BURRARD INLET WATER QUALITY PROPOSED OBJECTIVES

Water Quality Assessment and Proposed Objectives for Burrard Inlet: Physical Parameters Technical Report

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Tsleil-Waututh Nation
səlilwətaɬ

BRITISH COLUMBIA

This Technical Report forms part of a series of water quality parameter reports whose purpose is to inform updates to the 1990 Provincial Water Quality Objectives for Burrard Inlet. This report and others in the series assess the current state and impacts of contamination in Burrard Inlet; incorporate new scientific research and monitoring of water quality; and reflect a broader understanding of goals and values, including those of First Nations, to improve the health of the marine waters of Burrard Inlet. Updating the 1990 Provincial Water Quality Objectives is a priority action identified in the Tsleil-Waututh Nation's Burrard Inlet Action Plan which has been an impetus for this work.

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Cover Photograph:
Underwater monitoring equipment is installed from the Tsleil-Waututh Nation boat in Burrard Inlet.

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CHAPTER SUMMARY

This chapter presents proposed water quality objectives (WQOs) for physical parameters in Burrard Inlet, including water temperature, salinity, dissolved oxygen (DO), pH, total suspended solids (TSS) and turbidity. These proposed objectives were developed using up-to-date research on relevant values and potential effects, sources and factors influencing levels of physical parameters, benchmark screening, and historic and recent monitoring data for Burrard Inlet.

The most sensitive value to changes in physical parameters is aquatic life. Natural or anthropogenic events leading to disturbances in physical parameter levels have fundamental effects on whole aquatic ecosystems:

- Changes in **temperature** impact almost every physical property of seawater. This includes changes in DO saturation and density, which is also related to salinity, where shifts in water temperature can have detrimental effects on growth and survival of aquatic species.
- Any changes to **salinity** may impact the structure of communities and distribution of species.
- A decrease in **dissolved oxygen**, which is essential for the respiration of aquatic organisms, can have both sublethal and lethal effects in a variety of organisms.
- Reductions in **pH** result in ocean acidification which will directly impact organisms that rely on carbonate-based shells and skeletons, and organisms sensitive to acidity. Such changes can also have secondary effects on many other marine species.
- Increased **solids** concentration and **turbidity** can reduce the primary production of phytoplankton, which has several physical and biological impacts on aquatic organisms and their habitats.

Some of the most important natural processes affecting levels of physical parameters in Burrard Inlet are water column stratification (salinity and temperature driven), freshwater inputs, winds and tides, and currents. Global climate change is the major anthropogenic factor impacting physical parameters of ocean waters, including global warming being absorbed by the oceans; lower solubility of oxygen in warmer waters; rising atmospheric CO_2 concentrations leading to lower pH (ocean acidification); and reduced seawater salinity due to increases in precipitation and polar and glacial melt. Local anthropogenic activities related to land use and development also affect physical parameters. Potential local causes to thermal pollution in Burrard Inlet are heated municipal wastewater effluents, industrial cooling water, stormwater, and impoundments for hydropower generation or drinking water supply.

Potential nutrient-rich discharges, which may cause local hypoxia (low levels of oxygen) and acidification, are municipal and industrial wastewater discharges, fertilizer runoff and animal waste, and failing septic systems. Soil disturbing activities, wastewater discharges, boat wakes, dredging, and in-water construction activities are potential causes of suspended solids in Burrard Inlet. Potential local anthropogenic sources of salinity changes are wastewater discharges that can lower salinities locally within Burrard Inlet, and stormwater outfalls contaminated with road salts, which could increase salinity levels.

Existing BC Water Quality Guidelines and Washington State Water Quality Standards for Surface Waters for marine and/or estuarine aquatic life were used as screening benchmarks to assess collected data on physical water quality parameters in Burrard Inlet. Sensor-based monitoring data collected during cruises performed by Tsleil-Waututh Nation (TWN) in 2018-2020 were used to assess the status of physical parameters in Burrard Inlet. High resolution data collected during these cruises include temperature, oxygen saturation, salinity, and turbidity, every two weeks throughout the water column (surface, mid-, and bottom depth layers) in different seasons, and in all sub-basins of Burrard Inlet except False Creek.

