Modelling Potential Impacts of Sea-Level Rise on Fish Habitat Offsets

by

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Abstract

The numerical model MarshMorpho2D developed by G. Mariotti (2018, 2020) was used to simulate the potential impacts of sea-level rise on a tidal wetland offset to be built in the Fraser River near Vancouver, British Columbia. Eighteen simulations with a maximum length of 80 years were run using three sea-level rise conditions, three suspended sediment concentrations and two critical sheer stress values. Simulations with a higher rate of sea-level rise had greater sediment deposition and wider channel development. Due to sediment deposition, the model projected that the proposed marsh configuration will not persist until the end of the century. It remains uncertain how changes in marsh configuration may impact ecological function at the site. Offsetting is important for minimizing the risk of adverse impacts on the environment. It is also important to understand how changing environmental conditions may impact offset viability in the future. This research provides a first step in developing the tools necessary to model the impacts of sea-level rise on tidal wetlands within the Fraser River.

Keywords: Tidal wetland, marsh, offset, sea-level rise, numerical modelling, MarshMorpho2D

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Cheers,

Kevin

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List of Acronyms

BC	British Columbia
BCIT	British Columbia Institute of Technology
CSDMS	Community Surface Dynamics Modelling System
CSS	Critical Sheer Stress
DEM	Digital Elevation Model
DFO	Department of Fisheries and Oceans
HHW	Higher High Water
IPCC	International Panel on Climate Change
MOTI	Ministry of Transportation and Infrastructure
MSL	Mean Sea-Level
NHC	Northwest Hydraulics Consultants
RCP	Representative Concentration Pathway
RSL	Relative Sea-Level
SFU	Simon Fraser University
SLR	Sea-Level Rise
VLM	Vertical Land Movement

Chapter 1.

Introduction

1.1. Overview

A tidal marsh is defined by the United States Environmental Protection Agency (2018) as a wetland that is frequently or continually inundated with water, characterized by emergent soft-stemmed vegetation adapted to saturated soils. Tidal marshes may occur in fresh, brackish or saline water, but they are all influenced by the motion of ocean tides. Future sea-level rise (SLR) is projected to cause shifts in the extent of tidal wetland coverage on the Pacific coast of North America by the year 2100 (Oregon Climate Report 2010; Thorne et al. 2015; Best et al. 2018; Thorne et al. 2018). However, there is a large amount of uncertainty in SLR projections, both globally and regionally. Current SLR projections for the western coast of North America can range from 0.15 to 2.5 m over the next century (Parris et al. 2012; Kopp et al. 2017; Sweet et al. 2017; Thorne et al. 2018). As tides slowly rise, the necessary growth conditions for wetland plants will be altered. If sea-level rises past a certain threshold, some tidal wetlands may be converted to mudflats void of vegetation (Thorne et al. 2015; Drexler et al. 2019). This would cause a loss of many valuable ecosystem services provided by coastal wetlands such as attenuation of storm surge, carbon sequestration and habitat for diverse fauna (Mariotti & Fagherazzi 2010; Alizad et al. 2016). Understanding how the growing threat of SLR may impact tidal marshlands will provide support to guide their protection and restoration in the future (Alizad et al. 2016; Tabak et al. 2016).

The threat of future SLR therefore has important implications for the longevity of many tidal marsh restoration projects. One project that is potentially threatened by SLR is the Pattullo Bridge Replacement and Fish Habitat Offsetting. The project is located in the Fraser River, approximately 20 km southeast of Vancouver, British Columbia (BC). The Fraser River Basin drains 240,000 km^2 of BC and is made up of 13 major sub-watersheds (Déry et al. 2012). The Lower Fraser River has a flow regime driven by the annual melting of mountain snowpack in spring (March-June) when discharge typically reaches 6,000 to 10,000 m^3/s (Voss 2014). Peak flows dimmish over the course of the summer, often followed by a rain-driven fall peak. Throughout the rest of the year, baseflow runoff is driven by rainfall as well as some groundwater flow, with winter discharge typically in the range of 800 to 2,300 m^3/s (Voss 2014). The tidal portion of the Lower Fraser River extends near to Mission, BC, approximately 70 km upstream from the Strait of Georgia (Department of Fisheries and Oceans Canada 2021).

The BC Ministry of Transportation and Infrastructure (MOTI) has recently selected project contractors for the replacement of the Pattullo Bridge, with a joint partnership between Acciona Infrastructure Canada and Aecon Group Inc. In total, the project is expected to cost approximately $1.4 billion CAD (Chan 2020). Project components include, among others, the creation of a new four-lane, long-span bridge over the main channel of the Fraser River (MOTI n.d.). Habitat offsetting will be used to mitigate any potential project related impacts resulting from the installation of new bridge piers. Expected impacts include the loss of a small area of aquatic and riparian habitat as well as temporary exceedance of underwater noise thresholds (MOTI n.d.). As part of the habitat offsetting for this project, a tidal wetland will be constructed along the Fraser River, in close proximity to the newly built bridge. The offsetting site will be located at the Qiqéyt Foreshore, shown in Figure 1.

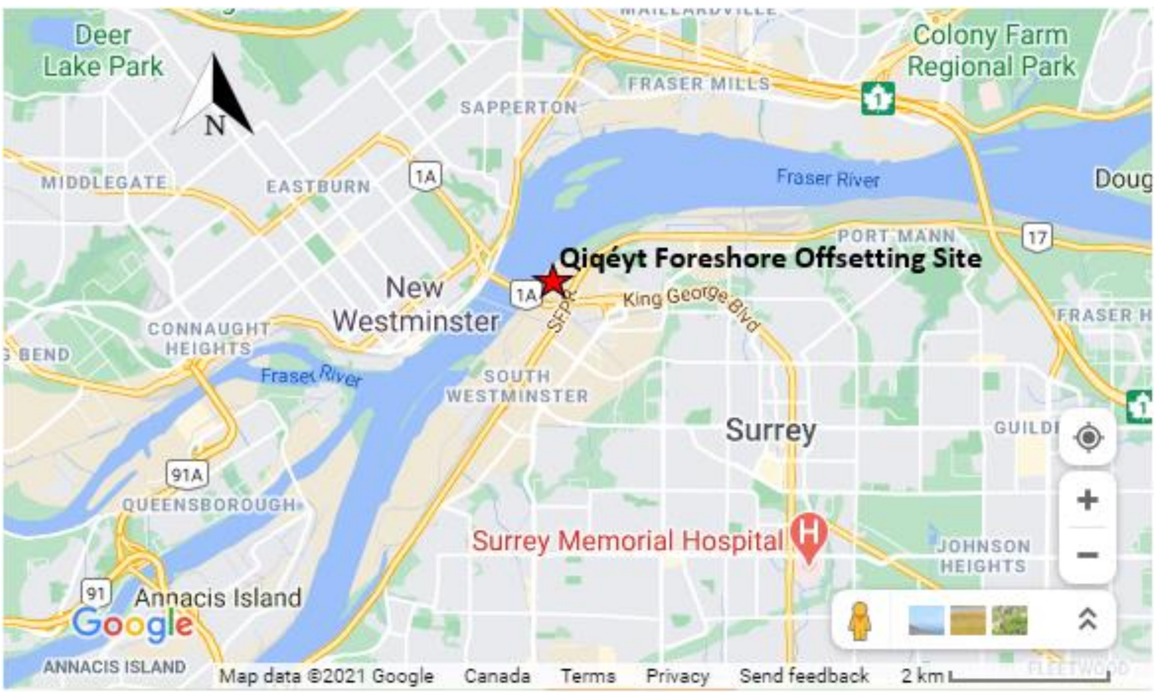

Figure 1 **Map displaying the location of the Qiqéyt Foreshore offsetting site in Surrey, BC. Base map taken from Google Maps ® (2021).**

The Qiqéyt Foreshore site is important for multiple reasons. This area is of great cultural and spiritual significance to multiple First Nations groups within the area, including Kwantlen First Nation, Kwikwetlem First Nation, Musqueam First Nation and Tsleil-Waututh Nation (Cook 2018). Historically, the village of Qiqéyt occupied from what is now Old Yale Road to 126th Street, approximately (Cook 2018). It is believed that the wetland areas along the riverbanks of Qiqéyt were artificially filled with rocks and earth to lay the foundations for a seasonal fishing village. In addition to having been a well-known fishing village, the area is also believed to have multiple historical burial sites (Cook 2018). Through discussions with First Nations groups, the site has been identified as a priority for indigenous cultural recognition (Fraser Crossing Group 2020). Part of this cultural recognition will incorporate an interpretive trail or cultural recognition area adjacent to the site (Fig. 2, black dashed line).

Currently, the Vancouver Fraser Port Authority has jurisdiction over the land, and was using it to dump scrap metal. MOTI is working to secure the land long-term to carry out offsetting. This site is also important from an ecological standpoint. This section of the Fraser River is used as a migratory passage by many species of fish. These species include the five species of Pacific salmon as well as white sturgeon, eulachon, steelhead, rainbow trout, Dolly Varden, bull trout and coastal cutthroat trout (Hatfield Consultants 2018). Certain species of fish also use the upland tributaries of the Fraser River for rearing and foraging. The presence of a tidal wetland at the Qiqéyt Foreshore may offer valuable habitat for juvenile fish to rest and forage before continuing their migration to the Pacific Ocean.

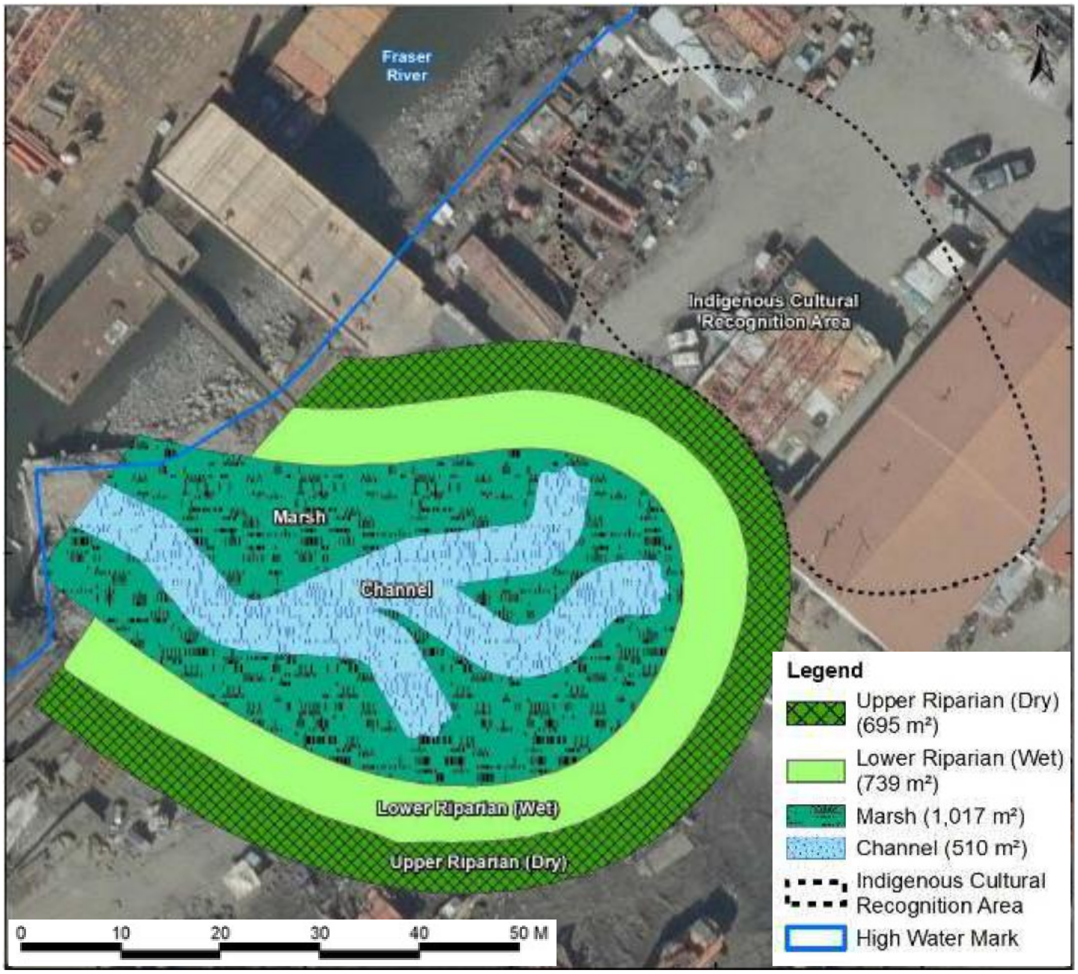

Figure 2 **The current Qiqéyt Foreshore wetland offsetting design. This figure was created by Fraser Crossing Group Project Corporation (2020) and provided by MOTI.**

Figures for the Qiqéyt Foreshore offset were developed by Fraser Crossing Group Project Corporation as well as Northwest Hydraulics Consultants (NHC). These were provided by MOTI and are presented in Figures 2 and 3. The proposed site will occupy approximately 4,450 m^2. This area will need to be excavated to lower the ground elevation by several meters, as elevation relative to the tidal frame is important for the ecological function of a wetland (Fraser Crossing Group 2020). A list of potential vegetation to be planted within the marsh area is provided in Appendix B. The marsh will be lined with 0.3 m of granular marsh subgrade covered in 0.7 m of marsh fill (Fraser Crossing Group 2020). The schematics illustrate that the marsh will include a channel system that will cover approximately 510 m^2. Marsh channels will be lined with 0.3 m of round cobble gravel material with grainsizes ranging from 50 to 200 mm. The marsh inlet leading to the Fraser River will be approximately 5 m long with a slope of 50% (Fraser Crossing Group 2020). When tides within the Fraser River rise, marsh channels will overflow to inundate the marsh area. Ground water is expected to play a minor role in increasing water levels within the marsh (Fraser Crossing Group 2020). Higher high water (HHW) at the site is currently 2.26 m above sea level (Fig. 3, source unknown). To inform offset designs about water levels in the area, Fraser Crossing Group used data from the Port Mann Bridge Pumping Station (station # 08MH126) from the past year. The pumping station at the Port Mann bridge is 6.5 km upstream from the Qiqéyt Foreshore site. It is expected that tidal effects will be greater at the site, due to the location being downstream from the pumping station (Fraser Crossing Group 2020). Daily average water elevations from October 2019 to October 2020 ranged from 0.3 to 1.8 m and average daily tidal range was 1.88 m (Fraser Crossing Group 2020).

The marsh area will be bound by sloping ground that connects to the existing ground level. This sloping ground will have a gradient of 50% and will be protected using erosion control matting (Fraser Crossing Group 2020). Riparian vegetation will be planted on the slope as well as on the existing ground-level. A list of potential riparian vegetation to be used in the project is provided in Appendix B. A fence will be constructed around the perimeter of the site and will have a length of approximately 390 m (Fraser Crossing Group 2020).

Elevations of the offsetting site have been designed to incorporate a variety of flooding patterns in different areas of the proposed marsh (Fraser Crossing Group 2020). In general, points of lower elevation such as the main marsh channel will presumably flood more frequently (when compared to higher marsh elevations). The marsh area outside of the proposed channel system will experience occasional flooding during periods of high tides and discharge from the Fraser River. Proposed elevations of the marsh area range from 0.8 to 1.8 m. This range of elevations may provide resilience to rising sea-levels because higher elevations might not be permanently inundated (Fraser Crossing Group 2020). The riparian area surrounding the marsh will be divided into the lower riparian area (wet) and the upper riparian area (dry) (Fig. 2, light and dark green areas, respectively). The lower riparian area will range from 1.6 to 2.2 m and will experience periodic flooding. The upper riparian area will have elevations of 2.2 m and above and will only experience flooding in non-typical periods of high water (Fraser Crossing Group 2020).

