissipates, resulting in no long term or large-scale impacts (Fong and Zedler 1993). Figure 2 shows a schematic of each plot and describes the sampling schedule; segments V and VI were not completed as originally planned due to a shortage in capacity to collect and process the samples. As well preliminary results from previous sampling periods (I through IV) provided enough information to determine a difference in pre-existing nutrient conditions between the two sites as well as a difference in responses to increase nutrients.

Table 1 Experimental design of plots

Treatment	**Site**	**Replicates**
+Nutrients	Mud Bay	8
Ambient (Control)	Mud Bay	8
+Nutrients	Crescent Beach	8
Ambient (Control)	Crescent Beach	8

Sampling

Throughout summer 2018, sampling was completed for seagrass characteristics, invertebrates and water quality at each site (Mud Bay and Crescent Beach) for each treatment (Ambient, or Control – *no treatment*). This included:

1) Water: A Quatro Yellow Strings Instrument (YSI) was used to measure water for dissolved oxygen, turbidity, pH, temperature, and salinity at each site. Two additional

water samples were collected per site to analyze chlorophyll-a and nutrient concentrations in the water column.

2) Key Biotic indicators: from the triangular area for each sampling period (as shown in Figure 2) we collected all seagrass, algae and invertebrates. This included all above ground biomass/shoots of seagrass, detritus, epiphytes, macroalgae, and invertebrates > 500 µm.
3) Sediment samples from each plot for chlorophyll-a concentration and organic content analysis.
4) Light and temperature was measured at 15 min intervals from May-September using Onset HOBO meters.

Mud Bay was sampled in May, June, and August 2018, with nutrient enrichment treatments placed on June 28, 2018. Crescent Beach was sampled in May, June, July and August 2018 and treatments were placed on June 25, 2018. 1-year post treatment and recovery sampling was not completed in 2019 due resource limitations; the plots were removed and sampling schedule segments V and VI were not completed as shown in Figure 2.

RESULTS

Currently, while the plots have been removed, no more samples will be collected and most sample data has been processed, an in-depth analysis and review is still required. The results here will give the initial findings and suggested directions for more in-depth analyses. The intent is to publish the research in an academic journal before the end of 2020.

Eelgrass Bed Morphometrics

Figure 3 Zostera marina (left) and Zostera japonica (right) in Mud Bay

Nutrient enrichment does not appear to have a significant effect on shoot length, width or Leaf Area Index (LAI) at either Mud Bay or Crescent Beach. Mud Bay eelgrass leaves were longer and wider compared to Crescent Beach throughout summer 2018. Mean LAI was higher in Mud Bay than at Crescent Beach during May and June 2018. Nutrient enriched plots at Crescent Beach had a lower LAI in August after three months of enrichment compared to ambient plots, however this was not significant. Mud Bay had a similar mean LAI at both ambient and nutrient enriched plots by summer's end, however ambient plots had more variability. *Zostera marina* (shown in Figure 3) shoot density (Shoots/m^2) at Crescent Beach (>300 shoots/m^2) was higher than that of Mud Bay (~200 shoots/m^2) in May 2018, prior to starting the field experiment, but it was not significant. At Mud Bay there was no difference between shoot density in nutrient enriched (+Nutrients) and control (Ambient) plots throughout the duration of the experiment. At Crescent Beach shoot density increased from June (initial) to July (1 Month) 2018 in ambient plots but decreased in plots that were nutrient enriched; this trend continued into August 2018 (Figure 4). Since the shoot density for Crescent Beach at both ambient and nutrient enriched plots were the same for May, June and July, only the August values were analyzed using a one-factor t-test. Nutrient enriched plots at Crescent Beach had a significantly lower shoot density after three months (Table 2). This relationship was not exhibited in Mud Bay.

$Mean_a - Mean_b$	t	df	P		
				one-tailed	0.0068165
-102	-2.82	14		two-tailed	0.013633

Table 2 one factor t-test of Crescent Beach Shoot Density in August

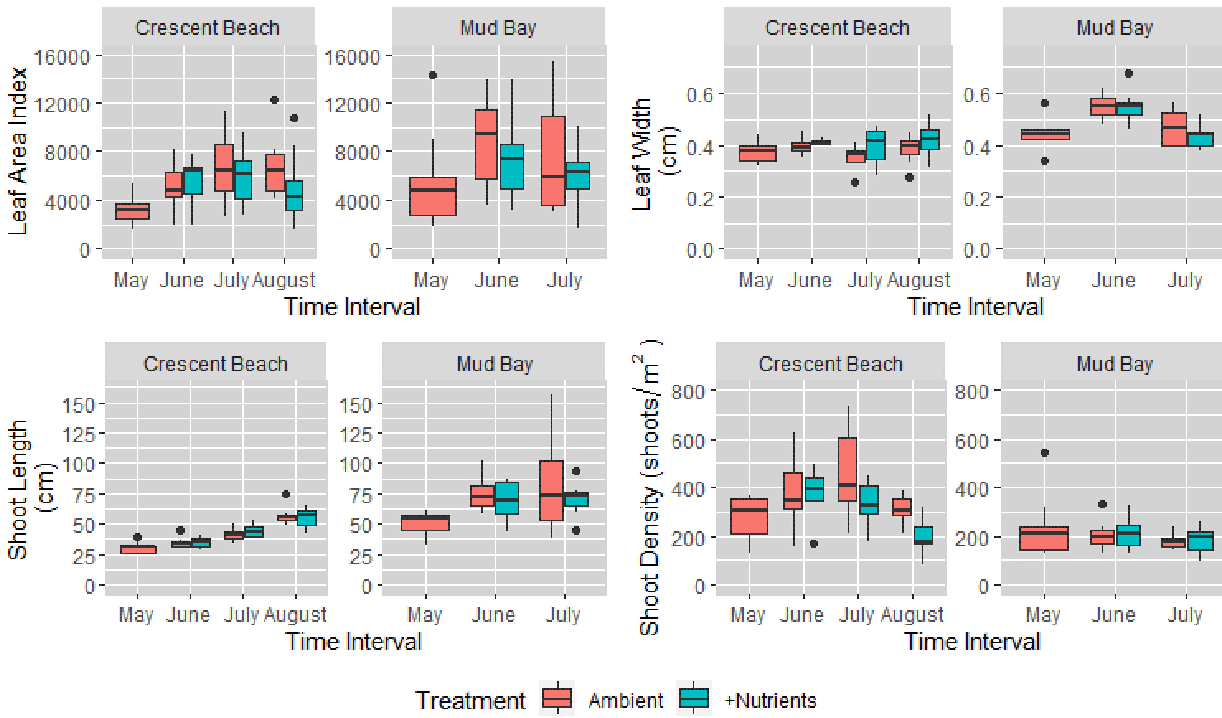

Figure 4 Leaf Area Index (LAI), Shoot Length (cm), Leaf Width (cm) and Shoot Density at Crescent Beach and Mud Bay for both ambient and nutrient enriched plots in 2018

Macroalgae

There was an increase in macroalgal biomass (g m-2) over time, however the effect of nutrient enrichment was not significant at either site (Figure 5). Further analysis is required as a sum of all macroalgal biomass may not be best indicator for the effects of nutrient enrichment to overall macroalgal abundance (i.e. Species morphology may be an

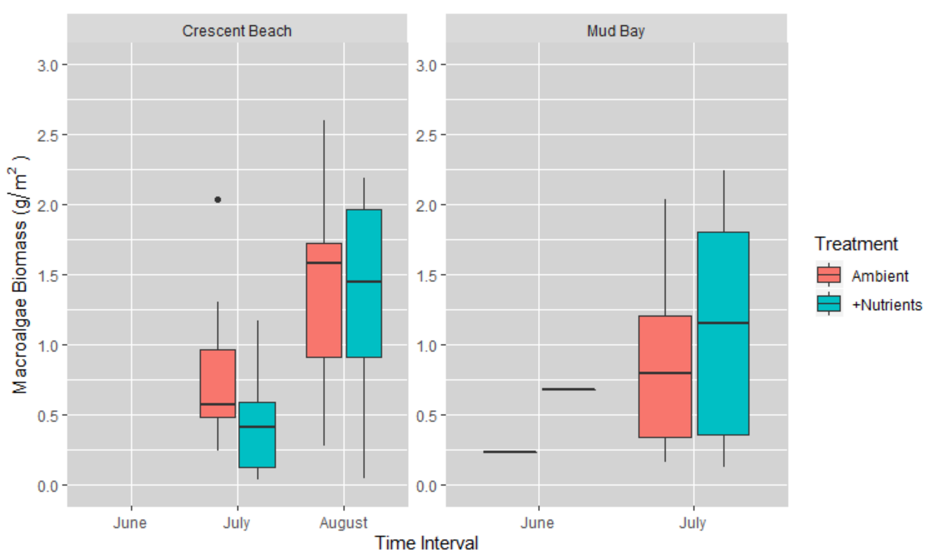

Figure 5 Macroalgal biomass over time for Crescent Beach (left) and Mud Bay (right).

influencing factor). The average number of macroalgal species found in each plot, increased from 0-1 species to 2- 3 species on average for both sites.

Detritus

As with shoot density, the amount of detritus (g m-2) in each plot was 2-3 times greater at Crescent Beach than Mud Bay. Detritus includes unattached, senescing eelgrass and since shoot density is higher at Crescent Beach so is the amount of detritus. At Crescent Beach, detritus increased from June to July (Figure 6). Nutrient enrichment at Crescent Beach had significantly higher detritus than both nutrient enriched and ambient Mud Bay sites. On average, nutrient enriched plots also had more detrital material in July at Mud Bay, but this was not a significant effect.

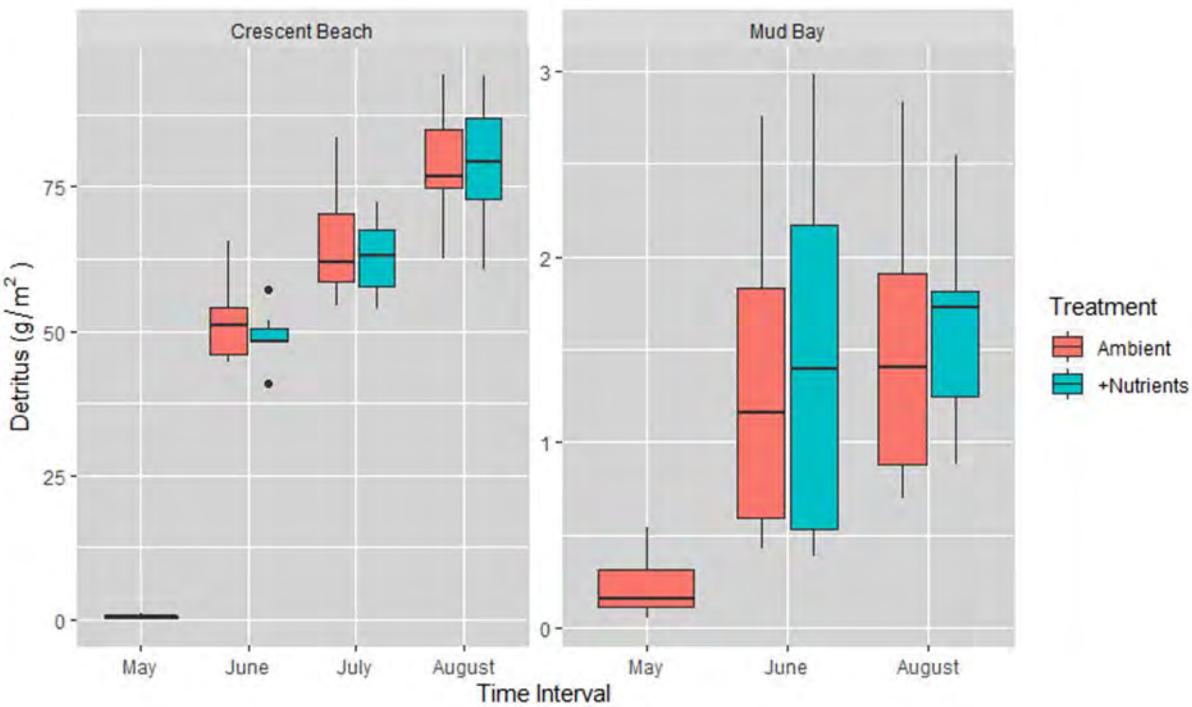

Figure 6 Detrital abundance measured as grams per m2 in each plot at Crescent Beach (L) and Mud Bay (R).

Epiphytes

Epiphyte load was measured as milligrams of Chl a per gram of seagrass biomass. Samples were collected in June, July and August. Nutrient enriched plots in Mud Bay had some evidence of increased epiphyte loading in Mud Bay by August. Crescent Beach had a significant decline in epiphyte load at both ambient and nutrient enriched plots in August compared to June and July sampling periods.

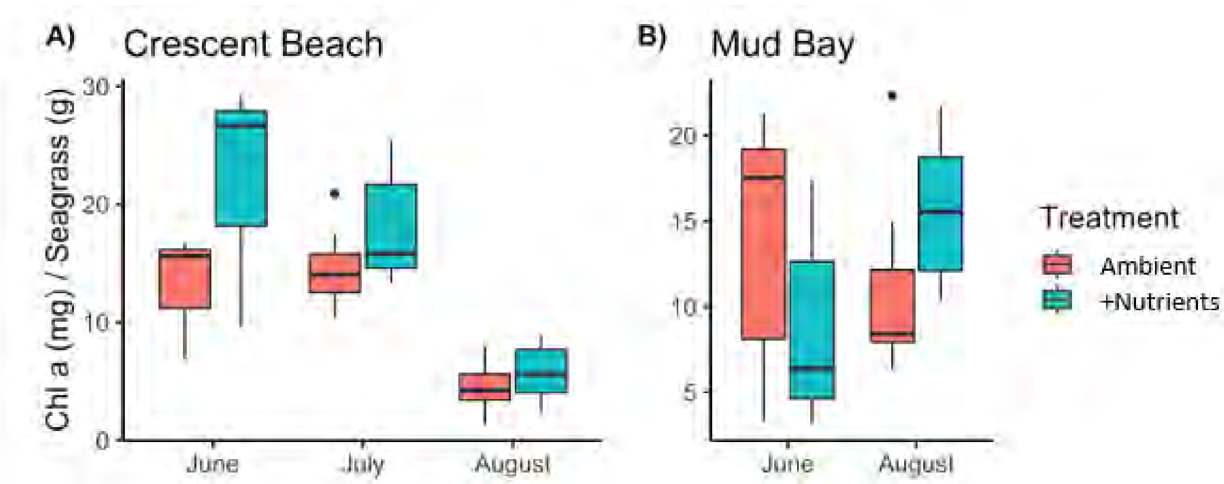

Figure 7 Epiphyte load measured as mg per g of seagrass and Crescent Beach and Mud Bay through the duration of the experiment.

Chlorophyll a

Water Column

The mean total chlorophyll (mg/300 mL) in the water column showed a significant change over time (F=5.1443, P=0.01665), however there was no difference between sites (F=1.2129, 0.34167). A third location that was also in Mud Bay was sampled in June 2018 as well. A peak in mean total chlorophyll is apparent in June 2018 (**Error! Reference source not found.**).

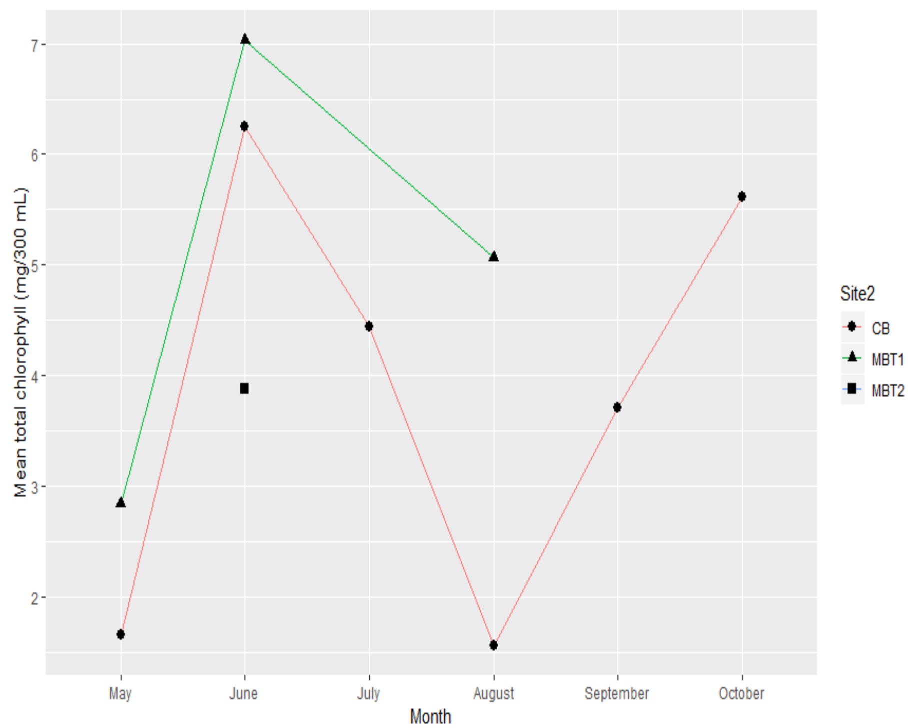

Figure 8 Mean total chlorophyll a in water column (mg/300 mL) over time at Crescent Beach and Mud Bay

Sediment (Microphytobenthos)

There was no significant change to chlorophyll a detected in sediment samples as a result of nutrient enrichment. There was also no significant difference in percent change of chlorophyll a between sites. The relationship between Chlorophyll-a concentration in the sediment and the water column had no significance between sites and treatments. Percent nitrogen and phosphorus in plant tissues is often used as a more reliable measure of nutrient loading into an estuary as nutrients are taken up by the plants from the water column. Therefore, water column measures are not a good indicator of total nitrogen or phosphorus loading. Nitrogen fixation assays can be completed as seagrass rhizomes are often associated with nitrogen fixing bacteria and nitrogen fixation may kick into high gear during the peak seagrass growing season. This may be why sediment chlorophyll was not variable across nutrient levels in this experiment.

Epifauna

Crescent Beach (n= 1707 (+/- 182 SEM)) has twice the number of invertebrates compared to Mud Bay (n= 785 (+/- 183 SEM)). Mud Bay has a greater diversity of species (54) compared to Crescent Beach (37).

