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Climate Change Indicators for Pacific Salmon in the Fraser River Estuary

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PACIFIC SALMON FOUNDATION

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Cover image by Peter Mather

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Executive Summary

Estuaries are dynamic ecosystems that provide important connections between land and ocean and are among the most productive ecosystems on the planet. Climate change is altering the hydrological cycle that heavily influences estuarine ecosystems and affects the species that inhabit them. The Fraser River estuary is the largest estuary in British Columbia and all five species of Pacific salmon migrate through the estuary twice in their life, as adults accessing spawning grounds, and as juveniles migrating out to the ocean. In this report we look to identify how climate change is affecting the Fraser River estuary and the impacts this may have on Pacific salmon. We do this by identifying climate indicators, which are environmental variables that are sensitive to change, relatively easy to measure, and representative of changes to the ecosystem. We then conduct data analysis on these climate indicators to look for changes through time. Finally, we discuss our findings, focusing on these indicators may affect salmon.

1.0 Introduction

1.1 Background Information

Estuaries are important areas that provide a connection between terrestrial and marine ecosystems. Estuaries support a diverse array of habitats and species, making them one of the most productive ecosystems in the world (Environmental Protection Agency 2022). Estuaries are also important economically for industries such as tourism, transportation, and commercial fishing as well as culturally for recreation, education, and traditional practices.

Estuaries play a vital role in the hydrological cycle as they connect freshwater from land with salt water in the marine environment. Estuaries are dynamic ecosystems that are constantly changing due to tidal influences and changing freshwater flows. Climate change is predicted to change the hydrological cycle, affecting the physical and chemical processes in both freshwater and marine environments. Estuaries are influenced by freshwater and saltwater and are therefore experiencing the effects of climate change in both environments. Aquatic ecosystems are influenced by the chemical and physical processes that occur within the hydrological cycle, therefore understanding the influence of climate change is vital for management efforts.

British Columbia has over 400 estuaries that drain much of Western North America (Rao 2022). The Fraser River estuary is the largest estuary in British Columbia, containing 36% of all estuarine habitat in the province (Rao 2022). The Fraser River estuary is also iconic to British Columbians (B.C.) because of its importance to large populations of Pacific salmon, which are an ecological and cultural keystone species and a symbolic species in the province. All five species of Pacific salmon spawn in the Fraser River, and migrate through the Fraser River estuary twice in their life: as juvenile salmon exiting freshwater to rear in the ocean and as adults returning to spawn. Salmon populations throughout the Fraser River have been declining in recent history, especially sockeye salmon. The Fraser River estuary is threatened by human development as the metropolitan area of Vancouver is situated around the estuary, and climate change poses an additional threat. To protect salmon populations, maintaining a healthy estuary is key to allow migration and spawning activities. Therefore, understanding the effects of climate change on the Fraser River estuary is vital for the management of salmon populations.

The effects of climate change are already being experienced throughout British Columbia and pose a threat to the Fraser River estuary. In 2021, many heat records were broken across B.C. due to an unusual heat dome that affected the region for several days. The effects of the heat dome were compounded with a drought that occurred across much of the Pacific Northwest and contributed to many forest fires that burned over 860,000 acres in B.C. Following the hot dry summer, B.C. experienced historic flooding in November that wiped out highways and destroyed many communities such as Merritt. These events show how climate change can alter the hydrological cycle and this poses a threat to estuarine habitats such as the Fraser River estuary, and aquatic species that rely on those habitats, including Pacific salmon. Climate change is expected to reduce precipitation, increase sea level, acidify the ocean, and increase the frequency of anomalous weather events such as the heat dome and historic flooding experienced in 2021. In this report, we aim to identify climate indicators for the Fraser River estuary that capture these effects, with a focus on indicators that are relevant to Pacific salmon.

Section 1.2 The Pacific Salmon Foundation Context

The Pacific Salmon Foundation was founded in 1987 with the goal of engaging communities, government, and the private sector to tackle the range of issues Pacific salmon face. The Salmon Watershed Program works to support the technical aspects of salmon conservation by making scientific information for Pacific salmon populations and their habitats available and accessible. The Pacific Salmon Explorer (www.salmonexplorer.ca) is an interactive data visualization tool developed by the Salmon Watershed Program that provides access to the best available data for salmon and their habitat in B.C. Currently, the Pacific Salmon Explorer contains data and information on the habitat status and population status of Pacific salmon Conservation Units but does not present information on the current and future impacts of climate change on salmon and their habitats. The work presented here is a portion of the work the Salmon Watershed Program is undertaking to incorporate climate indicators and climate vulnerability assessments into the Pacific Salmon Explorer.

2.0 Indicators

Climate indicators are parameters that show how the environment is changing under a warming climate. Indicators are useful tools for understanding how climate change is affecting species and their habitats. Indicators allow us to understand what is happening in the environment, which can then inform conservation and management efforts. Good indicators are parameters that are easy to measure, representative of the changes occurring in the environment, and are sensitive to change. To identify climate indicators, we conducted a literature review of the projected changes to estuarine habitats. A few candidate indicators, including dissolved oxygen, turbidity, dissolved nutrients, salinity and shoreline sensitivity to sea level rise were selected and are outlined below. Temperature was not selected as a candidate indicator in this project because both stream temperature and sea surface temperature are being considered as indicators under different components of the climate change work by the Salmon Watersheds Program.

2.1 Dissolved Oxygen

Dissolved oxygen is the amount of oxygen in water. Sources of dissolved oxygen are the atmosphere, marine plants, and groundwater discharge (Testa et al. 2018). Running water such as rivers and streams tend to contain higher amounts of dissolved oxygen than stagnant water such as lakes, ponds, and the ocean (Testa et al. 2018). The concentration of dissolved oxygen in water is measured in units of micrograms per litre (ug/L) using special sensors that can be portable or fixed to long-term monitoring stations. Dissolved oxygen is important for salmon and other fish species as they breathe it through their gills. When there is not enough oxygen in water to support aquatic life, dead zones are formed. Areas, such as the Mississippi Delta, already experience dead zones seasonally which are attributed to human causes which have been compounded with the effects of climate change (Osterman et al. 2006).

Climate change affects the amount of oxygen water can hold (Testa et al. 2018). In general, gasses, such as oxygen, are more soluble in cooler liquids. As climate change increases global temperatures, the amount of oxygen water will be able to contain will decrease (Testa et al. 2018). Increasing temperatures also increases stratification, where there is less vertical mixing of layers in the water column. Stratification limits the exchange of gasses throughout the water column, leading to less dissolved oxygen deeper in the water column.

2.2 Turbidity

Turbidity is the measure of the ability of water to transmit light, or the clarity of water (Glamore et al. 2016). This is influenced by the amount of suspended material in the water column. The most common and standardized way to measure turbidity is in nephelometric turbidity units (NTU) using a nephelometer that shines a known quantity of light through a sample of water onto a sensor to determine how much light was reflected and how much penetrated the water. Turbidity may also be measured as total suspended sediment where the weight of sediment in a water sample is measured per liter of water. Plants require light to photosynthesize, and turbidity affects their ability to access light (Environmental Protection Agency 2022). Turbidity also affects salmon as they avoid areas of high turbidity due to decreased visibility affecting their ability to see and navigate. Very high amounts of sediment suspended in water can compromise a salmon's ability to breathe by clogging their gills.