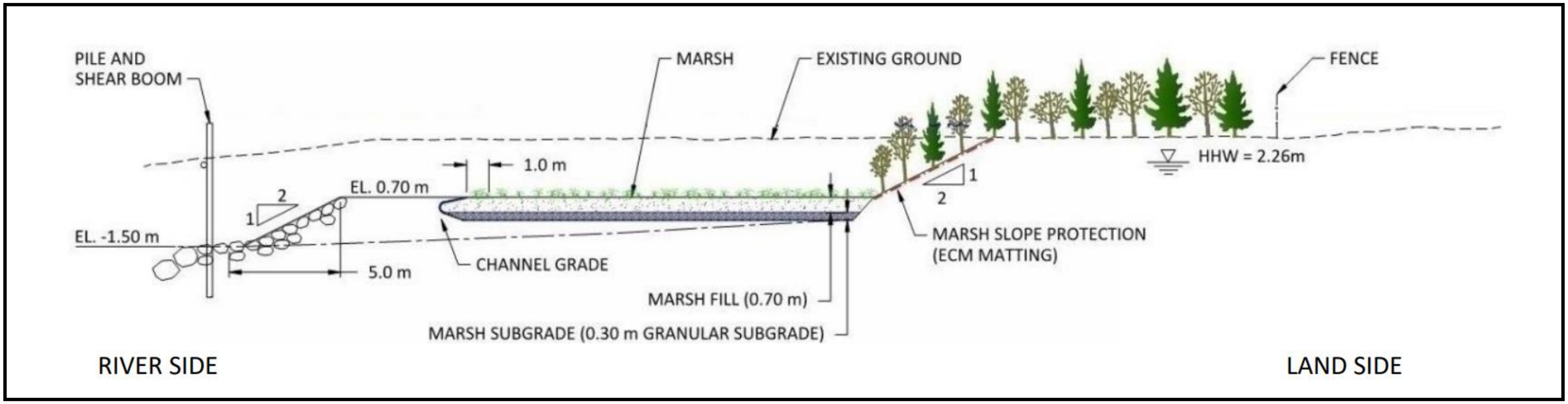

Figure 3 **Cross-section of the Qiqéyt Foreshore wetland offsetting design. Contains data on the elevation and slope of different features of the wetland. This schematic was created by Fraser Crossing Group Project Corporation (2020) and provided by MOTI.**

1.2. Literature Synthesis

To understand how coastal ecosystems are going to be impacted by SLR, it is useful to first gain an understanding of what causes SLR, and what methods are used to inform SLR projections. Since the year 1880, global mean sea-level (MSL) has increased by approximately 20 to 24 cm, with around 8 cm of that increase occurring after 1993 (Nerem et al. 2010; Church & White 2011; Hay et al. 2015). According to Parris et al. (2012), the two greatest causes of SLR in recent decades have been thermal expansion due to ocean warming and ice sheet loss. The relative contribution of these factors to SLR in the future remains uncertain. Thermal expansion and ice sheet loss are both driven by climate change, and the present climate change is driven mainly by anthropogenic emissions of greenhouse gases (Gehrels 2010; National Resource Council 2012). It is predicted that if society were to drastically reduce emissions in a short amount of time, SLR would still occur at an accelerated rate for centuries (Golledge et al. 2015; DeConto & Pollard 2016). Modern climate change projections incorporate what are known as representative concentration pathways (RCPs). The Intergovernmental Panel on Climate Change (IPCC) (n.d.) defines RCPs as scenarios that include time series of emissions, concentrations of greenhouse gases and land use/land cover. RCPs are categorized based on the amount of radiative forcing (expressed in Watts per square meter) that the pathway projects for the year 2100.

Regional SLR projections can vary between locations and be uncertain. For example, in the Pacific Ocean there are east to west differences in relative sea-level (RSL) and subsequent rates of SLR (Parris et al. 2012; Sweet et al. 2017). Even looking specifically at the west coast of North America, SLR projections vary along a north to south gradient. This is due, in part, to phenomena like El Niño and vertical land movement (VLM), which can occur due to processes like tectonic uplift and isostatic adjustment (National Resource Council 2012; Sweet et al. 2017). While there is a fair amount of confidence in SLR projections at shorter timescales, large uncertainties exist for projections out to the end of the century. Based on projections from the IPCC AR5 Report, and recommendations from the Provincial Government, the City of Vancouver is currently planning for 1 m of SLR by the year 2100. Updated recommendations are expected after the next report from the IPCC in 2022 (City of Vancouver Sustainability Group 2018). However, there is new evidence that has come out since the AR5 Report that indicates both the low-end and “worst-case scenarios” for future SLR are going to be greater than previously expected (Sweet et al. 2017). These SLR projections conclude that even under a low emissions pathway, it is very likely that sea-levels will rise at least 0.3 m above 2000 levels by 2100. Under the proposed “worst-case scenario”, sea-levels could be as high as 2.5 m above 2000 levels by 2100 (Kopp et al. 2017; Sweet et al. 2017). These SLR projections incorporate an RCP for which radiative forcing reaches greater than 8.5 W/m^2 by 2100.

Although sea-level will continue to rise in the future, it is possible for a tidal wetland to persist despite these changing conditions. There are two main pathways of marsh evolution that allow for this. The first pathway is through vertical accretion, wherein inorganic sediment and organic matter accumulate to raise the elevation of the marsh relative to MSL (Drexler et al. 2019). There are multiple factors that influence the rate of vertical accretion in a tidal wetland. Some studies have shown that the balance between sedimentation and erosion in salt marshes can be a determining factor for whether the bed-level will increase at a rate that matches SLR (Reed 1995; Morris et al. 2002; Baustian et al. 2012). However, this dynamic can also be dependant on factors such as storm frequency, sediment supply, VLM and vegetation productivity (Best et al. 2018). If a tidal wetland system is unable to adjust vertically to SLR, horizontal migration can occur. This is the second pathway in which marshes may adapt to SLR, wherein plants move landward as sea-levels slowly rise. Brophy and Ewald (2017) modelled potential landward migration of multiple tidal wetlands in Oregon under different SLR conditions. They found that due to steep topography and the small width of the coastal plain, many tidal wetlands were vulnerable to SLR, with considerable losses occurring under conditions of greater than 1.4 m SLR by 2100. Human development and steep topography often constrain the horizontal movement of wetlands (Thorne et al. 2018). This may also be the case for tidal wetland offsets in the highly developed Vancouver region.

Many of the processes involved in enabling a marsh to persist in tandem with rising sea-levels cannot be controlled by humans (e.g. storm intensity/frequency, VLM and in some cases, sediment supply). One factor associated with vertical accretion that can be controlled is vegetation. Vegetation can play an important role in tidal marsh ecosystem function and development (Schile et al. 2014). This is because the physical and biological components of marsh formation are tightly coupled. For example, marsh elevation and wave exposure influence vegetation growth. At the same time, vegetation can influence marsh and soil formation through mechanisms like the trapping and stabilization of sediment (Mariotti & Fagherazzi 2010; Möller et al. 2014).

It is well known that plant roots can stabilize sediment and reduce erosion. Vegetation in stable tidal marsh systems also increases the likelihood that vertical accretion will occur (Drexler et al. 2019). This is possible because vegetation in a salt marsh reduces the magnitude of tidal currents, wave action and erosion patterns that are typical of mudflats (Best et al. 2018). In Chapter 8 of The Principles of Tidal Sedimentology, multiple experiments measuring water flow in vegetated salt marshes are compared with measurements from non-vegetated environments (Bartholdy 2012, pp. 151 – 185). For example, in the Mississippi Delta, Wang et al. (1993) found that water currents in marshes were 10 to 20% of those in an adjacent creek. In another example from the Changjiang estuary in China, Shi et al. (2000) noted a 16% reduction in current velocity in a vegetated salt marsh compared to the adjacent mud flat. This flow attenuation also has an impact on marsh elevation when incorporated into models, such as in the work of Schile et al. (2014), where incorporating vegetation feedbacks into their model resulted in slower elevation losses. However, it is important to recognize that not all marsh vegetation will alter flow in the same way. The resistance to water flow of any plant species will also not remain constant under changing conditions. This includes changes in water depth or vegetation distribution (Tsihrintzis & Madiedo 2000). This is supported by data in a meta-analysis on the role of vegetation in flow resistance, where Tsihrintzis and Madiedo (2000) found that trends are complex and difficult to model.

While vegetation has been shown to increase sedimentation, it can also increase erosion. Wave dissipation within vegetation patches leads to increased relative bed shear stress between patches of vegetation (Best et al. 2018). If bed shear stress surpasses a critical value, erosion will occur and form small channels between vegetated patches within a marsh (Mariotti & Fagherazzi 2010). These channels subsequently permit drainage when tides go down. Drainage within the marsh area allows for improved vegetation growth and the expansion of intertidal vegetation communities (Mariotti & Fagherazzi 2010).

By improving knowledge of wetland dynamics, a forecast can be made as to how they may respond to changing conditions. Past research has collected data on vertical accretion rates to determine whether a wetland will adapt to SLR (Mudie & Byrne 1980; French et al. 1994; Chmura et al. 2001; Kemp et al. 2012). However, this technique is limited to already-existing wetlands where vertical accretion has been taking place for some time. In addition to this, Fagherazzi et al. (2020) argue that accelerated SLR due to anthropogenic climate change will make analyses based on historical accretion rates less reliable. Because of this, there has been an increase in the use of predictive models (like the one used in this study) to provide estimates of how future marsh evolution will occur under accelerated SLR.

Schile et al. (2014) conducted a study that modelled the role of vegetation, suspended sediment concentrations and upland habitat under different SLR conditions. They found that brackish marshes had slower elevation loss when they contained highly productive vegetation versus marshes that had less productive vegetation under the same conditions. Another modelling experiment carried out by Kirwan and Murray (2007) explored the response of Westham Island, BC, to SLR. Westham Island is a brackish tidal marshland located along the Fraser River delta, approximately 24 km downstream of the Qiqéyt Foreshore site. At the time the paper was written, sea-level was projected to rise approximately 50 cm by the year 2100. The experiment involved multiple SLR conditions and evaluated marsh evolution over 100 years. Low, medium and high conditions were chosen, corresponding to SLR of 8 to 28 cm, 45 to 65 cm and 80 to 100 cm, respectively. The authors found that under low SLR conditions, wetlands on Westham Island prograded slightly relative to sea-level, and vertical accretion occurred at a rate that matched historical measurements. Under the medium and high SLR conditions, although vertical accretion mediated some impacts of SLR, horizontal migration of vegetation occurred. In later years of the simulations, highly productive vegetation was replaced with less productive vegetation under increasing water depths, resulting in less overall biomass productivity. In the case of the Pattullo Bridge Replacement and Fish Habitat Offsetting project, a model could hypothetically be used to explore and examine the viability of the current offsetting design under different SLR conditions. This sort of analysis is possible provided accurate data pertaining to the project and surrounding environment is obtained. To maintain the ecological and societal benefits provided by this and other constructed wetlands, it is essential to be able to forecast how they may respond to SLR in the future (Tabak et al. 2016).

1.3. Novelty of this Research

To date, the majority of research on the impacts of SLR on tidal wetlands in the Pacific Northwest has been conducted in the United States. The Oregon Climate Report (2010) states that tidal wetlands in the Pacific Northwest are expected to experience greater rates of loss than any other area in the United States. This may also be the case in the Canadian context, however there is less data on the impacts of SLR on the Pacific Northwest of Canada. The experiment conducted by Kirwan and Murray (2007) may serve as a valuable comparison to the results of this study, due to the close proximity of their site to the Qiqéyt Foreshore.

Past research on the topic of wetland evolution under changing conditions has focused on existing wetlands, and regional losses due to SLR. This research is novel in that it attempts to model the impacts of SLR on a specific tidal wetland in the Pacific Northwest of Canada that is yet to be constructed. While most offsetting projects are designed to incorporate some resiliency to changing conditions, very few, if any, look as far ahead as the end of the century. Similarly, monitoring for these types of projects rarely goes on longer than 5 to 10 years. Therefore, this research is also novel in that it can open up a discussion around the topic of resiliency, and whether offsets are able to remain productive for the lifespan of the projects that they are offsetting.

Chapter 2.

Research Questions & Goals

The goal of this research is to provide First Nations and others involved with the Pattullo Bridge Replacement and Fish Habitat Offsetting project with a better understanding of the viability of the current tidal wetland offset design under different SLR conditions. A secondary goal is to develop the tools necessary for estimating the impacts of SLR on other tidal wetlands within the Fraser River. This research focuses on answering three questions:

1. How will SLR impact the tidal wetland offset constructed as part of the Pattullo Bridge Replacement and Fish Habitat Offsetting project?

2. How might other factors such as suspended sediment concentration, marsh substrate, and vegetation influence the evolution of this offset?

3. What kind of adaptive framework can be identified to help determine if the tidal wetland is able to keep pace with rising sea-levels?

It is important to note that at the time that this report is being written, designs for the tidal wetland offset to be constructed at the Qiqéyt Foreshore are not finalized. All references to the proposed marsh configuration in this report refer to the 30% draft. A 30% draft lays out the major design elements of a project and establishes an estimated cost and timeline. Through data collection at the Qiqéyt Foreshore site as well as feedback from First Nations and others involved with the project, the design may be modified in the future. The design is not expected to change significantly, but it is possible that the information included in this report may not be fully representative of the final product. As with all predictive models, the goal is to provide an informed perspective as to how future scenarios may unfold. Results of this study should be regarded as a projection of what overall trends may occur under future conditions at the Qiqéyt Foreshore.

Chapter 3.

Methods

The primary method for completing this study was numerical modelling. The MarshMorpho2D model version 2.0 developed by G. Mariotti was used and can be downloaded from the Community Surface Dynamics Modelling System (CSDMS) website. A detailed description of model parameters and functionality can be found in the work of Mariotti (2018, 2020). The programming language for this model is MATLAB®, developed by The MathWorks, Inc. (2021). MATLAB® version R2020a and R2021a (9.10.0.1602886) were used to complete this research (The MathWorks, Inc. 2020, 2021). MarshMorpho2D was selected for this research because it couples many mechanisms that exist in tidal wetlands such as tidal dynamics, wave dynamics, mass-conserving sediment transport, edge erosion, pond dynamics, and lateral migration of the marsh. The model also calculates the amount of vegetated area within the domain at each iteration of every simulation. A cell is considered vegetated if its elevation is greater than MSL (Mariotti 2018, 2020). In addition to this, while other models will focus on the relative rate of vertical accretion compared to SLR, MarshMorpho2D incorporates other mechanisms of marsh loss that are sometimes underestimated (Mariotti 2020).

Required inputs for this model are the initial topographic configuration of the wetland and surrounding area (provided by MOTI) and a grid with each cell type. Cell types can either be fixed grid cells representing open water or adjustable grid cells representing the marsh and adjacent areas. A digital elevation model (DEM) of the 30% design for the Qiqéyt Foreshore site was provided by the Fraser Crossing Group Project Corporation and is shown in Figure 4. Lidar data of the existing topography was obtained from the City of Surrey (2018). The proposed marsh DEM was merged with the Lidar data. The area of the merged files was 100 m by 100 m, although each edge of the DEM was extended out an additional 10 m. This was done to set the boundary conditions further from the domain of interest, making the final DEM 120 m by 120 m. Resolution of the file was then doubled using linear interpolation to decrease cell size of the DEM from 1 m^2 to 0.5 m^2. The final DEM used to represent “Year 1” conditions in every model simulation is shown in Figure 4.

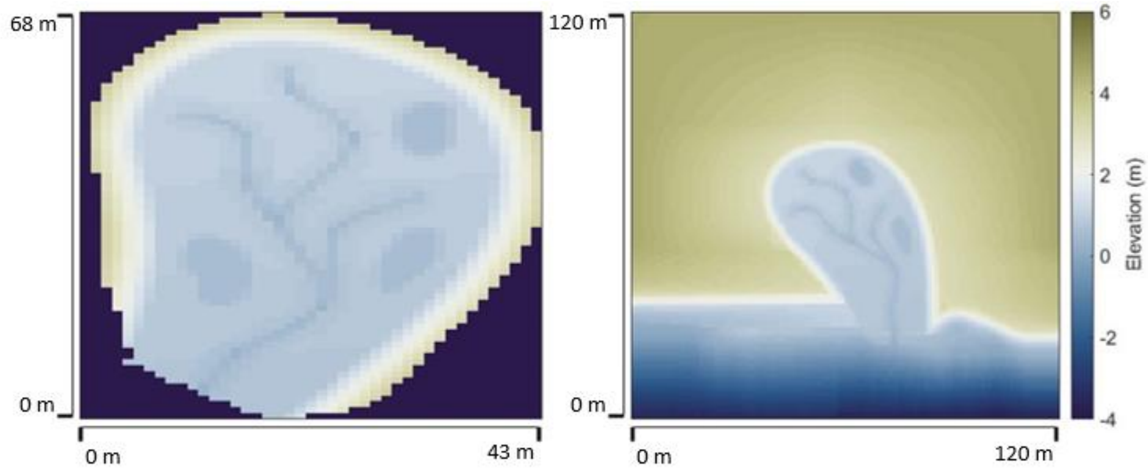

Figure 4 **DEM of the 30% design for the Qiqéyt Foreshore offsetting site (left) (Fraser Crossing Group 2020), and the final DEM used to represent marsh topography in the first year of every simulation (right).**

To adapt the model to the Qiqéyt Foreshore site some modifications were made after merging the DEM with the Lidar data. The edges of the proposed marsh DEM matched well with the existing topography. However, some features influenced outputs in a way that remove the model emphasis on examining evolution of the proposed marsh area. To address this, a portion of the topography outside the marsh (top-left corner of right-hand image in Fig. 4) was raised to constrain the model to the study area. There is also uncertainty about the final site grading so it is safer to assume the designers will not leave depressions overbank. A small “pool” that was present in the bottom left-hand side of the 30% marsh DEM was removed because it produced erosional patterns which controlled marsh evolution. The mouth of the main marsh channel needed to be extended and smoothed into the existing topography. The ponding function within the model was turned off because ponding increases spurious tidal channel development, and for a small area, may overprint site response without ponding. Finally, there was an issue with the main river being filled in by sediment over the course of each simulation because the model does not simulate river flows. Ideally, this issue would be fixed by modifying the model to simulate river flow that would prevent sedimentation within the main river channel. Unfortunately, this kind of modification is beyond the scope of this project. The issue was addressed by setting all cells that exist within the main river channel as “the open sea boundary” so that sedimentation did not occur there. Setting cells as “the open sea boundary” makes them non-active so that no change occurs there over the length of the simulation. The cells that were set as active and non-active for every simulation can be seen in Figure 5.