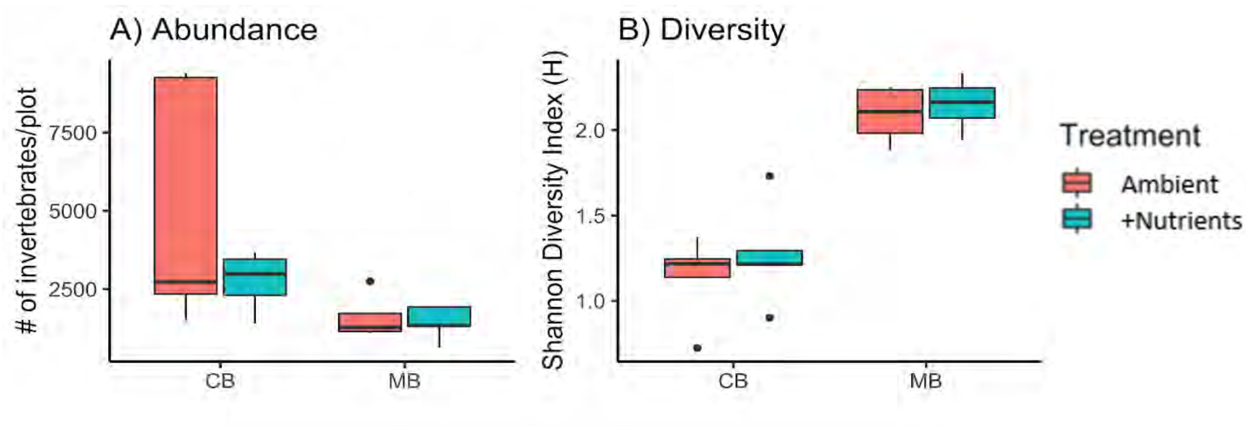

Figure 9 Comparison of abundance and diversity index for Crescent Beach and Mud Bay in June 2018

Table 3 All species of epifauna found in invertebrate samples analyzed for both Mud Bay and Crescent Beach

Alia_A	*Halacaroidea*	*Pentidotea wosnesenskii<ca>*
Alvania compacta	*Haminoea_A*	*Photis brevipes*
Alvania_A	*Harpacticoida<ca>*	*Phyllaplysia taylori<ca>*
Ampithoe lacertosa	*Ischyroceridae_A*	*Phyllodocidae_A*
Ampithoidae _A	*Lacuna*	*Phyllodocidae_B*
Anoplodactylus_A	*Leptochelia_A*	*Platynereis_A*
Aoridae_A	*Lottia alveus*	*Pontogeneia inermis*
Brachyura	*Lottia.alveus*	*Porcellidium_A*
Caprella	*Lottiidae_A*	*Nematoda*
Caprella laeviuscula<ca>	*Lottiidae_B*	*Nereididae_A*
Cardiidae_A	*Macoma_A*	*Nudibranchia_A*
Chironomidae_A	*Macoma_B*	*Nudibranchia_B*
Ciliatocardium ciliatum<ca>	*Maldanidae_A*	*Ostracoda_A*
Cirripedia spp.	*Mytilidae_A*	*Serpulidae*
Corophiidae spp.	*Mytilidae_A*	*Syllidae_A*
Cumace spp.	*Mytilidae_B*	*Tellinidae_A*
Cyclopoida<ca>	*Mytilidae_C*	*Tritia obsoleta*
Eulalia	*Paguroidea_A*	+ 13 unique unknown spp.
Foraminifera<ca>	*Pentidotea _A*	Eggs (5 different types)

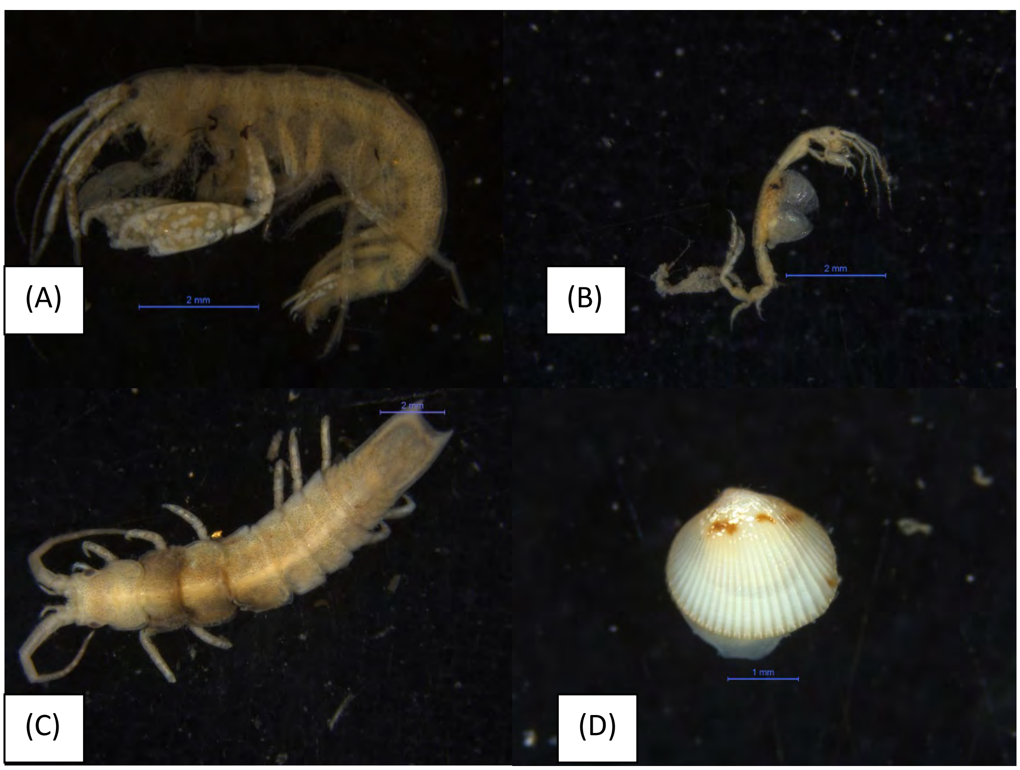

Figure 130. Epifauna found in invertebrate samples from Mud Bay and Crescent Beach study plots. All are < 1 mm in size. (A) Amphithoe lacertosa (B) Caprella laeviuscula (C) Pentidota resecata (D) Ciliatocardium ciliatum. Photo Credit: Felipe Amadeo

Preliminary results indicate that Mud Bay and Crescent Beach eelgrass epifauna communities differ in diversity and abundance, and both are subject to change throughout the season regardless of nutrient enrichment. Non-metric multidimensional scaling (NMDS) analysis has been started to compare differences in epifaunal communities against site, month and treatment factors There is some evidence of different epifaunal communities by August as a result of nutrient addition. This will be explored in more detail in the next iteration of analyses.

DISCUSSION

- Increased nutrient loading in Mud Bay and Boundary Bay as a potential result of climate change might alter eelgrass bed structure and community composition, thereby affecting the estuary productivity. Shift in eelgrass structure, whether it be its biotic community or its physical structure, can have cascading effects on the trophic food web. Smaller fish feed on microorganisms found in eelgrass. Some microorganisms regulate nutrients, carbon dioxide and oxygen in the system.
- The community structure (abundance and diversity) of epifauna differs between Mud Bay and Crescent Beach despite a small spatial difference between the two sites. As well the epifauna community shifts across time. Given this, decisions on location and timing of management actions matter.
- Crescent Beach eelgrass bed shoot density decreased when nutrients were applied, whereas Mud Bay bed densities remained relatively unaffected. Mud Bay may already be subject to nutrient loading at a scale where the field experiment concentration applied did not have an effect. There were no significant trends on other morphometrics. In general, nutrient enriched plots had reduced variability in leaf width and shoot length compared to ambient plots at Mud Bay. Crescent Beach nutrient enriched plots had some evidence of increased leaf width compared to ambient plots at the same site. Shoot length at both nutrient enriched and ambient plots at Crescent Beach was comparable. Nutrient enriched plots at Crescent Beach had some evidence of decline compared to ambient plots at the same site while Mud Bay nutrient enriched plots had less variability compared to ambient plots. It is hard to determine how increased nutrient loading will affect eelgrass morphometrics and what the drivers are with these results but the data warrants further investigation. A longer nutrient enrichment period and sampling period would inform what the responses of eelgrass morphology would be to nutrient loading.
- Further analysis is required to determine whether environmental characteristics such as nutrient status, light, temperature are significant contributing factors to the differences in eelgrass beds between Mud Bay and Crescent Beach.

Next steps

1. There is some evidence of a high nutrient environment at Mud Bay. CHN and stable isotopes will help determine if these are natural or anthropogenic levels. Sediment and seagrass samples were collected in June 2019 for stable Isotope analysis. Approximately

$5000 dollars will cover the cost of lab analyses and give preliminary indications on the nutrient sources for the area.

2. Tissue analysis of seagrass and macroalgae (% N and P by biomass) should be collected and analyzed to establish a baseline of levels of N and P in the system currently.
3. Further research and understanding is required for invertebrate community structure and dynamics including natural trends over space and time and impacts of stressors.
4. LAI is supposed to reflect changes in available seagrass habitat and thus diversity and abundance of species. This should be verified with Mud Bay and Crescent Beach invertebrate data and seagrass measurements collected during summer 2018. Validate with invert data.

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Chapter 4

Summary of Wind Monitoring Component to Date

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northwest hydraulic consultants ltd

NHC Ref. No. 3004163

28 November 2019

CITY OF SURREY
Engineering Department, Utilities Division – Drainage
13450 104th Avenue, Surrey, BC
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Attention: **Arvinder Heer**
Engineering Assistant
Via email: aheer@surrey.ca

Copy to: **Matt Osler, P.Eng., MBA**
Sr. Project Engineer

Re: **City of Surrey OceanMet Monitoring Program**
Summary of Wind Monitoring Component to Date
November 2019

Dear Mr. Heer

Northwest Hydraulic Consultants (NHC) has been working with the City of Surrey (the City) since September 2018 to develop their OceanMet monitoring program. Key components of this program include monitoring waves offshore and nearshore, and wind offshore, nearshore, and onshore in the Boundary Bay and Mud Bay area. This letter summarizes work completed for the wind monitoring component of this program to date, reviews wind data collected to date, provides an overview of planned wind monitoring work, and makes recommendations for future wind monitoring.

1 INTRODUCTION

NHC was retained by the City in September 2018 to support the development of their OceanMet monitoring program. Originally, the City requested NHC install real-time wind monitoring stations on Border Marker F and Wickson Pier, upgrade an existing weather monitoring station at Beecher Place, and install an archiving wave monitoring station that would be relocated annually to fixed piles throughout Mud Bay. Following discussions with the City that helped refine the goals of the OceanMet monitoring program, several enhancements to the program were requested by the City. Enhancements include improved locations for wind monitoring stations, installation of two permanent wave monitoring stations, and long-term sensor comparisons for both wind and wave monitoring equipment. NHC understands the City would like to use wind monitoring data to understand and model spatially varying wind fields in the Boundary Bay and Mud Bay areas. Modelled wind fields will support improved wave modelling to establish future dike construction elevations and corresponding flood construction levels that consider climate change impacts.

2 WIND MONITORING PROGRAM DEVELOPMENT

NHC has worked with the City to develop a wind monitoring program that meets the OceanMet monitoring goals. As part of this work, NHC investigated several possible wind monitoring locations and instrumentation options, and selected a configuration that best suits the City's needs. A summary of options considered, the recommended program, as well as the current configuration is provided in the sub-sections below.

2.1 Location Selection

Figure 2-1 shows the locations investigated by NHC for possible wind sensor installation.

Figure 2-1 All locations considered for possible wind monitoring stations.

The following locations were selected for incorporation into the City's OceanMet monitoring program:

- **Crescent Beach Starboard Channel Marker**
  The Crescent Beach Starboard Channel Marker was selected for monitoring offshore winds as it is located entirely in Canadian waters and has a support platform large enough to accommodate wind monitoring equipment. Additionally, this location could accommodate real-time wave monitoring equipment. The Crescent Beach Starboard Channel Marker is made of a single steel vertical pile that supports a galvanized steel personnel platform, which carries a Starboard Day beacon and Red Light for channel marking, operated by the Canadian Coast Guard (CCG). This site experiences a significant bird presence, which limits suitable wind monitoring sensors, and it

will be important to ensure that wind sensor equipment is located such that it does not impact the navigational purpose of the lights on the tower.

- **Crescent Channel Starboard Channel Marker**
  The Crescent Channel Starboard Channel Marker was selected for monitoring nearshore winds as it has a reasonably sized personnel platform and is ideally situated in the area of interest to monitor the growth of waves which propagate into the Mud Bay area with no local obstructions. Additionally, this location could accommodate real-time wave monitoring equipment. The Crescent Channel Starboard Channel Marker is a vertical pile supported by two additional angled piles. The pile supports an irregularly shaped personnel platform, a channel marker light, and a starboard day beacon operated by the CCG. The marker light is powered by a separate solar panel, and a battery box is mounted on the decking. This site experiences a significant bird presence, which limits suitable wind monitoring sensors, and it will be important to ensure that wind sensor equipment is located such that it does not impact the navigational purpose of the lights on the tower.

- **Colebrook Road Pump House**
  The Colebrook Road Pump House was selected for monitoring onshore winds as its location is in line with selected nearshore and offshore wind monitoring stations and there are minimal trees or sheltering influences nearby. The Pump House is scheduled for upgrades in the next few years and NHC reviewed proposed plans for the upgrade to ensure a wind monitoring station will be compatible with both the current and upgraded Pump House configuration.

The following locations were inspected by NHC, but rejected for incorporation into the City's OceanMet monitoring program:

- **Border Marker 'E'**
  Border marker 'E' is used be the City of Delta for water elevation monitoring. NHC investigated this site only as a reference for how the City of Delta has set up their monitoring station.

- **Border Marker 'F'**
  Border marker 'F' was rejected for wind and wave monitoring due to its location along the Canadian-USA border requiring additional permitting for installation and future maintenance work . Also, the intense commercial crabbing in the area could interfere with wave monitoring equipment.

- **White Rock Breakwater**
  The White Rock Breakwater was rejected for wind monitoring as it is located some distance away from the area of interest for growth of waves that propagate into the Mud Bay area. Also, there is a large amount of pedestrian traffic and thus a higher risk of interference, vandalism, or equipment theft.

- **Wickson Pier**
  Wickson Pier was rejected for wind monitoring as it is a non-secure, nearshore structure, with known public interaction and thus a higher risk of interference, vandalism, or equipment theft.

- **Sullivan Point**
  Sullivan Point park was rejected for wind monitoring as it would require a tower installation in a

park space. Special efforts would be required to make the construction non-climbable or to provide a security fence to prevent interference, vandalism, or theft. Also, it is expected there would be general public disapproval of the structure as it would impact ocean views.

- **Beecher Place**
  Beecher Place was not selected for wind monitoring due to mechanical turbulence from the surrounding trees and buildings. The existing weather monitoring equipment at this location was inspected and identified as a Rainwise Inc. Mk III weather monitoring station. This station incorporates a mechanical combined propeller and vane wind sensor, a temperature sensor, tipping-bucket rain gauge, a 418 MHz radio transmitter, a solar charger, and a battery. The battery was dead at the time of inspection and the tipping bucket funnel was plugged with dirt and algae (subsequently cleaned by NHC). The reed switch on the tipping bucket was checked and appeared to be functioning. The propeller and vane wind sensor spun freely, but the output was not checked as there was no clear pinout on the circuit board. No corresponding radio telemetry receiver was found anywhere on the premises. NHC contacted Rainwise Inc., who suggested replacement of the system rather than refurbishing or replacing any component of the unit. This location may be useful as a backup for onshore wind monitoring, however the station would need significant upgrades in order to collect high quality data, including raising the wind sensor several meters to reduce the effects of mechanical turbulence.

2.2 Instrumentation Selection

Following selection of the recommended wind monitoring locations, appropriate sensors for each location were chosen. Both mechanical and solid state wind sensor were considered, including cup, propeller-vane, and ultrasonic styles. Since two of the recommended monitoring locations are heavily used by birds, instruments that require cross arms were rejected as they would encourage perching.

Mechanical wind sensors have been in use for many years and are a proven technology with a reasonable service life. NHC recommends a combined propeller and vane style sensor over a cup anemometer. The combined propeller and vane style sensors may have a slightly slower response to gusts of changing wind direction than other sensor types as the entire sensor must align itself with the wind to read appropriately. However, the units are robust and likely to outlast individual cup anemometers and wind direction sensors. NHC recommended the RM Young – Heavy Duty Wind Monitor (Model 05108) for wind velocity and direction with a digital (SDI-12) interface. These sensors are used on many offshore buoys.

Ultrasonic solid-state sensors have no moving parts, which is appealing from a maintenance perspective, and these sensors respond very quickly to gusts and changes in wind direction. Additionally, some models have closed tops, which prevents bird droppings, feathers, and fish debris from accumulating on the sensing surface. These sensors do not require maintenance apart from cleaning, however, when they fail, they tend to fail completely, requiring removal and servicing or replacement by the manufacturer rather than simple repairs. As the sensor is stationary, bird spikes, or other means of deterring birds from using the top as a perch would be required for locations with significant bird presence. Ultrasonic sensors are relatively new technology. NHC recommended a long term comparison between the ultrasonic and mechanical sensors, and this comparison is now being implemented at the Colebrook Road Pump House Onshore Wind Monitoring Station. If the ultrasonic sensors prove accurate and reliable over time, then installation at other locations may be recommended.

2.3 Current Wind Monitoring Program Configuration

The City, supported by NHC, has initiated permitting with the CCG for installing wind and wave monitoring equipment on the Crescent Beach Starboard Channel Marker and Crescent Channel Starboard Channel Marker. Following extensive correspondence, the CCG has requested a detailed design of all proposed station components to demonstrate the additional loads they will put on the existing structures and a review of steps to limit the impact new equipment will have on the environment (25 October 2019). NHC is working with the City to develop these detailed designs and anticipates assisting with installation and maintenance of these stations once permitting is obtained.

Following selection of the Colebrook Road Pump House for onshore wind monitoring, the City initiated a discussion with BC Hydro to evaluate the feasibility of installing an anemometer on one of two hydro poles located nearby. NHC reviewed sensor mounting options with BC Hydro and they determined installation on the hydro poles was not possible.

A 10 metre high tilt-up lattice tower was installed on the Colebrook Road Pump House flood box structure, adjacent to the existing pump house building, on 30 August 2019. The tower base is bolted into the concrete deck of the flood box with 3 guy wires anchored to the flood box deck and the abutting ground. The tower supports both a mechanical RM Young Marine Wind Monitor sensor and an ultrasonic Gill WindSonic sensor. The tower also supports a radio antenna, for future connection with nearshore and offshore monitoring stations, and a cellular antenna to transmit data in real-time to the City's and NHC collection platforms. A kiosk enclosure is fastened to the flood box deck near the tower, which houses a datalogger with cellular and radio modems, solar charge controller, and battery bank. A solar panel is mounted to a short mast next to the kiosk enclosure. Photo 2-1 shows the Colebrook Road Pump House Onshore Wind Monitoring Station.

The Colebrook Road Pump House is scheduled for upgrades in the next few years. NHC has reviewed proposed plans for the upgrade to ensure the current monitoring configuration is compatible with both the existing and upgraded pump house. NHC understands the flood box structure will remain throughout the upgrade works, but has installed a tower and enclosure that are versatile and easily transferred to a different mounting location if required.

Following initiation of real-time data feeds from the Colebrook Road Pump House Onshore Wind Monitoring Station, NHC has set up e-mail notifications for wind conditions of interest to the City. Specifically, high winds (9 m/s average speed over 2-minutes) from the south or south-west (between 180-280 degrees from true north) will result in an email sent to key personnel at the City to assist with evaluating developing and occurring storms in order to inform response planning. The parameters triggering this notification can be adjusted as additional data are collected and the threshold of interest is refined.

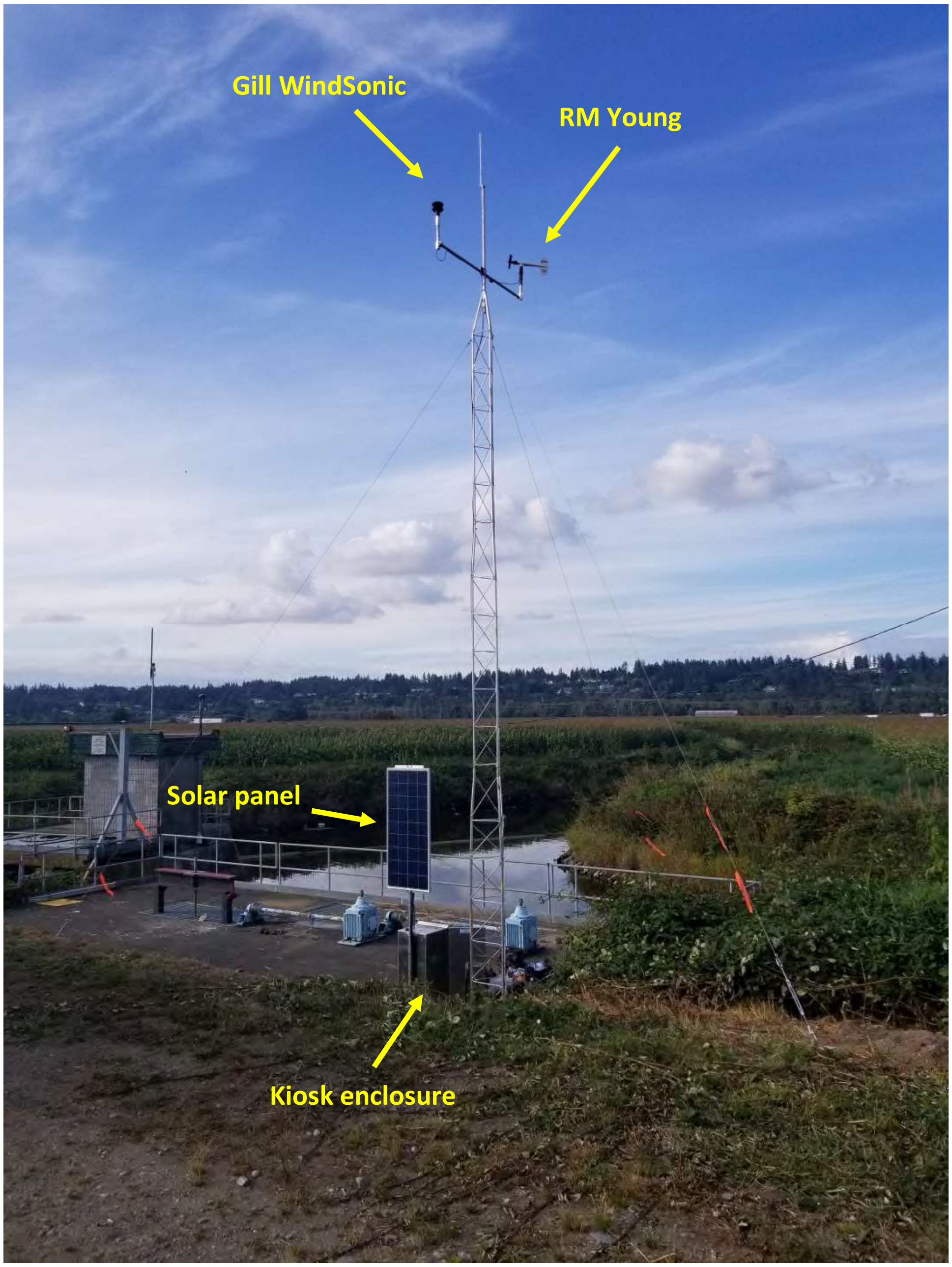


Photo 2-1 Configuration of the Colebrook Road Pump House Onshore Wind Monitoring Station at the time of installation on 30 August 2019.