Water temperatures in Burrard Inlet generally follow the same seasonal patterns as salinity since temperature variations are mainly driven by density differences in the water column. The highest temperatures are observed in the surface waters of Port Moody followed by Indian Arm during summer. Winter water temperatures in all sub-basins are rather uniform at all depths. Long-term time series of deep-water data collected in Indian Arm by Fisheries and Oceans Canada (DFO) show that water temperatures have increased over time. The highly variable and generally low salinities (usually below 30[1]) observed in all sub-basins of Burrard Inlet, particularly in the upper portion of the water column, are due to seasonal variations in precipitation and freshwater inputs.

Burrard Inlet is generally characterized by a relatively high DO content. Surface DO concentrations reach a peak in spring in all sub-basins, due to high oxygen production by phytoplankton through photosynthesis, after which it declines over the year, with the lowest surface DO concentrations usually found in fall, due to lower gas solubility and increased rate of decomposition of organic matter. The lowest DO levels are found in the mid- and bottom-depth layers of Indian Arm and Outer Harbour, the deepest sub-basins of Burrard Inlet. Dissolved oxygen in these basins is at concentrations below the 5 mg/L minimum instantaneous benchmark for protection of all life stages other than buried embryo/alevin. In deeper layers during spring and summer and in all layers during fall and winter, average DO concentrations typically fall below the long-term DO benchmark of 8 mg/L in all sub-basins, with some exceptions.

TSS and turbidity are the most visible indicators of water quality. When suspended solids and turbidity exceed background levels, aquatic life can be negatively impacted. Suspended solids were not monitored during the TWN cruises, but surface concentrations of suspended particulate matter from the Fraser River plume have been estimated at ≤ 10 mg/L, with the highest concentrations near the Inlet entrance. Turbidity in Burrard Inlet, primarily in Outer Harbour, is largely affected by the silty waters of the Fraser River. Existing turbidity data cannot be assessed against the short-term (24 h) benchmark as monitoring was not performed as frequently. Turbidity data from Indian Arm (winter and fall), Port Moody (winter), and Outer Harbour (all seasons) show larger variations than the ±2 NTU long-term benchmark.

pH was not monitored during the TWN cruises, but pH data have been collected by DFO during the years 2018 through 2020 in Outer Harbour. Observed pH ranges in Outer Harbour are above the lower limit of the BC-based benchmark "unrestricted change within 7.0 to 8.7", but observances above 8.7 (pH ≤ 8.855) occurred at all monitored locations in Outer Harbour, with the highest pH levels observed at the westernmost monitoring station.

The proposed WQOs for dissolved oxygen, pH, salinity, temperature, TSS, and turbidity across all sub-basins are as follows:

[1] Salinity is a ratio, and therefore dimensionless (no units).

Proposed Water Quality Objectives for Physical Parameters

Sub-basin	False Creek	Outer Harbour	Inner Harbour	Central Harbour	Port Moody Arm	Indian Arm
Temperature in Marine Water	No further increase in temperature; the natural temperature cycle[1] characteristic of the site should not be altered in amplitude or frequency by human activities.					
Salinity in Estuarine and Marine Water	No change in concentration (NaCl or equivalent) from the expected natural level[1] at that time and depth					
Dissolved Oxygen in Marine Water[2]	8 mg/L 30-day mean[3] 5 mg/L instantaneous minimum					
pH in Marine Water	7.7 to 8.8[4]					
Total Suspended Solids in Marine Water	No increase from the expected natural levels in the ambient background, defined by best available data[5] as 10 mg/L					
Turbidity in Marine Water	No increase from the expected natural levels in the ambient background, defined by best available data[5] as < 1 NTU[6]					

[1] Data are unavailable to conclusively define "natural" levels; until additional information becomes available, monitoring results can be compared to current conditions as described in Table 4 and Table 5. See section 4 for further details. The WQOs are intended to not exacerbate the ongoing effects of climate change.
[2] In cases where natural DO concentrations do not meet the criteria, no statistically significant reduction below natural levels should be permitted.
[3] A mean should be calculated from 5-in-30 sampling (i.e., five samples taken over 30 days).
[4] To be refined when data are available for additional sub-basins and/or more sensitive species.
[5] See Appendix B for details on how background was determined. Although other datasets may exist, the datasets used for determining the background (i.e., data available in ENV's Environmental Monitoring System database) were found to be the 'best available data' within the constraints of the project. As more data becomes available, the background concentration may be revisited.
[6] For comparison to the background, a mean should be calculated from 5-in-30 sampling (i.e., five samples taken over 30 days).