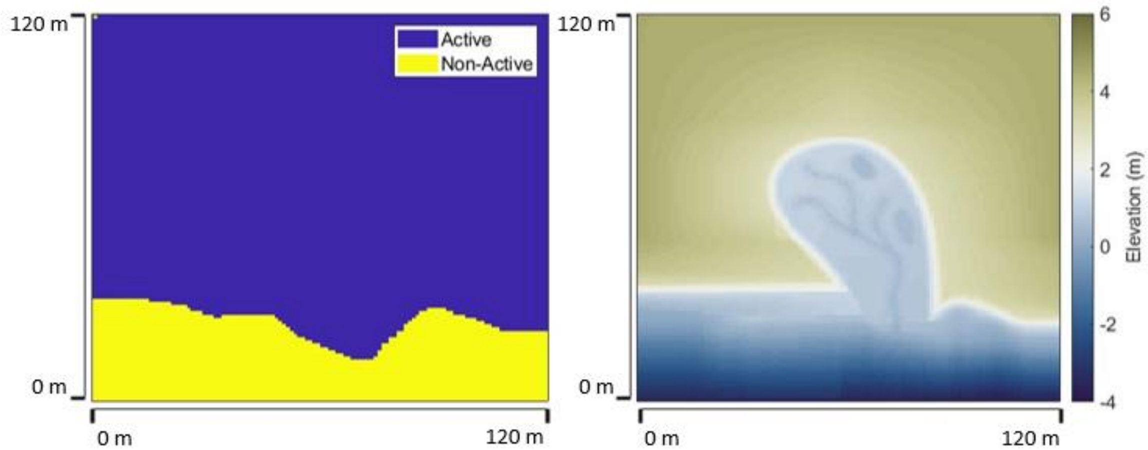

Figure 5 **Active and non-active cells in the Qiqéyt Foreshore DEM for every iteration of every simulation (left) and the merged DEM (right) for comparison. Cells that are listed as non-active do not experience any change throughout the simulation.**

The model has other inputs that use reference values. To increase the accuracy of the modelled simulations, data specific to the Qiqéyt Foreshore replaced certain reference values. Input parameters that were modified to match site conditions are listed in Table 1. All parameters used in the model along with their associated values are listed in Appendix A. Water density was lowered from 1030 kg/m^3 to 1000 kg/m^3 to reflect that the site is located in the freshwater, tidally driven portion of the Lower Fraser River. Tidal data used to estimate MSL, tidal period and tidal range were taken from the Department of Fisheries and Oceans (DFO) Canada, monitoring Station Number 7654 for the years 2015 to 2019 (Fisheries and Oceans Canada 2019). This station is located in New Westminster, approximately 2 km downstream of the Qiqéyt Foreshore site. The input for tidal range in MarshMorpho2D allows for only one tidal high for every tidal cycle. In Vancouver, there are typically two different tidal highs for each day, so another adjustment was made. This involved plotting an average daily tidal cycle (with two different tidal highs) and calculating the area under the curve. A new tidal cycle was interpolated that represented the same area under the curve, but uses two identical intermediate high tides. These high tide values were then used to determine the tidal range. Finally, average windspeed was estimated. To do this data was taken from Vancouver International Airport between the years 1953 to 2012 (Government of

Canada 2017). This data showed an average wind speed of approximately 3.5 m/sec, although it was collected at 10 m elevation. Because the Qiqéyt Foreshore site is relatively sheltered from the wind, a windspeed of 2 m/sec was chosen for this parameter.

Table 1 **List of parameters in MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020) that were modified for this research. Reference values indicate the original values used in MarshMorpho2D. Site values indicate the values used in this study.**

Parameter	Description	Reference Value	Site Value
M	Number of columns in DEM	300	240
N	Number of rows in DEM	500	240
x	Length of site (m)	500	120
y	Width of site (m)	300	120
z	Area of site (m^2)	500 x 300	120 x 120
rho	Water density (kg/m^3)	1030	1000
msl	Mean sea-level	2.5	1.95
Trange	Tidal range (m)	0.7	2.3
Ttide	Tidal period (hrs/day)	12.5	12.25
wind	Wind speed (m/s)	7	2
gR	Sea-level rise (mm/yr)	[1, 2.5, 5, 7.5, 10]	[0, 12.5, 31.25]
gC	Suspended sediment concentration ($g\ m^{-3}$)	[60, 30, 15, 7.5]	[5, 10, 20]
taucr	Critical shear stress value	0.2	[0.1, 0.2]

In order to predict marsh evolution under different conditions, certain input parameters are represented by a range of values. These values are then used in different combinations for all simulations (Table 1). The first parameter represented by a range of values is SLR. The values representing SLR projections for the region are from recent, authoritative and region-specific sources (Kopp et al. 2017; Sweet et al. 2017; City of Vancouver 2018). The first SLR condition that was used serves as a baseline simulation. Baseline is considered no SLR and will have 0 m SLR by the year 2100. As stated in Section 1.2, there is uncertainty regarding SLR, however the City of Vancouver is projecting 1 m SLR by the year 2100. Therefore, the next set of simulations applies 1 m SLR by the year 2100. Finally, in impact assessment it can be useful to evaluate low-probability, high-impact conditions (Jevrejeva et al. 2019). Therefore, the third set of simulations uses the extreme SLR condition of 2.5 m by the year 2100, which has been suggested in the work of Kopp et al. (2017) and Sweet et al. (2017) based on the RCP 8.5 scenario. This final set of simulations is useful for giving an idea of a “worst-case scenario” in future conditions. An increase in sea-level of 0, 1 and 2.5 m by the year 2100 corresponds to a SLR rate of 0, 12.5 and 31.25 mm per year, respectively. This assumes a linear rate of SLR and that the governing conditions of MarshMorpho2D do not change.

The next parameter that contains a range of inputs is the suspended sediment concentration (SSC) for mud sized fraction at the Fraser River boundary. Values used to represent SSC in this study are 5, 10 and 20 g/m^3 for low, medium, and high concentrations, respectively. Through personal communications, it was found that characterizing the sediment flux in the lower Fraser River can be difficult as SSC can vary with discharge and tidal stage (Ryan Bradley, pers. comm. 2020, SFU Faculty of Environment). Because of this, it was understood that collecting data to capture the average SSC in a daily tidal cycle of the Lower Fraser River was beyond the scope of this study. Data on the SSC of the Fraser River used for this study was collected by Attard et al. (2014) near Mission, BC. SSC data from Mission is generally thought to apply to the entire sand-bedded portion of the Fraser River (Ryan Bradley, pers. comm. 2020, SFU Faculty of Environment). Research by Attard et al. (2014) consisted of six sampling campaigns near Mission, BC. SSC data was collected during the rise, peak and fall of the annual hydrograph. SSC for silt and clay during that time generally ranged from 10 to 100 g/m^3 (Attard et al. 2014). Kirwan and Murray (2007) obtained SSC data for their study from the Vancouver Port Authority, which reported SSC at 10 different monitoring stations on a monthly basis during high tide between May to October 2004. This data showed that SSC near the major channels of the Lower Fraser River was on the order of 10 g/m^3. The concentrations chosen for this study attempt to capture the average annual SSC in a daily tidal cycle of the Fraser River, and are roughly based on the work of Kirwan and Murray (2007) and Attard et al. (2014).

There is uncertainty regarding the grain size distribution of the material that will comprise the marsh substrate, as well as that which may be deposited with simulated daily tidal cycles. The model assumes unvegetated surfaces (i.e. elevations below MSL) consist of mud sized particles. The model author assumes a critical shear stress (CSS) value of 0.2 Pascals for these areas (Mariotti 2020). Provided these present limitations, the model was applied to the Qiqéyt Foreshore site assuming that the cobble-lined proposed marsh channels will explicitly not erode under any future condition but will adjust through sediment deposition with the daily tidal cycle. It is also assumed that all out of marsh channel surfaces (Fig. 4) that are free to adjust in response to SLR will consist of mud sized particles. The assumption regarding the proposed cobble-lined channels is not unreasonable because placed cobbles will have an increased drag on the water column relative to surrounding material. An increase of fluid drag can promote fine sediment deposition during the tidal cycle periods when flow depths drop below the settling velocity of cobble fill material diameter and smaller. In addition to the model CSS value of 0.2 Pascals for unvegetated areas, an additional set of simulations was run using a CSS value of 0.1 Pascals. This was done to test the differences that might occur if the material used to fill the marsh (or that which is deposited with simulated daily tidal cycles) is on the order of a very fine sand or coarse silt (Berenbrock & Tanmer 2008). For vegetated surfaces (i.e. elevations above MSL), the model author’s default CSS value of 0.5 Pascals was applied (Mariotti 2020).

Once all inputs are entered, the model can output multiple data sets pertaining to the Qiqéyt Foreshore site at each iteration (in this case each year) of every simulation. Most highway bridges last approximately 80 years (Caner et al. 2008), and the current Pattullo Bridge has been in use for 83 years. For the purposes of this research, all simulations last for a maximum of 80 years. This corresponds with the approximate amount of time that the new Pattullo Bridge will be in use, as well as SLR projections made for the year 2100. In addition to evaluating marsh evolution at 80 years in the future, it was also analysed at years 20 and 50. These two dates were selected arbitrarily to give the most even spread of analyses over the entire range. Data that was saved at each iteration for this project was marsh elevation, elevation change, water depth, water velocity, local SSC, vegetated area and MSL. In each simulation, MSL increases at a linear rate that corresponds with the annual rate of SLR. Different simulations were run using the parameters that include a range of inputs. This involved three SLR conditions, three SSC values and two CSS values. This resulted in 18 (3 x 3 x 2) different simulations. Each of these simulations was then analyzed visually over the three specified time periods. This allowed for an in-depth analysis of marsh evolution through time, with a focus on whether the proposed project configuration persists, or whether an adjusted configuration results due to simulated conditions. Analysing 18 different simulations at three different time periods (20, 50 and 80 years) resulted in a total of 54 separate model outputs to be analysed. Analysis consisted of visual observation of marsh evolution, including factors such as elevation and water depth change, SSC, the extent of vegetation and overall marsh loss/gain.

Based on the modelling results, any given SLR scenario that occurs in the future can be compared with the simulated impacts closest to that rate of SLR. This will give some basis of comparison for those who are carrying out monitoring at the Qiqéyt Foreshore site in the future. Depending on the rate of SLR that occurs in the future and its associated impacts, the adaptive framework at the end of this report will lay out a course of action to best maintain the intended outcomes of the offsetting project.

Table 2 List of simulations that were run using MarshMorpho2D v.2.0 model developped by G Mariotti (2018, 2020). Includes information on simulation name, abbreviation and parameter values.

Simulation Name	Abbreviation	SLR	SSC	CSS
Baseline 1	B1	0	5	0.2
Baseline 2	B2	0	10	0.2
Baseline 3	B3	0	20	0.2
Baseline 4	B4	0	5	0.1
Baseline 5	B5	0	10	0.1
Baseline 6	B6	0	20	0.1
Simulation 1	S1	12.5	5	0.2
Simulation 2	S2	12.5	10	0.2
Simulation 3	S3	12.5	20	0.2
Simulation 4	S4	31.25	5	0.2
Simulation 5	S5	31.25	10	0.2
Simulation 6	S6	31.25	20	0.2
Simulation 7	S7	12.5	5	0.1
Simulation 8	S8	12.5	10	0.1
Simulation 9	S9	12.5	20	0.1
Simulation 10	S10	31.25	5	0.1
Simulation 11	S11	31.25	10	0.1
Simulation 12	S12	31.25	20	0.1

* SLR = Sea-Level Rise (mm/yr), SSC = Suspended Sediment Concentration (g/m^3), CSS = Critical Sheer Stress (Pascals)

Chapter 4.

Results

4.1. Sea-Level Rise

The top set of subplots in Figure 6 show the projected elevation in meters at the Qiqéyt Foreshore after 80 years for all simulations with a CSS value of 0.2 Pascals. The impacts of increasing SLR conditions under the same SSC conditions can be seen by looking left to right in each row. The impacts of increasing SSC under the same SLR condition can be seen by looking down each column. After 80 years, the proposed main channel of the marsh is filled in by sediment deposition in almost every simulation. The exceptions to this are simulations S1 and S4, that show small depressions where the proposed main marsh channel was originally. In almost all simulations, two new main channels form on the left-hand and right-hand side of the marsh mouth, at breaks in the slope at the lateral marsh margins. Projected water velocities show that local water velocities are relatively high in these locations. The only simulation where a new channel did not completely form on the right-hand side of the mouth is in simulation S6. Here, sediment deposition led to the formation of a levee-like structure at the interface between the marsh and the Fraser River.

Results between simulations with 0 m SLR by 2100 (B1, B2 and B3) and 1 m SLR by 2100 (S1, S2 and S3) are similar. In general, a higher rate of SLR results in greater sediment deposition and wider, deeper channels being formed. Higher SSC generally results in greater sediment deposition and longer, narrower channels being formed. Simulations with the highest rate of SLR (S4, S5 and S6) showed greater channel development in the topography surrounding the marsh area.

The projected relative change in elevation between year 1 and year 80 can be seen in the bottom set of subplots in Figure 6. Elevations within the marsh area in all simulations increased, except in areas where new channel/pool formation took place. The simulation with the greatest increase in elevation within the marsh area is S6. The simulation with the smallest increase in elevation within the marsh area is B1. In all simulations, the greatest increase in elevation occurs at the interface between active and non-active cells.