Climate change is expected to increase turbidity in estuaries (Glamore et al. 2016). The main source of debris suspended in the water column is from sediment being washed into water from precipitation and melting snow running off into streams and rivers (Environmental Protection Agency). Fast moving water also increases the amount of suspended sediment as particles are unable to settle to the bottom. Climate change is predicted to increase the frequency and intensity of storms, and cause more precipitation to fall as rain (Environmental Protection Agency). Increasing frequency and intensity of precipitation will lead to more sediment being washed into rivers and streams, increasing turbidity. Exact seasonal changes to precipitation are hard to predict, however for the West coast of North America more precipitation in the winter is expected to fall as rain which would increase turbidity in the winter (Okey et al. 2016). The West coast also receives about a quarter of its precipitation in the form of rain due to storms formed by atmospheric rivers that typically emerge in the fall and winter (Okey et al. 2016). These storms are predicted to increase in intensity and frequency increasing turbidity in the fall and winter. Salmon return to spawn in the fall, corresponding to the times increased turbidity is expected to occur which could cause increased mortality for adult salmon migrating through the Fraser River estuary.

2.3 Dissolved Nutrients (Silicon)

Dissolved nutrients are molecules that can be catabolized or used in the metabolic processes of aquatic species. Dissolved nutrients are measured in micrograms per liter (ug/L) using specialized equipment to separate the nutrient from water. Silicon is a dissolved nutrient that is important for cell wall formation of diatoms, which make up the majority of phytoplankton (Taucher et al. 2022). Amounts of silicon in the water column have shown to have a direct effect on the abundance of diatoms (Taucher et al. 2022). Diatoms account for 40% of marine primary production, indicating their importance in marine ecosystems (Taucher et al. 2022). Phytoplankton, including diatoms, form the basis of marine food webs, where they are eaten by zooplankton, and marine invertebrates which are then eaten by fish such as salmon. Maintaining a healthy ecosystem is important for salmon so that they have enough prey to sustain themselves.

Climate change is expected to decrease the amount of silicon in aquatic environments (Taucher et al. 2022). The main source of silicon in water is from eroding terrigenous rock that releases silica which dissolves into bodies of water (Statham 2012). Silicon dissolution is directly affected by the acidity of water, where increased acidity decreases the ability of silicon to dissolve (Taucher et al. 2022). Climate change is increasing the acidity of both fresh and saltwater, which decreases the dissolution of silicon, leading to less silicon in aquatic environments. Given the importance of silicon to phytoplankton like diatoms, marine food webs may be affected with negative consequences for prey availability for salmon.

2.4 Salinity

Salinity is the primary environmental variable that determines macroinvertebrate distribution in estuaries (Little et al. 2017). Estuaries are among the most productive ecosystems in the world, in part due to their large biodiversity where different species thrive in differing levels of salinity. As the salinity changes in estuaries, so will the distribution of species, and as salinity increases, we may see a local loss of fresh and brackish water species (Little et al. 2017). Eelgrass beds in estuaries are an important habitat for salmon as they provide a suitable nursery to juvenile salmon, are home to prey species of salmon, and allow salmon to hide from their predators. Shifting salinity gradients may alter the abundance and distribution of eelgrass beds which in turn would affect the survivability of salmon that rely on them. Salinity gradients may also be one cue salmon use in their migration to and from spawning grounds, changes in the salinity gradient may then affect their migration ability.

Climate change will alter salinity in estuarine habitats. Salinity is measured in parts per thousand (ppt) where 1 ppt is equal to 1 gram of salt per 1,000 grams of water. As the globe warms, ice caps will continue to melt which will increase sea level while decreasing salinity in the ocean. Climate change is also predicted to change freshwater flows in rivers and estuaries as precipitation patterns change and glaciers melt. On the West coast of Canada, more precipitation will fall as rain rather than snow, which will alter peak river flows as rain enters streams and rivers more quickly than snow which takes time to melt (Okey et al. 2016). Salinity is a dynamic characteristic of estuaries that changes daily due to tidal influences and seasonally with differing freshwater inputs. Therefore, predicting how salinity may be affected by climate change is challenging. The decreasing salinity of the ocean may lead to decreased salinity in estuaries, however as sea levels rise, salt water may push further into estuaries. Additionally, freshwater inputs will change as more precipitation falls as rain, and as storms become increasingly frequent and intense.

2.5 Shoreline Sensitivity to Sea Level Rise

Shallow areas in estuaries provide important habitat for salmon, such as eelgrass beds as described above. With sea levels rising due to melting icecaps as the global climate warms, these shallow areas will become deeper which may affect their ability to persist. Where shorelines allow, these shallow environments may migrate inland as sea level rises. However, the Fraser River estuary sits in the metropolitan area of Vancouver, where much of the shoreline is developed. These developed shorelines will prevent the migration of shallow habitats inland, risking their extinction. Quantifying sea level rise along the West coast of B.C. is complicated by the fact that the coast of B.C. is still rising from post-glacial rebound (Ministry of Environment 2016). As shallow water environments provide important habitat for salmon on their migration path, salmon will be negatively affected through the loss of suitable habitat, prey, and protection from predators. The Resilient Coasts project (https://resilientcoasts.ca/), a partnership between the Pacific Salmon Foundation and the Stewardship Centre for B.C., is working to ensure that coastal habitats and human infrastructure are not lost as sea levels rise.

3.0 Data

Environment and Climate Change Canada collects water quality data throughout British Columbia under the Canada-British Columbia Water Quality Monitoring Agreement. Data are collected from buoys located in many major bodies of water throughout the province to provide water quality information that informs freshwater management. The program has 14 water quality buoys along the Fraser River, including one located in the Fraser River estuary and one near the town of Hope. The buoys collect data on the levels of different ions, metals, dissolved nutrients and physical properties of the estuary. For the purpose of our study, we downloaded data on the climate change indicators identified in the previous section including dissolved oxygen, turbidity, salinity from the Fraser River estuary Buoy and silicon From the Fraser River Buoy at Hope.

The dataset includes information on the location, date, and time that the sample was collected. For each variable of interest, there is also a valid method variable (VMV) code that indicates the specific method that was used for measuring the variable. The minimal detectable amount is also included, which indicates the smallest unit of measurement that can be detected. Additionally, the unit of measurement and value of measurement is given. These data were plotted in R to determine seasonal trends and identify a baseline for each climate indicator, and are summarized below.

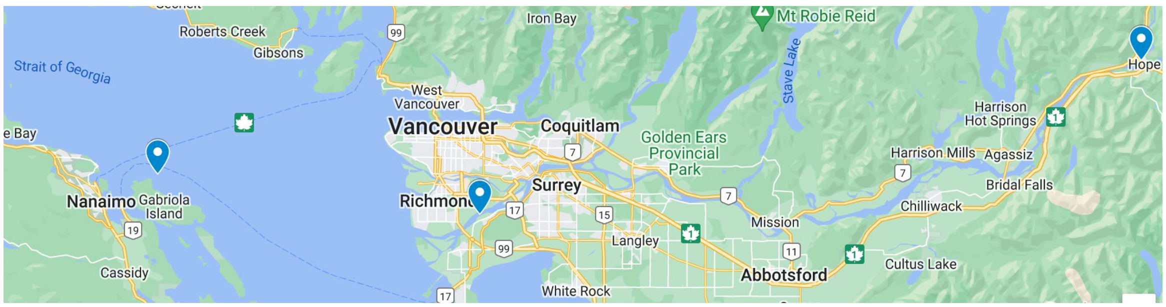

Figure 1: Map indicating location where data was collected by the blue pins. Leftmost pin corresponds to the Departure Bay Lighthouse, middle pin to the Fraser River estuary buoy, and rightmost pin to the Fraser River Buoy at Hope.

Table 1: List of datasets used for each climate indicator with links to the websites data was downloaded from, and locations where data was collected.