3 DATA ASSESSMENT

NHC understands the City will use wind monitoring data to better understand and model spatial varying wind fields in the Boundary Bay and Mud Bay areas as the City's OceanMet monitoring program develops. Data currently available for assessment are limited. NHC expects future analysis of wind data will involve statistical assessments of wind speed and direction at each of the City's monitoring stations, as well as an investigation of local wind variability based on wind profiles collected regularly at and near each of the City's monitoring stations. Comparisons and/or correlations with data from other proximate monitoring stations operated by other agencies will likely also be relevant to understanding and modeling wind fields in the area of interest. NHC has performed preliminary assessments using the data currently available. While these assessments will need to be updated as additional data are collected, they are useful as part of initial quality assurance and quality control (QA/QC) of the Colebrook Road Pump House Onshore Wind Monitoring Station data, as well as to explore which methods will likely prove most useful during future analysis.

The City is also interested in comparing ultrasonic and mechanical wind sensor data. This comparison will be used to confirm data from ultrasonic sensors are reliable and accurate. NHC expects qualitative investigations of overlapping time series data from adjacent ultrasonic and mechanical sensors, as well as quantitative correlation analysis including regressions of wind speed and direction, will demonstrate ultrasonic sensor performance.

The following subsections summarize the data currently available from the City's OceanMet monitoring program, and presents a preliminary analysis of the wind data.

3.1 Summary of Wind Data Collected to Date

The Colebrook Road Pump House Onshore Wind Monitoring Station is currently the only active station in the City's OceanMet monitoring program. The station was installed on 30 August 2019. Preliminary assessments were completed in November 2019 based on a two month data period from 1 September to 31 October 2019. The station includes both an RM Young mechanical and Gill WindSonic ultrasonic wind sensor. Each sensor samples wind speed and direction every 3 seconds and records the following parameters:

- 2-minute average wind speed
- 2-minute average wind direction
- 2-minute maximum (gust) wind speed
- Time of 2-minute maximum (gust) wind speed
- 10-minute average wind speed
- 10-minute average wind direction
- 10-minute maximum (gust) wind speed
- Time of 10-minute maximum (gust) wind speed
- Direction of 10-minute maximum (gust) wind speed

Table 3.1 provides a summary of data currently available from each of the Colebrook Road Pump House Onshore Wind Monitoring Station wind sensors. Wiring issues prevented the RM Young sensor from collecting wind direction data when it was first installed. The sensor was removed for testing on 4 October and re-installed on 15 October 2019, resulting in 11 days of missing wind speed data and 44 days of missing wind direction data during the 1 September to 31 October preliminary assessment period. Preliminary data QA/QC showed the Gill WindSonic sensor has been periodically reporting anomalously high wind speed and direction values (e.g. >50 m/s). These values have been removed during preliminary data QA/QC and replaced with interpolated values based on data from before and after each instance. Both sensors have also periodically recorded prolonged unchanging wind direction data. These sections of unchanging direction data are not concurrent between sensors and are not associated with calm wind conditions, suggesting they are erroneous and may indicate sensor malfunction. The unchanging direction data will be removed from the record during subsequent data QA/QC, but have been included for the preliminary analysis to demonstrate how they affect results and how similar analysis can be used to identify similar anomalies during future data QA/QC. NHC is working with sensor manufacturers to identify the cause of the anomalous wind speed and unchanging direction values.

Table 3.1 Summary of available Colebrook Road Pump House Onshore Wind Monitoring Station wind speed and direction data.

Sensor	Parameter	Start Date	End Date	Missing Periods
RM Young	Wind speed	2019-Aug-30	2019-Oct-31	2019-Oct-04 to 2019-Oct-15
RM Young	Wind direction	2019-Aug-30	2019-Oct-31	2019-Aug-30 to 2019 Oct-15
Gill WindSonic	Wind speed	2019-Aug-30	2019-Oct-31	none
Gill WindSonic	Wind direction	2019-Aug-30	2019-Oct-31	none

3.2 Comparison of Mechanical and Ultrasonic Sensors

A preliminary analysis of available data from the Gill WindSonic ultrasonic and RM Young mechanical wind sensors installed at the Colebrook Road Pump House Onshore Wind Monitoring Station included a visual comparison of overlapped time series data, as well as a regression analysis. The preliminary analysis used the 2-minute average of 3 second sampled wind speed and direction values from 1 September to 31 October 2019. As additional data are collected, the analysis should be updated to include longer data records as well as 10-minute average and 2-minute and 10-minute maximum (gust) data. Results from the extended analysis may be used to quantify the reliability and accuracy of ultrasonic vs mechanical sensors.

Figure 3-1 shows wind speed data from the RM Young mechanical sensor and Gill WindSonic ultrasonic sensor installed at the Colebrook Road Pump House Onshore Wind Monitoring station. The series were inspected visually on a sub-daily time-step using Aquatic Informatics Aquarius Time Series software and track each other well, with changes in wind speed showing similar magnitudes and timing. However, the

Gill WindSonic wind speed values are consistently higher than the RM Young wind speed values. Figure 3-2 shows a regression between the preliminary wind speed data from each sensor. The regression confirms a strong correlation, with the Gill WindSonic wind speed data consistently higher than the RM Young data throughout the range of observed speeds. As additional data are collected, over a larger range of wind speeds, a more thorough correlation analysis should be completed. Also a similar analysis should be conducted for the maximum (gust) wind speed data. If a continued discrepancy is noted between the sensors, comparison with a third independently calibrated sensor or factory recalibration will be recommended.

Figure 3-3 shows wind direction data from the RM Young mechanical sensor and Gill WindSonic ultrasonic sensor installed at the Colebrook Road Pump House Onshore Wind Monitoring station. Wiring issues prevented the RM Young sensor from collecting wind direction data until 15 October 2019, limiting data available for comparison during the 1 September to 31 October 2019 preliminary assessment period. The overlapped wind direction series were inspected visually on a sub-daily time-step, however visual inspection of wind direction data is complicated when wind direction transitions between 360 and 1 degrees. Overall the series appear to track each other well, however the Gill WindSonic wind direction values are consistently lower than the RM Young wind direction values, except when wind direction transitions between 360 and 1 degrees. The difference suggests one of the sensor mounts may need adjusting to better align with true North.

Figure 3-4 shows a preliminary regression between the wind direction data from the RM Young mechanical sensor and Gill WindSonic ultrasonic sensor installed at the Colebrook Road Pump House Onshore Wind Monitoring station. The regression confirms the Gill WindSonic direction data is consistently lower than the RM Young data except when wind direction transitions between 360 and 1 degrees. Future correlation analysis will need to account for the effects of this transition. The regression also shows the effect of the sections of unchanging direction data identified during preliminary QA/QC of the data. Future regressions can be used to statistically identify any sections of unchanging direction data missed during initial data QA/QC. As additional data are collected, a more thorough correlation analysis should be completed, including a similar analysis for the direction of the 10-minute maximum (gust) wind speed data. The effect of using 10-minute or hourly averaged data should also be analyzed.

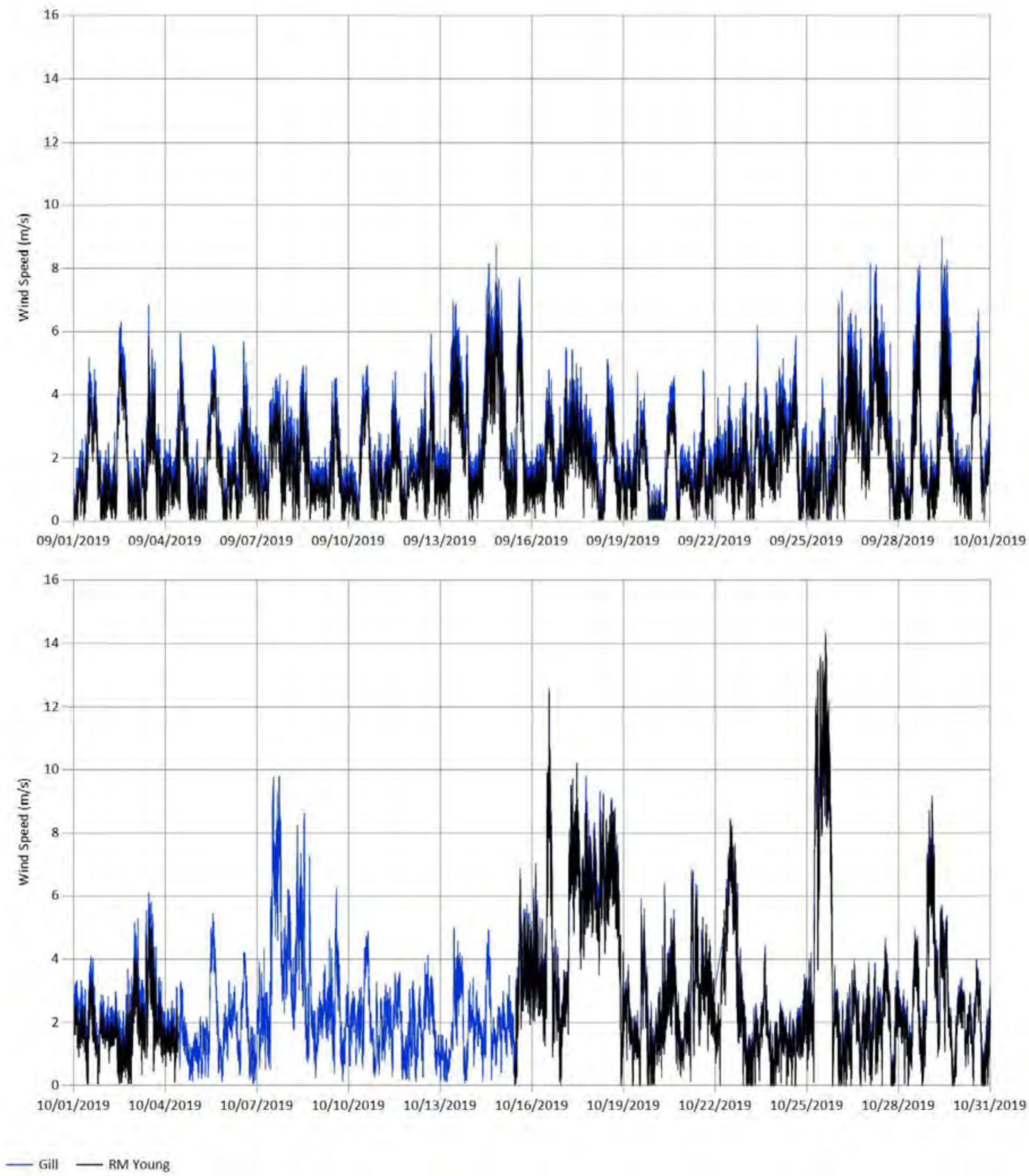


Figure 3-1 Wind speed data during the 1 September to 31 October 2019 preliminary assessment period from the RM Young mechanical and Gill WindSonic ultrasonic wind sensors installed at the Colebrook Road Pump House Onshore Wind Monitoring Station. Data are 2-minute average values based on 3 second samples.

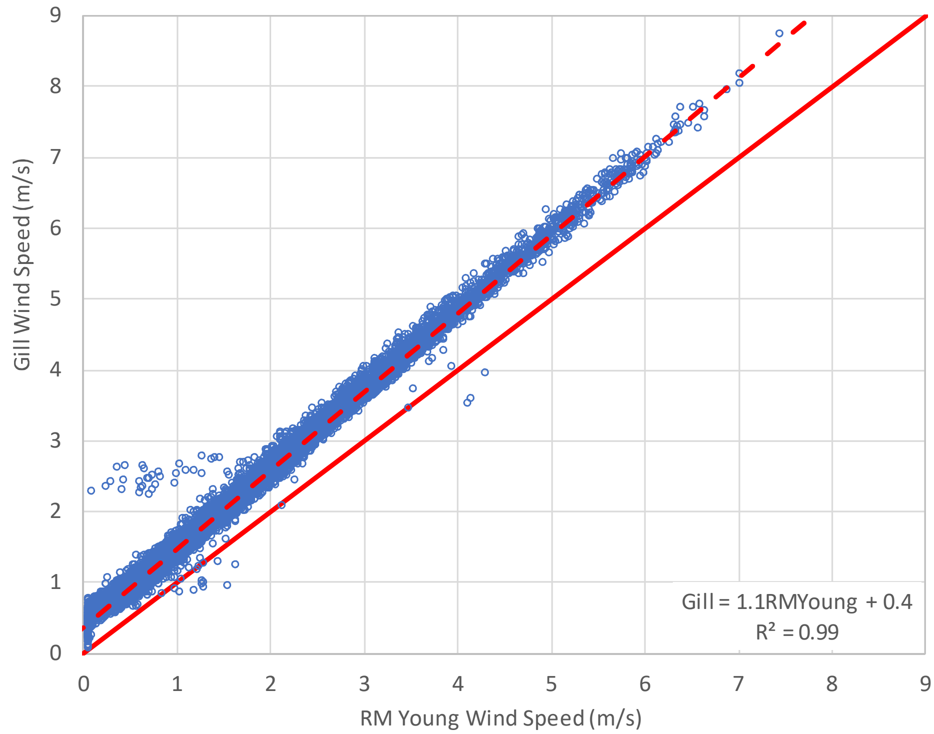


Figure 3-2 Comparison of wind speed data during the 1 September to 31 October 2019 preliminary assessment period from the RM Young mechanical and Gill WindSonic ultrasonic wind sensors installed at the Colebrook Road Pump House Onshore Wind Monitoring Station. Data are 2-minute average values based on 3 second samples.

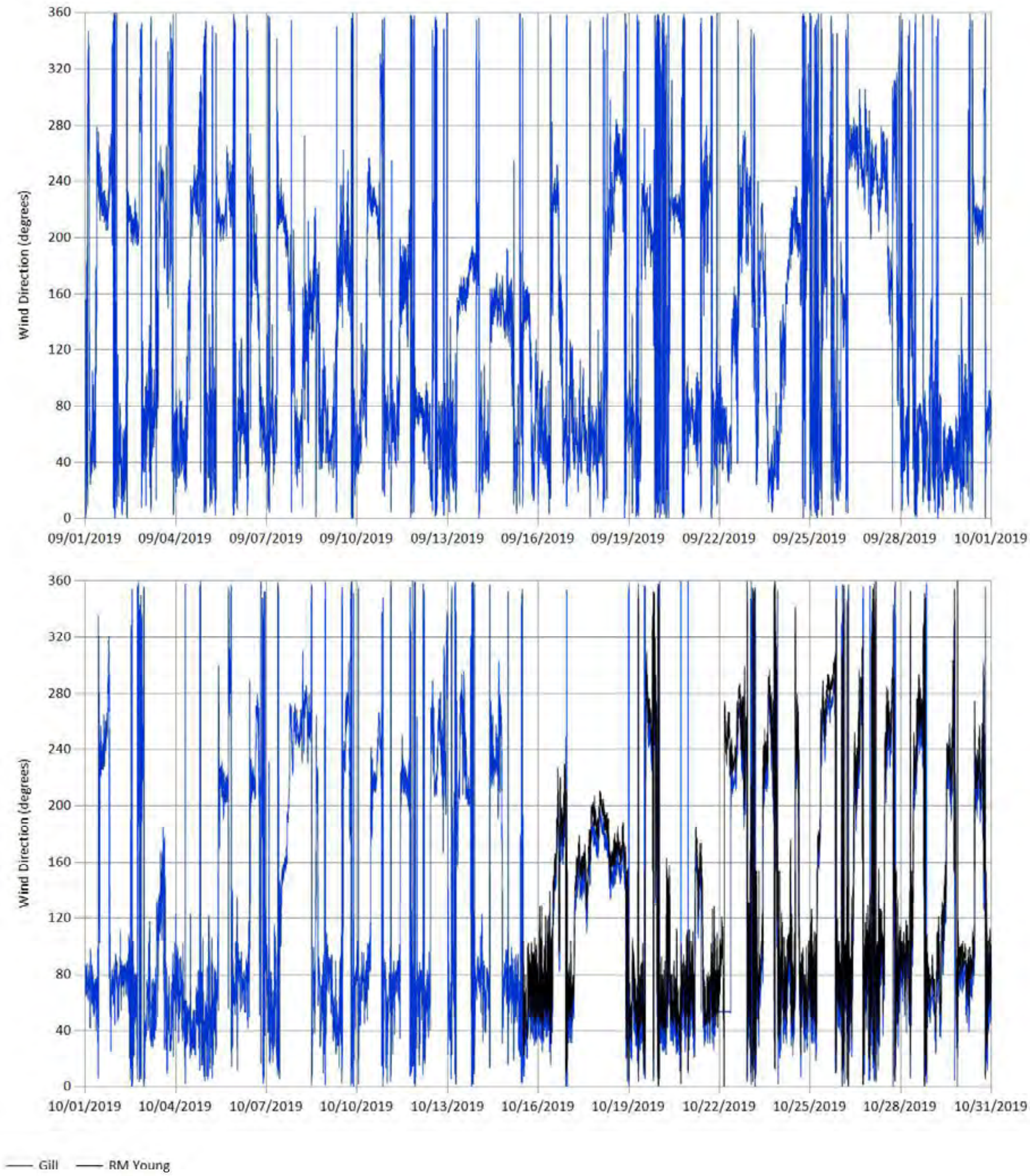


Figure 3-3 Wind direction data during the 1 September to 31 October 2019 preliminary assessment period from the RM Young mechanical and Gill WindSonic ultrasonic wind sensors installed at the Colebrook Road Pump House Onshore Wind Monitoring Station. Data are 2-minute average values based on 3 second samples.

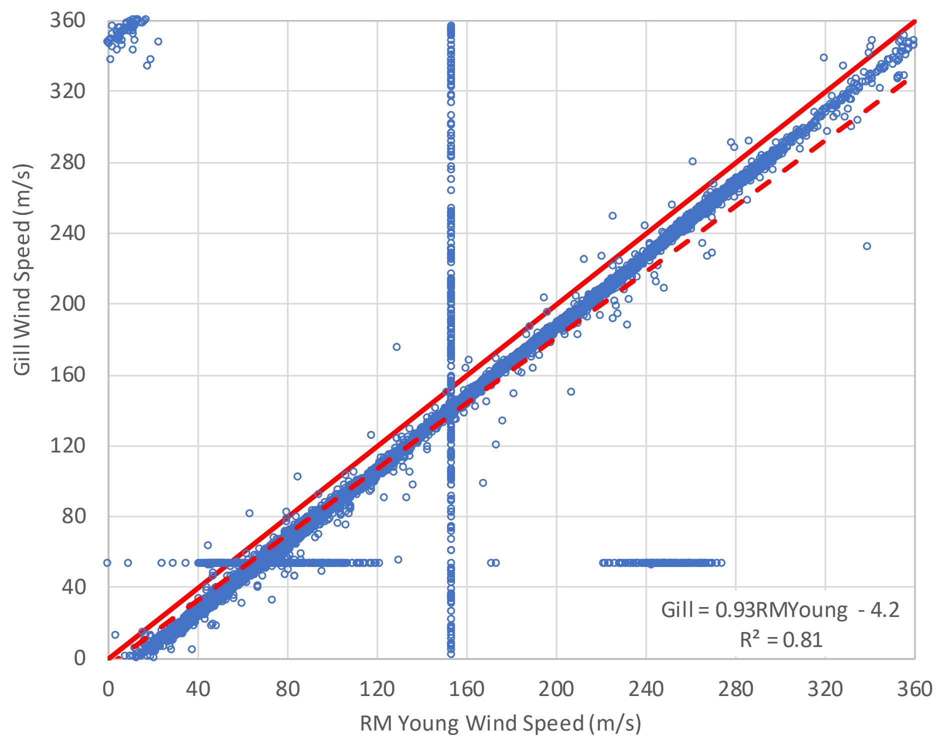


Figure 3-4 Comparison of wind direction data during the 1 September to 31 October 2019 preliminary assessment period from the RM Young mechanical and Gill WindSonic ultrasonic wind sensors installed at the Colebrook Road Pump House Onshore Wind Monitoring Station. Data are 2-minute average values based on 3 second samples.

A frequency distribution was calculated from available wind speed and direction data during the 1 September to 31 October 2019 preliminary assessment period for both the RM Young mechanical and Gill WindSonic ultrasonic wind sensors. Because wiring issues prevented the RM Young sensor from collecting wind direction data until 15 October 2019, the frequency distributions from each sensor are based on different monitoring periods, and so are not directly comparable. Also, the sections of unchanging direction data identified during preliminary data QA/QC will affect preliminary results. As additional data are collected and data are more thoroughly QA/QC'd, frequency distributions should be recalculated based on concurrent data periods, possibly considering individual wind events or seasonal monitoring periods.

Table 3.2 Wind speed and direction frequency distribution, given in percent occurrence, based on available wind speed and direction data during the 1 September to 31 October 2019 preliminary assessment period for both the RM Young mechanical sensor and Gill WindSonic ultrasonic sensor installed at the Colebrook Road Pump House Onshore Wind Monitoring Station.