As most objectives are expressed as maximum permissible human-caused changes from expected natural levels in the ambient background, specific objectives were not proposed for each sub-basin. Recommendations for future physical parameter monitoring in Burrard Inlet include continuing the existing programs, adding False Creek to monitoring programs, and adding the monitoring of pH and TSS in all sub-basins and at a range of depths. Monitoring should be done as part of ambient monitoring programs, and around known discharge points. Monitoring should be at a frequency sufficient to record patterns of both ambient diurnal and human-induced variations, to allow for assessment of WQOs.

Recommendations to reduce the anthropogenic impacts on physical parameters in Burrard Inlet include implementing stormwater management, including green infrastructure in urban areas to mitigate surface runoff, erosion and flooding; removing unneeded dams and impoundments; improving sanitary and industrial wastewater treatment to further reduce levels of organic material and nutrients; reducing vessel wakes and limit dredging and in-water construction activities to reduce TSS and turbidity concentrations; and protecting and restoring ocean habitats such as seagrasses and salt marshes in Burrard Inlet to sequester carbon dioxide from the atmosphere.

CONTENTS

FIGURES

TABLES

APPENDICES

ACRONYMS

BC	British Columbia
BOD	Biological oxygen demand
CTD	Conductivity, temperature, and depth (refers to a package of electronic instruments that measure these properties)
DFO	Fisheries and Oceans Canada
DO	Dissolved oxygen
EMS	BC ENV's Environmental Monitoring System database
ENV	Ministry of Environment and Climate Change Strategy
ISMP	Integrated Stormwater Management Plan
NTU	Nephelometric Turbidity Units
ONC	Ocean Networks Canada
OSD	Ocean Sciences Division of DFO
SPM	Suspended particulate matter
TSS	Total Suspended Solids
TWN	Tsleil-Waututh Nation
WQG	Water Quality Guideline
WQO	Water Quality Objective

1. INTRODUCTION

This chapter proposes water quality objectives (WQOs) for physical parameters of most concern in Burrard Inlet, in particular the following:

- Temperature and salinity
- Dissolved oxygen (DO)
- pH
- Suspended solids and turbidity.

This chapter includes relevant background information, an overview assessment of trends in levels of physical parameters in the marine water of Burrard Inlet, comparison to benchmarks, and a rationale for the proposed objectives. Recommendations for future monitoring as well as management options to help achieve these objectives are also included. Detailed context for this work and the Burrard Inlet area is provided in Rao *et al.* (2019).

Temperature and salinity are important characteristics of seawater as they control water density, the major factor governing the vertical and horizontal movement of ocean waters. Water temperature affects most water quality parameters and plays a major role in aquatic life and habitats. Salinity of seawater is defined as the total amount by weight of dissolved salts in one kilogram of seawater. The salinity of surface seawater is controlled primarily by the balance between evaporation and precipitation (BC Ministry of Environment Lands and Parks, 2001; Pawlowicz, 2013).

Oxygen is the most important component of surface water for its self-purification mechanisms and for the survival of aquatic organisms that use aerobic respiration, including plants, bacteria, and animals. Oxygen is introduced to water through the air or as a by-product of aquatic plant photosynthesis. A minimum amount of DO is required in an aquatic system to protect aquatic life (BC Ministry of Environment Lands and Parks, 1997; Laffoley and Baxter, 2019).

The pH of water is a measure of the activity of hydrogen ions in a solution and the pH scale defines how acidic or basic a body of water is, with the ocean's average pH currently around 8.1. Ocean pH is mainly governed by the amount of carbon dioxide dissolving into the ocean water. Even small decreases in ocean water pH, called ocean acidification, affect many marine organisms, and could alter marine ecosystems (Turley *et al.*, 2010).

Solids suspended in marine waters consist of silt, clay, inorganic matter, and organic matter such as algae and plankton. Turbidity is an optical determination of water clarity, measured by the amount of light scattered in the water column caused by suspended solids and colored dissolved organic matter.

Since turbidity is related to particle concentration, it can be loosely correlated with total suspended solids (TSS). However, if an exact TSS value is required then this should be directly measured. High levels of suspended solids and turbidity inhibit photosynthesis by blocking sunlight and lead to increased water temperatures and decreased DO levels in water (CCME, 2002; BC ENV, 2021c).

2. BACKGROUND

A general description of Burrard Inlet, including the water uses, land uses and other factors that affect water quality and values in the inlet, is available in the first volume of this technical series (Rao *et al*. 2019). This technical report supplements that general description with information specific to physical parameters in Burrard Inlet.