Indicator	**Dataset**	**Sample Location**
Dissolved oxygen (ug/L)	https://aquatic.pyr.ec.gc.ca/WQMSDOnlineNationalData2019/en/Home/Details/BC08MH0453	Fraser River estuary
Turbidity (NTU)	https://aquatic.pyr.ec.gc.ca/WQMSDOnlineNationalData2019/en/Home/Details/BC08MH0453	Fraser River estuary
Dissolved nutrients (silicon; ug/L)	https://aquatic.pyr.ec.gc.ca/WQMSDOnlineNationalData2019/en/Home/Details/BC08MF0001	Fraser River at Hope

Salinity (PSU)	https://aquatic.pyr.ec.gc.ca/WQMSDOnlineNationalData2019/en/Home/Details/BC08MH0453 https://open.canada.ca/data/en/dataset/719955f2-bf8e-44f7-bc26-6bd623e82884	Fraser River estuary and Departure Bay Lighthouse
Shoreline sensitivity to sea level rise (categorical ranking)	https://hub.arcgis.com/datasets/9ae186ea826a48df9588807352b09bf8/explore?location=49.209373%2C-123.995841%2C8.57	All B.C. coastline

3.1 Dissolved Oxygen

There was considerable seasonal variability in dissolved oxygen concentrations that was common among years (Figure 2). Dissolved oxygen was highest in winter months and lowest in the late summer and early fall. This was likely due to seasonal fluctuations in temperature because as temperature increases the amount of oxygen water can hold decreases, so in the warmer summer months the amount of dissolved oxygen is the lowest.

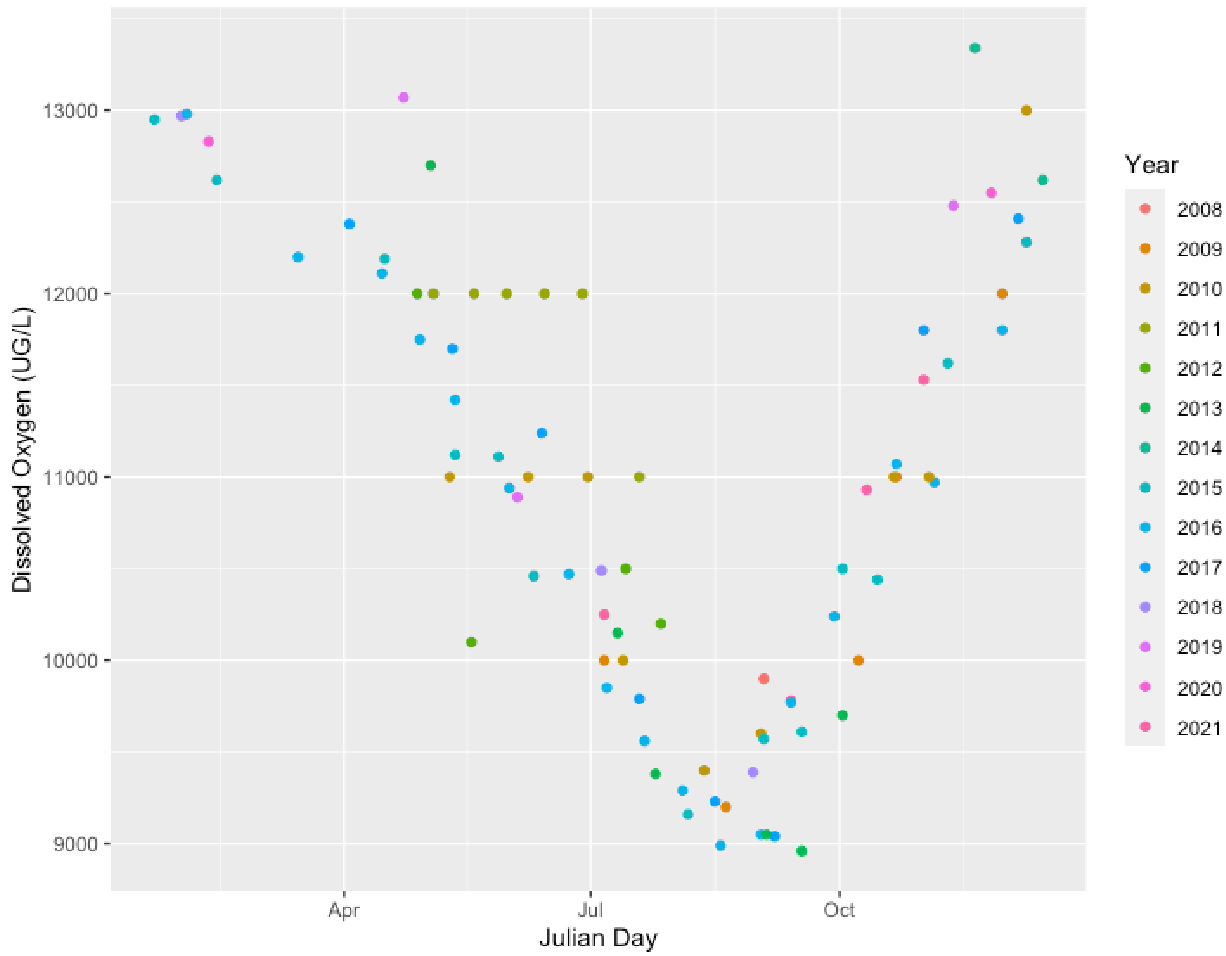

Figure 2: Dissolved oxygen throughout the year in the Fraser River estuary from 2008 to 2021.

To test for interannual trends in dissolved oxygen, accounting for strong seasonal patterns, we fitted the following non-linear sine curve to the data using least squares:

$$y_i = (a_0 + a_1(x_i - 2010)) + bsin\left(\frac{2\pi}{365}(t - t_0)\right) \tag{1}$$

In this equation the response variable, y_i, is dissolved oxygen. The parameter a_0 is the annual average dissolved oxygen and a_1 is the linear trend (i.e., slope) in the annual average dissolved oxygen. Variable x_i is the year, which was standardized by subtracting 2010 so that a_0 represents the average dissolved oxygen in 2010. The parameter b is the amplitude of the sine curve, representing the range of DO measurements within a year. The variable t is the day-of-year, and t_0 is a parameter that controls the day-of-year where we see a peak in dissolved oxygen.

We estimated parameters a_0, a_1, b, and t_0 from the data using the nls() function in R.

The fitted model showed that average dissolved oxygen is decreasing by about 0.05ug/L per year ($p = 0.0413$; Figure 3). A similar second model was also fitted to determine if the timing of the peak in dissolved oxygen (t_0) was changing through time. The results were not statistically significant, and have therefore been left out of this report.