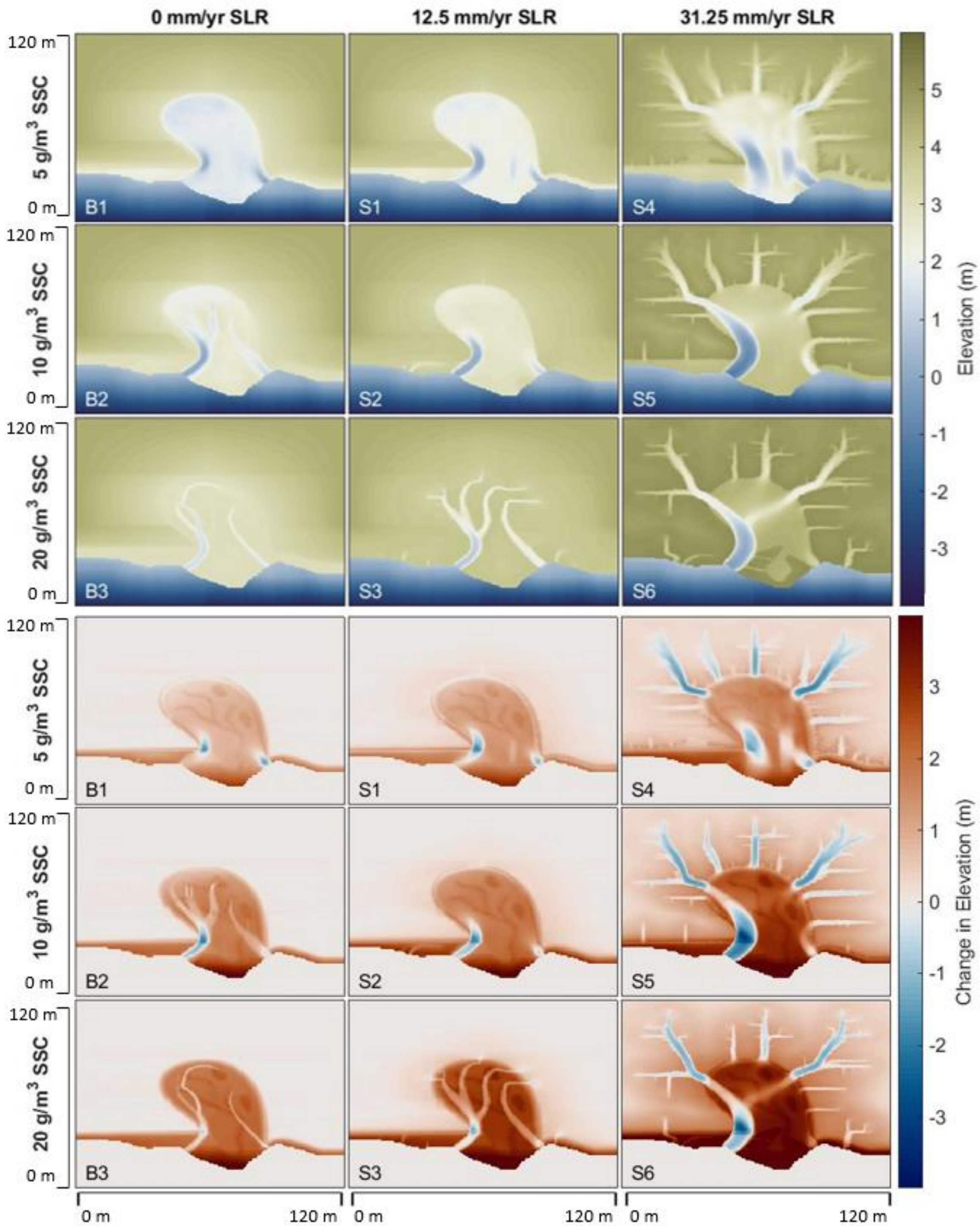

Figure 6 **Results from MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020). The top set of subplots show elevation in meters at the Qiqéyt Foreshore site for year 80. The bottom set of subplots show change in elevation in meters at the Qiqéyt Foreshore site for year 80 relative to year 1. All simulations have a CSS value of 0.2 Pascals.**

The different rates of SLR used in this research and their corresponding MSL at each year can be seen in Figure 7. For simulations with 2.5 m SLR by 2100, MSL is 4.45 m after 80 years. In contrast, for simulations with 1 m SLR by 2100, MSL is 2.95 m after 80 years. MSL in all baseline simulations remains at the initial MSL of 1.95 m. In simulations with the highest rate of SLR, MSL surpasses the elevation of the embankment surrounding the marsh area by approximately year 40 to 50. Between these years, MSL reaches approximately 3 to 3.5 m. Once water interacts with the topography surrounding the marsh, many new channels begin to form in that area. As MSL continues to rise and expand over the upland topography, so do the newly formed channels. In simulations with 1 m SLR by the year 2100, MSL starts to surpass the embankment surrounding the marsh area by year 80, although no new channel formation takes place.

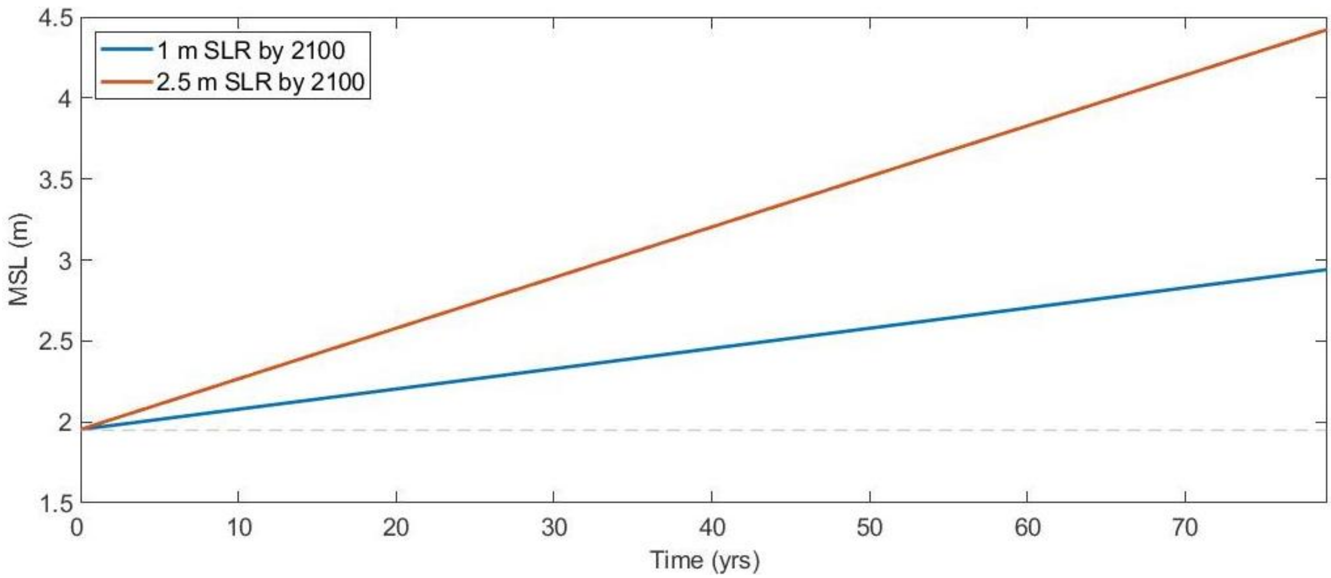

Figure 7 MSL for each year in every simulation that had a SLR condition of 1 m by 2100 (blue line) and 2.5 m by 2100 (red line). Simulations that had a SLR condition of 0 m by 2100 remained at the original MSL of 1.95 m (grey dashed line).

The top set of subplots in Figure 8 show the projected water depth at MSL in all simulations with a CSS value of 0.2 Pascals. In all simulations, the areas of greatest water depth (excluding the Fraser River) are in the newly formed marsh channels. In general, simulations with higher rates of SLR have greater water depths within the marsh area compared with simulations with lower rates of SLR and the same SSC. In the case of simulations B3 and S3, there is only a small difference in projected water depth between the two simulations. The greatest difference in projected water depth for simulations with the same SSC is between S1 and S4. All simulations with 2.5 m SLR by 2100 show an increase in water depth in the area surrounding the marsh. Simulations with a higher SSC have shallower water depths within the marsh area compared with simulations that have a lower SSC and the same rate of SLR.

The bottom set of subplots in Figure 8 show the projected change in water depth at MSL for year 1 relative to year 80. Overall, most simulations show a projected decrease in water depth within the marsh area after 80 years. The exception to this is simulation S4, which projects an overall increase in water depth within the marsh area over 80 years. In general, simulations with a higher SSC have a greater projected decrease in water depth within the marsh area. Simulations with a higher rate of SLR generally have a smaller projected decrease in water depth (and in the case of S4, an increase in projected water depth). In all simulations, the areas with the greatest relative increase in projected water depth are the newly formed marsh channels/pools. The area that shows the greatest relative decrease in projected water depth for all simulations is the interface between the active and non-active cells.

The greatest projected decrease in water depth between the different SLR conditions is in the 0 m SLR by 2100 simulations (B1, B2 and B3). In simulation B3 there is no noticeable increase in water depth in the entire marsh area. For simulations with 1 m SLR by 2100 (S1, S2 and S3), relative water depth within the marsh area generally decreases, with greater decreases in simulations with higher SSC. In simulation S1, aside from the proposed marsh features that filled in and the newly formed channels/pools, water depth within the marsh area remains almost the same as it was in year 1. For these simulations there is also a slight increase in water depth in the topography surrounding the marsh area, indicating that MSL is just beginning to surpass that elevation. Aside from S4, simulations that had 2.5 m SLR by 2100 (S5 and S6) also show a projected decrease in water depth within the marsh area. For S5 this decrease mainly takes place in the proposed marsh channels and pools, and the rest of the marsh (aside from areas that had new channel formation take place) have approximately the same water depth as in year 1. All simulations with 2.5 m SLR by 2100 show a relative increase in water depth in the topography surrounding the marsh, although this increase is greater for simulations with a lower SSC.

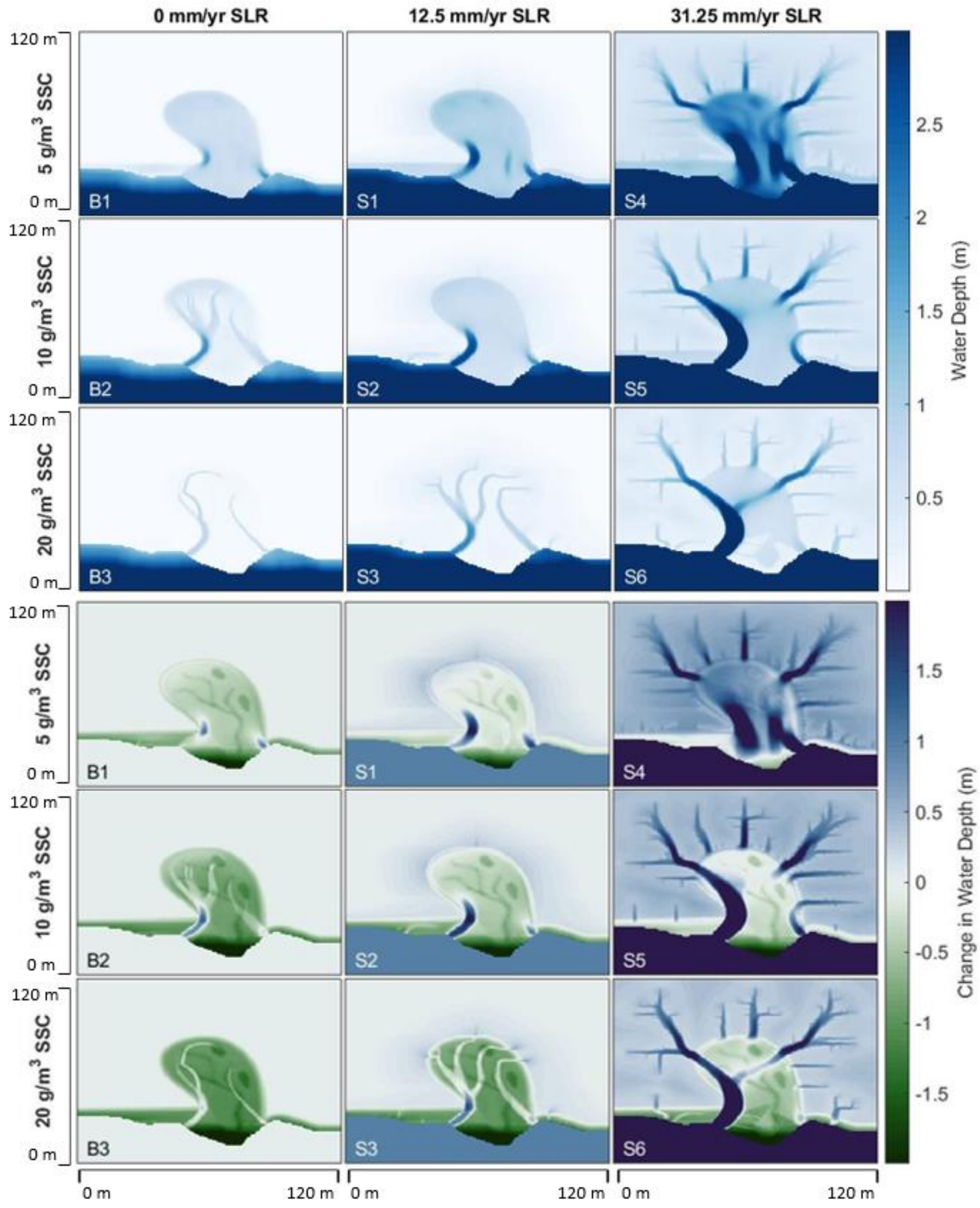

Figure 8 **Results from MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020). The top set of subplots show projected water depth at MSL in meters at the Qiqéyt Foreshore site for year 80. The bottom set of subplots show the projected change in water depth at MSL in meters at the Qiqéyt Foreshore site for year 80 relative to year 1. All simulations have a CSS value of 0.2 Pascals.**

4.2. Suspended Sediment Concentration

Projected local SSC for each simulation at MSL for year 80 is shown in Figure 9. In each case the SSC within the Fraser River represents the SSC condition for the simulation. For all simulations, local SSC is highest within the Fraser River and main marsh channels. Simulations with a higher SSC have a more distinct difference in local SSC between channels and the rest of the marsh area. In simulations with higher SLR (and therefore higher MSL), SSC is higher within the entire marsh area overall. For example in simulation S6, with the exception of the levee-like formation at the mouth of the marsh, SSC within the main channel is approximately 20 g/m^3 and then gradually decreases outside of the channel. For simulations with the same SSC condition but lower rate of SLR (B3 and S3), there is a sharper drop in local SSC outside of the newly formed marsh channels. Simulations with 1 m SLR by 2100 (S1, S2 and S3) and 2.5 m SLR by 2100 (S4, S5 and S6) also have some suspended sediment above the embankment surrounding the marsh area.

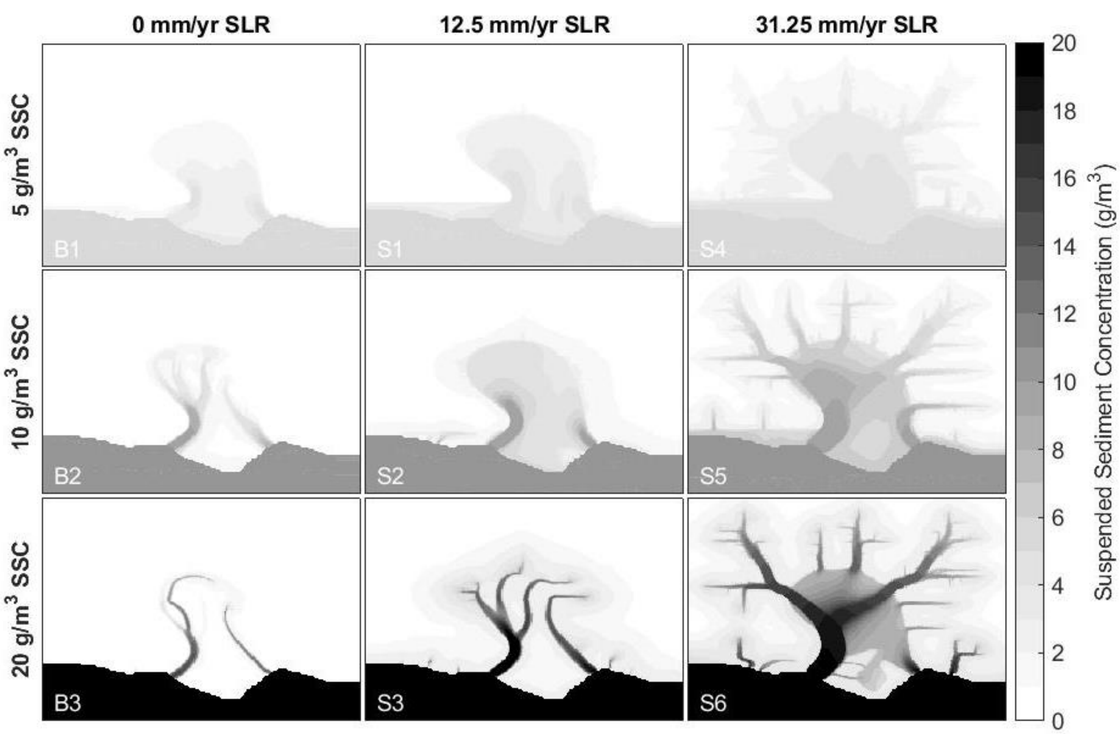

Figure 9 **Results from MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020). Each plot shows the SSC in g/m^3 at MSL at the Qiqéyt Foreshore site for year 80. All simulations have a CSS value of 0.2 Pascals.**

4.3. Critical Sheer Stress

Results for simulations with a CSS value of 0.1 Pascals at year 80 are shown in Figure 10. Each simulation in Figure 10 can be compared with the corresponding simulation in Figure 6 to observe the impacts of running the model with a lower CSS value. In general, results are similar to those in Figure 6. Elevation in the two sets of simulations is almost identical. Simulations with a lower CSS also show an infilling of the proposed marsh features through sediment deposition. Two new main channels on the left-hand and right-hand side of the mouth of the marsh also develop in these simulations. Simulation S12 develops a levee-like formation at the marsh-river interface that is similar to that of S6. The main difference between simulations using different CSS values is that a lower CSS value led to increased development of the new channel near the right-hand side of the mouth of the marsh. For certain simulations (B4, S7, S10 and S11) the newly formed channel on the right-hand side is equally or more developed than the new channel on the left-hand side of the mouth of the marsh.