Direction	RM Young						Gill WindSonic					
	0-1 m/s	1-3 m/s	3-6 m/s	6-9 m/s	>9 m/s	Total	0-1 m/s	1-3 m/s	3-6 m/s	6-9 m/s	>9 m/s	Total
ENE	-	12.14	3.57	0.24	-	15.95	-	15.85	1.90	0.47	-	18.225
NE	-	4.05	2.62	0.24	-	6.91	-	10.03	1.90	0.07	-	11.992
NNE	-	1.19	-	-	-	1.19	-	4.54	0.68	0.20	-	5.42
N	-	-	-	-	-	0.00	-	0.61	0.20	-	-	0.813
NNW	-	0.24	-	-	-	0.24	-	0.47	-	-	-	0.474
NW	-	0.71	-	-	-	0.71	-	0.41	-	-	-	0.407
WNW	-	0.71	0.71	0.48	0.71	2.62	-	0.81	0.20	0.07	-	1.084
W	-	3.33	2.14	0.24	0.95	6.67	-	2.17	1.36	0.20	0.54	4.268
WSW	-	3.33	1.91	0.24	0.24	5.71	-	3.18	2.37	0.14	0.07	5.759
SW	-	2.86	1.19	0.71	0.00	4.76	-	4.07	4.68	0.34	-	9.079
SSW	-	1.91	1.43	0.71	0.00	4.05	-	2.58	3.05	0.34	-	5.962
S	-	0.24	2.14	3.57	0.48	6.43	-	1.56	1.42	0.75	0.07	3.794
SSE	-	0.24	1.67	2.62	0.24	4.76	-	0.95	2.51	1.42	0.21	5.081
SE	-	1.91	1.19	-	-	3.10	-	1.29	1.42	0.47	0.07	3.252
ESE	-	5.24	0.95	-	-	6.19	-	1.56	0.54	0.07	-	2.168
E	-	15.71	0.95	0.24	-	16.91	-	8.06	0.75	0.07	-	8.875
Calm	13.81	-	-	-	-	13.81	13.35	-	-	-	-	13.347
Total	13.81	53.81	20.48	9.29	2.62	100.00	13.35	58.13	22.97	4.61	0.95	100

3.3 Comparison with Wind Profile Data

One of the City's OceanMet monitoring program goals is to investigate local wind variability around each of their wind monitoring stations. Wind profiles will be collected regularly at each of the monitoring stations, and where and when possible at several locations some distance away from each station. These profiles will be used to show whether monitoring station data is representative of surrounding locations. Wind profiles will be collected using a portable telescoping mast that supports a 3-cup style anemometer. Profiles will include wind speed measurements at 2 m, 5 m, 8 m, and 10 m elevations above the ground or water surface. Wind direction during each measurement will be visually approximated using a flag and compass.

While final wind profile measurement equipment has not yet been procured and configured, a preliminary set of wind profiles was collected at and near the Colebrook Road Pump House Onshore Wind Monitoring Station during a moderate wind event on 25 October 2019. A Metone 013A 3-cup anemometer was used to collect win profile data, sampling win speed every 3 seconds and recording the following parameters:

- 2-minute average wind speed
- 2-minute maximum (gust) wind speed
- Time of 2-minute maximum (gust) wind speed
- 10-minute average wind speed
- 10-minute maximum (gust) wind speed
- Time of 10-minute maximum (gust) wind speed

Preliminary analysis are based on the 2-minute average wind speed data.

The anemometer was positioned at the designated elevations using a towable boom lift. The boom lift is not as versatile as the planned portable telescoping mast, and measurement locations were limited to the road surface along the dyke adjacent to the Colebrook Road Pump House Onshore Wind Monitoring Station. The telescoping mast will allow collection of future measurements at preferred locations such as on the flood box deck near the monitoring station's tower and near the railway bridge crossing the mouth of the Serpentine river approximately 1 km west of the pump house. Preliminary locations for wind profiles included:

- Station 1: On top of the dyke directly adjacent to the flood box
- Station 2: 110 m west along the dyke road from the flood box
- Station 3: 270 m west along the dyke road from the flood box

Figure 3-5 shows wind speed profiles measured during the moderate wind event on 25 October 2019. As expected, these profiles indicate generally increasing wind speed with elevation, with some spatial variability in wind speed gradients. Figure 3-6 shows wind direction profiles measured during the moderate wind event on 25 October 2019. These profiles indicate relatively stable wind directions, however values are approximate as they are based on manual measurements using a flag and compass. Table 3.3 presents wind profile data collected during the moderate wind event on 25 October 2019 compared to wind data recorded at the Colebrook Road Pump House Onshore Wind Monitoring Station during this event. As additional wind profiles are collected, an in depth comparison between profiles and station data is recommended.

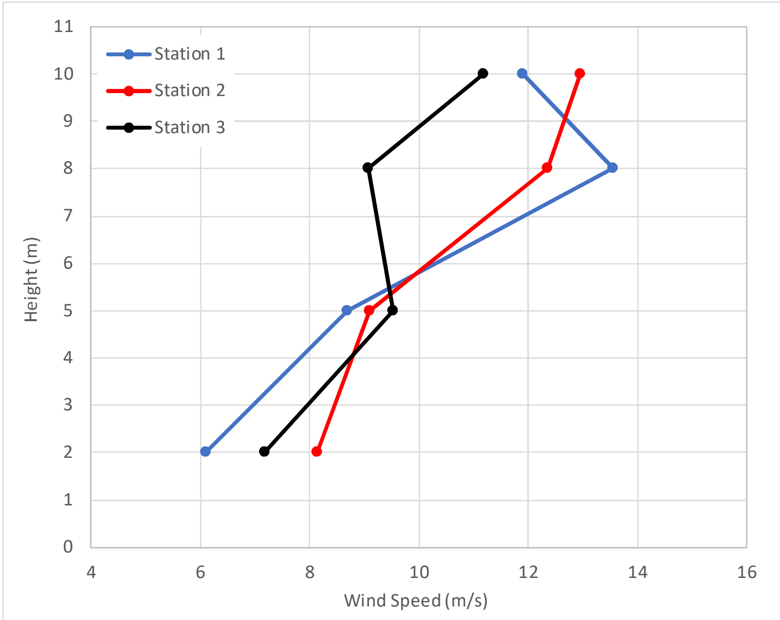


Figure 3-5 Wind speed profiles during a moderate wind event on 25 October 2019, collected adjacent to the Colebrook Road Pump Station (station 1) and 110 m and 270 m west along the dyke road from the pump station (station 2 and 3 respectively).

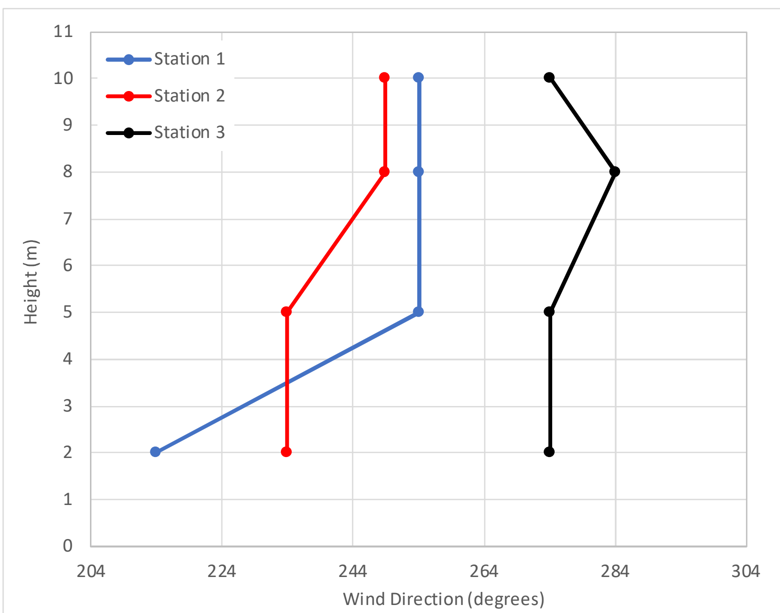


Figure 3-6 Wind direction profiles during a moderate wind event on 25 October 2019, collected adjacent to the Colebrook Road Pump Station (station 1) and 110 m and 270 m west along the dyke road from the pump station (station 2 and 3 respectively).

Table 3.3 Wind profile data collected during a moderate wind event on 25 October 2019, compared to wind recorded at the Colebrook Road Pump House Onshore Wind Monitoring Station.

Height of 3-cup anemometer	Wind Speed (m/s)			Wind Direction (degrees)		
	3-cup	RM Young	Gill	3-cup	RM Young	Gill
Station 1: On top of the dyke directly adjacent to the Colebrook Road Pump House flood box						
2	6.1	8.2	8.3	214	274	262
5	8.7	9.6	9.7	254	284	270
8	13.6	12.2	12.5	254	272	258
10	11.9	10.5	10.5	254	268	255
Station 2: 110 m West along the dyke from the Colebrook Road Pump House						
2	8.1	9.5	9.9	234	253	240
5	9.1	9.6	9.9	234	258	245
8	12.4	12.0	12.2	249	271	258
10	13.0	11.7	11.8	249	273	259
Station 3: 270 m West along the dyke from the Colebrook Road Pump House						
2	7.2	11.3	11.4	274	282	268
5	9.5	11.5	11.7	274	280	267
8	9.1	11.1	11.4	284	286	272
10	11.2	12.6	12.9	274	286	273

3.4 Comparison with Nearby Long-term Monitoring Stations

There are not yet any long term wind monitoring stations within Boundary Bay or Mud Bay, however there are several proximate monitoring stations operated by other agencies that may be relevant to understanding and modelling wind fields in this area. Table 3.4 summarizes existing ocean and costal Meteorological Service of Canada (MSC) and National Oceanic and Atmospheric Administration (NOAA) stations with hourly wind speed and direction data available within 50 km of the Boundary Bay and Mud Bay areas.

Seven of the identified proximate monitoring stations were selected for preliminary analysis, noted in bold in Table 3.4. Data available for each of these stations during the 1 September to 31 October 2019 preliminary assessment period were accessed online[1] on 6 November 2019. Data from additional stations may be included in future analysis depending on the objectives of future projects. The 2-minute

[1] Data from MSC stations was retrieved from https://climate.weather.gc.ca/historical_data/search_historic_data_e.html
Data from NOAA stations was retrieved from https://www.ndbc.noaa.gov/station_page.php?station=cpnw1

average wind speed and direction data from the Colebrook Road Pump House Onshore Wind Monitoring Station were resampled at an hourly time step to conform with MSC an NOAA monitoring conventions, and then were compared with hourly data from the selected proximate stations. The amount of overlapped data are as yet insufficient for a true correlation, but a qualitative comparison was possible.

Table 3.4 Ocean and coastal MSC and NOAA stations with current hourly wind speed and direction data within 50 km of the Boundary Bay and Mud Bay areas.

Station	Station ID	Station Location	Station Elevation (m)	Operating Agency	Distance from Colebrook Road Pump House (km)
White Rock Campbell Scientific	1108910	122.78 W 49.02 N	13.0	MSC	9.13
Cherry Point North Dock*	**9449427**	**122.76 W 48.86 N**	**4.6**	**NOAA**	**25.87**
Tsawwassen Ferry Auto*	**1108291**	**123.13 W 49.00 N**	**7.3**	**MSC**	**25.94**
Vancouver Sea Island CCG	1108380	123.19 W 49.18 N	2.1	MSC	30.80
Vancouver Intl A*	**1108395**	**123.18 W 49.19 N**	**4.3**	**MSC**	**31.05**
Vancouver Harbour CS	1108446	123.12 W 49.30 N	2.5	MSC	33.00
Saturna Island CS*	**1017101**	**123.04 W 48.78 N**	**24.4**	**MSC**	**37.54**
Sandheads CS*	**1107010**	**123.30 W 49.11 N**	**11.0**	**MSC**	**38.70**
Saturna Capmon CS	1017099	123.13 W 48.78 N	178	MSC	41.97
Point Atkinson	1106200	123.26 W 49.33 N	14.0	MSC	44.67

* Stations shown in bold were selected for inclusion in preliminary analysis.

Wind vector plots can be used to visually compare wind speed and direction at multiple stations, particularly over short times such as for individual wind events[2]. Figure 3-7 presents a sample wind vector plot for the Colebrook Road Pump House Onshore Wind Monitoring Station and selected proximate stations. This plot indicates some spatial variation in speed and direction between stations. NHC recommends this type of plot be used in future analysis to visually assess spatial variability of individual wind events depending on the objectives of future projects, as well as during QA/QC of the City's OceanMet data.

[2] Each line or 'stick' on a wind vector plot represents the time, direction, and magnitude of an individual data point. The position of the stick along the central x-axis represents the time of the measurement, the length of the stick represents the magnitude of the wind speed, and the direction of the stick represents the direction the wind was blowing. It can be helpful to visualize an arrow on the end of each stick to better understand the direction component of a wind vector plot. Wind speed can be added to a wind vector plot as a time series line above the central x-axis to better display magnitude.

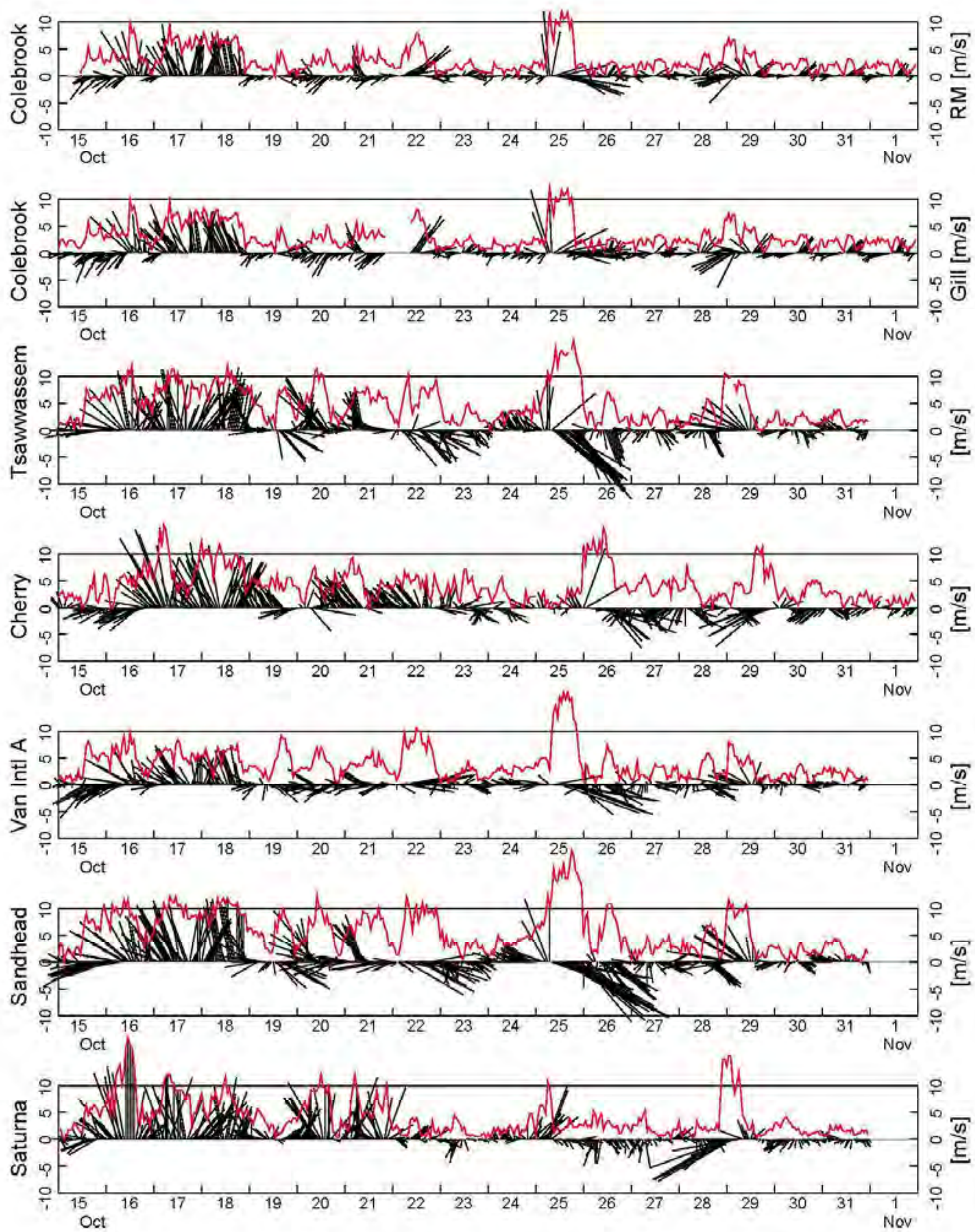
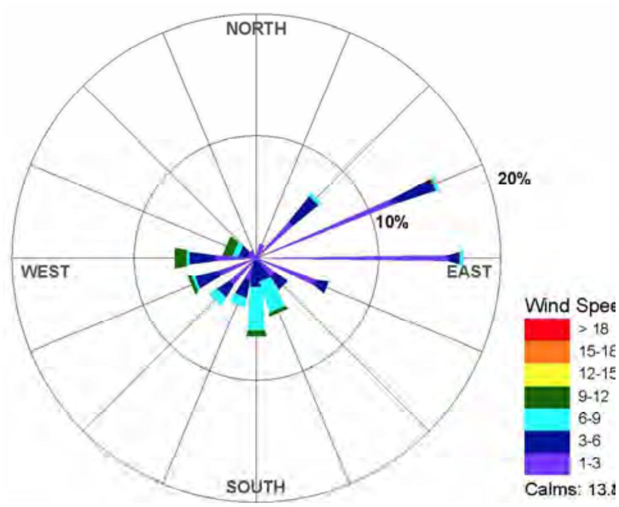


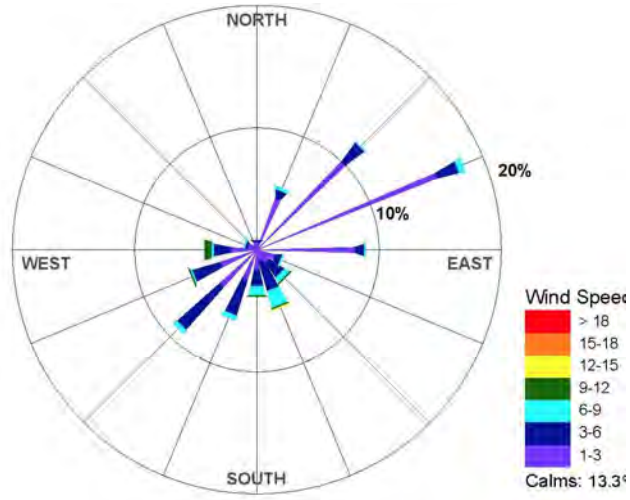
Figure 3-7 Wind vector plot[2] for the Colebrook Road Pump House Onshore Wind Monitoring Station and selected proximate stations from 15-31 October 2019

Figure 3-8 presents wind rose frequency distributions for the Colebrook Road Pump House Onshore Wind Monitoring Station and selected proximate station based on data available during the 1 September to 31 October 2019 preliminary assessment period. This plot indicates spatial variation in speed and direction between stations. As not all stations had data available throughout the entire preliminary assessment period and the frequency distributions are based on different monitoring periods, they are not directly comparable. As additional data are collected, frequency distributions should be recalculated based on concurrent data, possibly considering individual wind events or seasonal monitoring periods depending on the objectives of future projects.