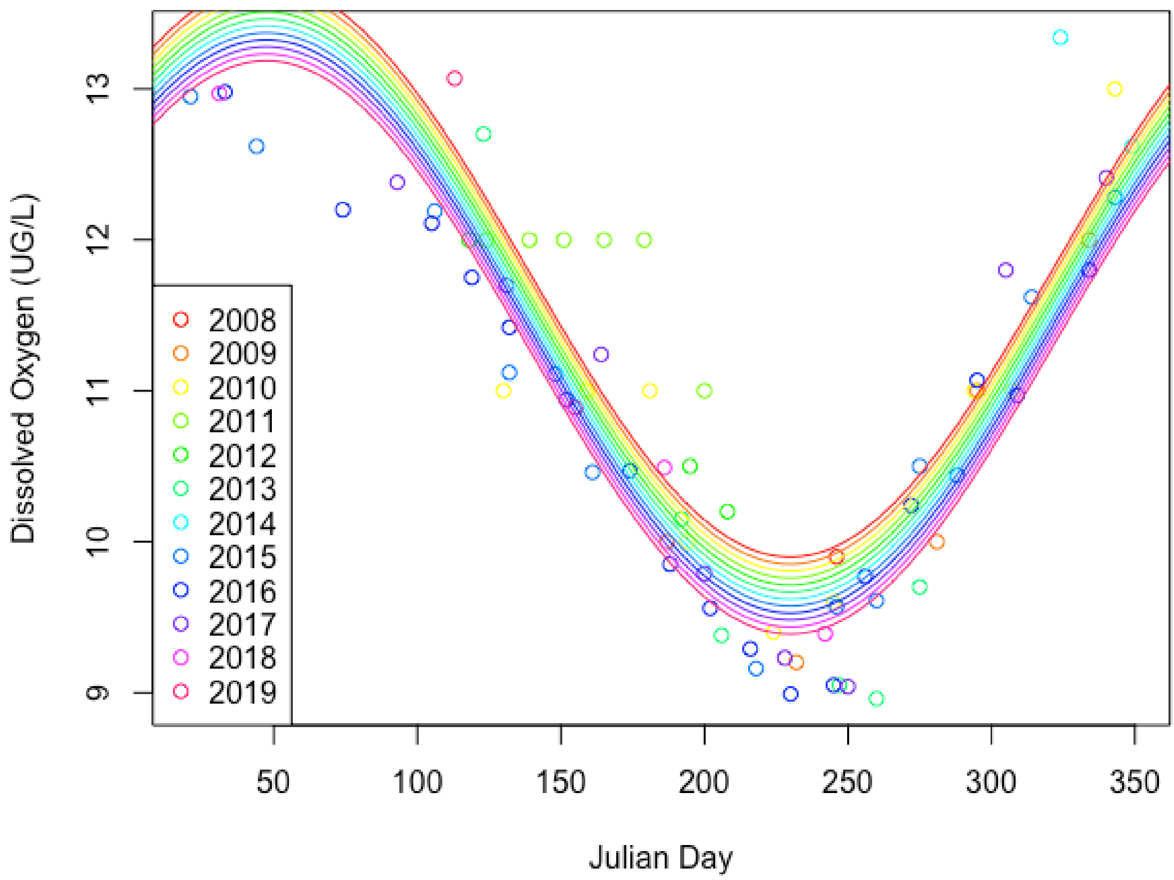

Figure 3: Model fitting for average yearly dissolved oxygen using least squares.

3.2 Turbidity

Turbidity data in the Fraser River estuary shows seasonal patterns, with higher turbidity occurring in the spring and early summer (Figure 4). This corresponds to times with increased rain, snow and glacier melt, which washes sediment into the river and estuary. There is relatively large variation in peak turbidity among years, this is likely due to differing weather patterns among years, where some years have larger snowpacks and earlier or later springs. Peak turbidity occurs around the same time as when juvenile salmon are migrating towards the ocean.

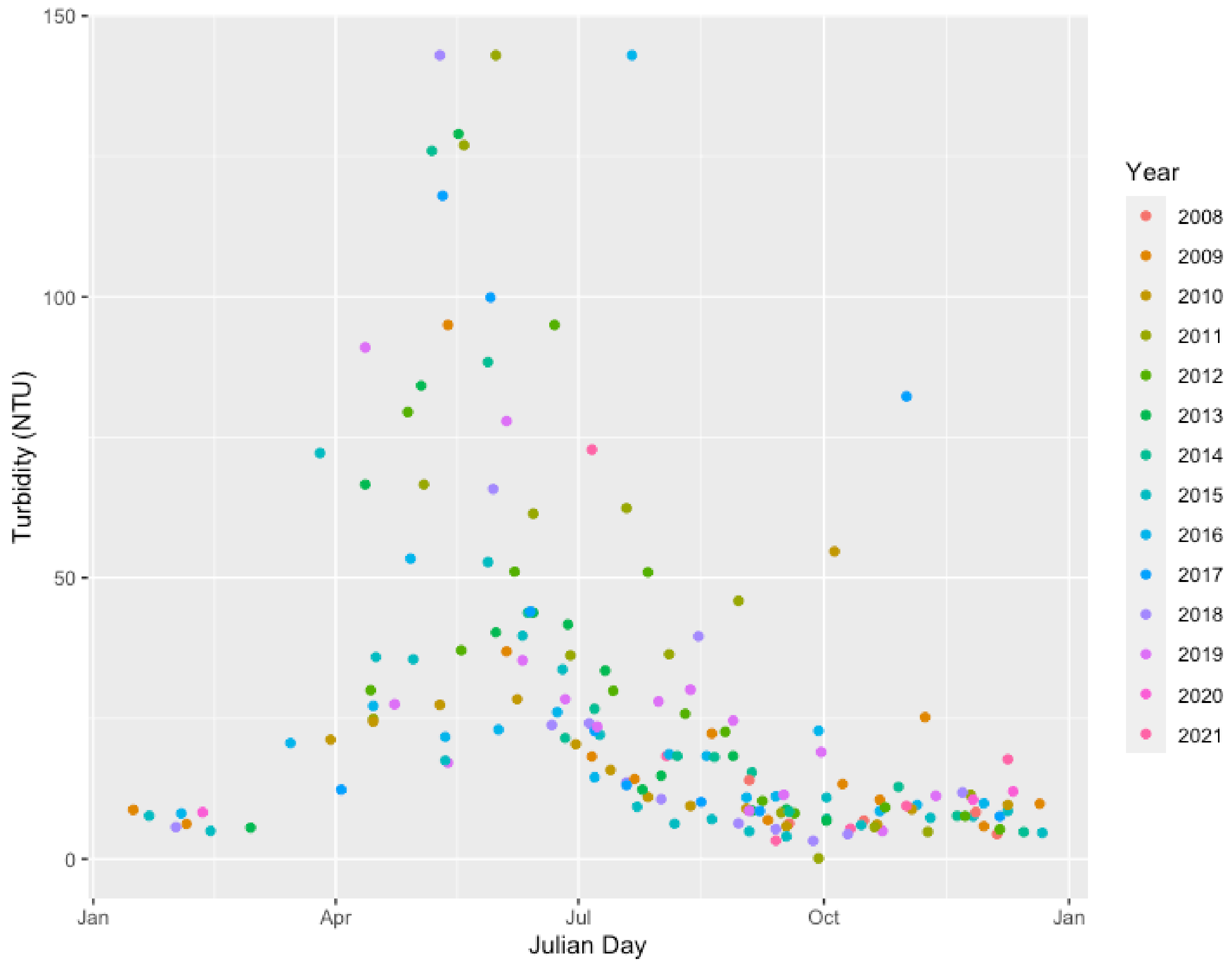

Figure 4: Turbidity data from the Fraser River estuary buoy from 2008 to 2021.

We fitted the following Gaussian curve to the annual pattern of turbidity throughout the year:

$$y = a + be^{\left(-\frac{(t-t_0)^2}{2c^2}\right)} \qquad (2)$$

In this equation the response variable, y, represents turbidity. The variable a represents the background level of turbidity through the winter months. The variable b represents the maximum increase in turbidity during the peak and t_0 represents the day of the year when turbidity reaches its peak, and c is the standard deviation. We tested for interannual trends in the background level turbidity (d), the timing of peak turbidity (b), and the standard deviation of the curve (c), however none of those relationships were statistically significant.

3.3 Dissolved Silicon

Dissolved silicon shows seasonality with a peak in late spring or early summer, and its lowest point in late summer or early fall (Figure 5). The main source of silicon is from eroding terrigenous rock, which would increase in the spring as rain and storms erode the rock which then washes into the river. Silicon is more soluble in water that is less acidic, and water becomes more acidic at higher temperatures. In the late spring and early fall water temperatures would be at their peak, which explains why silicon is at its lowest during this time. It is important to note that silicon data was taken from a location on the Fraser River near Hope which is upstream of the Fraser River estuary. Silicon data were not available for the Fraser River estuary, however we assume trends in dissolved silicon upstream would be similar to those in the estuary. Model fitting was not conducted on silicon data due to the small dataset that spans just over 2 years.