2.1 Values and Potential Effects

The most sensitive value identified in Rao *et al.* (2019) to changes in physical parameters is aquatic life. Natural or anthropogenic events leading to disturbances in physical parameter levels have fundamental effects on whole aquatic ecosystems, and are described in the following points:

- Temperature - Changes in temperature impact almost every physical property of seawater. This includes changes in DO saturation and density, which is also related to salinity, where shifts in water temperature can have detrimental effects on growth and survival of aquatic species.
- Dissolved Oxygen – Decrease in DO, which is essential for the respiration of aquatic organisms, can have both sublethal and lethal effects in a variety of organisms.
- Salinity - Any changes to salinity may impact the structure of communities and distribution of species.
- pH - Reductions in pH result in ocean acidification which will directly impact organisms that rely on carbonate-based shells and skeletons, and organisms sensitive to acidity. Such changes can also have secondary effects on many other marine species.
- Turbidity - Increased solids concentration can reduce the primary production of phytoplankton, which has several physical and biological impacts on aquatic organisms and their habitats.

In general, changes in physical parameters lead to reduced growth of several aquatic species (further described in subsections 2.1.1. through 2.1.4.), ultimately leading to reduced food availability and affecting entire ecological food webs.

Most physical parameter changes are not expected to pose a direct risk to human consumption of seafood and recreational activities; however, changes in physical parameters may have secondary effects on humans. For example, lower pH levels will affect animals with carbonate-based shells (see section 2.1.3), resulting in impacts to important cultural harvests such as Tsleil-Waututh Nation's clam harvest[2]. Reduced fish growth is a likely impact of changes to physical parameters, potentially leading to reduced food availability for consumption by humans. In addition, increasing water temperatures may be related to an increase in harmful algal blooms, some of which produce toxins that accumulate in shellfish and can affect human health (NCCOS, 2017). Also, if visually perceptible by primary and secondary contact users[3], increased turbidity and solids may impact water-based recreation and cultural practices.

While DO and salinity are not direct concerns for water uses other than aquatic life, ocean acidification can modify the abundance and chemical composition of harmful algal blooms in such a way that shellfish toxicity increases. Changes in pH can also contribute to the propagation of contaminants through marine systems, intensifying the exposure and bioaccumulation of metals in marine systems. Therefore, all changes in physical parameters will affect the quantity and quality of aquatic resources and hence indirectly affect cultural practices, seafood consumption and fisheries (Falkenberg *et al.*, 2020).

[2] Currently a very limited food, social and ceremonial harvest.

[3] Health Canada considers immersive activities such as swimming, bathing and wading to be primary contact, and defines secondary contact as activities in which only the limbs are regularly wetted and in which greater contact, including swallowing water, is unusual (Health Canada 2012).

2.1.1 *Water Temperature and Salinity*

Temperature and salinity are closely related as they both impact water density, together with depth. Density differences in oceans contribute to a global-scale circulation system of water and constituents, also called the global conveyor belt.

Water temperature has a paramount role in water quality, ultimately affecting aquatic organisms. It influences metabolic rates and photosynthesis, governs abundance and composition of aquatic organisms, controls concentrations of DO and other gases, impacts compound toxicity, and influences other water quality parameters. Major factors impacting water temperature are solar radiation, heat transfer from the atmosphere, stream and urban outfall discharges, water depth, and turbidity. Temperatures of shallow and surface waters are more easily influenced by these factors than deep water (BC Ministry of Environment Lands and Parks, 2001; Pawlowicz, 2013).

Salinity is a measure of the weight of dissolved salts in seawater and is now determined by conductivity measurements. The Practical Salinity Scale (PSS-78) defines a ratio of measured conductivity in a sample to a standard potassium chloride (KCl) solution conductivity. Since salinity is a ratio, it is dimensionless (no units); however, salinity is commonly reported using the unit 'parts per thousand' (ppt or ‰). Ocean salinity varies slightly from about 32 to 40, with an average of 35. Most of the dissolved salts that make up ocean salinity originate from terrestrial rocks, which release ions that are washed into the seawater via rivers and streams. Two of the most prevalent ions in seawater are sodium (Na^+) and chloride (Cl^-), making up around 85% of all dissolved ions in the ocean (Pawlowicz, 2013; Smyth and Elliott, 2016; Webb, 2022).