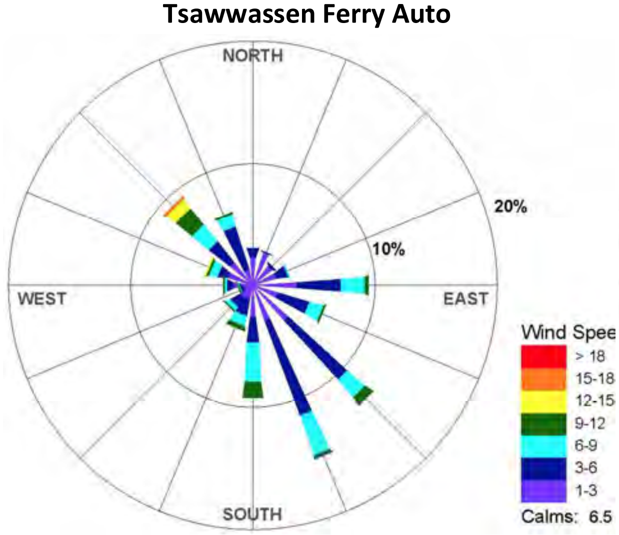
Colebrook RM Young



Colebrook Gill WindSonic



Tsawwassen Ferry Auto



Cherry Point

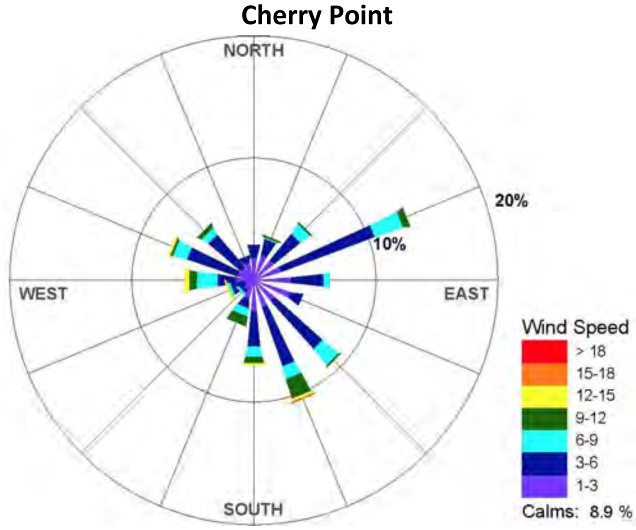
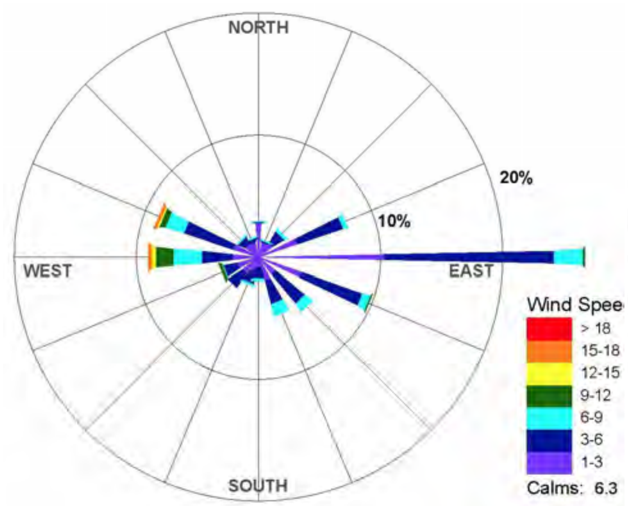
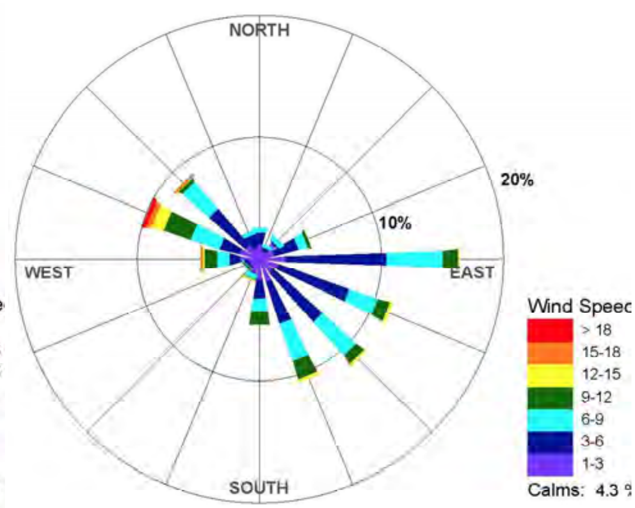


Figure 3-8 Wind rose frequency distributions, given in percent occurrence, at Colebrook Road Pump House Onshore Wind Monitoring Station and selected proximate stations based on available wind speed and direction data during the 1 September to 31 October 2019 preliminary assessment period.

Vancouver Intl A



Sandheads CS



Saturna Island CS

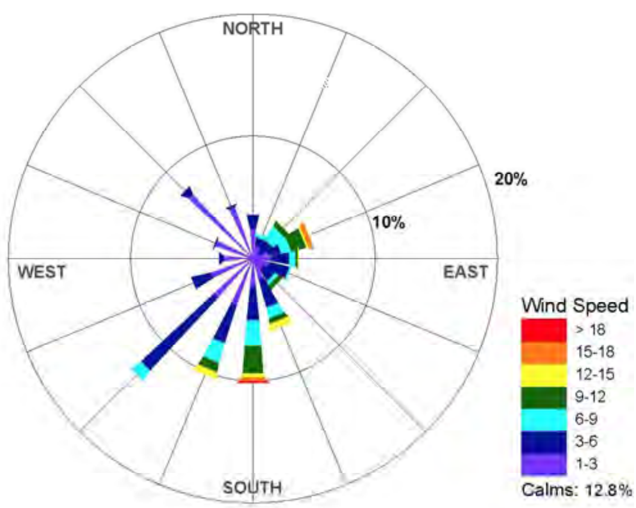


Figure 3-8 cont. Wind rose frequency distributions, given in percent occurrence, at Colebrook Road Pump House Onshore Wind Monitoring Station and selected proximate stations based on available wind speed and direction data during the 1 September to 31 October 2019 preliminary assessment period.

Table 3.5 provides a summary of wind speed at the Colebrook Road Pump House Onshore Wind Monitoring Station compared to selected proximal stations from 15 to 31 October 2019. The 15 to 31 October 2019 period was selected as it has continuous data coverage from both the Colebrook Road

Pump House wind sensors and all proximal stations selected for preliminary analysis. The average, minimum, and maximum wind speeds were calculated for each station, based on hourly data. Hourly data represent the average value during the 2-minue period ending at the time of observation. The summary indicates spatial variation in speed between stations, with the Colebrook Road Pump House Onshore Wind Monitoring Station recording lower average hourly and maximum hourly wind speeds during the 15 to 31 October 2019 period than all other proximal stations. This may change as additional data from a wider range of wind events are collected.

Table 3.5 Summary of wind speed at Colebrook Road Pump House Onshore Wind Monitoring Station and selected proximate stations based on concurrent hourly data from 15 to 31 October 2019.

Station	Average Hourly Wind Speed (m/s)	Minimum Hourly Wind Speed (m/s)	Maximum Hourly Wind Speed (m/s)	Direction of Maximum Hourly Wind Speed (degrees)
Colebrook Road Pump House RM Young	2.99	0.00	11.96	279
Colebrook Road Pump House Gill	3.20	0.15	12.18	163
Cherry Point North Dock	4.45	0.00	15.40	160
Tsawwassen Ferry Auto	4.92	0.00	16.67	320
Vancouver Intl A	4.00	0.28	17.22	280
Saturna Island CS	4.05	0.00	18.89	180
Sandheads CS	5.98	0.00	20.83	300

NHC has previously relied upon wind data from the Saturna Island CS station as input for wave modelling. The longest fetch direction, that will produce the largest waves, is towards the south of Boundary Bay. As the Saturna Island CS station is located on the edge of the main body of water south of Boundary Bay, it is the station nearest to this exposed fetch. Ideally, wind measurements in the middle of the fetch (or body of water) would be used, but in the absence of over-water wind measurements a long term station adjacent to the area is preferred. What remains to be determined is how well the winds at Saturna Island correlate with winds at the entrance to Boundary Bay.

The initial review of data given above in Table 3.5 shows wind speeds at Saturna Island CS to be notably stronger than at the Colebrook Road Pump House, which was anticipated. Indeed, mariners and boaters know that winds are typically stronger in the middle of the Strait of Georgia than in Boundary Bay, and wind models of the area also predict on-land winds in Mud Bay will be lower than over-water winds (see Figure 3-9). Yet waves generated offshore and south of Bounday Bay can propagate into the Bay. The present study to measure winds at Colebrook, as well as to record winds at navigation aids in Boundary Bay will significantly improve the understanding of wind patterns during storm events in this area.

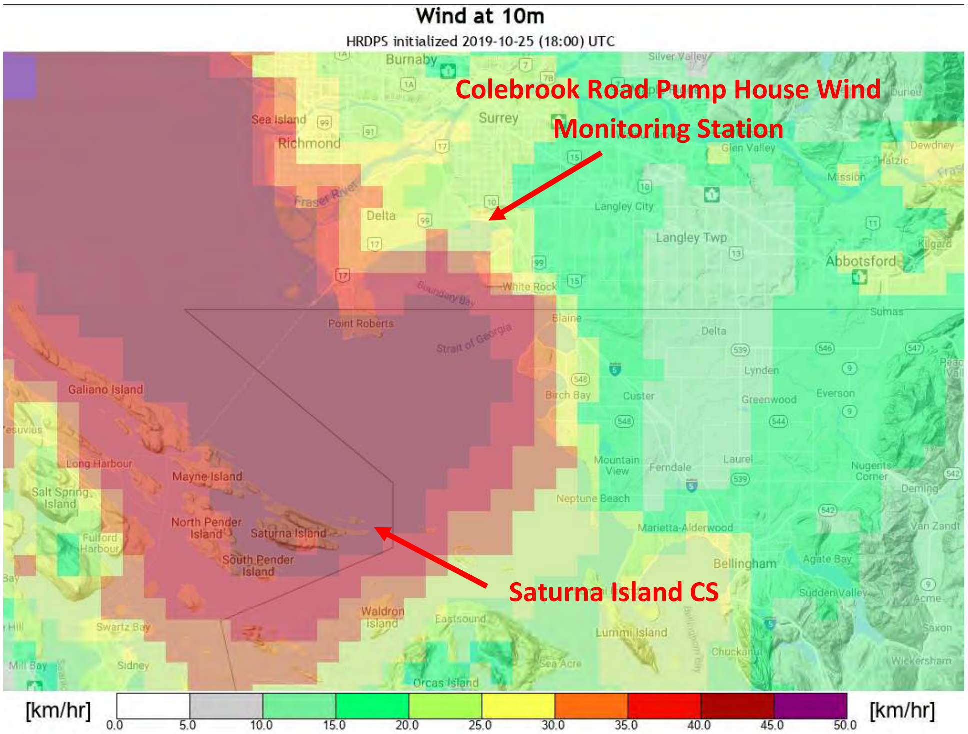


Figure 3-9 Wind speed plots from the High Resolution Deterministic Prediction System (HRDPS) by Environment and Climate Change Canada from October 25, 2019 showing spatial variability of the predicted wind fields at 9 am.

4 PLANNED FUTURE WORK AND RECOMMENDATIONS

The City, supported by NHC, is actively pursing permitting from the CCG to proceed with the installation of proposed offshore and nearshore wind and wave monitoring stations on the Crescent Beach Starboard Channel Marker and Crescent Channel Starboard Channel Marker respectively. These stations will each include a mechanical RM Young – Heavy Duty Wind Monitor propeller and vane sensor. Once operational, these stations, in conjunction with the existing Colebrook Road Pump House Onshore Wind Monitoring Station, will provide a detailed understanding of wind fields in the Boundary Bay and Mud Bay areas to support improved wave model development. Also, as these stations will report data in near real-time, they can be used to evaluate developing and occurring storms to inform response decisions.

NHC recommends future analysis include statistical assessments of wind speed and direction at each of the City's monitoring stations, including a long term comparison between the ultrasonic and mechanical wind sensors at the Colebrook Road Pump House Onshore Wind Monitoring Station, as well as an investigation of local wind variability based on wind profiles collected regularly at and near each of the City's monitoring stations. Section 3 of this report presents a preliminary analysis of wind data currently available from the City's OceanMet monitoring program. As the program is still in development, data currently available are limited and NHC makes several specific recommendations throughout Section 3 for updates and expansion of the preliminary analysis as additional data are collected and future project objectives are defined.

NHC also recommends additional comparisons or correlations with data from other agencies' proximate monitoring stations as the City's OceanMet monitoring program is further developed and more data are collected. Future analysis could include visual assessment of wind vector plots for individual wind events, calculation of wind rose frequency distributions for concurrent data, possibly considering individual wind events or seasonal monitoring periods, or more in-depth correlation analysis and the development of transform equations to generate long term synthetic wind series at each of the City's monitoring stations, depending on objectives of future projects.

NHC appreciates the City's wind and wave monitoring initiatives, and looks forward to using the data to improve calibration of wave models in the area.

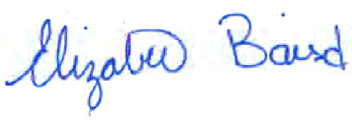
5 CLOSURE

I hope this information is of use and can help inform the City in upcoming decisions related to work in the Boundary Bay and Mud Bay area. Please feel free to contact Elizabeth via email at ebaird@nhcweb.com or phone at 604.980.6011 with any questions about this report or if you would like to discuss the wind monitoring program further.

Sincerely,

Northwest Hydraulic Consultants Ltd.

Prepared by:



Elizabeth Baird, MSc, GIT
Hydrologist

DISCLAIMER

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Chapter 5

Green Infrastructure Recommendations – Reducing Wave Model Uncertainty

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northwest hydraulic consultants ltd

NHC Ref. No. 8900006

5 November 2019

City of Surrey
Engineering Department
4th Floor, 13450 -104 Ave, Surrey
BC, V3T 1V8

Attention: **Matt Osler, P.Eng., MBA**
Sr. Project Engineer

Copy to:

Via email: mfosler@surrey.ca

Re: **Coastal Flood Risk Reduction**
Green Infrastructure Recommendations – Reducing Wave Model Uncertainty

1 INTRODUCTION

This letter summarizes recommendations to reduce data uncertainty related to planning and design for green infrastructure projects in Mud Bay area. Specifically, recommendations to improve coastal wave model input data and to improve coastal wave model methodologies for establishment of dike construction elevations and corresponding flood construction levels are given.

2 WAVE MODEL INPUT DATA

Waves are generated from the blowing of wind across the water causing the growth and propagation of waves. Exceptions include tsunami waves (generated by seismic events or from landslides) and daily tides (due to astronomical forces) which are waves with periods in the order of hours instead of seconds.

2.1 Types of Wave Models

There are different methods for estimating the wind generated seastate (wave height, wave period, and wave direction) near a shoreline. These include:

- Empirical calculations based upon fetch length, wind speeds, and wind duration.
- Phase averaged (or spectral) wave models which model the growth and evolution of the wave energy spectrum. The output of the model is a statistical description of the seastate at the scale of the model grid.

- Phase resolving wave models which resolves individual waves at small timesteps (fractions of a second). A phase resolving wave model is most useful at small scales for resolving wave-structure interactions and wave runup on shorelines.

Each of the types of wave models has their advantages and disadvantages. It is not uncommon to use several types in a given study. Empirical calculations allow for a quick "first estimate" of the design seastate in a given area, and for doing long-term wind-wave hindcasts. Phase averaged models are useful for simulating multiple day extreme storm events over large areas while phase resolving models are excellent for looking at wave-structure interactions for a small set of individual waves, which is useful for examining wave runup and confirming coastal flooding predictions.

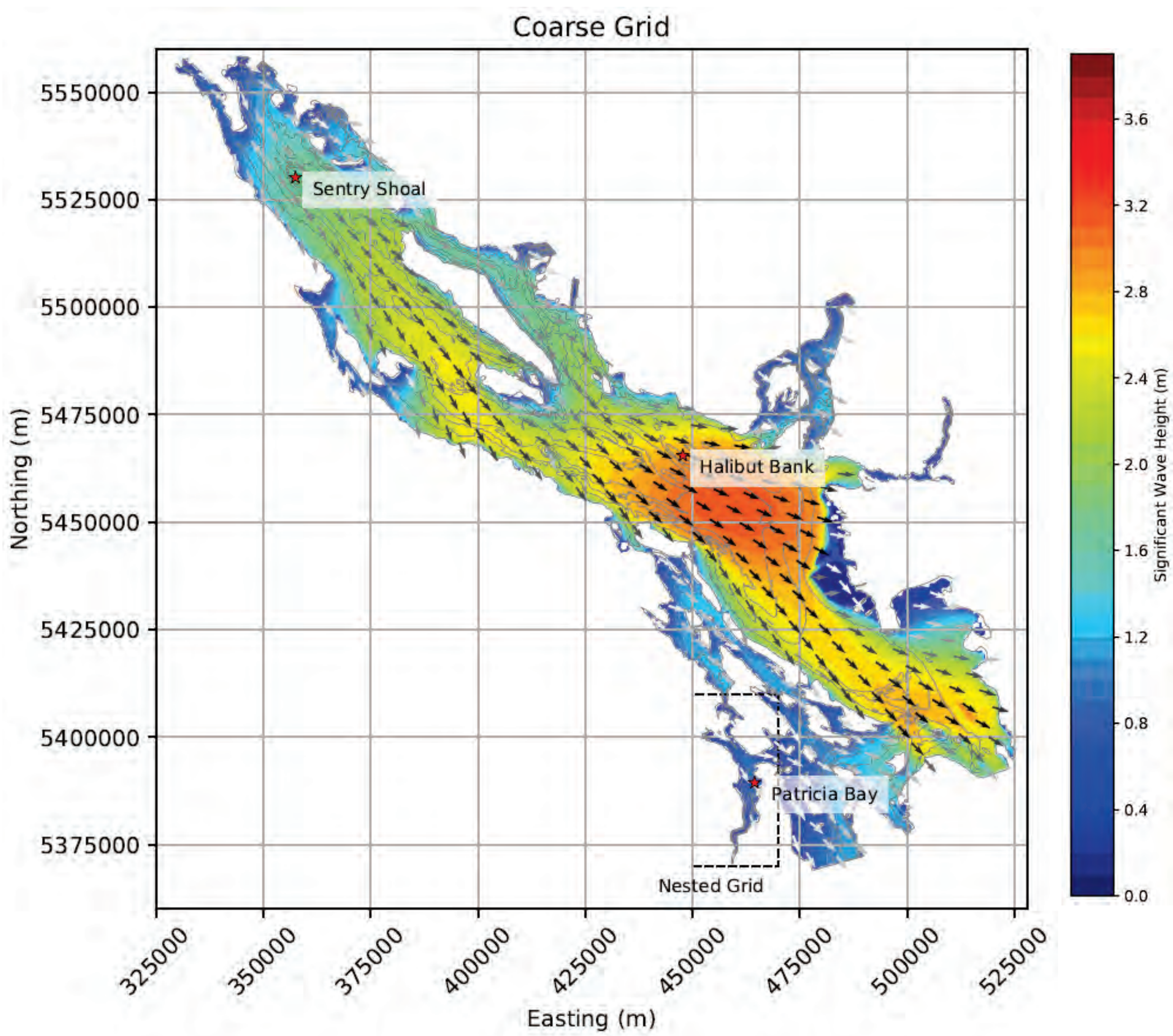

Figure 2.1 An example of output from a phase averaged wave model (NHC, SWAN model), utilizing a spatially varying wind field developed using measured winds from airports, lighthouses, and wave buoys.

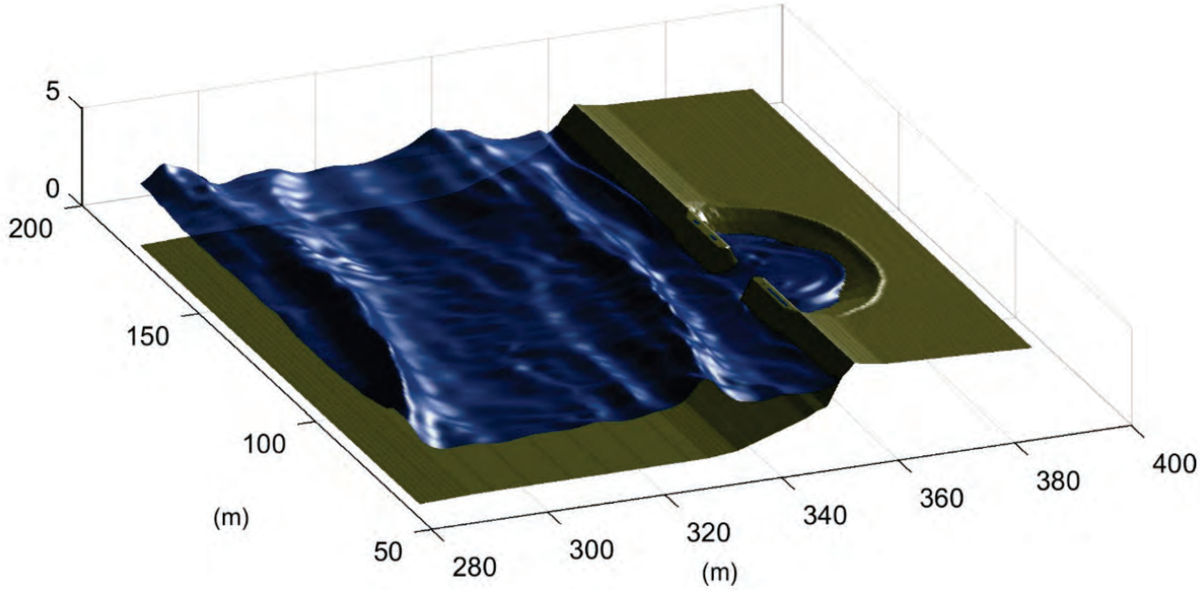

Figure 2.2 **An example of output from a phase resolving wave model (NHC, SWASH model), used to examine wave-structure interactions along a section of dike that has been opened to enhance ecological habitat (Vertical scale enhanced).**

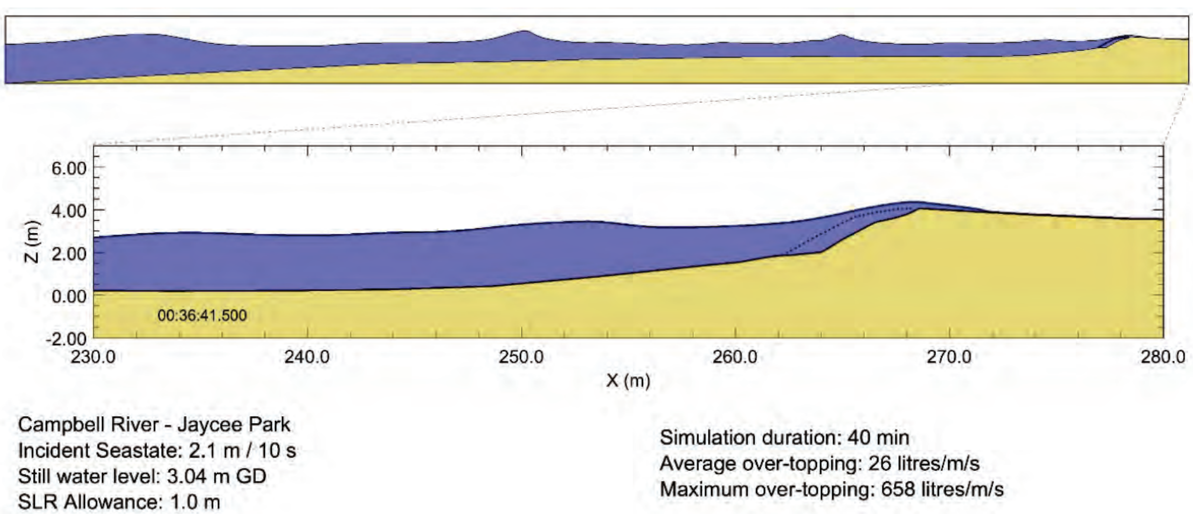

Figure 2.3 **An example of output from a phase resolving wave model (NHC, SWASH model), used to examine wave runup along existing shorelines accounting for future sea level. Model included the effects of riprap slopes and a cobble intertidal zone on wave shoaling, breaking, and runup.**

2.2 Wave Model Inputs

Wave models vary in their required inputs, and some have many settings that can be altered. For empirical formulae the inputs may be as little as the wind speed, wind duration, and fetch length. Water depths may or may not be needed depending on the situation. For wave models, most minimum required inputs include:

- Bathymetric data for the model domain or extents
- Water level data (either static or varying)
- Wind data for the model domain (either constant or varying)

Additional data can be required depending upon the complexity of the model required to support the project. The following sub-sections discuss some of the additional inputs commonly utilized.