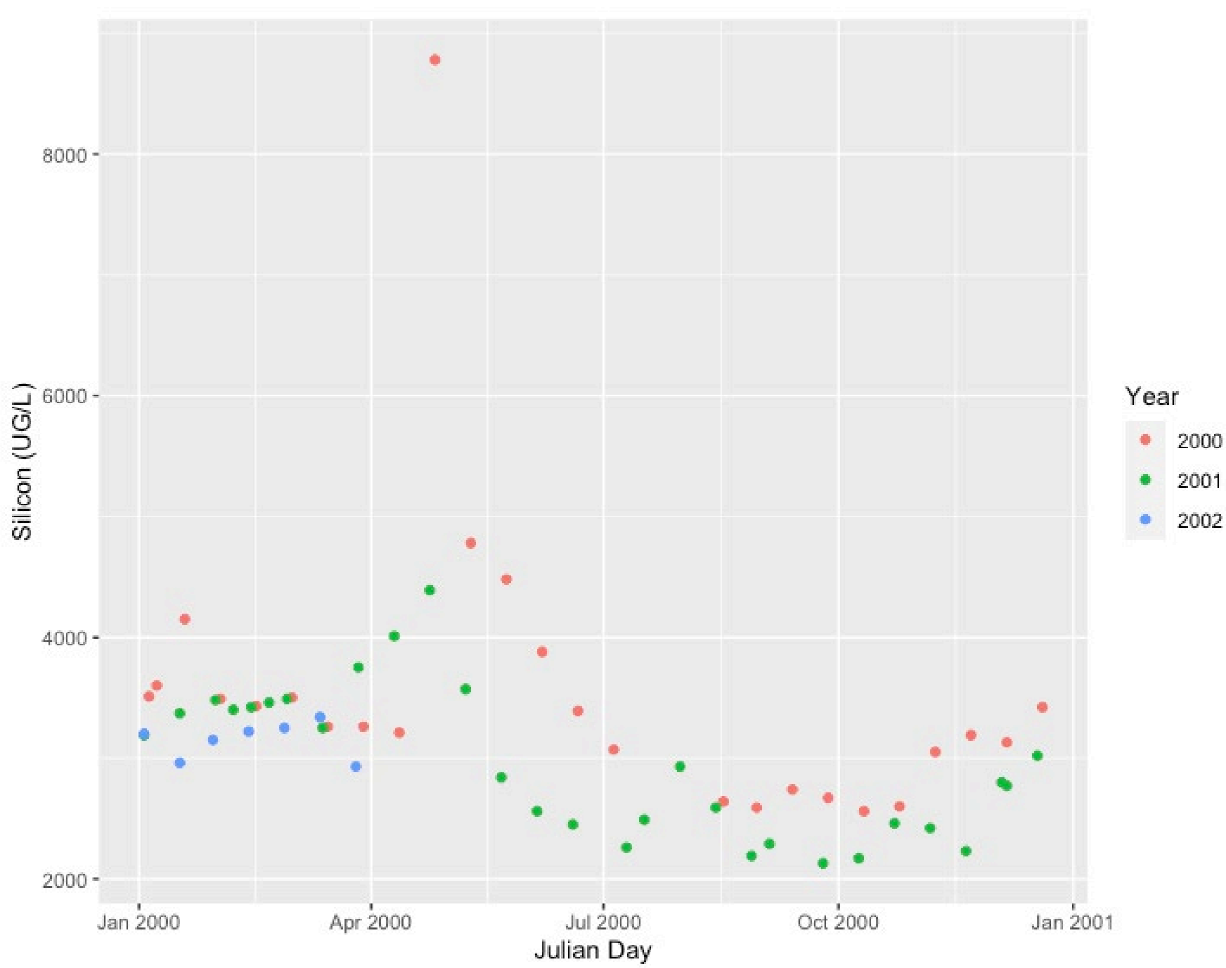

Figure 5: Dissolved silicon data from the Fraser River buoy at Hope from 2000 to 2002.

3.4 Salinity

Salinity data show seasonality with salinity being lowest in the late spring and early summer (Figure 6). This corresponds with when freshwater inputs would be at their highest due to melting snow packs and increased precipitation in the spring. Throughout the fall and winter we see increasing salinity as freshwater inputs would be lower due to more precipitation falling as snow rather than rain. Salinity data from the Fraser River estuary water quality buoy showed values consistent with freshwater, indicating the buoy was farther upstream than originally thought. To understand how salinity was changing in the brackish water of the estuary, the Fraser River estuary water quality buoy was supplemented with salinity data from the Entrance Island lighthouse which is located across the Strait of Georgia at the opening of Discovery Bay near Nanaimo. Understanding how salinity changes seasonally in both the freshwater and marine environments around the Fraser River estuary will allow us to understand how the salinity in the brackish water is also changing. To test for interannual trends in dissolved oxygen, accounting for strong seasonal patterns, we fitted a non-linear sine curve. The model fit was similar to the curve fit for dissolved oxygen shown in equation 1. The curves were used to determine if annual average salinity or the timing of peak salinity changes between years, however both models were statistically insignificant.

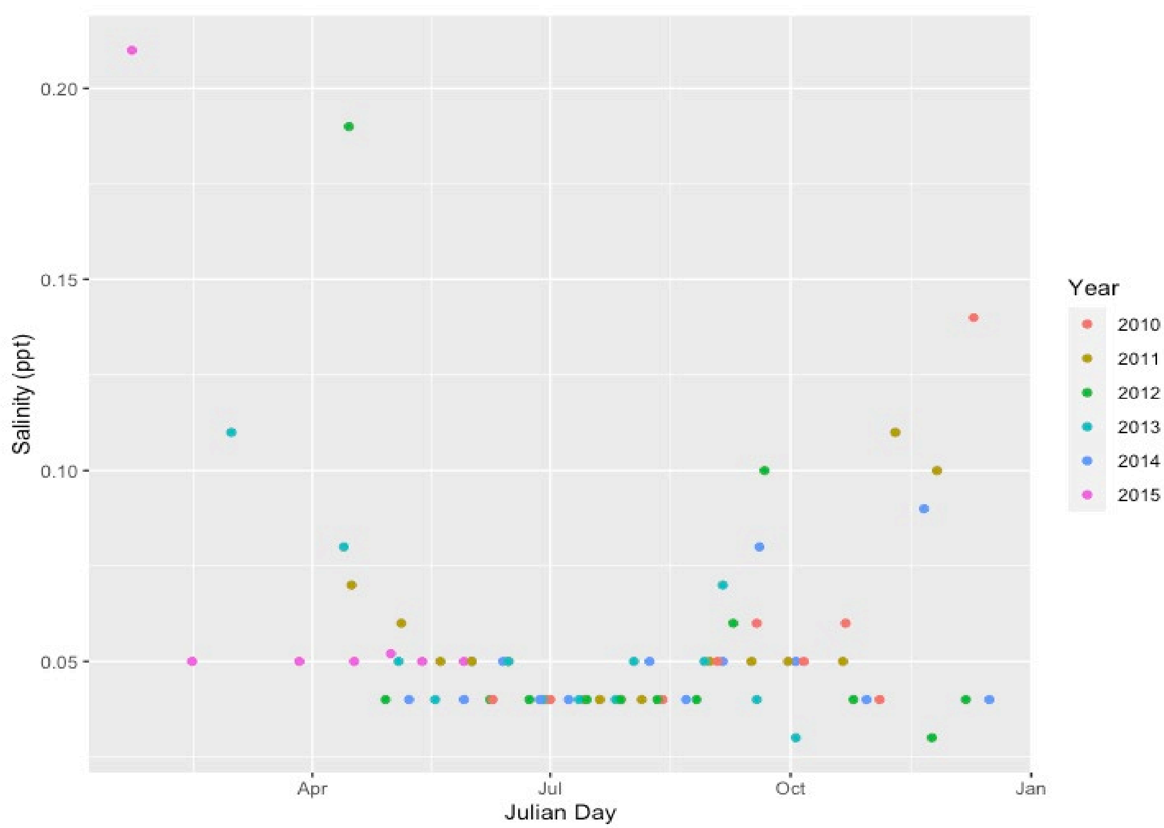

Figure 6: Salinity data from the Fraser River estuary buoy for 2010 to 2015.