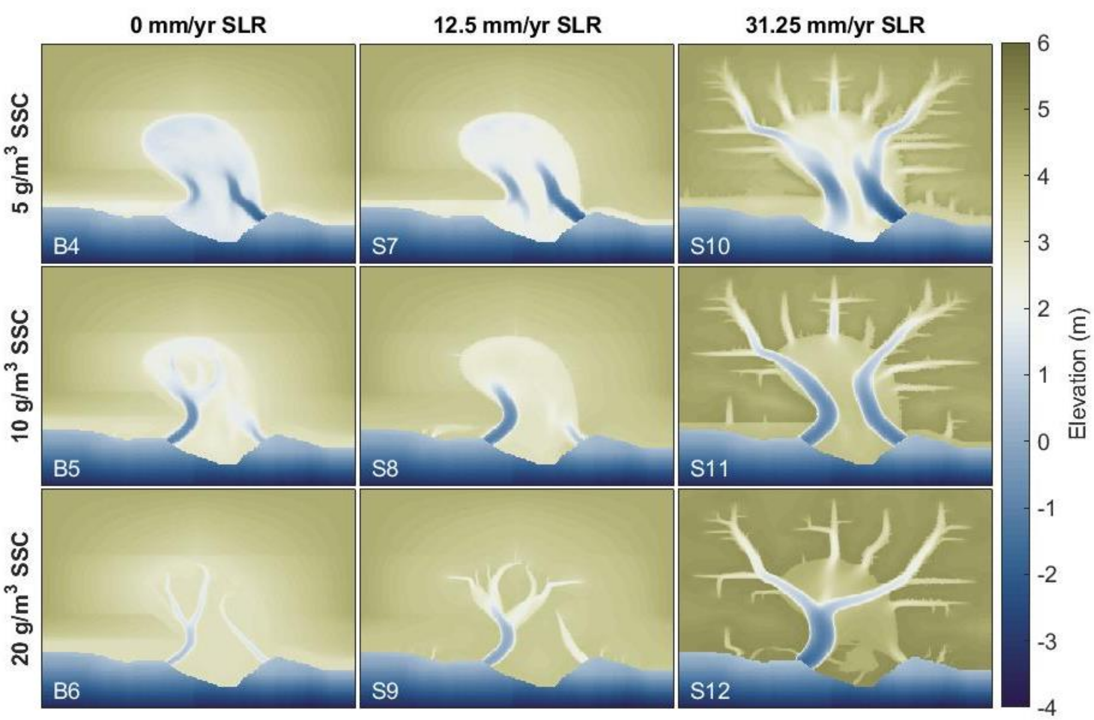

Figure 10 **Results from MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020). Each plot shows elevation in meters at the Qiqéyt Foreshore site for year 80. All simulations have a CSS value of 0.1 Pascals.**

4.4. Temporal Changes

The top set of subplots in Figure 11 show the projected elevation in meters at the Qiqéyt Foreshore after 20 years for all simulations with a CSS value of 0.2 Pascals. After 20 years, results for different SLR conditions with the same SSC are almost identical. The main difference in these simulations is between the different SSC conditions. For simulations with the lowest SSC (B1, S1 and S4), the proposed marsh features are still present. The projected relative change in elevation between year 1 and year 20 can be seen in the bottom set of subplots in Figure 11. In general, the relative elevations within the marsh area for simulations B1, S1 and S4 have changed by less that 0.5 m compared with year 1. At the back of the marsh area (furthest from the Fraser River) there is a small band where marsh elevation decreases relative to year 1. Simulations with an intermediate SSC condition (B2, S2 and S5) also have features of the proposed marsh design present, although some infilling is beginning to occur. The relative increase in elevation for these simulations between year 1 and year 20 is greater than that of the simulations with the lowest SSC but less than that of simulations with the highest SSC. In simulations with the highest SSC (B3, S3 and S6), the proposed marsh channels and pools are almost completely infilled by sedimentation after 20 years. The projected change in marsh elevation between year 1 and year 20 is greatest for the highest SSC simulations, and increased by about 1 m in general.

There are some trends that are noticeable across all simulations in Figure 11. At year 20, there is no development of new channels in the topography surrounding the marsh area. For all simulations, a small pool develops near the left-hand side of the mouth of the marsh. There is also a small depression that forms at the right-hand side of the mouth of the marsh, where the other new channel develops in longer simulations. Similar to the year 80 plots for these simulations (Fig. 6), the greatest increase in elevation for all simulations is at the interface between the marsh and the Fraser River. The elevation increase in this area is greatest in simulations with higher SSC conditions.

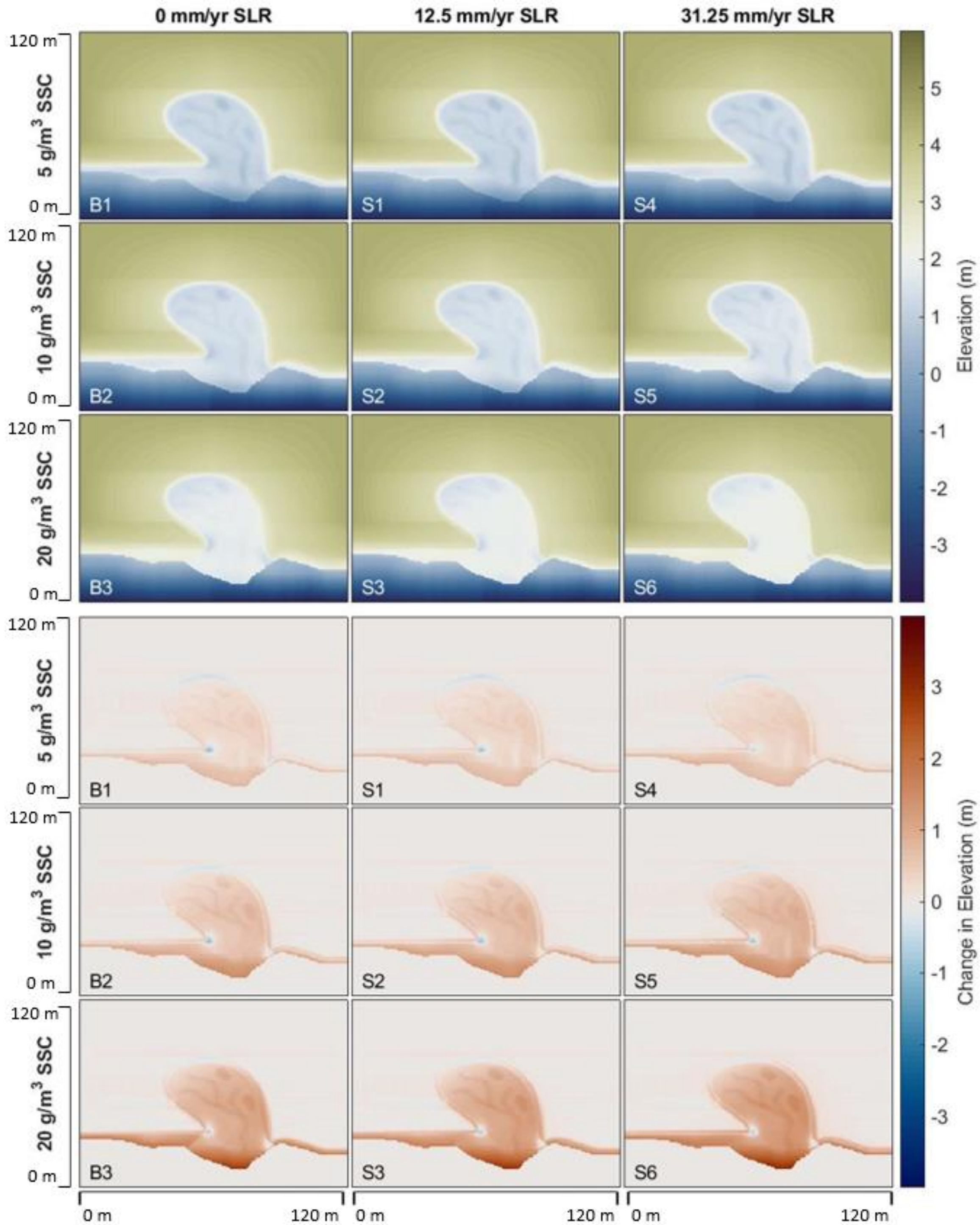

Figure 11 **Results from MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020). The top set of subplots show elevation in meters at the Qiqéyt Foreshore site for year 20. The bottom set of subplots show change in elevation in meters at the Qiqéyt Foreshore site for year 20 relative to year 1. All simulations have a CSS value of 0.2 Pascals.**

The top set of subplots in Figure 12 show the projected elevation in meters at the Qiqéyt Foreshore after 50 years for all simulations with a CSS value of 0.2 Pascals. Results show that by 50 years marsh evolution differentiates between simulations with different SLR conditions. Trends that can be seen in the simulations at 80 years begin to emerge at year 50. For example, results between the 0 and 1 m SLR by 2100 simulations are similar while the 2.5 m SLR by 2100 simulations are quite different. Under the highest SLR condition, water levels surpassed the embankment surrounding the marsh area and new channels have started to develop.

Similar to Figure 6, simulations with higher rates of SLR and higher SSC have greater sedimentation and a faster rate of infilling of marsh features. The new channels that form on the left and right-hand side of the mouth of the marsh are more developped after 50 years than those at 20 years. Simulations with a higher rate of SLR have wider, deeper channels while simulations with higher SSC have longer, narrower channels. After 50 years, only simulations with the lowest SSC condition show traces of the proposed marsh design.

The projected relative change in elevation between year 1 and year 50 can be seen in the bottom set of subplots in Figure 12. Again, projected trends that were observed after 80 years are present after 50 years. Elevations within the marsh area in all simulations increased except in areas where new channel/pool formation took place. The simulation with the smallest increase in elevation within the marsh area is B1. In all simulations, the greatest increase in elevation occurred at the interface between active and non-active cells.

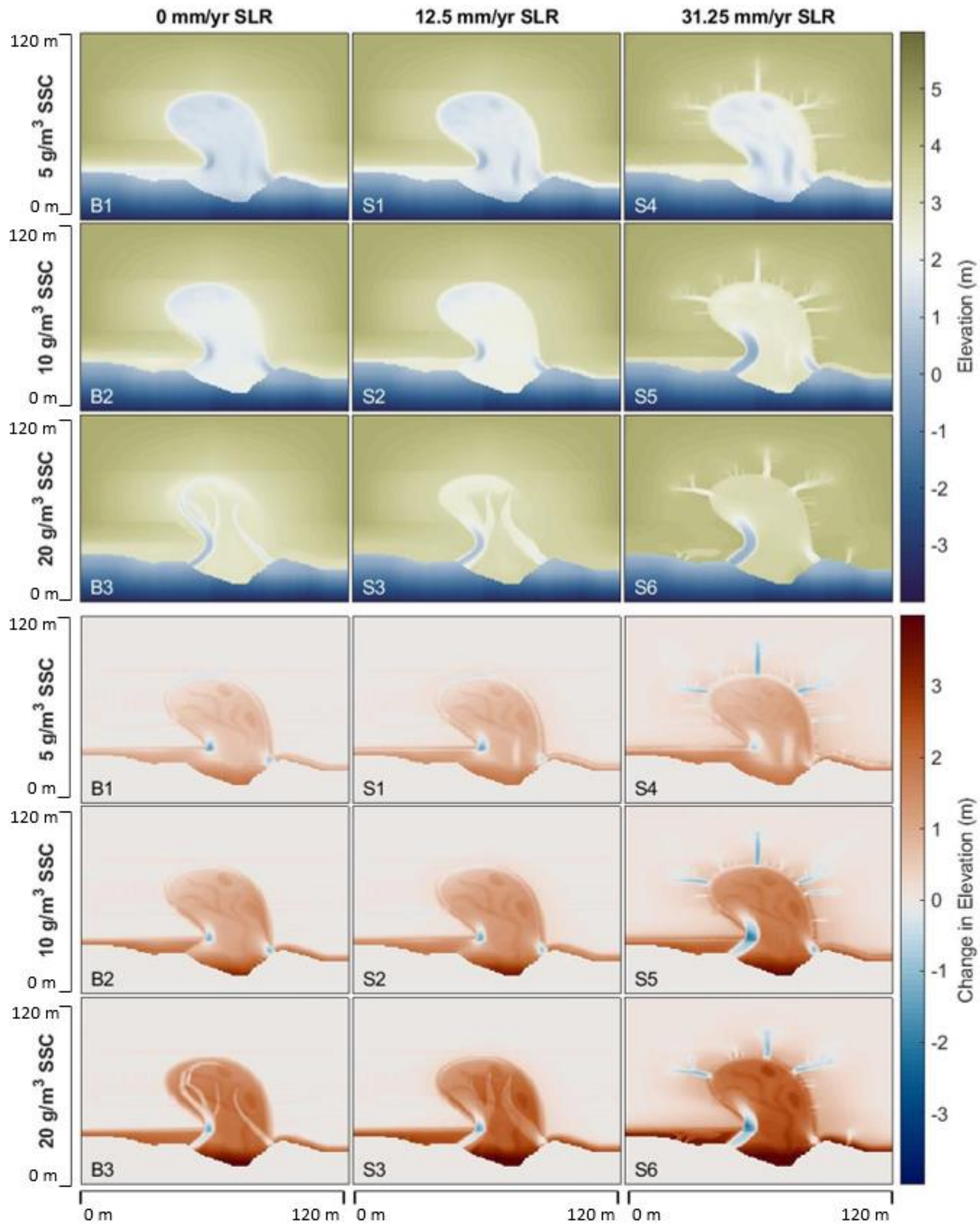

Figure 12 **Results from MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020). The top set of subplots show elevation in meters at the Qiqéyt Foreshore site for year 50. The bottom set of subplots show change in elevation in meters at the Qiqéyt Foreshore site for year 50 relative to year 1. All simulations have a CSS value of 0.2 Pascals.**

4.5. Vegetation

The proportion of initial vegetation projected to be within the modelled area at each iteration of every simulation is shown in Figure 13. Results for vegetation gain/loss between simulations with different CSS values with all other parameters being equal are almost identical. In general, simulations with higher SSC have a higher proportion of initial vegetated area after 80 years, followed by the intermediate and then low SSC simulations. Baseline simulations with 0 m SLR by 2100 have a projected increase in vegetated area for every SSC condition. After 80 years, the high (B3 and B6), intermediate (B2 and B5) and low (B1 and B4) SSC simulations have a projected increase in vegetated area of approximately 28, 24 and 6%, respectively.

In simulations with 1 m SLR by 2100 (S1 to S3 and S7 to S9), the projected proportion of initial vegetation that remained throughout the 80-year simulation generally remains the same or increases. The simulations in this group with the lowest SSC (S1 and S7) experience some decrease in vegetated extent but remain close to 1. Simulations with intermediate SSC (S2 and S8) show approximately a 5% increase in vegetated area over 80 years. Simulations with the highest SSC (S3 and S9) show an increase in vegetated area of approximately 24% over 80 years.

For simulations with 2.5 m SLR by 2100 (S4 to S6 and S10 to S12) there is an overall decrease in vegetated area for almost all simulations. Simulations with the lowest SSC show the greatest loss of vegetated area with a decrease of approximately 56% (S4) and 51% (S10) by year 80 (not shown in Fig. 13). Simulations with intermediate SSC (S5 and S11) show approximately a 17% decrease in vegetated area over 80 years. Simulations with the highest SSC (S6 and S11) show an initial increase in vegetated area of approximately 4% near year 30, although that increase changes to a 0 to 5% loss of vegetated area by year 80.