Changes in Ocean Temperature and Salinity

Over the past century, the Earth's surface temperature has increased, primarily as an effect of increasing greenhouse gases, leading to rising water temperatures. From 1901 through 2020, the overall sea surface (down to 700 m depth) temperature increased by approximately 0.08°C per decade (Laffoley and Baxter, 2016; US EPA, 2021). Observations of sea surface temperatures between 1935 and 2014 in BC's coastal waters showed that temperatures have increased significantly, between 0.6 and 1.4°C per century depending on location (Environmental Reporting BC, 2017).

Temperature and density have an inverse relationship above 4° C, while density increases with increasing salt concentration (Webb, 2022). Higher density waters sink, and lower density waters rise. The difference in density of cold versus warmer water is responsible for ocean currents, with salinity variations affected by precipitation, evaporation, runoff, and ice freezing and melting. Evaporation increases salinity and density while the addition of freshwater decreases salinity and density (Pawlowicz, 2013; Smyth and Elliott, 2016; Webb, 2022).

Effects of Temperature and Salinity Changes on Aquatic Organisms

As water temperature and salinity changes, organisms may be subjected to conditions that result in adverse physiological effects, changes in the biogeography of species, and alterations in their interactions (Coppola *et al*., 2020; Bindoff *et al.,* 2019). The influence that is exerted by water temperature on most biological and physiological processes makes it the most important physical factor to marine organisms (Claireaux and Lagardere, 1999; Brierley *et al.,* 2009). Temperature changes interacting with other environmental factors, such as DO and salinity can have potentially far-reaching impacts on marine organisms and systems through synergistic or antagonistic interactions. For example, when water temperature increases and salinity decreases, it may result in an increasing uptake of metal ions by organisms. This can be partially explained by the competitive interactions with major cations for sensitive transport sites which can affect exposure to metal pollution (Velasco *et al*., 2018).

Responses to temperature and salinity changes will greatly depend on the rate and duration of change, as well as the tolerance level of organisms. Temperature preferences vary among species with most aquatic organisms living in an optimal temperature range between 5 and 25°C. This optimal temperature range is inclusive of the key life stages, such as adult migration, spawning, incubation, rearing, and smoltification. However, some salmonid species have stringent temperature criteria while other species have less stringent criteria. All species can tolerate slow, seasonal changes better than rapid changes in temperatures (BC Ministry of Environment Lands and Parks, 2001).

Tolerance to changing salinities can depend on temperature, such that unfavourable salinities are more tolerated at optimum temperatures. During rapid and extreme changes in temperature and salinity, more resilient species can revert to pre-disturbance states once these water quality parameters return to normal levels (Brierley *et al*., 2009). However, resilience to higher temperature and salinity fluctuations during such events or over long-term events usually favours only a small number of species, while other species will either be displaced or perish (Brierley *et al*., 2009). This can result in changes in interactions between marine fauna, favouring introduced species that may be more tolerant to such changes.

Individual organisms respond differently to changing temperatures and salinities. Studies done on clams (*Anodonta anatina*) and mussels (*Mytilus galloprovinciali*) indicate that temperatures exceeding the organism's thermal tolerance range can result in adverse physiological changes, with consequences to growth, reproduction, and reduced metabolic and respiratory capacity (Coppola *et al*., 2020). Laboratory studies on mussels subjected to temperature ranges within their normal range demonstrated an ability of the mussels to oxy-regulate, but as temperatures increased beyond this, oxy-regulation decreased and eventually stopped. These results reveal how thermal limitations relate to respiratory capacity of mussels (Jansen *et al*., 2009). In addition to this, the increase in water temperature has also shown to affect native and introduced clams (*R. decussatus* and *R. philippinarum*), by affecting biochemical functions including increased antioxidant capacity and cellular damage (Coppola *et al*., 2020).

For non-sessile species such as fish, temperature changes are likely to determine their distribution and behaviour since they are able to avoid such non-ideal conditions. However, the use of thermal refuges during unfavourable temperature conditions can pose a challenge in terms of access to resources as well as a potential decrease in available oxygen if the refuges are in deeper, cooler waters (Freitas *et al*., 2021). Such temperature effects were explored in a study that acoustically tracked Atlantic cod (*Gadus morhua*), pollack (*Pollachius pollachius*) and ballan wrasse (*Labrus bergylta*) over a three-year period (2015-2018) and used a mixed-effect model to show that thermal preferences were the main driver of behaviour and habitat use in a southern Norwegian fjord (Freitas *et al*., 2021).