Salinity data collected from the Entrance Island lighthouse near Nanaimo (Figure 1) gives average monthly surface salinity dating back to the 1930s. The temporal resolution of these data differs from the Fraser River estuary water quality buoy, which gives daily salinity measurements. The Entrance Island lighthouse data show seasonality with lowest salinity occurring in June and July (Figure 7). This likely corresponds to times when freshwater inputs are the highest due to spring run off and the melting of glaciers and snow pack in the warmer months.

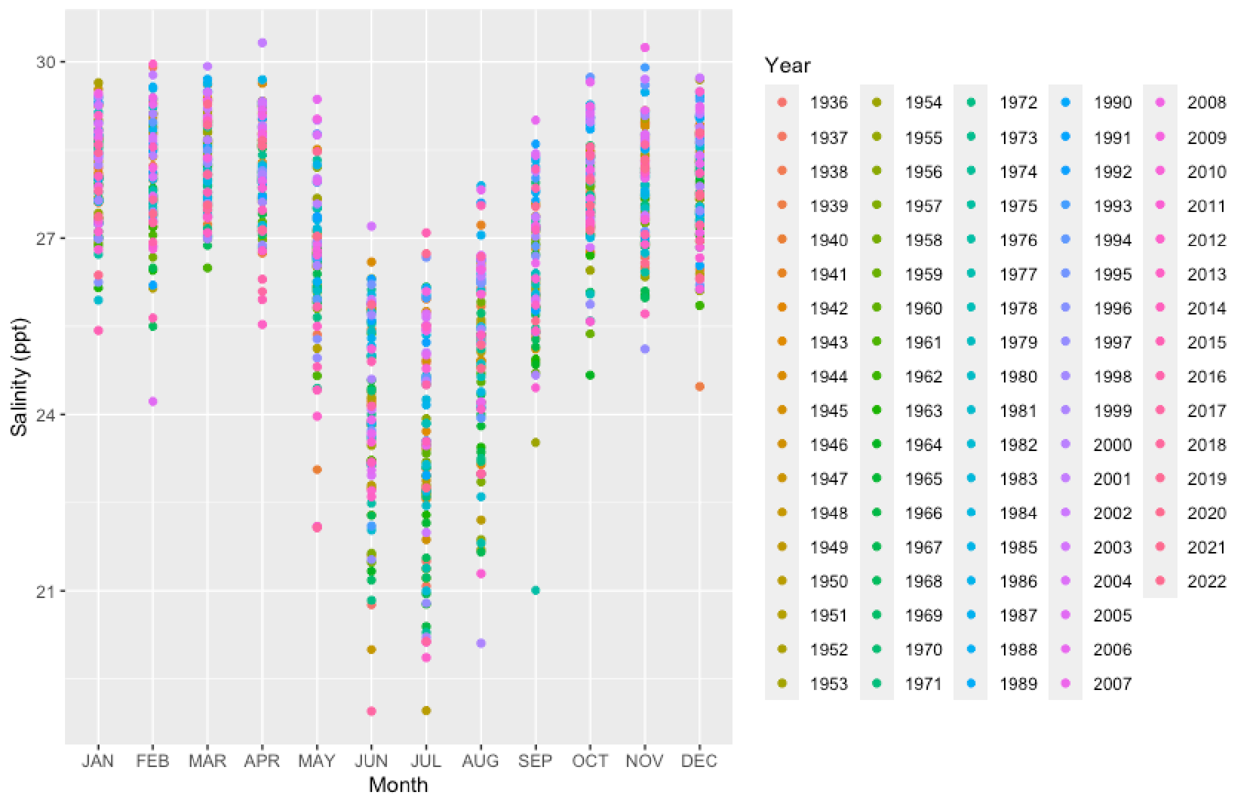

Figure 7: Salinity data from the Entrance Island lighthouse from 1936 to 2022.

To test for inter-annual trends in salinity from the Entrance Island lighthouse, three linear models were fitted. The three models were 1) salinity as a function of month, representing the hypothesis that salinity has not changed over time, 2) salinity as a function of month and year where year was a categorical variable, representing the hypothesis that there are interannual differences in salinity but no long-term trend, and 3) salinity as a function of month and year where year was a numeric variable, representing the hypothesis that salinity shows a long-term directional trend. To determine which model best represents the data, the Akaike information criterion was calculated for each model (Table 2). The second model using year as a categorical variable was the best fit. We used the best fit model to calculate predictions in salinity over the time series (Figure 8), which showed that there is considerable inter-annual variability in salinity, but there is no directional trend over the time series.

Table 2: Akaike information criterion for salinity linear model fitting.

Model	Fixed effects	Number of parameters	AIC	ΔAIC
1	Month	13	3351.60 9	275.826
2	Month + Year (categorical)	99	3075.78 3	0
3	Month + Year (numeric)	14	3346.37 2	270.589

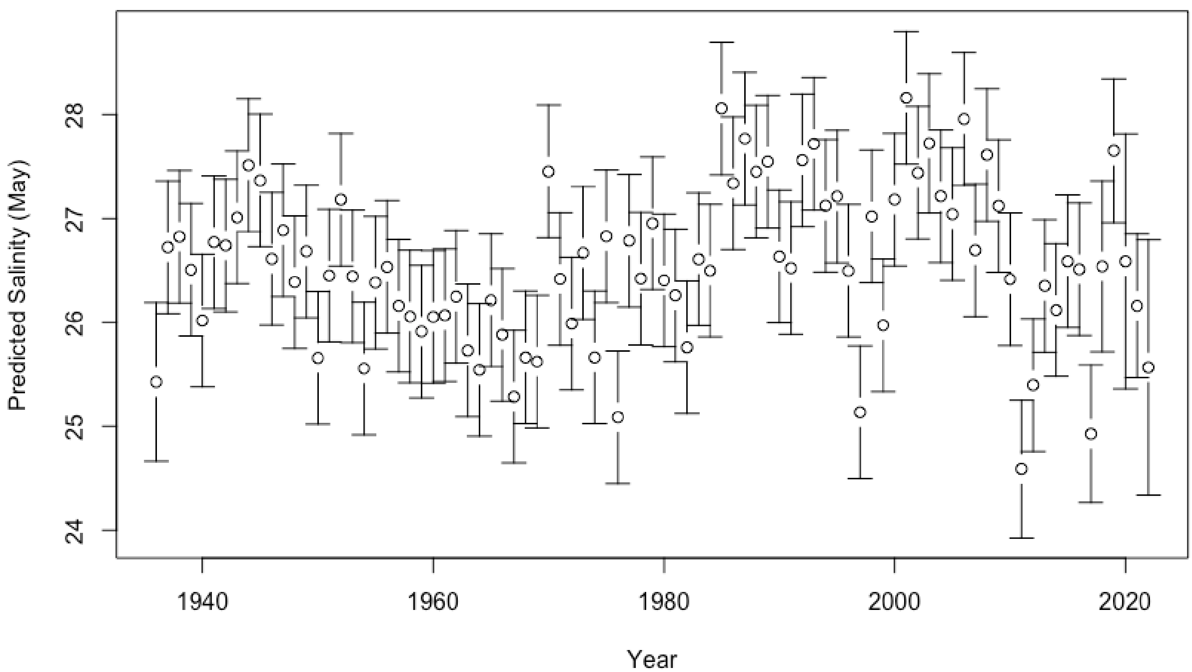

Figure 8: Predicted monthly salinity for the month of May over the entire time series, including confidence intervals.