2.2.1 Phase Averaged Models

A simple phase averaged wave model could include a steady and constant wind across the entire model domain. More complex models utilize wind fields that are both spatially and temporally varying. It is also possible to couple wave models with hydrodynamic model outputs. Such wave models may have additional inputs that include:

- Spatially and temporally varying water levels,
- Spatially and temporally varying tidal currents, and
- Spatially and temporally varying wind driven currents.

Additionally, if there are shallow water areas then the seabed conditions become important for estimating wave shoaling, refraction, and propagation. The seabed roughness can affect the bed friction coefficient settings in the model, and if there are mud and silts on the seabed this can also affect wave breaking and wave propagation. More recent versions of phase averaged models such as SWAN can also account for seabed vegetation and damping effects this has on waves, although there has to date been limited validation of these aspects of the models.

Vegetation inputs is possible in some models such as SWAN with horizontally varying density of vegetation allowed as an input. Seabed vegetation is modelled with inputs as the plant height, diameter of the plant stem, and number of stems in a square metre.

2.2.2 Phase Resolving Models

For a phase resolving model that is attempting to simulate details of wave run-up on a complex shoreline, the details of the rock armour and vegetation are often critical parameters for the proper estimation of the wave runup along with proper resolution of shoreline structures such as seawalls, roadway elevations, and such.

The general inputs for phase resolving models is similar to that required for phase averaged models but on a much higher resolution for the phase resolving model domain. The grid resolution for a phase averaged model is typically between 20 and 500 metres, while for a phase resolving model the grid resolution can be on the order of tenths of a metre to properly resolve breaking waves on a shoreline.

Specific inputs to a phase resolving model include:

- Offshore boundary conditions for incident (or offshore) seastate,
- Winds and currents within the model domain, if the domain is sufficiently large,
- High resolution bathymetry features,
- Shoreline and upland topographic details, and
- Shoreline vegetation details (similar to those required for phase averaged models)

3 RECOMMENDATIONS

The classic saying of “garbage in, garbage out” or GIGO applies to wave modelling. As such, if the inputs to the wave models are poorly resolved or incorrect, then the accuracy of the model results is similarly affected. Additionally, if the model is poorly setup such that important seabed features are not resolved, or the wind fields are not properly setup, then the model results will not be accurate.

This section will touch at a high level on general recommendations related to improving wave modelling, and then makes specific recommendations related to wave modelling for Boundary Bay and Mud Bay.

3.1 General Recommendations

As for any modelling exercise, it is always important to decide early in the process what the purpose of the model is. If this is not done, then it is possible to develop a model that is not suitable to answer the questions being posed by the project. As such, general recommendations include:

- Clear understand of the purpose of the model, and clear decisions on which type of model (or models) are required.
- Early identification of gaps in available input information.
- Transparent and full documentation of input data gaps and steps undertaken to fill those gaps.

The first point is perhaps the most important. For example, using a phase averaged model to estimate the design seastate at a harbour entrance while utilizing the default settings of the model (which do not account in any way for wave reflections from structures) is entirely inappropriate. In such a model the seastate would be significantly underestimated and not properly designed for at the harbour entrance. Similarly, using a phase averaged model with model grid resolutions of 5 m would entirely fail to resolve the details of a complex living dike design, and the wave – structure interactions including wave reflections would not properly be accounted for.

3.2 Coastal Model Methodology

One improvement in recent years that can be applied to better establishing dike construction elevations and flood construction levels is coupling phase averaged wave models with site specific phase resolving models of select locations on shorelines. The phase resolving models, when properly setup and run, are able to examine wave – shoreline interactions such as wave runup and overtopping volumes. The volume of overtopping water can be an important design parameter for understanding upland flood hazard and risk that has not been well utilized in past studies. The phase resolving models also allow for examination of the potential benefits of various adaptations of the shoreline and are thus able to provide measurable predictions of future performance and allow for comparison of proposed mitigations.

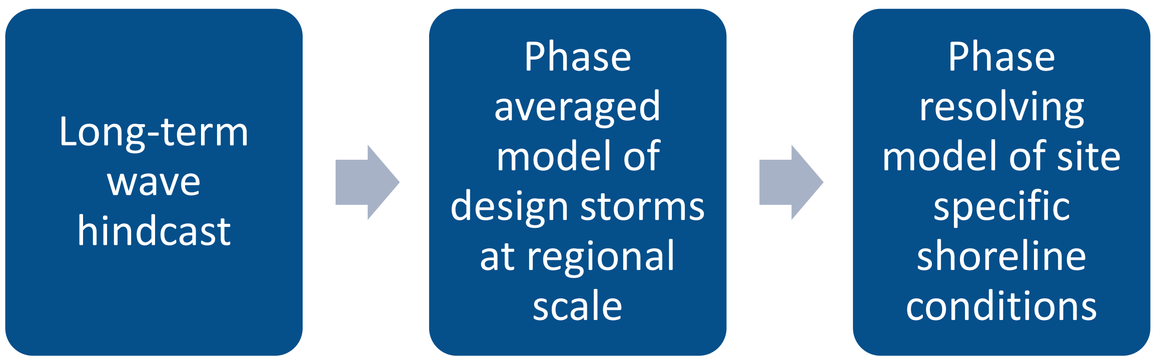

Figure 3.1 A flow diagram for wave modelling, with increasing focus and detail.

It has been common practice to utilize empirical formulae such as those provided in the EurOtop manual to estimate wave runup and overtopping on dikes and shorelines. For relatively simple structures and shorelines that conform to the empirical assumptions regarding uniform slopes and uniform surface properties, the results are known to be robust from the empirical formulae. However, where the shorelines are complex, or have different types of materials and vegetation, the empirical approach is no longer appropriate. As such, NHC presently utilizes phase resolving models, including Computational Fluid Dynamic models such as OpenFOAM and Flow3D as well as Smooth Particle Hydrodynamic (SPH) models to examine wave structure interactions on complex shorelines.

This fall, an engineer from NHC (Jessica Wilson) is undertaking both CFD and physical model studies to better understand the effects of woody debris on shoreline response, and to develop design guidance for the use of woody debris on shorelines. CFD analysis and validation in physical model studies is useful for unusual shoreline conditions that are not well accounted for in the traditional engineering studies that form the basis of the empirical formulae for wave-shoreline interactions. Such studies can strengthen the understanding of the limitations of numerical modelling, and provide design guidance criteria for nature based shoreline solutions.

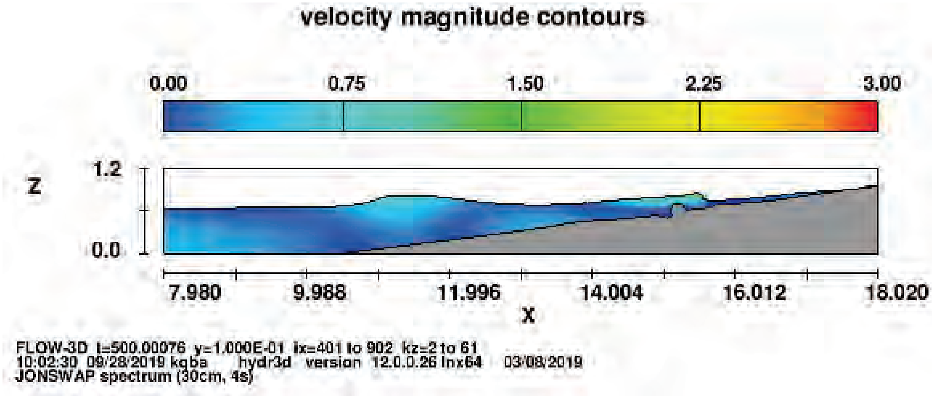

Figure 3.2 Output from a Flow3D CFD model of wave-shoreline interactions. (J. Wilson, NHC)

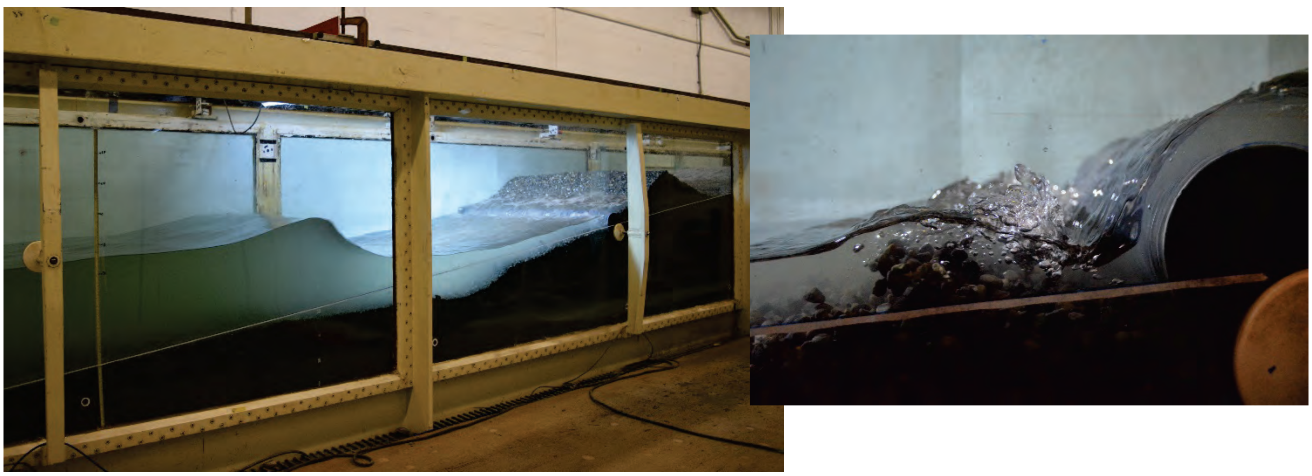

Figure 3.3 Photos of physical model studies undertaken by J. Wilson of the effects of woody debris on shoreline response during storm events at the National Research Council, Fall 2019 (J. Wilson, NHC)

3.3 Specific Recommendations

There are several ways in which the wave modeling can be improved within the Boundary Bay and Mud Bay area in support of the design and planning of nature based projects for climate adaptation.

3.3.1 Spatially Varying Wind Fields

It is widely understood that wind conditions in Boundary Bay, and in the waters south of Boundary Bay can have different winds than those experiences at the Vancouver Airport (YVR), Sand Heads, or Saturna Island. There are interesting flow patterns that develop due to the influence of topography around Point Roberts and White Rock and larger scale regional wind patterns.

Better understanding and modeling of spatially varying wind fields will improve the predictions of the spatial distribution of wave heights within the area. To this end, the availability of wind measurements in Boundary Bay and at the Colebrook pump station in Mud Bay will allow for regional wind models to be better calibrated.

3.3.2 Improved Bathymetric Data in inter-tidal areas

The intertidal flats in the area are not regularly surveyed by the Canadian Hydrographic Service as they are outside of navigation channels for shipping and can be generally marked as a hazard on charts. However, for accurate wave modelling it is important to understand the ground elevations in these wide and flat intertidal areas. Small increases in water depths can result in markedly different seastates near to the shoreline due to wave breaking.

It is not easy to survey the intertidal flats. Bathymetric surveys are only possible during high tide periods with small vessels, and even at high tides the water depths are very shallow and thus limits the width of a multi-beam survey. This in turn restricts the area that can be surveyed on a given high tide making a multi-beam survey little better than a single beam in coverage.

At low tides a large and wide intertidal area is exposed and can be surveyed in the dry. However, ground based surveys are very difficult as travelling across the intertidal flats is difficult. Drone surveys are possible but for accuracy proper ground control is required. New RTK drones are increasingly available, but even with those some ground control is recommended.

Flying aerial LiDAR at low tide windows remains the best method for quickly obtaining large area coverage of the intertidal zones. Again, there are issues of ground control and post-processing that need attention. Most challenging is that it is common for shallow pools to form at low tide on the intertidal flats, and distinguishing these from actual ground points requires care. Provided the depth of the pools is low (ie. Less than 0.1 m) the induced errors on wave modelling will be limited.

3.3.3 Calibration with wave measurements

Perhaps the best method for confirming the accuracy of a wave model is comparison of predicted waves with actual wave measurements from a hindcast storm event. Surrey is in the process of installing wave measurement devices at locations in Boundary and Mud Bay that will allow in the future for wave models to be checked and their performance calibrated.

3.3.4 Better mapping of inter-tidal and shoreline vegetation

As wave models improve and are able to better simulate the effects of seabed type and vegetation, there is a need to upgrade and improve the input data available.

Aerial photos and baseline environmental mapping contain much useful information related to vegetation extents and sediment type distribution. However, as there is often a seasonal component to wave modelling in this region (winter storms tend to be the most severe), it is important the vegetation mapping for inclusion in wave models is appropriate for the season. It is also important that season dieoff is correctly accounted for as a nature based solution for shoreline protection must be robust during the winter months.

Specific measurements required as input for the wave models beyond spatial extent are:

- average height of plants above the seabed,
- number of stalks per square meter (typical),
- average diameter of the plant stalks, and
- season for this the data is valid.

4 CLOSURE

I hope this information is of use in your on-going work and can help inform Surrey in upcoming decisions related to work in Mud Bay. I am very pleased with the wind monitoring and wave monitoring initiatives being supported by Surrey as this will help greatly to improve the calibration of wave models in the area.

Please do not hesitate to contact me (glamont@nhcweb.com) should you wish to discuss any of this letter in further detail.

Sincerely,

Northwest Hydraulic Consultants Ltd.

Prepared by:

Grant Lamont, M.A.Sc., P.Eng,

Principal, Sr. Coastal Engineer

DISCLAIMER

Chapter 6

Coastal Flood Mitigation DEM Workshop

nhc
northwest hydraulic consultants ltd

NHC Ref. No. 3005240

22 November 2019

City of Surrey, Engineering Department, Utilities Division
4th Floor, 13450 104 Ave
Surrey, BC
V3T 1V8

Attention: **Matt Osler**
Sr. Project Engineer

Via email: mfosler@surrey.ca

Re: **Coastal Flood Mitigation DEM Workshop**
Draft Summary

Dear Mr. Osler,

NHC recently attended a Coastal Flood Mitigation DEM Workshop on behalf of the City of Surrey. The workshop was held September 23rd to 27th and October 21st to 23rd at the Ocean Networks Canada (ONC) facility on the University of Victoria campus in Victoria, BC. Mr. Josef Drechsler attended as NHC's representative. This memo provides a summary of the material covered and recommendations on how to improve the coastal DEM for Boundary Bay.

The workshop was hosted by Ocean Networks Canada (ONC) and instructed by two experts from the US National Oceanic and Atmospheric Administration (NOAA). The instructors reviewed their process for DEM development and had the participants follow along on their own computers. The following is an overview of what was covered in the workshop and how it can be applied to improving an existing DEM. A detailed workshop outline is provided in Appendix A.

1 WORKSHOP OVERVIEW

The instructors from NOAA are spearheading the Digital Coast project focused on generating a DEM of the entire US coastline. Their mandate is to use free data and data that has been provided with permission to create a DEM that will be made freely available for research purposes. Certain preconditions are required when designing a DEM for such a large area. Firstly, the coordinate system needs to be globally referenced. We typically use UTM Zone 10 in the Lower Mainland, but this is a projected coordinate system that uses three different zones in British Columbia (BC) alone (two of which are found along our coastline). This would not be suitable for a DEM that spans both sides of the North American Continent. Instead, NOAA decided to use Geographic Coordinates (latitude and longitude).

This coordinate system is consistent throughout the globe and is therefore suitable for a large, continuous DEM. Secondly, the resolution must be consistent in order to generate seamless DEM tiles. In this case, NOAA uses 1/9 arc-seconds for combined topographic and bathymetric DEMs and 1/3 arc-second for bathymetric DEMs (deep ocean). This ensures that the map panels will line up consistently. Finally, repeatable work flows with quick processing times and advanced data editing capabilities are needed because not all data is of the same quality. NOAA uses Linux-based tools for processing their data. Linux is fast, stable and free. There are many GIS utilities that can be run in command-line, therefore allowing scripting options. Workshop participants were able to run these scripts with numerous different data sources, correct problems and re-run the process. Through this iterative methodology we were able to address many of the problems associated with using such a wide variety of data. The resulting DEM was consistent and accurate. Quality assessments were made using Mascot benchmark data and showed acceptable elevation accuracy throughout the DEM.

1.1 Data Acquisition

The NOAA Coastal DEM project required that all data be provided free of charge. Before and during the workshop, ONC actively gathered topographic and bathymetric data from numerous sources, including the City of Surrey, other municipalities, the Province of BC and the Fraser Basin Council. Where there were gaps due to lack of data, CDEM (Canadian Digital Elevation Model) data was used. Smoothing and masking techniques were applied to minimize the coarseness of this data in the areas where it was needed.

1.2 GIS Approach

As mentioned, NOAA uses Linux for their spatial data processing. They currently run General Mapping Tools 5 (GMT5) on Linux. There are many reasons why using a command line, opensource operating system such as Linux is a benefit for the work that NOAA does. When dealing with multiple agencies for data acquisition, there can be problems related to differing software versions and file formats. By using Linux and requesting data in ASCII/XYZ format, they are able to avoid many of these complications. In addition, Linux is fast, efficient and relatively secure. When processing consistent data formats and knitting a giant coastal DEM together, this approach makes sense; however, for more regional work involving municipalities (such as the City of Surrey), government agencies and other engineering firms, NHC uses Esri ArcGIS. After learning NOAA's approach in the workshop, NHC has a new appreciation for these methods, but similar results can be achieved using Esri software. An argument may be made for increased efficiency when processing large datasets, but the flexibility and extensive toolset offered in Esri ArcMap and ArcPro are very useful when working on a variety of different projects with different requirements.

Some of the Quality Control methods that were introduced in the workshop are similar to current practice at NHC, however, the course introduced methods for using local, freely available data for verifying the accuracy of the final DEM product. In both cases, root mean square (RMS) analysis is used to evaluate differences between datasets, however, the workshop introduced the idea of drawing on external benchmarks from sources such as Mascot to evaluate overall consistency of DEMs covering large areas. NHC has recently used this method to evaluate DEMs from other clients and plan on using this approach to validate the Boundary Bay DEM.

2 COLLABORATION

This workshop brought together 22 people from different disciplines and government agencies. Participants were given a unique opportunity to learn new things together and share our own knowledge and experience. This was an international collaboration that traded expertise from NOAA for data from BC to produce a cohesive coastal DEM that can be added to the massive NOAA Coastal DEM project and used for future research in BC. Tsunami research, coastal erosion and climate change flooding research will all benefit from a common DEM that can be used to evaluate results based on a consistent surface. It should be noted that bathymetric DEMs quickly become out-dated due to currents and wave action affecting bed morphology. That said, a common DEM across multiple disciplines holds the potential for major strides in coastal research and engineering.

3 RECOMMENDATIONS FOR IMPROVED BOUNDARY BAY DEM

3.1 Data Comparison

The following description provides a comparison of the SWAN model DEM created by NHC in 2012 for the City of Surrey to the NOAA Coastal DEM created in the ONC Workshop.