In addition to temperature changes, salinity changes can also directly affect the ability of organisms to osmo-regulate. Marine organisms osmo-regulate to maintain volume, distribution, and ionic composition of body fluids. If salinity changes result in the inability of an organism to properly osmo-regulate, this will affect their ability to carry out vital biological functions, since salinity is an important factor in reproduction, recruitment, larval dispersal, behaviour and distribution of marine life. For example, in an experiment done on cockles (*Cerastoderma edule*) over a wide range of salinities over four days, salinities of less than 15 ppt yielded a 100% mortality rate in thread drifters and sedentary settlers (Peteiro *et al*., 2018). Similarly, Charu mussels (*Mytilus charruana*) within similar salinity ranges responded with closure of their valves and depressed physiological responses to avoid any osmotic shock[4] over short periods of time (Peteiro *et al*., 2018). For marine fish, changing salinities can influence

[4] Osmotic shock is defined as a sudden change in the movement of water across an organism's cell membrane due to rapid changes in the surrounding solute concentrations.

growth and development (egg fertilization, incubation, yolk sac resorption, early embryogenesis, swim bladder inflation, larval growth) (Boef and Payan, 2001). For example, if fish are unable to move away from unfavourable changes in salinity, more energy will be required to regulate their internal osmolality[5] so that metabolic systems can function. This increased use of energy will then inhibit growth and reproduction.

Changes in temperature and salinity over time will likely result in shifts in ecosystem structure and function in Burrard Inlet. This will result in major impacts on food webs, which can affect fisheries. The most sensitive value to such changes is aquatic life, whereas the risk to human consumption is limited to indirect effects; however, salinity concentrations can affect an organism's ability to osmo-regulate[6] as well as affect the amount of metal uptake by organisms, thus affecting risk levels for human consumption of seafood.

2.1.2 Dissolved Oxygen

Dissolved oxygen mainly enters water through the air by gas diffusion from the atmosphere to the ocean, or as a by-product of photosynthesis from phytoplankton, algae, seaweed, and other aquatic plants. Gas diffusion is driven by wind, which accelerates the addition of oxygen to water. Surface waters are usually rich in DO while waters below 100 to 150 m in depth do not readily gain oxygen directly from the ocean surface. Oxygen is required for respiration in marine plants, algae, and animals. Oxygen solubility has an inverse relationship with water temperature and salinity; both affecting oxygen saturation. Seawater holds about 20% less oxygen than freshwater at the same temperature (BC Ministry of Environment Lands and Parks, 1997).

Changes in Dissolved Oxygen Concentrations

Oceans have lost more than 2% of the DO content since 1960, mainly driven by increasing temperatures caused by climate change (Copernicus Marine Services, 2021). Higher water temperatures lead to lower solubility of oxygen, and excessive growth of primary producers. The increased growth of primary producers consumes more oxygen as they decay at a higher rate than oxygen is replaced by the atmosphere or photosynthesis.

Under a business-as-usual greenhouse gas emission scenario, the oceans' DO inventory is expected to decline 1 to 7 % over the next century, although the decline is predicted to vary regionally. Much of the global oxygen reduction is concentrated in the upper 1000 m of the ocean, where biodiversity and biota abundance are highest (Laffoley and Baxter, 2019; Webb, 2022).

Areas of low DO levels are referred to as hypoxic zones, with some parts of the oceans experiencing seasonal or temporary periods of hypoxia, while in other areas these conditions are more permanent. Typical DO levels in a hypoxic zone are below 2.0 mg/L of oxygen (Spietz *et al.*, 2015). Hypoxic zones can occur naturally; however, excess nutrients discharged from coastal areas can lead to an overgrowth of algae followed by decomposition and increased oxygen consumption (Webb, 2022).

Effects of Dissolved Oxygen Changes on Aquatic Organisms

Low oxygen levels can adversely affect entire marine systems, with effects occurring at varying oxygen concentrations for different organisms; fish populations require between 7 and 10 mg/L of DO to thrive, while bottom feeders (crabs, oysters, and worms) typically require between 1 and 6 mg/L (Fondriest Environmental, 2013). Literature values of hypoxia thresholds show a wide range throughout different species, but a DO concentration below 2 mg/L is commonly considered the threshold for fisheries

[5] Defined as the number of particles of solute per kilogram of solvent within an organism.
[6] Defined as the process that keeps the sugars and salts in body fluids at ideal concentrations.

collapse and indicate “dead zones” for many higher trophic level animals (Keeling, Körtzinger and Gruber, 2009).