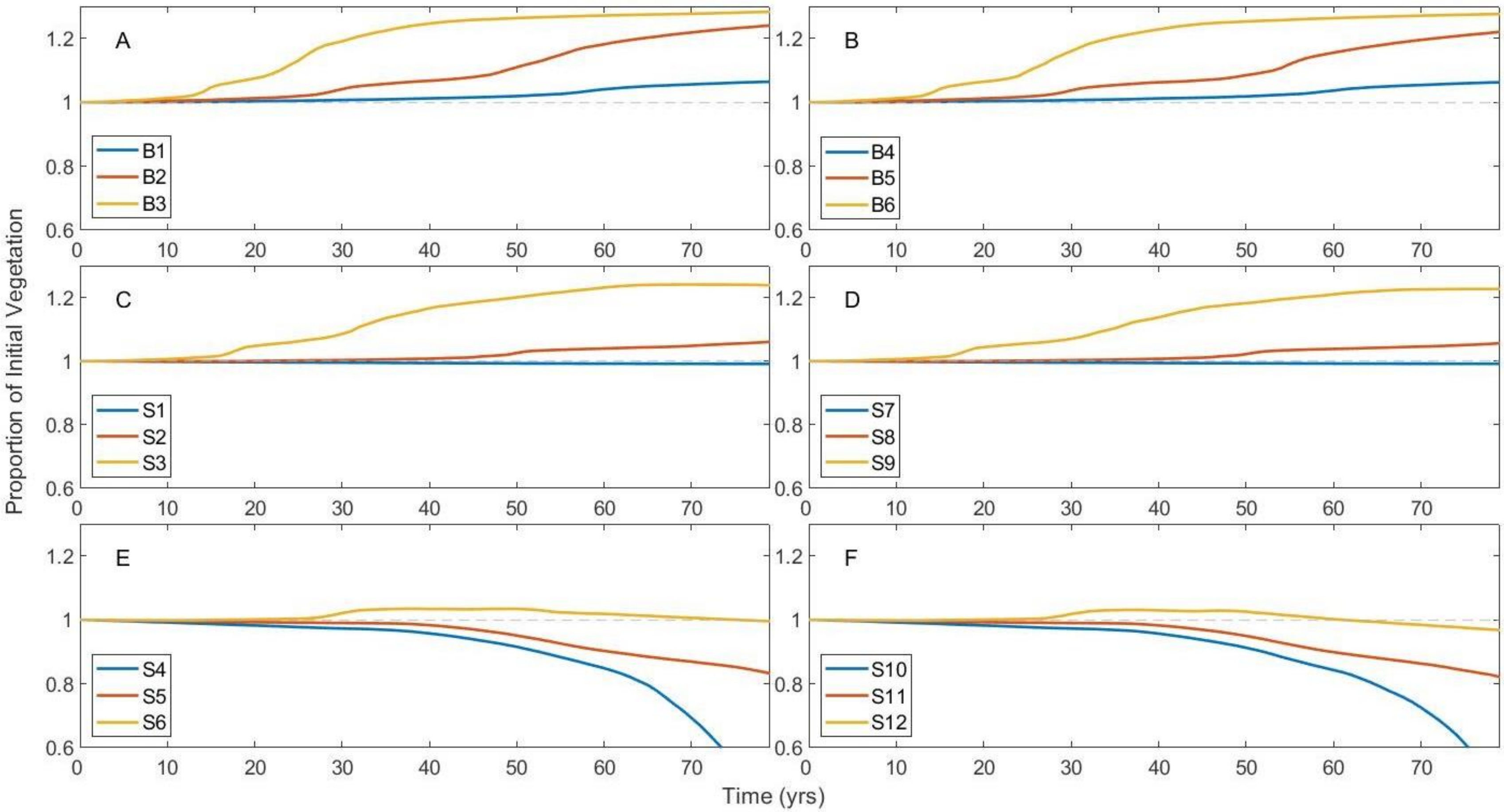

Figure 13 **Projected amount of vegetation present in each simulation relative to the initial amount at year 1. Each plot is categorized based on SLR condition and CSS value, where A = 0 m SLR, 0.2 Pascals CSS, B = 0 m SLR, 0.1 Pascals CSS, C = 1 m SLR, 0.2 Pascals CSS, D = 1 m SLR, 0.1 Pascals CSS, E = 2.5 m SLR, 0.2 Pascals CSS and F = 2.5 m SLR, 0.1 Pascals CSS. Each line indicates either a low (blue), intermediate (red) or high (yellow) SSC condition.**

Chapter 5.

Discussion

5.1. Model Projected Future Marsh Conditions

Based on model results, it seems most likely that within the short-term (20 years), SSC within the Fraser River will have a greater impact on marsh evolution at the Qiqéyt Foreshore site than SLR (Fig. 11). Looking down each column of subfigures, it is evident that a higher SSC results in more sedimentation and infilling of marsh features. This result suggests that the proposed Qiqéyt Foreshore configuration is not stable with respect to how the model simulates 2-dimensional flow within the marsh, as well as sediment entrainment and deposition. The extent of vegetation after the first 20 years of each simulation also provides information on the balance between the tendency to erode vs. deposit suspended sediment in the marsh. When interpreting vegetation results, it is important to remember that any cell with an elevation greater than MSL is considered vegetated. Therefore, the amount of vegetated area in the domain of interest is closely linked to the balance between sedimentation and SLR.

After 20 years, simulations with an intermediate rate of SLR (Fig 13C & 13D), generally have no projected change in vegetated area for low and intermediate SSC conditions. For the higher SSC condition (S3 & S9), there is a projected increase in vegetated area of about 5% relative to initial conditions. At 20 years, water levels are still contained within the marsh area. Therefore, it is assumed that there is no change in vegetated area in the topography surrounding the marsh, and all change in vegetated area is occurring within the marsh. An explanation for this result could be that due to sedimentation, marsh elevations increase at about the same rate as MSL, and the calculated vegetated area remains approximately the same. Under the highest SLR condition (Fig. 13E & 13F), vegetated area generally stays the same or decreases slightly by year 20. Simulations with intermediate (S4 and S10) and low (S5 and S11) SSC conditions show a small decrease in vegetated area after 20 years (less than 5% difference). This could indicate that in these simulations, the rate of sedimentation within the marsh is slightly lower than the rate of increase for MSL.

At year 50, differences begin to appear between simulations with different rates of SLR (Fig. 12). These differences have to do with rates of sedimentation and channel formation. At year 50, only a few simulations (B1, S1 and S4) show traces of the proposed marsh channel/pool configuration. Simulations with greater SSC conditions show more infilling of proposed marsh features, with longer narrower channels under the highest SSC condition. Simulations with the highest SLR condition also show slightly wider channels than those with lower SLR conditions. However, although marsh configuration may have changed at year 50, it is still uncertain how this may impact ecological functioning at the site.

By year 50, simulations with an intermediate rate of SLR (Fig. 13C & 13D), have a projected increase in vegetated area for all but the lowest SSC condition. In the high (S3 and S9) and intermediate (S2 and S8) SSC condition, vegetated area increases approximately 20 and 4%, respectively. In the lowest SSC condition, vegetated area at year 50 remains approximately the same as it was in year 1. These results suggest that if sea-levels were to rise by 12.5 mm/year for 50 years, it is possible that the amount of vegetation within the marsh would either remain the same or increase, despite the marsh configuration having changed. Under the highest SLR condition (Fig. 13E & 13F), vegetated area increases slightly for the highest SSC condition (S6 and S12) after 50 years. In simulations with intermediate (S4 and S10) and low (S5 and S11) SSC conditions, vegetated area within the domain decreases by approximately 5 to 10% after 50 years. One explanation for this result could be that after 50 years, MSL has risen by almost 3.5 m in simulations with the highest SLR condition. This could cause more frequent inundation in the marsh riparian area and surrounding topography, subsequently causing more channel formation in those areas and leaving less area for vegetation.

At year 80, trends that were seen in simulations at year 50 persist (Fig. 6). In all cases, proposed marsh features are no longer present, although new channels have developed. Simulations with a higher SSC typically have a higher marsh elevation while simulations with a higher rate of SLR will typically have wider channels. This finding is consistent with the work of Mariotti (2020), where it was found that when using MarshMorpho2D, an increase in SLR causes greater channel widening and an increase in SSC will result in greater marsh elevations. Because the model is not designed to simulate river flow that would take place in the Fraser River, the sedimentation that takes place at the interface between the active and non-active cells may not occur (at least to the extent that it did in simulations). A hypothesis for why sedimentation would not occur at this location could be because water velocities would be greater within the river and cause increased erosion in that area.

By year 80, the model projects that there is an overall decrease in water depths within the marsh area for all simulations except S4 (Fig. 8). Despite having a greater rate of sediment deposition, simulations with the highest rate of SLR do not show the greatest relative decrease in water depths within the marsh area. A possible explanation for this is that even though other simulations (such as B2, B3 and S3) have a lower rate of sediment deposition, they also had a smaller increase in MSL. This could have caused the decrease in projected water depth over 80 years to be greater for those simulations despite a lower rate of sediment deposition. For simulations S1, S2 and S5, aside from newly formed channels there is very little change in projected water depth over the course of 80 years. This result is interesting in that it suggests that under certain circumstances it may be possible for vertical accretion within the marsh to match the pace of SLR. On the other hand, simulation S4 also suggests that under certain circumstances water depths within the marsh could increase over 80 years. As discussed in Chapter 1, if water depths surpass a certain threshold some tidal wetlands may convert to a mudflat void of vegetation (Thorne et al. 2015; Drexler et al. 2019).

The locations for new channel development on either side of the mouth of the marsh may be linked with increased modelled water velocities in those areas. Because of the way the DEM is merged with the surrounding topography, there is a steep bank on either side of the mouth of the marsh (Fig. 4). The model projects that water velocities at the bottom of those corner slopes at the mouth of the marsh will be relatively fast compared with water velocities in other parts of the marsh. Increased water velocities on either side of the mouth of the marsh could initiate the erosion that leads to the development of the two new main channels seen in later years (Fig. 6). In simulations with a CSS value of 0.1 Pascals (Fig. 9), the new channel on the right-hand side of the mouth of the marsh develops more relative to simulations with a CSS value of 0.2 Pascals. It is possible that this channel develops more due to less shear stress being required to erode the sediment that is there in simulations with a CSS value of 0.1 Pascals. In general, if marsh evolution is controlled by a lower CSS value, the model projects that deeper channels will form. Although channel morphology may appear different, the amount of vegetated area between simulations with different CSS values and all other factors being equal is projected to be almost the same.

5.2. Implications

Model outputs project that over the course of the next 80 years, the proposed marsh configuration at the Qiqéyt Foreshore site will not persist under any SLR condition. Sediment deposition at the site is projected to cause infilling of the proposed marsh features, and new channels develop. It is beyond the scope of this research to determine how a change in marsh morphology may impact ecological function. Although, there are simulations in this research (Fig. 8, S1, S2 and S5) that suggest the rate of vertical accretion that takes place within the marsh could match the rate of SLR under certain conditions. If this were to be the case in the future, there would be a decreased chance that the marsh at the Qiqéyt Foreshore site would convert to a mudflat ecosystem under rising sea-levels.

Another important consideration for this research is that the final design for the Qiqéyt Foreshore offsetting site will most likely have features that could not be modelled here (uncertainties and limitations are discussed further in Section 5.4). These design differences could significantly alter marsh evolution at the Qiqéyt Foreshore. However, based on the outputs from the model, some recommendations can be made for how to potentially preserve the proposed marsh configuration.

In all modelled simulations, there is a tendency for new channels to develop on either side of the mouth of the marsh. Channel development at the lateral margins of the marsh near the mouth may occur because modelled water velocities are relatively high in those areas. Based on this assumption, there are two possible ways to adjust the proposed marsh topography to increase the likelihood that the marsh configuration persists under future SLR projected conditions. The first would be to reduce the steepness of the slopes near the mouth of the marsh, thereby reducing water velocities in those areas. The second would be to include a marsh substrate with a coarser grain size on either side of the mouth of the marsh, where new channels are likely to develop, thereby reducing the potential for erosion. Although not modelled here, the impacts on marsh evolution from implementing features like this into the marsh design could be explored in future research.

There are some important lessons that can be taken away from this modelling experiment. This model was originally developed and validated by simulating marsh evolution through history up to the present and obtaining results that were similar to the present marsh configurations at different real-world marshes (Mariotti 2018, 2020). In this case, MarshMorpho2D is being used to simulate marsh evolution into the future for a tidal wetland that has not yet been constructed, and more importantly, would not occur naturally at the proposed location. This makes validation of the future marsh configuration at the Qiqéyt Foreshore difficult. However, there are trends evident in the simulation results that can inform decisions regarding refinements to the proposed marsh configuration. Two of these features (slope and marsh substrate) and the impacts they may have on marsh evolution are discussed above.

Therefore, models provide tools for testing the viability of tidal wetland offset designs before they have been built. In addition to this, as Fagherazzi (2020) points out, in a period of changing climate and accelerated SLR, predictive models are necessary to be able to project how future marsh evolution might take place. This notion then raises the question of how models such as MarshMorpho2D can be adapted to best work for the situation they are modelling. In the case of tidal wetlands within the Fraser River, future adaptations to MarshMorpho2D can come in the form of including an improved representation of river flows outside the marsh. Other possible additions to the model could be allowing for multiple grainsizes of marsh substrate and allowing for a more dynamic tidal cycle with two daily highs and lows.

5.3. Adaptive Framework

The Fraser Crossing Group Project Corporation has formed an outline for planned monitoring at the Qiqéyt Foreshore site in the Pattullo Bridge Replacement Project DFO File # 20-HPAC-00518 (2020). Monitoring at the Qiqéyt Foreshore will take place over 10 years following marsh construction. The site will be monitored for different water quality indicators during and after construction. This will include evaluation of temperature, dissolved oxygen, turbidity, salinity and conductivity for a period of 5 years as well as the collection of other physical, metal, nutrient and organic parameters twice per year for 10 years (Fraser Crossing Group 2020). The Fraser Crossing Group Project Corporation will also monitor and maintain the structural integrity of the offsetting site for a period of 10 years. Based on monitoring results, the offsetting site will be adaptively managed to achieve project goals and is expected to be self-sustaining after the 10-year monitoring period. Long term maintenance is expected to prevent the accumulation of debris at the mouth of the marsh (Fraser Crossing Group 2020). The data that comes from this monitoring period will be important for First Nations and others involved in the project to understand the type of management required at the Qiqéyt Foreshore. The knowledge that is gathered from this project can also be applied to similar offsetting sites in the future.

The model projects that accelerated SLR may only start to have an impact on marsh evolution after approximately 20 years or more. For this reason, an adaptive management plan will be outlined here that can inform First Nations and others on how to stay up to date on information that may be important to marsh evolution into the future. An outline of the steps for adaptive management is shown in Figure 14 and discussed further below. The framework used for this adaptive management strategy was developed by Ashton et al. (2016) and used by the Resource Stewardship Division at Rocky Mountain National Park to guide their decision-making process for park management. Here the framework has been recreated and adapted to match the needs of the Qiqéyt Foreshore site. This adaptive framework provides flexible management that is built upon a cyclical structure with five main steps: Monitor, Review, Learn, Plan and Act. Steps should be followed in order but are not necessarily mutually exclusive of one another.

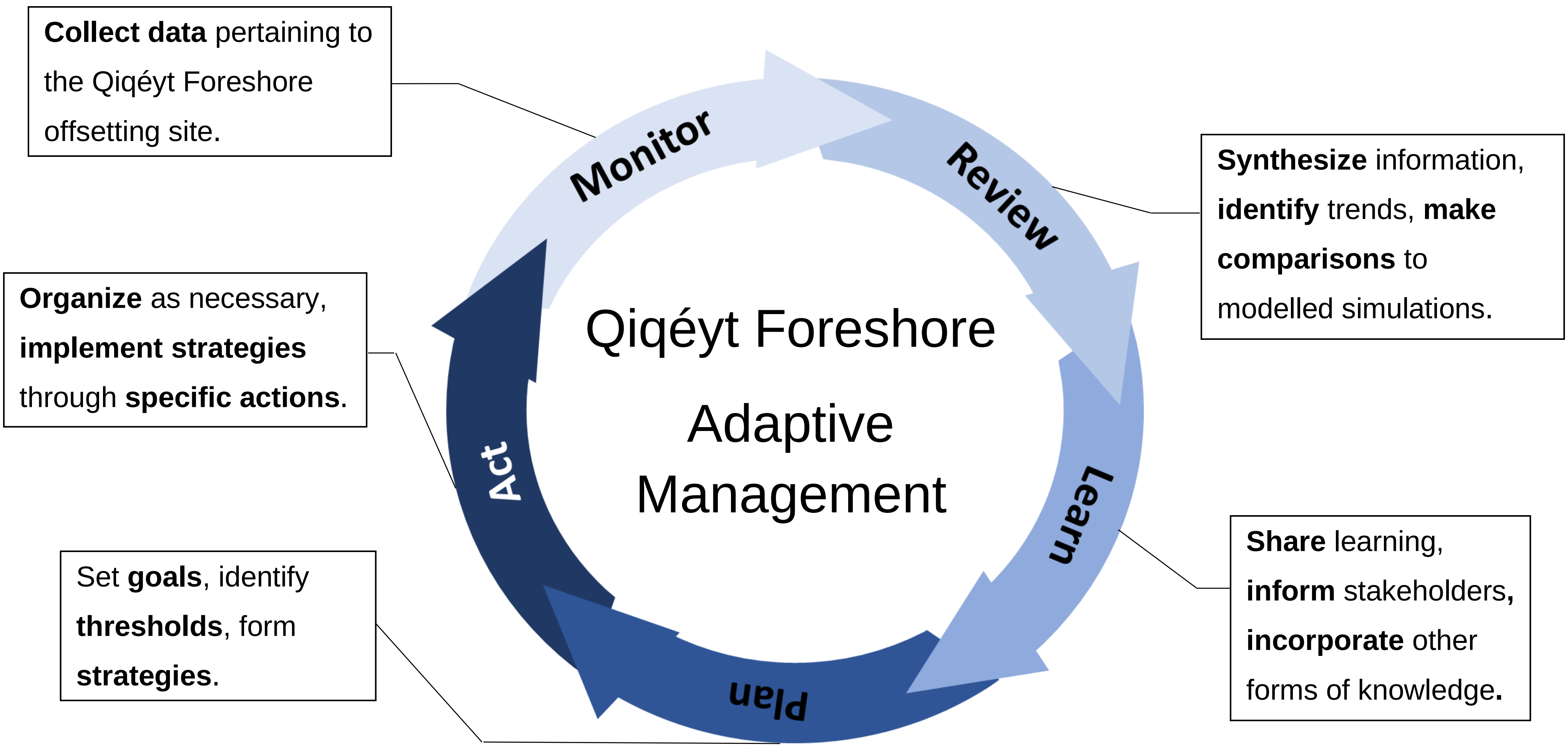

Figure 14 Adaptive management framework for the Qiqéyt Foreshore site. This framework was developed by Ashton et al. (2016) and adapted for the purposes of this project. Steps should be followed in order but are not necessarily mutually exclusive of one another.