- SWAN model (DEM from 2012)
  - Nearshore area (Mud Bay)
    - The 2012 SWAN model mesh has a node spacing that ranges from 10 to 1000 m (based on a 1 m raster)
    - The 2012 SWAN model is based on a combination of LiDAR (along the shore), CHS point data (spaced at 160 m) and CHS survey data (high density sections; 10 to 50 m spacing)
  - Deep sea area (Strait of Georgia)
    - CHS data
- The NOAA/ONC DEM (2019)
  - Nearshore area (Mud Bay)
    - The NOAA DEM ranges between 1/9 arc second (Approx. 3 m) and 1/3 arc second (Approx. 10 m)
    - The NOAA DEM is based on similar data (provided by CHS, Delta, White Rock and Surrey)
  - Deep sea area (Strait of Georgia)
    - CHS, ONC and NCEI data

The NOAA/ONC DEM uses data that is more up to date than what is in the 2012 SWAN model. The DEM resolution required for the model is sufficient with either data set. The 2012 SWAN model used a Finite Element mesh but more recent modelling uses a nested grid method. In either case, the models use larger grid elements in the deep sea areas and smaller grid elements in the study area. The data in the study area is of sufficient resolution in either the 2012 SWAN DEM or the newer NOAA/ONC DEM considering the requirements of the modelling software.

3.2 Data Extent

The NOAA/ONC DEM incorporated the northernmost panels from the NOAA Digital Coast Project, therefore the DEM extends farther south that the existing SWAN model. This area passes through a narrow portion of the Strait of Georgia and into the sheltered waters of Samish Bay, as a result, extending the model domain south. The effect of extending the model further south is unlikely to significantly alter design wave heights in Mud Bay due to the narrowing of the channels and the lack of wave energy expected to propagate through those narrow channels.

4 CLOSURE

Thank you for inviting NHC to attend this worthwhile DEM Workshop. We look forward to applying the methods learned and information obtained to future City of Surrey projects. Please feel free to contact Josef Drechsler via email at jdrechsler@nhcweb.com if you have any questions or would like to further discuss the workshop.

Sincerely,

Northwest Hydraulic Consultants Ltd.

Prepared by:

Josef Drechsler, GISP
GIS Analyst

Reviewed by:

M. Sarah North, GISP
Associate / GIS Analyst

Monica Mannerstrom, PEng
Principal/ Hydrotechnical Engineer

Grant Lamont, PEng
Principal/Coastal Engineer

APPENDIX A – ONC DEM Workshop 2019 Outline/Schedule

Part 1: DEM Development (5 Days)

Day 1: Data Sources and File Formats

- Introduction to DEMs
    - New developments with NOAA NCEI DEMs
        - Tiled DEMs
        - DEM consistency across spatial scales
        - DEM uncertainty estimates and spatial metadata
        - Improved DEM discovery and data access
    - Computer access and setup
    - Data for Workshop DEMs
        - Discuss participants DEM region and data
            - Determine boundaries and resolution
            - Participants will each have their own DEM region and data

Day 2: Data conversions and transformations

- Common data formats and conversion methods
        - ASCII xyz data for developing DEM
        - GDAL
    - Common horizontal datums and transformation methods
        - Proj.4
    - Common vertical datums and transformation methods
        - CGVD1928 - CGVD2013
            - http://webapp.geod.nrcan.gc.ca/geod/tools-outils/gpsh.php
        - NAVD88
        - Tidal Datums
            - (MHW, MHHW, MSL, MLW, MLLW, Etc.)
        - VDatum (USA only)
        - Tide Gauges
            - Applying constant vertical offset
        - Conversion Grids
        - Determining appropriate Vertical datum
            - Users needs

Day 3: Data Evaluation and editing

- GNU/Linux command-line tools for ASCII xyz data
        - Awk, grep, sed, head, less, etc.
    - Visualizing ASCII xyz data
        - Convert to common vector format
            - Ogr2ogr
        - Grid/TIN data
    - Visual assessment
        - ArcGIS
        - Hillshades

Day 4: Digital Coastline and Bathymetry Grid

- Introduction to use of digital coastline in DEM development
        - Wet/Dry mask
    - What to include/exclude in digital coastline

        - Water-flow
        - Common features along coastlines:
            - Piers
            - Jetties
            - Marinas
        - Rivers and canals
    - Bathymetry grid
        - Use of bathymetry grid for poor near-shore bathymetry coverage
        - GMT commands
            - Blockmedian, surface, etc.
        - Bathymetry Grid evaluation
            - Visualize
            - Comparison with source data

Day 5: Building DEMs

- Software and tools for DEM development
        - MBSystem
        - GMT
        - GDAL
    - Assigning weights to datasets
        - MBSystem
        - GMT
    - Interpolation methods
        - Spline
    - Formatting and datum transformations

Part 2: DEM Evaluation (3 Days)

Day 1 & 2: DEM Evaluation

- Visual QA/QC
        - Hillshades
        - Slope Map
    - Accuracy Assessment
        - Split-sample
        - Control Points
        - Comparison with original data
    - Estimating DEM Uncertainty

Day 3: DEM Documentation

- Dataset documentation
    - Metadata

Etcetera

Software Requirements and Recommendations:

- Free/Open-Source software
    - GNU/Linux OS and core utilities
    - Python
    - GMT 5.x

- MBsystem
- GDAL
- LASTools (free version)
- QGIS
- *Guile & GeoMods*

- Commercial software (optional)
  - ArcGIS
  - Global Mapper
  - LASTools (licensed version)

Chapter 7

Conceptual Fish Passage for Serpentine River Sea Dam

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northwest hydraulic consultants ltd

NHC Ref. No. 3005324

12 December 2019

City of Surrey, Engineering Department, Utilities Division
4th Floor, 13450 104 Ave
Surrey, BC
V3T 1V8

Attention: **Matt Osler, P. Eng., MBA**
Sr. Project Engineer

Re: **Conceptual Fish Passage for Serpentine River Sea Dam**
Preliminary Draft Report

1 INTRODUCTION

In October 2015, Northwest Hydraulic Consultants Ltd. (NHC) completed a conceptual design of a fish passage gate in the Nicomekl River Sea Dam for City of Surrey (the City). As per the City's email of 4 October 2019, a similar but somewhat simplified assessment is now required for the Serpentine River Sea Dam. Under the City's Disaster Mitigation and Adaptation Fund (DMAF) program the Serpentine Sea Dam is to be replaced and relocated roughly 2.6 km downstream of its current location (near King George Blvd) to near the Highway 99 Bridge. The present sea dam fish slot assessment is to assume the proposed new location of the dam but the same side-mounted gate design as for the existing dam.

NHC (2015) outlined fish passage problems associated with the Nicomekl sea dam gates, particularly during the month of October when salmon return to spawn in the river. Tidal gates are open only when hydraulic forces are sufficient to open them. When the gates are closed, the returning adult salmon are subject to increased predation in the estuary. On rising tides, when fish often move upstream, tidal gates are closed and this limits critical fish passage. A common modification of large tidal gates is the installation of a "fish door" – essentially a small flap gate activated by differential head – that opens on the rising tide. (For a summary of background information, please refer to the NHC 2015 report.)

With the planned replacement of the Serpentine Sea Dam, other fish passage methods such as fishways can also be considered. However, as a starting point, fish slot designs similar to the three Nicomekl slots previously evaluated, are to be assessed. The slot design would generally be closed outside of the fish migration period in October to minimize saltwater intrusion upstream of the dam. For the purpose of the present project, it was assumed that the type of fish and timing of their return in the Serpentine are the same as in the Nicomekl, however operating procedures would need to be established and may vary from year to year.

2 SCOPE OF WORK

The City requested that similar modelling and analysis be performed for the Serpentine dam as completed for the Nicomekl. However, due to time constraints, the 3D water quality modelling was eliminated from the present project. The following two sections outline the specified scope of work.

2.1 Modelling and Analysis

The design of the fish slot, assumed to be installed in one of the Serpentine sea dam gates, needs to balance hydraulic, water quality and fisheries requirements. Between 2012 and 2015, NHC developed and refined a HEC-RAS model of the Serpentine and Nicomekl Rivers for the City's Climate Change Floodplain Review Phase 1 and Phase 2 projects (CCFR I and II). A continuous simulation approach was applied to analyze the joint probability of ocean and riverine levels.

The CCFR II HEC-RAS model was used for the present work and the assessments were based on typical and extreme water level conditions for the month of October. The typical and extreme water level conditions were selected from a 47-year record.

There are some limitations related to modelling fish slots in HEC-RAS. It is not possible to insert slots within gates, and consequently the slots were modelled as independent openings within the channel section. The gates themselves are modelled as openings having rule curves for when they open and close. These hydraulic modelling simplifications likely have minor impacts on results.

The following impacts were investigated for three slot configurations:

1. **Hydraulic impacts**: changes in water levels upstream of the sea dam. The largest changes in water level are expected to occur during periods of high tide levels when the gates are completely closed (no river outflow) and very low river inflows from upstream.,. In this instance, the proposed fish slot is expected to have little impact on upstream river flood water levels, as the slot size is relatively small.
2. **Water quality impacts:** anticipated changes in water salinity upstream of the sea dam. A fish slot will allow saline water to flow upstream when the main sea dams are closed and will potentially increase the salinity of water in the Serpentine River which could have potential impacts to water license holders.
3. **Fisheries impacts**: anticipated changes in fish successfully migrating upstream of the sea dam. The larger the fish slot, the higher the probability that the fish will find and swim through the slot.

2.2 Conceptual Design and Reporting

Based on model results, the optimum slot design is to be developed and any operational issues summarized. A tentative configuration is shown at the end of this report.

3 HYDRAULIC MODELLING

3.1 Typical and extreme water level conditions

The available 47-year historic record, with a 30 minute interval, was analysed for all Octobers and resulting water level percentiles are shown in **Figure 1** and **Table 1**. These percentiles were used to set the height of the three fish slots modelled (i.e. the 90th percentile is the value below which 90% of the water levels occur).

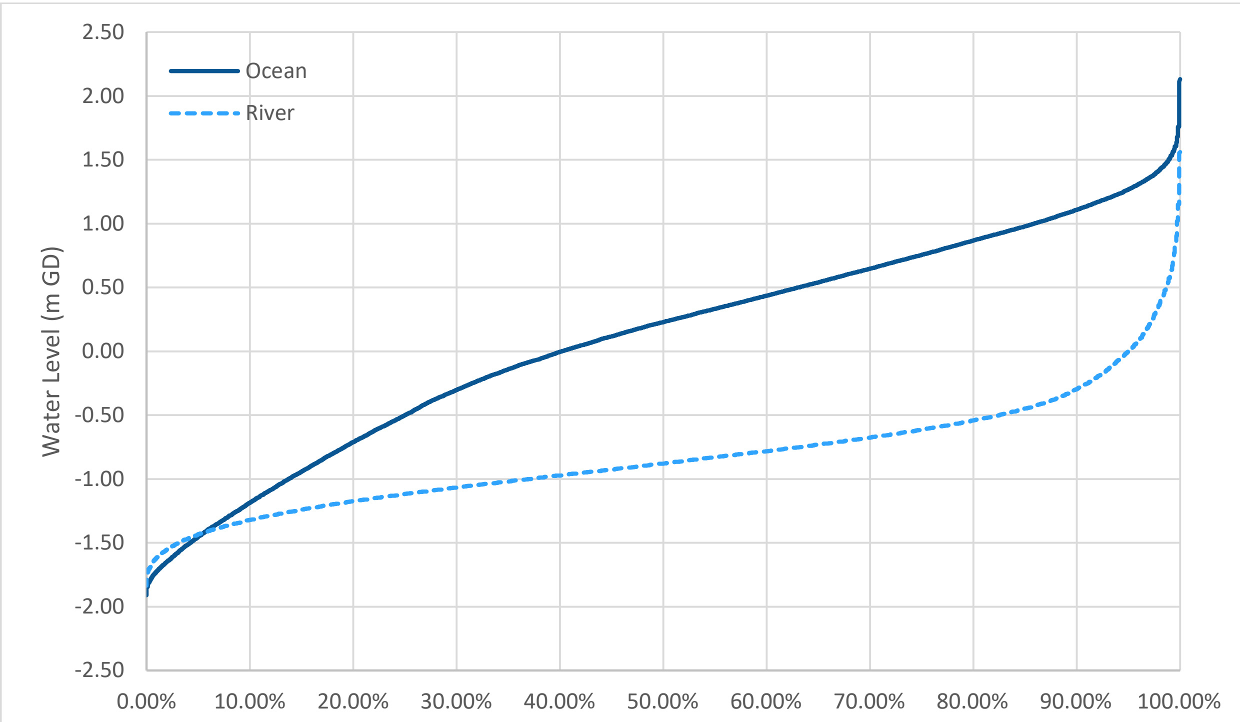


Figure 1. Percentile plot of modelled ocean and river water levels at the current Serpentine sea dam for October (1964 to 2010).

Table 1. Modelled water level percentiles at current Serpentine River sea dam for October (1964 to 2010) using CFPR R1.

Percentile	Modelled Ocean Water Level (m GD)	Modelled River Water Level (m GD)	Difference in Water Level Across Sea Dam (m)
Maximum	2.13	1.56	3.06
99th	1.52	0.60	2.59
98th	1.42	0.37	2.47
95th	1.27	0.00	2.24
85th	0.98	-0.45	1.84
75th	0.75	-0.61	1.57
65th	0.54	-0.73	1.32
55th	0.33	-0.83	1.07
50th	0.23	-0.88	0.94
45th	0.12	-0.93	0.80
35th	-0.14	-1.02	0.50
25th	-0.50	-1.12	0.16
15th	-0.95	-1.24	-0.06
10th	-1.19	-1.32	-0.14
5th	-1.45	-1.43	-0.21
2nd	-1.65	-1.55	-0.28
1st	-1.72	-1.62	-0.34
Minimum	-1.91	-1.84	-1.00

The record was also analyzed to identify extreme and typical water level conditions for model simulations. The selected periods for model simulations are listed in **Table 2** and include the maximum head difference that occurred in October across the current location of Serpentine sea dam and peak flood levels upstream of the sea dam. The largest head difference occurs during high tide and low river water levels.

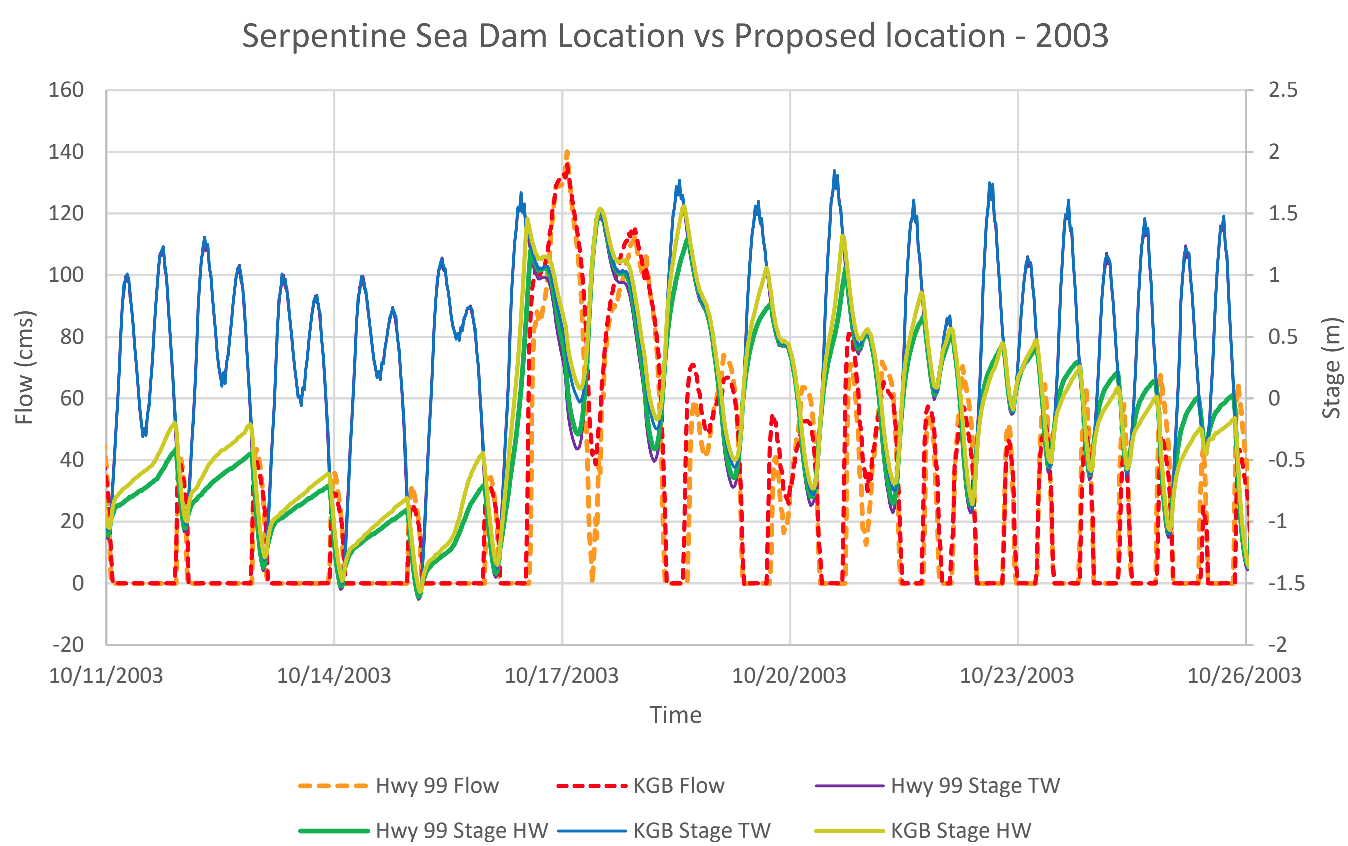
Table 2. Selected simulation periods for typical and extreme water levels.

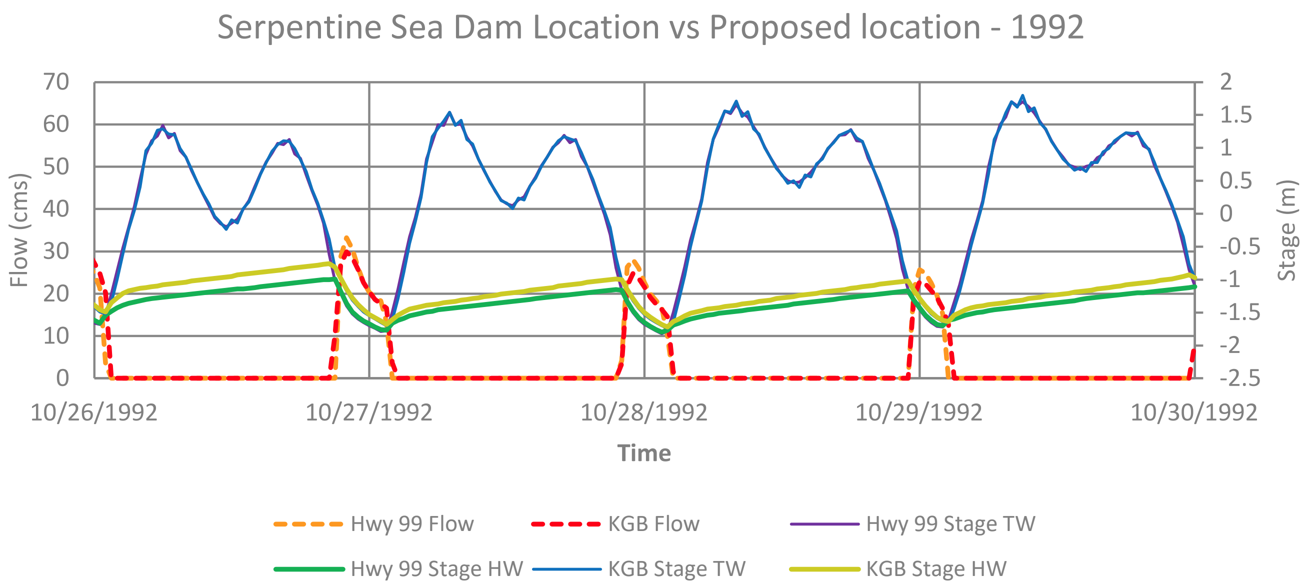
Condition	Date
Maximum Head Difference (3.06 m)	25-Oct-1992 to 29-Oct-1992
Large Flood Event	10-Oct-2003 to 27-Oct-2003
Typical Conditions	01-Oct-2008 to 31-Oct-2008 01-Oct-2009 to 31-Oct-2009 01-Oct-2010 to 31-Oct-2010

3.2 Relocated Sea Dam

The Serpentine Sea Dam will be replaced and relocated roughly 2.6 km downstream from its current location. The 1D HEC-RAS model was used to assess the effect of relocating the sea dam over a range of flood conditions. The modelling was done for future system conditions consisting of no dike overtopping except at spillway locations. All spillways were represented using design ultimate rather than existing geometry and invert elevations.

The impact of moving the sea dam on the hydraulics is fairly minimal, as seen in **Figure 2**. There is essentially no impact to the tailwater elevations of the dam. A slightly higher impact is seen on the headwater. During high river inflows; the stage at the current sea dam location is up to 0.5 m higher (typically 0.15 m higher). By shifting the sea dam downstream, more channel storage volume is achieved, lowering the upstream flood levels. The flows are also very similar (generally within 10 m^3/s), with the peak flow at the proposed new location of the dam being slightly higher than at the current location.