Even small reductions in DO levels can induce oxygen stress in marine organisms. At low oxygen levels, aquatic organisms must pump more water over their gills to deliver a higher volume of oxygen per unit time and begin to show signs of reduced growth, survivability and reproduction (Breitburg *et al*., 1994). Fish and other non-sessile organisms will typically begin to move away from low-oxygen areas; however, organisms that are less mobile or immobile often cannot survive in low-oxygen areas. As water temperatures also increase, metabolic activity increases leading to further increase in demand for oxygen (Laffoley and Baxter, 2019).

A decrease in oxygen levels not only affects individual physiological process but has also been shown to change species interactions. A laboratory study on estuarine predators and fish larvae indicated that at low oxygen concentrations (≤ 2 mg/L), predation rates increased on naked goby (*Gobiosolna bosc*), a bottom-dwelling fish, by sea nettles (*Chrysaora quinquecirrha*), a jellyfish species, in Chesapeake Bay, USA. In contrast to this, at similar DO concentrations, there was decreased predation by juvenile striped bass (*Morone saxatllis*) on adult naked goby (Breitburg *et al*., 1994). This indicated that low oxygen concentrations resulted in an impaired ability of the prey to escape the sea nettle, as well as reduced attack rates by adult and juvenile fish. Sea nettles however were not affected by low oxygen levels, and therefore their predation rates remained the same (Breitburg *et al*., 1994).

Exposure of shellfish to periodic low oxygen concentrations can negatively affect their survival, growth, and reproduction, and can also increase their susceptibility to disease. In a laboratory study performed by Keppel *et al*. (2015) on hypoxia effects on oysters, low oxygen levels were shown to be able to increase the acquisition and progression of some parasite infections *(Perkinsus*) and impair immune system functions in the eastern oyster (*Crassostrea virginica*). The magnitude and fluctuation of oxygen levels can therefore severely affect immune system functions and hinder current population growth or the re-establishment of shellfish by creating areas that serve as parasite reservoirs (Keppel *et al*., 2015).

A decrease in DO in Burrard Inlet has the potential to impact marine systems, with some mobile organisms being able to move to surface waters that are usually more oxygen-rich. This can reduce fish and shellfish catches by altering the balance of a system by favouring hypoxia-tolerant species, such as microbes, jelly fish and squid (IUCN, 2022). Therefore, low oxygen levels in Burrard Inlet would be likely to directly affect aquatic life.

2.1.3 pH

The ocean plays a major role in the global carbon cycle and the storage of carbon dioxide. Around 30% of the carbon dioxide (CO_2) in the atmosphere dissolves in the seawater and produces aqueous CO_2 ($CO_{2(aq)}$) and carbonic acid (H_2CO_3) (Figure A). In an aqueous environment, carbonic acid rapidly dissociates to produce bicarbonate ions (HCO_3^-), which can further dissociate into carbonate ions (CO_3^{2-}). This dissociation into bicarbonate and carbonate ions produce protons (H^+) that lower the pH of water (Barker and Ridgwell, 2012; Jiang *et al*., 2019). The chemical species in the carbonate system can release and take up hydrogen ions, i.e., the pH can change, when equilibrium is shifted due to an increase in reactants or products (Figure A).

Salt water generally has a higher alkalinity, i.e., a better capacity to neutralize acid and buffer against rapid pH changes, than freshwater due to the higher content of carbonate species and other dissolved salts (e.g., borates, silicates, hydroxides, and some nutrients) that can take up positively charged hydrogen ions. The high salinity leads to less variable pH levels in marine waters compared to freshwater environments. The buffering capacity of seawater will decrease as more CO_2 is added and CO_3^{2-} is progressively consumed (Barker and Ridgwell, 2012).