The adaptive management cycle begins with monitoring, where data that is important to future marsh development should be collected. There are many possible sources for this data. Table 3 provides an overview of monitorable parameters that could be useful in understanding how future marsh evolution may take place. One major source of information will be from the 10-year monitoring effort that will be carried out at the Qiqéyt Foreshore site following marsh construction. This monitoring will provide accurate site data that can be compared against the input parameters that were selected for this research. Collecting recent and authoritative projections of SLR is also important for understanding how conditions at the Qiqéyt Foreshore will change. The scientific understanding of SLR is advancing at a rapid pace. Information on SLR projections can be obtained from peer-reviewed journals as well as the IPCC's Assessment Reports on the state of knowledge concerning climate change. IPCC Assessment Reports are located online (https://www.ipcc.ch/). The IPCC AR6 Report is expected to be released in 2022, with subsequent reports typically released every six to seven years after that. It was suggested by Griggs et al. (2017) that SLR projections used for management should be updated every five years, or whenever new data becomes available that will significantly modify existing projections.

Table 3 Overview of parameters that are important for marsh evolution at the Qiqéyt Foreshore offsetting site. Values for these parameters can be obtained from monitoring directly at the site or from recent, authoritative sources.

Parameter	Description	Resource
SLR Projections	As the science around climate change advances, SLR projections will change. It will be important to be aware of these changes and compare them to the rates of SLR modelled here.	IPCC Reports, Peer-reviewed journals
SSC	SSC was found to be an important parameter for model projected marsh evolution. Data on the average SSC in the Fraser River will be useful in making comparisons to the range of values used in this research.	Monitoring at site
Marsh Elevation	Understanding how marsh elevations may be changing will be helpful in confirming if the proposed marsh configuration is maintained.	Monitoring at site, City of Surrey Lidar Data
Water Depth	Understanding how water depths at the site may be changing will provide insight to vegetation and fish habitat suitability.	Monitoring at site, visual observation
Vegetation	Changes in vegetation abundance at the site should be monitored and managed to align with project goals.	Monitoring at site, visual observation

Following the conclusion of the 10-year monitoring carried out by the Fraser Crossing Group Project Corporation, any sort of continued monitoring being carried out at the site would be helpful in documenting whether the marsh adapts to SLR and suspended sediment supply from the Fraser River. If data collection is to continue, the same methods that were used in the 10-year monitoring program should be applied so that results are comparable. Visual observation of how the site is evolving can also serve as a form of monitoring. In addition, Lidar data from the City of Surrey can serve as an update of how elevations in the marsh are changing. City of Surrey Lidar data (1 m by 1 m resolution raster data) is updated periodically and can be obtained online from the City of Surrey website.

In the Review phase (Fig. 14), data should be synthesized. Trends should be identified, and the information that is gathered can be compared to the input parameters used in this research as well as the model outputs. In the Learn phase, information that has been gathered through review should be shared with First Nations and others to gather opinions on how best to move forward based on that information. This phase is also a good opportunity for the incorporation of other forms of knowledge that may be useful to all those involved in the project. This step should involve the incorporation of knowledge from all disciplines involved in the development of this offsetting project, such as Traditional Ecological Knowledge, climate science, ecology and engineering.

In the Plan phase, there should be development of realistic and achievable goals for wetland maintenance (for example, maintain X% of vegetated area within the marsh). Thresholds can also be identified that can guide future reassessment of marsh viability (for example, if MSL at the project site increases by a certain amount, a new monitoring program can be initiated for X number of years). As part of identifying goals and thresholds for marsh maintenance, strategies should be developed to achieve those goals and make sure that thresholds are being monitored. Finally, in the Act phase, strategies should be implemented through specific actions in order to achieve project goals. After strategies have been implemented, the cycle begins again to collect new data and understand how the implemented actions may have altered the trajectory of future marsh development.

5.4. Uncertainties & Limitations

There are many uncertainties and limitations involved with this project, and it is important to be aware of them when considering the model outputs. Input values can significantly change the way the model projects marsh evolution at the Qiqéyt Foreshore site. One source of uncertainty in this project has to do with how conditions may change at the Qiqéyt Foreshore in the future. This uncertainty could impact all the input parameters that are described in Table 1. The values listed in Table 1 were collected using region specific data sources, but those values remained the same throughout the entire simulation. It is possible that in the future environmental conditions will differ from the parameter values used to complete the numerical analysis reported here. Notably, differences of environmental conditions could lead to future marsh conditions that differ from the numerical projections (Figs. 6, 8, 9, 10, 11, 12 & 13). There are also other external factors such as the accumulation of debris at the mouth of the marsh and waterfowl grazing that were not included in the model but may impact marsh evolution and vegetation coverage.

In terms of future SLR conditions, there is uncertainty regarding how much sea-levels will rise globally as well as regionally. In addition to this, there is uncertainty as to the actual rate of future SLR. In this research, a linear rate of SLR is applied to the project site. However, researchers have questioned whether the rate of future SLR will occur linearly, exponentially or in pulses that coincide with large ice sheet melting events. The general scientific consensus now is that the rate of SLR occurring globally will continue to accelerate into the future (Kopp et al. 2014; Griggs et al. 2017; Kopp et al. 2017; Sweet et al. 2017).

Another source of uncertainty that needs to be considered when interpreting model outputs is SSC. As discussed above, there can be a lot of variability in SSC depending on discharge and tidal characteristics. This makes it difficult to determine an “average” SSC value that is representative of an entire year. In addition to this, for this research each simulation is assigned one SSC value that is used for the entire simulation. There is uncertainty about whether the SSC values within the Fraser River will remain the same on an annual basis into the future. It is possible that with climate change, an increase in precipitation in the form of rain will cause a higher amount of sediment to be transported and deposited by the Fraser River. Tsuruta et al. (2019) used a large-scale mechanistic sediment transport model to project future sediment dynamics within the Fraser River Basin. Model projections showed an increase in hillslope erosion and in-channel transportation as well as a longer sediment signal throughout the year. If this is the case in the future, it is possible that the amount of sediment being deposited at the Qiqéyt Foreshore site will increase.

There is also uncertainty with respect to the final project design for the Qiqéyt Foreshore site. As discussed above, at the time that this project is being completed only the 30% design is available. Consultation with First Nations and data collection are expected to inform any necessary changes in habitat features and elevations for the completion of future offsetting designs (Fraser Crossing Group 2020). One aspect of marsh design that may impact future evolution is the topography of the area surrounding the marsh. It was found in this research that if water levels were to someday reach the top of the embankment surrounding the marsh, the topography of the surrounding area would have an impact on future channel formation. In this case the surrounding topography was made to be very symmetrical, and the resulting patterns of channel development reflected the topography and high rate of SLR. It is uncertain how the topography surrounding the marsh will be shaped and therefore difficult to determine how channel formation may take place in the event of a high SLR condition of 2.5 m by 2100. Finally, there is uncertainty with respect to what marsh substrate will be used in the final offsetting design. It is likely that different grain sizes will be used in the marsh substrate, as well as erosion control matting on the surrounding slopes, which will impact marsh evolution. Unfortunately, as discussed above, attempting to create these features within the model is beyond the scope of this project.

5.5. Conclusion

This research has shown how predictive numerical models can be useful in projecting the impacts of SLR on the evolution of a tidal wetland offset within the Fraser River. Relative to the original project goals, a better understanding of how marsh evolution may take place at the Qiqéyt Foreshore has been provided, and this research is a first step towards developing the tools necessary for estimating the impacts of SLR on other tidal wetlands within the Fraser River. However, there is still room for improvement with respect to how the model functions that can be considered for future research. These improvements are related to how flows within the Fraser River are modelled and the incorporation of an improved representation of physical marsh attributes.

There is no question that sea-levels will continue to rise into the future, the only question is by how much. As the science surrounding this issue continues to advance the answer will become clearer. Model projections in this study suggest that a higher rate of SLR will lead to greater sediment deposition and wider channels at the Qiqéyt Foreshore. The model projections also suggest that under any future SLR condition it is unlikely the proposed marsh configuration at the Qiqéyt Foreshore will persist for the expected lifetime of the reconstructed Pattullo Bridge. The possible role that other factors such as SSC and marsh substrate will have on marsh evolution have also been explored. In general, the model projects that higher SSC will lead to greater sediment deposition and longer, narrower channels within the marsh compared to lower SSC. Model projections for the impact of a smaller grainsize composing the marsh substrate were found to be minimal, although there is some differentiation in channel development. In the end, although the model projected that marsh configuration may change with time, it is beyond the scope of this research to determine how these changes may impact the ecological function of the tidal wetland offset. These changes could impact the role that this tidal wetland plays in attenuating storm surge, carbon sequestration and providing habitat for diverse fauna.

Finally, one of the greatest benefits of this research is that it can help to start a discussion around the viability of modern offsetting projects. The results here demonstrate that in future offset projects, it may be important to consider how changing environmental factors will influence offset evolution. If it is found that some offsetting projects will not maintain ecological function for the lifetime of the project that they are supposed to be offsetting, perhaps more thought needs to be put into the offsetting process. This may include changes such as revising offsetting guidelines, improving site selection or increasing monitoring efforts. By implementing changes that increase the probability that an offset will remain functional despite changing conditions, the benefits that they provide to our environment and society can be enjoyed for generations to come.

References

Alizad, K., Hagen, S. C., Morris, J. T., Medeiros, S. C., Bilskie, M. V. and Weishampel, J. F. (2016). Coastal wetland response to sea-level rise in a fluvial estuarine system. Earth's Future, 4(11), 483–497. https://doi.org/10.1002/2016EF000385

Ashton, I., Baldwin, B., Bobowski, B., Esser, S. and McLaughlin, P. (2016). Honoring the past and celebrating the present: 100 years of research at Rocky Mountain National Park. Park Science. 32. 68-69.

Attard, M. E., Venditti, J. G. and Church, M. (2014). Suspended sediment transport in Fraser River at Mission, British Columbia: New observations and comparison to historical records. Canadian Water Resources Journal/Revue canadienne des ressources hydriques, 39(3), 356-371.

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. (2012). Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Global Change Biology, 18(11), 3377-3382.

Bartholdy, J. (2012) Salt Marsh Sedimentation. In: Davis Jr. R., Dalrymple R. (eds) Principles of Tidal Sedimentology. Springer, Dordrecht. https://doi-org.proxy.lib.sfu.ca/10.1007/978-94-007-0123-6_8

Berenbrock, C. and Tranmer, A.W. (2008). Simulation of flow, sediment transport, and sediment mobility of the Lower Coeur d'Alene River, Idaho: U.S. Geological Survey Scientific Investigations Report 2008–5093, 164 p.

Best, S. N., Van der Wegen, M., Dijkstra, J., Willemsen, P. W. J. M., Borsje, B. W. and Roelvink, D. J. A. (2018). Do salt marshes survive sea level rise? Modelling wave action, morphodynamics and vegetation dynamics. Environmental Modelling and Software, 109(August), 152–166. https://doi.org/10.1016/j.envsoft.2018.08.004

Bradley, R. (2020). Personal communication. Post Doctoral Researcher, Department of Geography, Faculty of Environment, Simon Fraser University, Burnaby BC, Canada.

British Columbia Ministry of Transportation and Infrastructure. (no date). PATTULLO BRIDGE REPLACEMENT PROJECT EAC APPLICATION – APPLICATION SUMMARY. Retrieved from:

https://projects.eao.gov.bc.ca/api/document/5b7343145bc7e60024dc0f6e/fetch/Section_0.3_Application_Summary

British Columbia Ministry of Transportation and Infrastructure. (no date). PATTULLO BRIDGE REPLACEMENT PROJECT EAC APPLICATION – PART B SECTION 4.3 FISH AND FISH HABITAT. Retrieved from: https://projects.eao.gov.bc.ca/api/document/5b73431b5bc7e60024dc0fba/fetch

Brophy, L. and Ewald, M. (2017). Modeling sea level rise impacts to Oregon's tidal wetlands: Maps and prioritization tools to help plan for habitat conservation into the future. 10.13140/RG.2.2.19021.79845.

Caner, A., Yanmaz, A. M., Yakut, A., Avsar, O. and Yilmaz, T. (2008). Service Life Assessment of Existing Highway Bridges with No Planned Regular Inspections. Journal of Performance of Constructed Facilities. 2008;22(2):108-114. doi:10.1061/(ASCE)0887-3828(2008)22:2(108)

Chan, K. (2020). BC government selects contractor for new $1.4-billion Pattullo Bridge. Daily Hive. Retrieved from: https://dailyhive.com/vancouver/pattullo-bridge-replacement-acciona-aecon-contractor

Chmura, G. L., Helmer, L. L., Beth Beecher, C. and Sunderland, E. M. (2001). Historical rates of salt marsh accretion on the outer Bay of Fundy. Canadian Journal of Earth Sciences, 38(7), 1081–1092.

Church, J. A. and White, N. J. (2011). Sea-Level Rise from the Late 19th to the Early 21st Century. Surv Geophys 32, 585–602 (2011). https://doi.org/10.1007/s10712-011-9119-1

City of Vancouver Sustainability Group. (2018). Climate Change Adaptation Strategy: 2018 Update and Action Plan. https://vancouver.ca/files/cov/climate-change-adaptation-strategy-2018.pdf (Accessed December 11, 2020).

Cook, D. (2018). Pattullo Bridge Replacement Project Historical Heritage Study. Prepared for: Translink, Hatfield Consultants. Retrieved from: https://projects.eao.gov.bc.ca/api/document/5b73439a5bc7e60024dc108b/fetch/Appendix_18.13_Historical_Heritage_Study.pdf

DeConto, R. M. and Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591-597. doi:10.1038/nature17145

Department of Fisheries and Oceans Canada. (2021). BC Tidal area 29 – Lower Mainland, Sunshine Coast, Fraser River: Recreational fishing limits, openings and closures. Retrieved from: https://www.pac.dfo-mpo.gc.ca/fm-gp/rec/tidal-maree/a-s29-eng.html#map

Department of Fisheries and Oceans Canada. (2019). Canadian Tides and Water Levels Data Archive. Station number 7654, New Westminster, BC. http://www.isdm-gdsi.gc.ca/isdm-gdsi/twl-mne/inventory-inventaire/sd-ds-eng.asp?no=7654&user=isdm-gdsi&region=PAC (Accessed December 19, 2020).

Déry, S. J., Hernández-Henríquez, M. A., Owens, P. N., Parkes, M. W., and Petticrew, E. L. (2012). A century of hydrological variability and trends in the Fraser River Basin. Environmental Research Letters, 7(2), 24019. https://doi.org/10.1088/1748-9326/7/2/024019

Drexler, J. Z., Woo, I., Fuller, C. C. and Nakai, G. (2019). Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States. Restoration Ecology, 27(5), 1117–1127. https://doi.org/10.1111/rec.12941

Fagherazzi, S., Mariotti, G., Leonardi, N., Canestrelli, A., Nardin, W. and Kearney, W. S. (2020). Salt Marsh Dynamics in a Period of Accelerated Sea Level Rise. Journal of Geophysical Research: Earth Surface, 125(8), 1–31. https://doi.org/10.1029/2019JF005200

Fraser Crossing Group. (2020). Pattullo Bridge Replacement Project (DFO File # 20-HPAC-00518). Responses to October 8, 2020 Comments from DFO on File # 20-HPAC-00518 Application for a Fisheries Act Authorization.