3.5 Shoreline Sensitivity to Sea Level Rise

BC Parks conducted a shoreline sensitivity analysis for the 35,000 km coastline in the province in the early 2000s. The purpose of this study was to understand how the coastline will change as sea levels rise due to climate change, and allow government planners, non-governmental organizations and others to plan and prepare for a changing coast. In their study, B.C. Parks ranked sections of the coastline as very low, low, moderate, high or very highly sensitive to sea level rise. These rankings were based on two categories, foreshore sensitivity and backshore sensitivity, each of which had two subcategories to determine their overall ranking.

Foreshore sensitivity ranking had previously been undertaken in a study by Howes et al. in 1997, and these rankings were taken as the starting point for B.C. Park's work. The ratings done by Howes et al. were based on the physical features of the coast and ranked as non-sensitive, low sensitivity, moderate sensitivity, highly sensitive and very highly sensitive, which are summarized in Table 2. BC parks took the coastal classes from Howes et al. and then modified the sensitivity rankings based on exposure and erosion. Professionals ranked segments of the coast as accretional, erosional or stable to reflect whether the segment was gaining or losing sediment or staying constant. If the segment was ranked as erosional or accretional the sensitivity ranking identified by Howes et al. was increased by one level. If the segment was ranked stable the sensitivity was not modified. Professionals also ranked the exposure of coastal segments as very protected, protected, semi-protected, semi-exposed, exposed. If the segment was ranked as exposed the sensitivity ranking was increased by one level, and if it was ranked very protected the sensitivity was decreased by one level.

Table 3: Summary of the foreshore sensitivity ranking conducted by Howes et al. 2007.

Coastal Class Code (Howes et al. 1997)	Coastal Class Name (Paterson 2009)	Initial Rating of Sensitivity to Sea Level Rise
1	Rock ramp, wide	Very low
2	Rock platform, wide	High
3	Rock cliff	Not sensitive
4	Rock ramp, narrow	Low
5	Rock platform, narrow	Moderate
6	Ramp with gravel beach, wide	Moderate
7	Platform with gravel beach, wide	High
8	Cliff with gravel beach	Low
9	Ramp with gravel beach	Moderate
10	Platform with gravel beach	High
11	Ramp with gravel and sand beach	Moderate
12	Platform with gravel and sand beach, wide	High
13	Cliff with gravel/sand beach	Low
14	Ramp with gravel/sand beach	Moderate
15	Platform with gravel/sand beach	High
16	Ramp with sand beach, wide	Moderate
17	Platform with sand beach, wide	High
18	Cliff with sand beach	Low
19	Ramp with sand beach, narrow	Moderate
20	Platform with sand beach, narrow	High
21	Gravel flat, wide	High
22	Gravel beach, narrow	Moderate
23	Gravel flat or fan	High
24	Sand and gravel flat or fan	High
25	Sand and gravel beach, narrow	Moderate
26	Sand and gravel flat or fan	High
27	Sand beach	Moderate
28	Sand flat	Very high
29	Mudflat	Very high
30	Sand beach	High
31	Estuaries	Very high
32	Man-made, permeable	High
33	Man-made, impermeable	Low
34	Channel	Low

Backshore sensitivity was ranked based on two categories: slope and habitat type. Slope was taken from an online provincial database of geospatial information and placed into three categories, slope of 0-3 degrees, 3-15 degrees, and over 15 degrees. The habitat type was taken from the B.C. Ministry of Environment's Broad Ecosystem Inventory, where the coastline was taken in 5km bands and the ecosystem was identified. Using these classes, B.C. Parks came up with a backshore sensitivity ranking based on Table 4.

Table 4: The final shoreline sensitivity ranking was taken as the higher sensitivity ranking of the backshore and foreshore rankings.

BEI Class (Habitat)*		Sensitivity by Slope Class		
		0-3°	**3-15°**	**>15°**
Coastal forest (CD, CG, CH, CP, CR, CW, DA, FR, GO, HB, HL, HS, MF, OA)		High	Low	Very low
Shrub and herb dominated (AV)		Low	Low	Low
Non-forested aquatic and wetland (BG, ES, FE)		Very high	High	Low
Forested wetland and riparian (CB, ME, MR, PB, RS, SC, SH, SR, SW, WL, YB, YM, YS)		Very high	Low	Very low
Urban and agriculture (CF, MI, RM, OV, TR, UR)		Very high	High	Medium
Aquatic (FS, LL, LS, SP)		Very high	Very high	Very high
Sparsely vegetated	CL, RO	Very low	Very low	Very low
	GB	High	Very low	Very low
	GL	Low	Low	Very low
	PO	High	Low	Very low
	UV	High	Medium	Low

** Details of each habitat type are available in Appendix 4 of BC Ministry of Environment (2004).*
Coastal Forest: *CD – Coastal Douglas-fir, CG – Coastal Western Redcedar – Grand fir, CH – Coastal Western Hemlock – Western Redcedar, CP - Coastal Douglas-fir – Shore Pine, CR – Black Cottonwood Riparian, CW – Coastal Westrn Hemlock – Douglas-fir, DA – Douglas-fir – Arbutus, FR - Amabilis Fir – Western Redcedar, GO – Garry Oak, HB – Western Hemlock – Paper Birch, HL – Coastal Western Hemlock – Lodgepole Pine, HS – Western Hemlock – Sitka Spruce, MF – Mountain Hemlock – Amabilis Fir, OA – Garry Oak – Arbutus;* ***Shrub and herb dominated:*** *AV – Avalanche Track;* ***Non-forested aquatic and wetland:*** *BG – Sphagnum Bog, ES – Estuary, FE – Sedge Fen;* ***Forested wetland and riparian:*** *CB – Cedars – Shore Pine Bog, ME – Meadow, MR – Marsh, PB – Lodgepole/Shore Pine Bog, RS – Western Redcedar Swamp, SC – Shurb - Carr, SH – Shrub Fen, SR – Sitka Spruce – Black Cottonwood Riparian, SW – Shrub Swamp, WL – Wetland, YB – Yellow Cedar Bog Forest, YM – Mountain Hemlock – Yellow Cedar, YS – Yellow Cedar – Mountain Hemlock – Skunk Cabbage;* ***Urban and agriculture:*** *CF – Cultivated Field, MI – Mine, OV – Orchard/Vineyard, RM – Reclaimed Mine, TR – Transmission Corridor, UR – Urban;* ***Aquatic:*** *LL – Large Lake, LS – Small Lake, FS – Fast Perennial Stream, SP- Slow Perennial Stream;* ***Sparsely vegetated:*** *CL – Cliff, RO – Rock, GB – Gravel Bar, GL – Glacier, PO – Lodgepole Pine Outcrop, UV - Unvegetated*

BC Parks has made all of these rankings available on an interactive map and in downloadable shapefiles. Using this information the shoreline sensitivity around the Fraser River estuary could be summarized. Additionally, using this information one could identify the percentage of coastline around the Fraser River estuary that is developed. Developed areas will prevent shallow environments from migrating as sea levels rise, leading to a loss of these environments, such as eelgrass beds, that are important for species such as salmon. This work was not completed as part of this project due to time constraints, but its relevance is worth noting, and future work should look to incorporate this into climate change indicators for salmon.