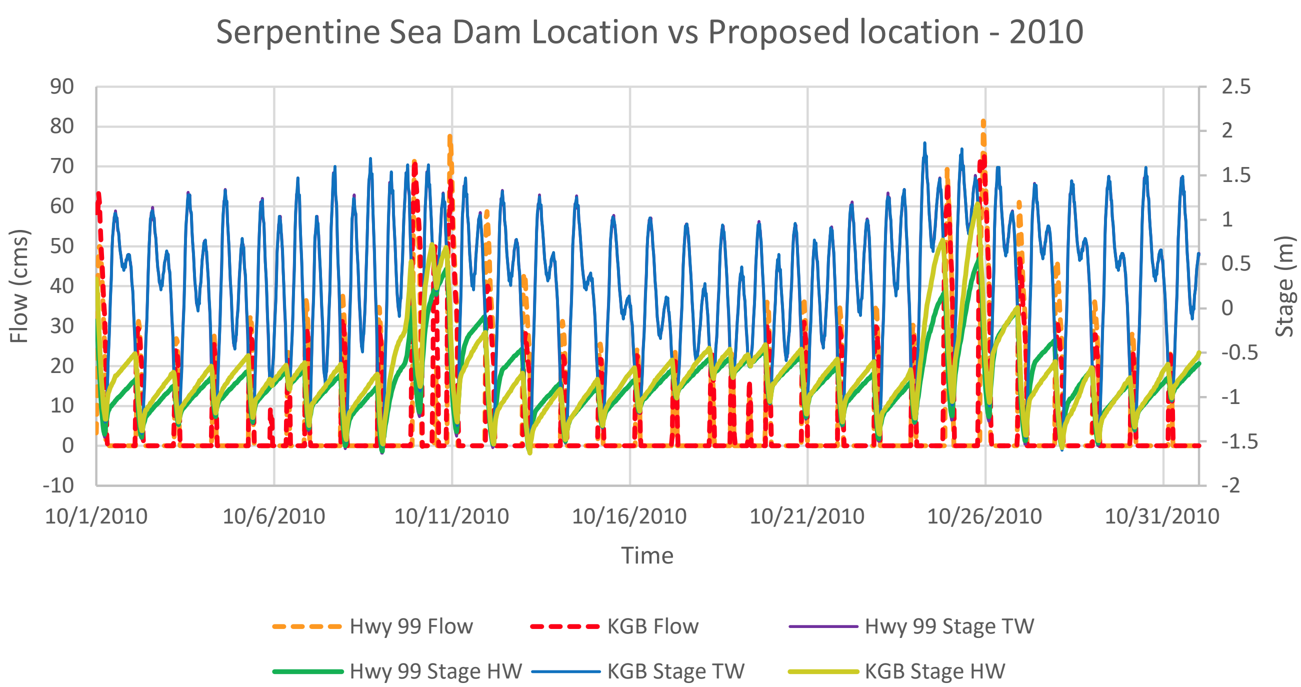


Figure 2: Modelled water levels for different flood conditions for the current location (KGB) and the proposed location (Hwy 99) for the Serpentine Sea Dam

3.3 Modelled fish slot geometry

Three fish slot heights/invert elevations were modelled (**Table 3)**. A typical fish passage width of 300 mm was selected while the invert and obvert elevations were selected based on the ocean water level percentiles summarised in **Table 1**. The 300 mm slot width is based on the standard width used in vertical slot fishways to allow passage of a wide range of salmon species and sizes.

Table 3. Fish slot geometry.

Geometry	Slot 1	Slot 2	Slot 3
Width	300 mm	300 mm	300 mm
Invert	5th percentile -1.45 m GD	15th percentile -0.95 m GD	25th percentile -0.50 m GD
Obvert	95th percentile 1.27 m GD	95th percentile 1.27 m GD	65th percentile 0.54 m GD
Height	2.7 m	2.2 m	1.0 m

3.4 Hydraulic Impacts

Hydraulic impacts consist of changes in water levels upstream of the sea dams. The 1D HEC-RAS model was used to assess the effects of the conceptual slot gate dimensions and configurations over a range of flood conditions with the current sea dam relocated downstream by 2.6 km. The slot gates were compared against the base case where no fish slot was included. The modelling was done for future system conditions consisting of no dike overtopping except at spillway locations. All spillways were represented using design ultimate rather than existing geometry and invert elevations (See NHC's CCFR Phase 2 Report for model details). Flood levels modelled under future system conditions are expected to be higher in the reach immediately upstream of the sea dam where the impacts from the fish slot would be most noticeable.

3.4.1 October 1992

The largest changes in water level are expected to occur during periods of low (insignificant) river flow and high tide level. As expected, simulation of the October 1992 tide showed that adding Slot 1 increased the base case peak water levels by 0.1 m. This effect was seen over a distance of 17 km upstream from the sea dam however peak water levels computed with Slot 1 (-0.5 m GD) correspond roughly to the 85th October percentile river levels (in height) and are about 1 m below typical flood levels and 2.5 m below peak modelled flood levels (December 2007).

3.4.2 October 2003

Simulation of the October 2003 flood event showed that adding Slot 1 did not affect the base case peak water levels (1.52 m). The Slot 2 and Slot 3 geometries had less significant impact on October 2003 water levels. Peak modelled water levels in October 2003 (1.52 m GD) are lower than the peak modelled water level from December 2007 (2.02 m GD). In conclusion, the proposed fish slots would have negligible or no impact on peak river flood levels anticipated during the month of October.

3.4.3 October 2008-2010

Simulation of the October 2008-2010 period with typical tides shows minimal impact, similar to the two extreme cases modelled. The largest changes occurred during large tidal differences, but the scale of those swings was not as large as for the 1992 event and did not see as large of an impact as the 1992 simulation. Large inflow events did not impact the hydraulics.

3.5 Water quality impacts

Moving the Serpentine sea dam downstream by 2.6 km, to between Highway 99 and Colebrook Pump Station, will reduce salt intrusion and have no negative impact to water licence holders. However, a fish slot would allow some saline water to flow upstream when the sea dam gates are closed and has the potential to increase the upstream salinity.

Results from the modelled periods in October provide average and maximum volumes of water moving upstream and downstream during one tidal cycle (defined by when the gate is activated until the gate is reopened) (**Table 4**).

Table 4. Modelled average and maximum volumes moving across the relocated sea dam during one tidal cycle.

	Simulation Period		Base Case	Slot 1	Slot 2	Slot 3
Total volume (m^3 x 1,000) moving upstream through fish slot during one cycle when sea dam gates are closed	Oct 1992 (5 days)	Max	-	124	87	48
		Mean	-	45	30	17
	Oct 2003 (17 days)	Max	-	100	66	39
		Mean	-	19	13	7
	Oct 2008, 2009 and 2010 (91 days)	Max	-	130	93	51
		Mean	-	33	22	12
Total volume (m^3 x 1,000) moving downstream through sea dam when gates are open	Oct 1992 (5 days)	Max	747	696	730	715
		Mean	457	399	439	422
	Oct 2003 (17 days)	Max	6,906	6,821	6,881	6,851
		Mean	1,176	1,137	1,164	1,151

	Oct 2008, 2009 and 2010 (91 days)	Max	1,788	1,743	1,766	1,757
		Mean	466	403	446	429

The method used to investigate the changes in salinity upstream of the sea dam resulting from the addition of the fish slot included a simple water balance model to estimate the salinity of a fully mixed volume of water over several tidal cycles. The fully mixed volume was estimated to cover a 2.6 km distance upstream of the sea dam. Time series of fresh and saline water flowing into and out of the control volume were obtained from the HEC-RAS model.

The model assumes a salinity of 25 ppt for water moving upstream through the fish slot during periods when the sea dam gates are closed. This salinity value was selected based on a series of 22 field measurements of conductivity on the downstream side of the Nicomekl sea dam (July 2012 to August 2014). These measurements were provided by the City and ranged in salinity from 0.6 ppt to 25.8 ppt. The higher value of 25 ppt is likely more representative of the salinity of water at high tide and provides a more conservative estimate for this analysis. Further collection of salinity in October would be recommended for more detailed analysis.

Simple Water Balance

Using a simple water balance model, the salinity of the fully mixed volume (St) was computed for all three fish slot configurations for the simulation periods listed in **Table 2**. Modelled output (30-minute intervals) from the HEC-RAS model were used with the following water balance equation:

$$St_i = \frac{(St_{i-1} * Vt_{i-1}) + (Ss_{i-1} * Vs_{i-1}) + (Sf_{i-1} * Vf_{i-1}) - (Sm_{i-1} * Vm_{i-1})}{(Vt_{i-1} + Vs_{i-1} + Vf_{i-1} - Vm_{i-1})}$$

where: V_t = total volume of mixed water 2.6 km upstream of Serpentine River sea dam (m^3)

V_s = volume of saline water moving in through fish slot (m^3)

V_f = volume of fresh water flowing in from flood boxes, tributaries, and the Serpentine (m^3)

V_m = volume of mixed water flowing out through Serpentine River sea dam (m^3)

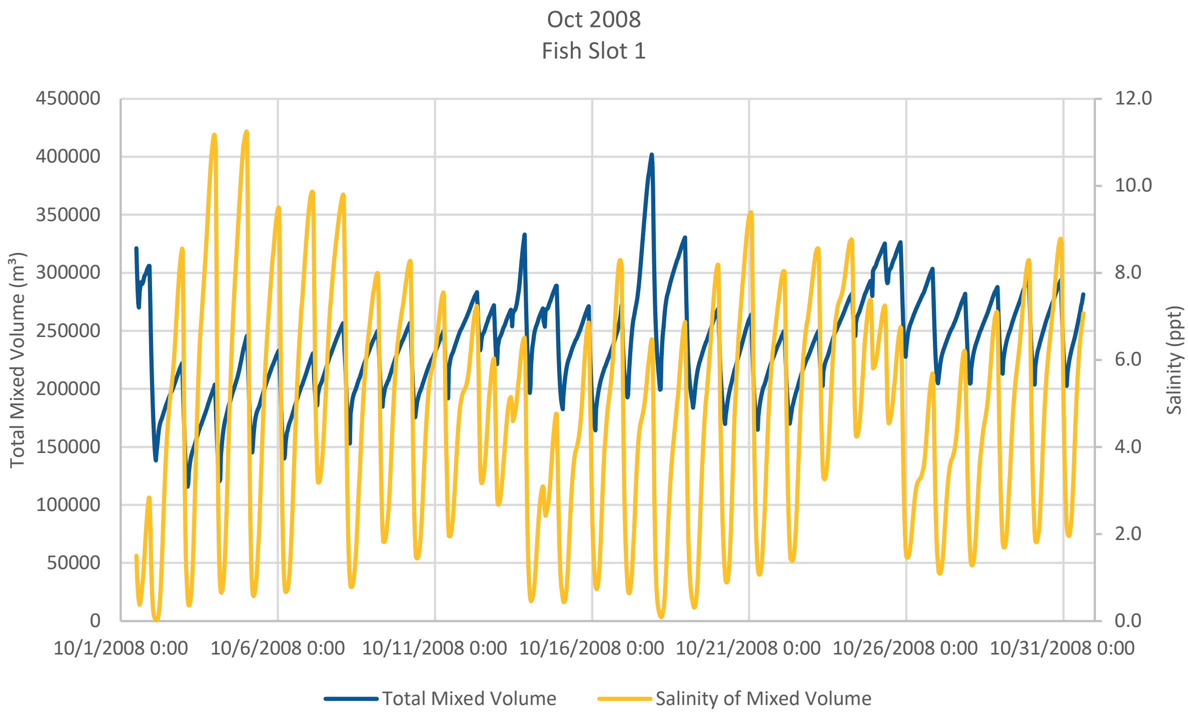
S_t = salinity of V_t (ppt)

S_s = salinity of V_s (25 ppt)

S_f = salinity of V_f (0 ppt)

S_m = salinity of V_m (ppt)

Example plots are included below in **Figure 3** for the October 2008 period with Fish Slot 1 and Fish Slot 3. Computed salinities are summarised in **Table 5**.



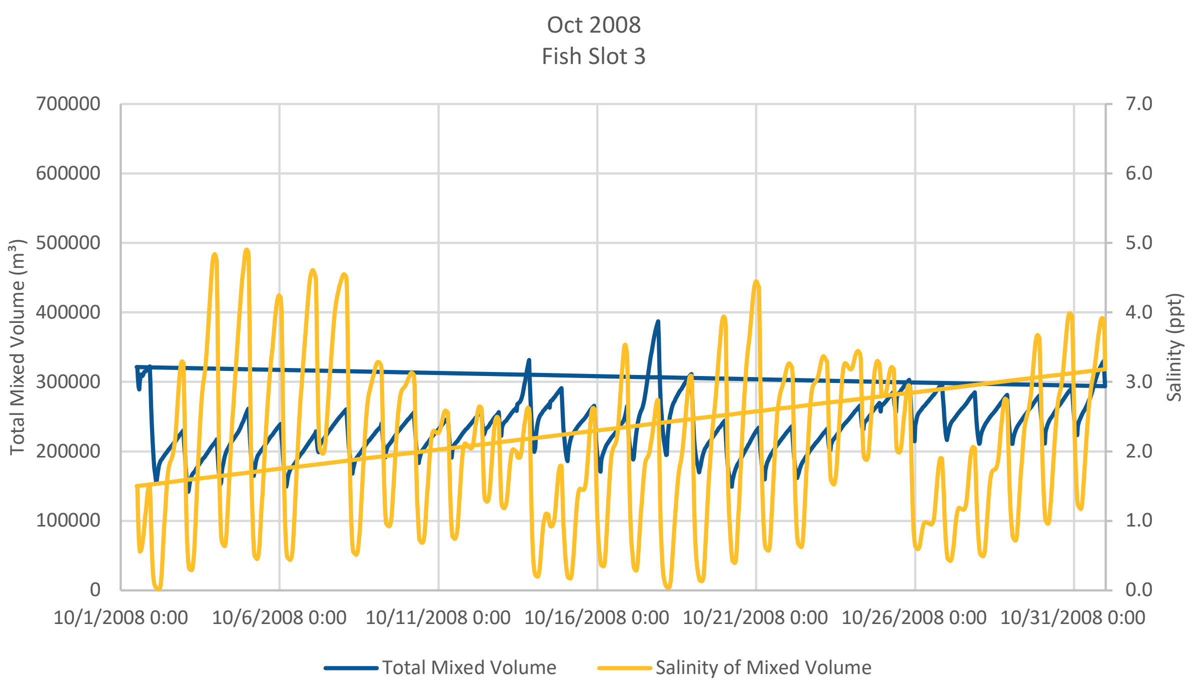


Figure 3. **Computed salinity of mixed volume of water 2.6 km upstream of relocated sea dam with fish slot 1 (above) and fish slot 3 (below).**

Table 5. Computed salinity of fully mixed volume of water.

	Computed salinity (St) (ppt)			
	Base Case	**Slot 1**	**Slot 2**	**Slot 3**
Max	0.0	11.7	9.4	5.8
Mean	0.0	4.2	3.0	1.9
Min	0.0	0.0	0.0	0.0

Notes:
- Statistics calculated for periods listed in Table 2.
- Salinity of water downstream of sea dam specified as 25 ppt
- Initial volume of water assumed to be 321,185 m³ for a distance of 2.6 km upstream of sea dam.

The modelling results provide an indication of the maximum range of salinity increases that can be expected with the three slot configurations modelled. The results assume a background salinity concentration of 0 ppt within the Serpentine River, actual background concentrations may vary.

The simple water balance results assume the system is fully mixed and that is not often the case in an estuary. Saltwater is denser than fresh water and there is typically some stratification of the layers where the two mix. Based on 3D modelling of the Nicomekl River, we can expect there will be some stratification of the water with the higher concentration saltwater at the bottom and the fresh water on the surface. A more detail analysis is required to estimate at what depth, and under what conditions the stratification exists.

3.6 Impacts to Fish Migration

The overall effectiveness of the fish slots is a function of the size of the door, the location of the slot on the sea dam gate, and the total number of slots introduced. The fish slot geometries modelled cover a range of heights for a standard width of 300 mm. It is not possible to accurately assess the biological fish movement and passage response to the slots prior to installation.

For the modelled slot geometries, there will be periods of time when the sea dam gates are closed, and the ocean water level is below the invert of the slot. During these periods, salmon will be unable to swim through the fish slot and will be vulnerable to predation. Field observations show that the sea dam gates do not close instantaneously as soon as the downstream water level exceeds the upstream water level. However, it was assumed that they do in order to estimate the number of hours when fish may be susceptible to predation.

The results are summarised in **Table 7** and indicate that for an average month of October, the addition of fish Slot 1, 2 or 3 will provide opportunities for fish passage 99.5%, 96% and 91% of the time respectively, compared to 18% under present conditions.

Table 6. Estimate of hours when fish are vulnerable to predation.

Hours for month of October only	Total for 47-year period (01-Oct-64 to 31-Oct-10)	Average month of October	Percentage of time when fish are vulnerable to predation
Total number of hours	34,968	744	-
Total number of hours when sea dam gates are closed	28,590	608	82%
Total number of hours when sea dam gates are closed, and ocean water level is below invert of Slot 1	204	4	0.5%
Total number of hours when sea dam gates are closed, and ocean water level is below invert of Slot 2	1,283	27	4%
Total number of hours when sea dam gates are closed, and ocean water level is below invert of Slot 3	3,419	68	9%

4 SUMMARY AND RECOMMENDATIONS

The impacts on flood levels and flows from relocating the Serpentine sea dam 2.6 km downstream of its present location was assessed. The preliminary hydraulic and water quality impacts of three conceptual designs of a fish slot in the relocated dam were then evaluated. The analysis assumed that the fish slot will be closed except during the October fish migration period.

The summarized findings are:

1. The CCFR II HEC-RAS model was used to assess the effects of relocating the Serpentine Sea Dam downstream 2.6 km near Hwy 99 crossing. Relocation of the sea dam is expected to have minimal impact on the hydraulics of the river. It will have no impact on the tailwater elevations, but the headwater elevations can be as much as 0.5 m lower but typically 0.15 m lower than the current location. The peak flows of the river are very similar and typically within 10 m^3/s.

2. Conceptual slot gate dimensions and configurations were modelled in the sea dams relocated position over a range of flood conditions. Under future conditions (no dike overtopping except at spillways set to ultimate geometry), hydraulic modelling showed that the operation of a slot gate will have no impacts on upstream flood levels from an event similar to the October 2003

flood. The modelled October 2003 event is the largest flood having occurred in the month of October from 1964 to 2011. Peak modelled water levels in October 2003 (1.52 m GD) are much lower than the peak modelled water level from December 2007 (2.02 m GD).

3. Conceptual designs were assessed for fish passage utility on the basis of the number of operational hours when the sea dam gates are closed. Slot 1 provides the highest percentage of fish passage opportunities (99.5%) relative to Slot 2 (96%) and Slot 3 (91%) compared to existing conditions (18%). Slot 1 is the largest opening (2.7 m x 0.3 m) and Slot 3 is the smallest (1.0 m x 0.3 m).

4. The 1D water quality modelling assessed potential changes in salinity upstream in the Serpentine River assuming fully mixed conditions. Average increases in salinity above background levels were simulated with Slot 1, Slot 2 and Slot 3 to be at 4.2, 3.0, and 1.9 ppt at a distance of 2.6 km upstream of the sea dam.

The assumptions used and technical findings of the study indicate potential small deteriorations of water quality. However, there would be significant benefits from restoring fish passage:

1. Of the three fish slot geometries modelled, Slot 3 geometry had the least impacts on water quality and provided a large range of upstream fish passage opportunities (91% of time when sea dam gates are closed). The design suggests that a small slot will have no measurable hydraulic effects, minor water quality effects, and potentially large environmental benefits.

2. The period of upstream fish migration and potential use of the fish slot – month of October - is outside of the agricultural growing season but water may be withdrawn for other uses. NHC suggests that further assessment of water intake locations and depths may be required to see if intakes are within the zone of influence, based on the modelling and monitoring.

3. A preliminary fish slot gate design is provided. It is adjustable in terms of size and elevation and can be closed completely at any time. The flexible operation of the gate provides an opportunity to field test and monitor different configurations and adjust to potentially changing conditions in the Serpentine River. The gate is relatively small and can be fabricated and installed on an existing tide gate assembly.

With the relocation of the Serpentine sea dam comes different options to improve fish passage. A modern replacement structure will be subject to more stringent regulations and the installation of a fish slot is only one alternative. Other alternatives, such as fish ladders, should be considered early in the design and approval processes for relocating the sea dam.

5 CLOSURE

If you have any questions, please do not hesitate to contact us at our North Vancouver office.

Sincerely,

Northwest Hydraulic Consultants Ltd.

Prepared by:	**Reviewed by:**
Vanessa Bennett, P.Eng, Hydrotechnical Engineer	Monica Mannerström, P.Eng Principal

DISCLAIMER

This document has been prepared by **Northwest Hydraulic Consultants Ltd.** for the benefit of **City of Surrey** for specific application to the **Conceptual Fish Passage for Serpentine River Sea Dam**. The information and data contained herein represent **Northwest Hydraulic Consultants Ltd.** best professional judgment in light of the knowledge and information available to **Northwest Hydraulic Consultants Ltd.** at the time of preparation, and was prepared in accordance with generally accepted engineering practices.

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