French, P. W., Allen, J. R. L. and Appleby, P. G. (1994). 210-Lead dating of a modern period saltmarsh deposit from the Severn Estuary (Southwest Britain), and its implications. Marine Geology, 118(3-4), 327–334.

Gehrels, R. (2010). Sea-level changes since the Last Glacial Maximum: an appraisal of the IPCC Fourth Assessment Report. 25, 26–38. https://doi.org/10.1002/jqs

Golledge, N. R., Kowalewski, D. E., Naish, T. R., Levy, R. H., Fogwill, C. J. and Gasson, E. G. (2015). The multi-millennial Antarctic commitment to future sea-level rise. Nature, 526(7573), 421-425.

Government of Canada. (2017). Climate Data: Homogenized Wind Speed Data Access. Station Number 1108447, Vancouver International Airport, BC. https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data/wind-speed-access.html (Accessed December 19, 2020).

Griggs, G., Árvai, J., Cayan, D., DeConto, R., Fox, J., Fricker, H.A., Kopp, R.E., Tebaldi, C. and Whiteman, E.A. (2017). Rising Seas in California: An Update on Sea-Level Rise Science. California Ocean Protection Council Science Advisory Team Working Group. California Ocean Science Trust.

Hatfield Consultants. (2018). Pattullo Bridge Replacement Project: Fish and Fish Habitat Report. Prepared for: Translink. Retrieved from: https://projects.eao.gov.bc.ca/api/document/5b73437e5bc7e60024dc102c/fetch/Appendix__18.4_Fish_and_Fish_Habitat_Report.pdf

Hay, C. C., Morrow, E., Kopp, R. E. and Mitrovica, J. X. (2015). Probabilistic reanalysis of twentieth-century sea-level rise. Nature, 517(7535), 481-484. doi:10.1038/nature14093

Intergovernmental Panel on Climate Change. (no date). Definition of Terms Used Within the DDC Pages. Retrieved from: https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html

Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S. and Nikitina, D. (2012). Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology, 12,40–49.

Kirwan, M. L. and Murray, A. B. (2008). Ecological and morphological response of brackish tidal marshland to the next century of sea level rise: Westham Island, British Columbia. Global and Planetary Change, 60(3–4), 471–486. https://doi.org/10.1016/j.gloplacha.2007.05.005

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H. and Tebaldi, C. (2014). Probabilistic 21st and 22nd Century

Sea-Level Projections at a Global Network of Tide-Gauge Sites. Earth’s Future, 2(8), 383–406.

Kopp, R. E., DeConto, R. M., Bader, D. A., Hay, C. C., Horton, R. M., Kulp, S., Oppenheimer, M., Pollard, D. and Strauss, B. H. (2017). Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. Earth’s Future, 5(12), 1217–1233.

Mahaney, W.M., Wardrop, D.H. and Brooks, R.P. (2005). Impacts of sedimentation and nitrogen enrichment on wetland plant community development. Plant Ecol 175, 227–243. https://doi.org/10.1007/s11258-005-0011-2

Mariotti, G. (2020). Beyond marsh drowning: The many faces of marsh loss (and gain). Advances in Water Resources, 144(April), 103710. https://doi.org/10.1016/j.advwatres.2020.103710

Mariotti, G. and Fagherazzi, S. (2010). A numerical model for the coupled long-term evolution of salt marshes and tidal flats. Journal of Geophysical Research: Earth Surface, 115(1), 1–15. https://doi.org/10.1029/2009JF001326

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B. K., Wolters, G., Jensen, K., Bouma, T. J., Miranda-Lange, M. and Schimmels, S. (2014). Wave attenuation over coastal salt marshes under storm surge conditions. Nature Geoscience, 7(10), 727.

Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B. and Cahoon, D. R. (2002). Responses of coastal wetlands to rising sea level. Ecology, 83, 2869–2877. https://doi.org/10.2307/3072022

Mudie, P. J. and Byrne, R. (1980). Pollen evidence for historic sedimentation rates in California coastal marshes. Estuarine and Coastal Marine Science, 10(3), 305–IN3.

National Research Council. (2012). Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: The National Academies Press. https://doi.org/10.17226/13389.

Nerem, R. S., Chambers, D. P., Choe, C. and Mitchum, G. T. (2010). Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions Estimating

Mean Sea Level Change from the TOPEX and Jason Altimeter Missions. 0419. https://doi.org/10.1080/01490419.2010.491031

Oregon Climate Change Research Institute. (2010). Oregon Climate Assessment Report, K.D. Dello and P.W. Mote (eds). College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR

Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., Horton, R., Knuuti, K., Moss, R., Obeysekera, J., Sallenger, A. and Weiss, J. (2012). Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO, 1–37. Retrieved from http://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf

Reed, D. J. (1995). The response of coastal marshes to sea-level rise: Survival or submergence? Earth Surface Processes and Landforms, 20(1), 39-48.

Schile, L. M., Callaway, J. C., Morris, J. T., Stralberg, D., Parker, V. T. and Kelly, M. (2014). Modeling Tidal Marsh Distribution with Sea-Level Rise: Evaluating the Role of Vegetation, Sediment, and Upland Habitat in Marsh Resiliency. 9(2). https://doi.org/10.1371/journal.pone.0088760

Shi, Z., Hamilton, L.J. and Wolanski, E. (2000) Near-bed currents and suspended sediment transport in salt marsh canopies. J Coast Res 16:909–914

Sweet, W. V., Kopp, R. E., Weaver, C. P., Obeysekera, J., Horton, R. M., Thieler, E. R. and Zervas, C. (2017). Global and Regional Sea Level Rise Scenarios for the United States. (NOS CO-OPS 083), 75. Retrieved from https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

Tabak, N. M., Laba, M. and Spector, S. (2016). Simulating the effects of Sea Level Rise on the resilience and migration of tidal wetlands along the Hudson River. PLoS ONE, 11(4), 1–25. https://doi.org/10.1371/journal.pone.0152437

The Math Works, Inc. (2020). MATLAB Version 2020a. The Math Works, Inc., 2020. Computer Software. www.mathworks.com/.

The Math Works, Inc. (2021). MATLAB Version 2021a. The Math Works, Inc., 2021. Computer Software. www.mathworks.com/.

Thorne, K. M., Dugger, B. D., Buffington, K. J., Freeman, C. M., Janousek, C. N., Powelson, K. W., Gutenspergen, G. R. and Takekawa, J. Y. (2015). Marshes to mudflats: sea-level rise effects on tidal marshes along a latitudinal gradient in the Pacific Northwest: U.S. Geological Survey Open-File Report 2015-1204, 54 p plus appendixes. Retrieved from http://dx.doi.org/10.3133/ofr20151204

Thorne, K., MacDonald, G., Guntenspergen, G., Ambrose, R., Buffington, K., Dugger, B., Freeman, C., Janousek, C., Brown, L., Rosencranz, J. and Holmquist, J. (2018). U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. Science Advances, 4(2), 1–11. https://doi.org/10.1126/sciadv.aao3270

Tsihrintzis, V. A. and Madiedo, E. E. (2000). Hydraulic resistance determination in marsh wetlands. Water Resources Management, 14(4), 285–309. https://doi.org/10.1023/A:1008130827797

Tsuruta, K., Hassan, M.A., Donner, S.D. and Alila, Y. (2019). Modelling the effects of climatic and hydrological regime changes on the sediment dynamics of the Fraser River Basin, British Columbia, Canada. Hydrological Processes. 33: 244–260. https://doi.org/10.1002/hyp.13321

United States Environmental Protection Agency. (2018). Classification and Types of Wetlands. Retrieved from: https://www.epa.gov/wetlands/classification-and-types-wetlands#marshes

Voss, B. M. (2014). Spatial and temporal dynamics of biogeochemical processes in the Fraser River, Canada: a coupled organic-inorganic perspective. https://doi.org/10.1575/1912/6919

Wang, F.C., Tiesong, L. and Sikora, W.B. (1993). Intertidal marsh suspended sediment transport processes, Terrebonne Bay, Louisiana, USA. J Coast Res 9:209–220

Appendix A.

List of all parameters in MarshMorpho2D v.2.0 model developed by G. Mariotti (2018, 2020). Reference values indicate the original values used in MarshMorpho2D. Site values indicate the values that were used in this study.

Parameter	Description	Reference Value	Site Value
A	0: not in the domain, 1: a normal cell, 2: the open sea boundary	0, 1 or 2	-
Active	0: Not Active, 1: Active	0 or 1	-
M	Number of columns in DEM	300	240
N	Number of rows in DEM	500	240
dx		10	-
x	Length of site (m)	500	120
y	Width of site (m)	300	120
z	Area of site (m^2)	500 x 300	120 x 120
g	Gravity	9.81	-
rhos	Sediment Density	2650	-
ss	Relative Density	rhos-rho/rho	-
kro	Minimum Water Depth for Hydrodynamics	0.1	-
Diffsmud	Coefficient for Tidal Dispersion	1	-
DoMUD	Base Diffusivity of Suspended Mud	1	-
RSLR	Sea Level Rise (m/day)	gR/1000/365	-
msl	Mean sea-level	2.5	1.95
rho	Water density (kg m^{-3})	1030	1020
gR	Sea-level rise (mm/yr)	[1, 2.5, 5, 7.5, 10]	[0, 12.5, 31.25]
gC	Suspended sediment concentration (g m^{-3})	[60, 30, 15, 7.5]	[5, 10, 20]
Trange	Tidal range (m)	0.7	2.3
Ttide	Tidal period (hrs/day)	12.5	12.25

Parameter	Description	Reference Value	Site Value
wind	Wind speed (m s^{-1})	7	2
taucr	Critical shear stress value	0.2	[0.1, 0.2]
TrangeVEG	Tidal Range for Vegetation	Trange	-
aw	Wave Edge Erodability	0.3/365	-
maxedgeheight		2	-
fox	Fraction of Edge Eroded Material that is Oxidized	0	-
hwSwelltransport		1	-
hwSea_lim	Limiter Water Depth of Sea Waves	0.2	-
co2	Sea Boundary Suspended Sediment	gC/1000	-
Cb	Manning Coefficient	0.02	-
d50_2	Mud Grain Size (m)	0.02/1000/1000	-
ws2	m/s	0.2/1000	-
por2		0.7	-
me	per day	0.1*10^-4*24*3600	-
crMARSH	Creep Coefficient Vegetated	0.1/365	-
crMUD	Creep Coefficient	3.65/365	-
alphaMUD	Coefficient for Bedload Downslope Mud	0.25	-
dBlo		0	-
dBup		TrangeVEG/2	-
Cv	Manning for Vegetated Area	0.1	-
wsB	Mud Settling Velocity	1/1000	-
taucrVEG	Critical Sheer Stress for Vegetation	0.5	-
AccreteOrganic	Organic Accretion (mm/yr)	1	-
Korg	Organic Accretion for Vegetation (mm/yr)	6/1000/365	-
VEGETATION	Vegetation Resistance and Settling	1	-

Parameter	Description	Reference Value	Site Value
computeSeaWaves		1	-
computeEdgeErosionSea		1	-
computetide		1	-
periodic		0	-
imposeseaboundary-depthmorphoALL	To use when a channel mouth is at a boundary	1	-
calculateponddynamics		1	-
Epondform	Probability of new pond formation per year (area/area)	0.4*10^-5	-
zpondcr	Base of New Pond Formation with Respect to MSL	0.2	-
minponddepth	Minimum depth to define a pond after you identified the "lakes"	0.1	-
maxdpond	Maximum depth scour of a new pond		-
zntwrk	Depth above MSL that define the channel network	(P.Trange/2)*0.5	-
aPEXP	Isolated pond expansion rate (m/yr)	0.015*10	-
ponddeeprate		0.003	-
limitdeltaz	Meters	2	-
limitmaxup	Meters	1	-
tmax	Max number of time step	100	-
tINT	Iteration length for plotting	1	-
anglewindserie	Sea wave direction	Rand(numerserie,1) *360	-
numberserie		10000	-
dtOserie		Ones(numberserie,1) *365	-

Appendix B.

Preliminary planting list for the riparian area at the Qiqéyt Foreshore. This planting list was developped by the Fraser Crossing Group Project Corporation (2020) through consultation with First Nations groups. More details on planting specifications are available in the Pattullo Bridge Replacement Project DFO File # 20-HPAC-00518.

Species (Scientific / Common)	Quantity	Spacing	Notes (Feedback from Indigenous Groups)
Acer circinatum / Vine maple	10	5 m	
Corylus cornuta / Beaked hazelnut	50	1 / m^2	Usually prefers drier well drained sites close to water, plant only if site is suitable.
Crataegus douglasii / Black hawthorn	25	1 / m^2	Prefer species that provide cover and/or food for birds and wildlife – black hawthorn provides songbird nesting habitat
Holodiscus discolor / Ocean-spray	25	1 / m^2	Usually prefers drier well drained sites close to water, plant only if site is suitable.
Mahonia nervosa / Dull Oregon grape	25	1 / m^2	
Malus fusca / Western crabapple	10	5 m	
Oemleria cerasiformis / Indian plum	25	1 / m^2	
Physocarpus capitatus / Pacific nine-bark	25	1 / m^2	
Polystichum munitum / Sword fern	50	Up to 3 / m^2	Can be clumped together, near larger trees, areas that will be shaded; not in flooded area
Pteridium aquilinum / Bracken fern	50	Up to 3 / m^2	Can be clumped together, near larger trees, areas that will be shaded; not in flooded area
Ribes sanguineum / Red flowering currant	50	1 / m^2	
Rosa nutkana / Nootka rose	35	1 / m^2	
Rubus parviflorus / Thimbleberry	25	1 / m^2	
Sambucus racemose / Red elderberry	35	1 / m^2	Prefers drier well drained sites close to water, plant only if site is suitable – e.g. dry edges

Species (Scientific / Common)	Quantity	Spacing	Notes (Feedback from Indigenous Groups)
Taxus brevifolia / Western yew	25	5 m	Elevation needs to be considered.
Picea sitchensis / Sitka spruce	8	5 m	
Pinus contorta / Shore pine	8	5 m	
Prunus emarginata / Bitter cherry	8	5 m	
Thuja plicata / Western red cedar	8	5 m	
Tsuga heterophylla / Western hemlock	TBD	5 m	Riparian vegetation provides shade for cool water, bank stabilization, litterfall and insect habitat (fish food)

Preliminary planting list for the marsh area at the Qiqéyt Foreshore. This planting list was developped by the Fraser Crossing Group Project Corporation (2020) through consultation with First Nations groups. More details on planting specifications are available in the Pattullo Bridge Replacement Project DFO File # 20-HPAC-00518.

Species (Scientific / Common)	Quantity	Spacing	Notes (Feedback from Indigenous Groups)
Alisma plantago-aquatica / Water-Plantain	150	3 / m^2	
Calamagrostis canadensis / Bluejoint		3 / m^2	Requested that this be added as an alternative to tall mannagrass
Carex lyngbyei / Lyngbye's sedge	250	3 / m^2	Critical in terms of supporting food webs (Tsawwassen FN)
Carex obnupta / slough sedge	100	3 / m^2	
Carex scoparia / Pointed Broom Sedge	100	3 / m^2	
Carex sitchensis / Sitka sedge	250	3 / m^2	
Carex stipata / Sawbeak sedge	100	3 / m^2	
Carex utriculate / Beaked sedge	100	3 / m^2	
Eleocharis palustris / Spikerush	100	3 / m^2	
Glyceria elata / Tall mannagrass	200	3 / m^2	Requested to be replaced by Bluejoint
Juncus articulates / Jointed rush	100	3 / m^2	
Juncus balticus / Baltic rush	100	3 / m^2	

Species (Scientific / Common)	Quantity	Spacing	Notes (Feedback from Indigenous Groups)
Juncus effusus / Common rush	150	3 / m^2	
Juncus oxymeris / Pointed rush	100	3 / m^2	
Lysichiton americanus / Western skunk cabbage	TBD	3 / m^2	
Mimulus guttatus / Yellow monkeyflower	100	3 / m^2	
Sagittaria latifolia / Wapato	250	3 / m^2	Highly recommended food plant for eco-cultural restoration.
Schoenoplectus tabernaemontani / Soft-stemmed bulrush	100	3 / m^2	Recommended for eco-cultural restoration, used for baskets and building material.
Scirpus microcarpus / Small-flowered bulrush	100	3 / m^2	
Vaccinium uliginosum / Bog blueberry	TBD	3 / m^2	Similar to bog cranberry, may be planted in test spots to determine it is suitable for the site