4.0 Discussion

4.1 Data Analysis

4.1.1 Dissolved Oxygen

Our analysis found that there was a statistically significant change in the annual average amount of dissolved oxygen decreasing each year from 2008 to 2019. This is consistent with climate change predictions discussed in section 2.1. If this trend continues, it is possible that in the future, the Fraser River estuary will not contain enough dissolved oxygen to support salmon. We looked at a linear trend over the available timeseries, but as climate change is picking up so too will rates of change of these estuarine indicators. Our analysis did not find any significant changes in the timing of when dissolved oxygen reaches its peak, however there may still be a trend that our data did not capture. Collecting more data over a longer timeframe would be beneficial in detecting any trends we were not able to find.

4.1.2 Turbidity

As discussed in section 2.2, turbidity is predicted to increase with climate change. Our analysis did not find any statistically significant trends in the level of background turbidity, timing of peak turbidity or standard deviation, however this does not mean that a trend does not exist. Our analysis is limited by a relatively small dataset over a short time series. Increasing the amount of data, and the timespan of the data would be beneficial in detecting these trends if they exist.

4.1.3 Silicon

Our dataset for silicon was extremely small, leaving us unable to test for trends in silicon over time. Obtaining more data over a longer time span would be beneficial in detecting any trends. Additionally, we were unable to find silicon data for the Fraser River estuary, so we obtained silicon data from a location upstream in the Fraser River estuary. We assumed any trends in silicon upstream of the estuary would be similar to what would occur in the estuary. Obtaining silicon data in the Fraser River estuary would also be beneficial, as opposed to assuming a similar relationship, which may not be correct.

4.1.4 Salinity

As discussed in section 2.4, ocean salinity is projected to decrease with climate change as ice caps and glaciers melt. Sea level is also expected to rise due to climate change, which could increase salinity in estuaries as saltwater intrudes farther into the freshwater. Our marine salinity data shows there is inter-annual variability in salinity, however this is no directional trend, which means we cannot conclude if the ocean here is decreasing in salinity. The salinity data we have for the Fraser River showed no statistically significant trends in the average annual salinity, or the timing of peak salinity. This could be due to the small dataset not allowing us to detect any trends. Obtaining more data over a longer time period would be beneficial. Additionally, obtaining more spatial data throughout the estuary would be beneficial as it would allow us to determine if the estuary itself is increasing in salinity due to saltwater intrusion. Chandler et al. (2016) have found a general decrease through time in sea surface salinity during the spring months when juvenile salmon are in their early marine phase - a key period of growth that influences their survival. Low salinity is associated with reduced food availability, creating concerns over potential impacts on salmon survival.

4.2 Benchmarks

Developing benchmarks for the indicators we have investigated in this report would be useful. Being explicit about what levels of each indicator are good, moderate or poor for salmon would aid in interpreting these indicators to understand how climate change will affect salmon populations. We looked at existing benchmarks for our indicators in the Skeena estuary status assessments on the Pacific Salmon Explorer, however there were several limitations in applying them to our data. Below we will discuss existing benchmarks for each indicator applied in the Skeena estuary and the limitations with applying them to our data.

4.2.1 Dissolved Oxygen Benchmarks

Dissolved oxygen in the Skeena estuary was separated into benchmarks of above 5 mg/L, between 2 and 5 mg/L and under 2 mg/L. The data we used was measured in ug/L and always fell in the under 2 mg/L category. It is possible that the Fraser River estuary is low in dissolved oxygen and always falls in the lowest benchmark category. Salmon have continued to survive in the Fraser River estuary despite the dissolved oxygen falling in the lowest category. Therefore it may be beneficial to adjust the benchmarks to levels where dissolved oxygen is too low for salmon to survive, in a range that induces stress in salmon, or above a level that is ideal for salmon. This may be complicated by different species and different life stages requiring different oxygen levels. Levy and Slaney (1993) found that salmonids show initial signs of dissolved oxygen deprivation at about 6mg/L. They report that salmonids can still survive at dissolved oxygen levels below 6mg/L, however this occurs at the expense of growth and swimming efficiency. Dissolved oxygen levels below 3mg/L are lethal to salmon embryos and alevins, these life stages occur at the bottom of the water column among the sediment, and it should be noted that dissolved oxygen concentrations here can be significantly lower than at the surface (McMahon 1983) . McMahon (1983) also found that adult coho salmon exhibit avoidance behaviour when dissolved oxygen levels are less than 4.5mg/L.

4.2.2 Turbidity Benchmarks

Turbidity benchmarks in the Skeena estuary are based on measurements of total suspended sediment (TSS), whereas the data we used are measured in nephelometric turbidity units (NTU). TSS is a measure of the weight of sediment in a liter of water, whereas NTU is a measure of how much light is reflected by a sample of water. It is not possible to convert between these units of measurement unless a specific correlation is developed. This is because the amount of light that is reflected is dependent on the mineral composition of the sediment and is unique to each area (Choubey 1994). Developing this correlation for the Fraser River estuary may be useful and allow us to apply existing TSS benchmarks in the Skeena estuary to the Fraser River estuary. Alternatively benchmarks for turbidity based on NTU measurements could be developed.

4.2.3 Silicon Benchmarks

The Pacific Salmon Explorer currently does not contain silicon data, and we have not been able to find benchmarks for silicon in relation to salmon. This is likely because silicon is indirectly related to salmon. Silicon has a more direct effect on diatoms and phytoplankton, which in turn has an effect on the ecosystem and food web that salmon are a part of. The Pacific Salmon Explorer does contain chlorophyll data as a proxy for phytoplankton. We were unable to acquire chlorophyll or phytoplankton data and used silicon as a proxy, however it may be beneficial to acquire chlorophyll data and apply the same benchmarks from the Skeena estuary to the Fraser River estuary. The Pacific Salmon Foundation is exploring the possibility of including information on chlorophyll-a concentrations as a marine indicator in the Pacific Salmon Explorer, which may provide more broadly available and accessible information on primary productivity than dissolved silicon concentrations.

4.2.4 Salinity Benchmarks

The Skeena estuary on the Pacific Salmon Explorer contains benchmarks for salinity that are displayed spatially on a map. This is useful in understanding how salinity changes across the estuary where salmon migrate. Our salinity data are from two points, one located in the freshwater of the Fraser River, and one located across the Strait of Georgia at Entrance Island. Obtaining more spatial salinity data would be useful to implement the same benchmarks on a map for the Fraser River estuary.

4.3 Integration with Pacific Salmon Explorer

The Pacific Salmon Explorer is a powerful tool that contains a plethora of data on salmon and their habitats and allows it to be visualized by users. Integrating the climate indicators we have identified and analyzed would expand the realm of the Pacific Salmon Explorer into estuarine habitats beyond just the Skeena estuary. It would be ideal to have more spatial data on the indicators we identified to allow the visualization of how these indicators change throughout the estuary. Unfortunately, we are constrained by a lack of consistently collected and accessible data, however including the point data we do have may still give some valuable information to users on the state of the Fraser River estuary and how it is predicted to change with climate change. Estuaries are unique habitats that have a direct effect on salmon populations, so integrating this data with the Pacific Salmon Explorer would be beneficial to give a more holistic view of salmon throughout all the habitats they inhabit. Expanding our work to all estuaries across B.C. that salmon inhabit would be desirable, however this will likely be limited by data availability in the more remote regions of the coast.

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