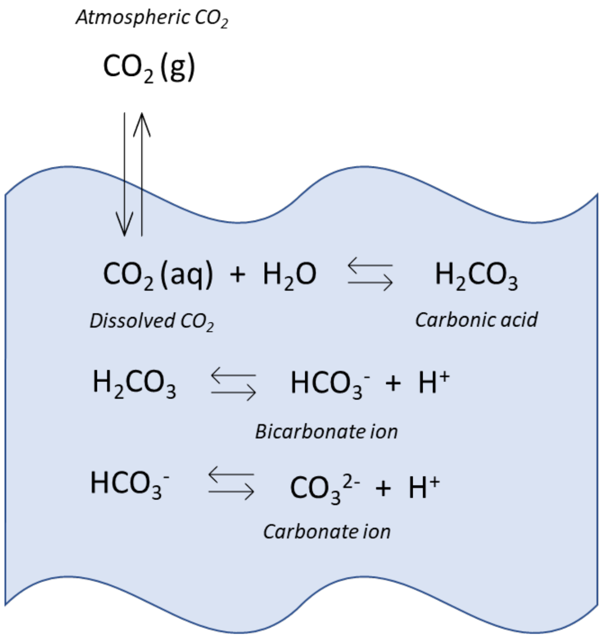


Figure A. Carbonate equilibria system.

Ocean Acidification and its Causes

In the past 200 years, since the start of the industrial revolution, ocean water has become more acidic, and the global average pH of the surface ocean has decreased by approximately 0.11 from 8.2 to 8.1, which corresponds to a 30% increase in the hydrogen ion concentrations (NOAA, no date). The main reason for ocean acidification is the rise in the atmospheric CO_2 concentration, caused by burning of fossil fuels. The ocean's buffering capacity has decreased over time, and it is expected that its role in absorbing anthropogenic CO_2 from the atmosphere will gradually decrease and ocean acidification will accelerate over time (Jiang *et al.*, 2019). The buffering capacity is estimated to diminish by up to 34% between the years 2000 and 2100 (NOAA, 2019).

The pH of the open ocean is not static but falls within a narrow range, typically ± 0.3, while the pH of coastal waters varies by a greater range, sometimes more than ± 1, and can show local variations (Waldbusser and Salisbury, 2014). The CO_2 levels in coastal water can increase as an effect of nutrient inputs, stimulating primary production such as phytoplankton blooms that subsequently decompose and produce large amounts of carbon dioxide. Such eutrophication-based acidification is expected to increase as coastal human populations are growing. Water rich in CO_2 flowing from land can also contribute to pH levels in marine systems, particularly in developed areas where water is not absorbed into the ground at the same degree as in natural areas. Rising water temperatures, caused by global climate change as well as export of warmer water from developed land, and increased decomposition can all further lead to decreasing concentrations of dissolved CO_2 in coastal waters (US EPA, 2018; Hall *et al.*, 2020).

Effects of Ocean Acidification on Aquatic Organisms

Extreme pH values in marine waters can have wide range impacts on various marine life depending on local environmental stressors, physiology of species, and life history. This includes a reduction in calcification, survival, growth, and development. The magnitude and type of physiological responses with either low or high pH values varies among taxonomic groups (Kroeker *et al*., 2013). Decreasing pH in marine waters also has secondary effects on aquatic biota, such as increasing solubility of toxic metals.

Calcification processes for calcified marine organisms are affected at lower pH. As waters become more acidic, carbonate which is used to build shells and exoskeletons becomes less available, which can result in a change to the shell or exoskeleton (Taylor *et al*., 2015). For example, a laboratory study that exposed shrimp (*Lysmata californica*) to pH of 7.53 over 21 days, indicated adverse effects on exoskeleton mineralization. This impacted the shrimp's crypsis (the ability to avoid observation or detection by predators), defence and predator avoidance, because the calcium to magnesium ratio was increased resulting in mechanical changes to the exoskeleton function.

Although the impact of acidification on crustaceans is usually a decrease in calcification processes, an increase in calcification has also been observed in barnacles (*Amphibalanus amphitrite*), prawns (*Panaeus occidentalis*), crab (*Callinectes sapidus*), shrimp (*Penaeus plebejus*) and lobster (*Homarus americanus*) (Taylor *et al*., 2015). Increases in metabolic investment during such net calcification events may, however, come at the expense of negatively affecting other physiological processes. This was observed in reduced growth and increased mortality in barnacle larvae (*Amphibalanus improvises*) and shrimp (*Palaemon pacificus*).

At low pH, fish can have adverse neurological effects which can have repercussions on their behaviours (Kroeker *et al*., 2013). If pH is reduced, physiological processes are also disrupted, and fish will often use extra energy to expel excess acid out of its blood system through the gills, kidneys, and intestines (Wang *et al*., 2018). This will in turn affect fish growth, feeding efficiency, protein efficiency ratio, and affect crude protein content (Tegomo *et al*., 2021). For example, black sea breams (*Acanthopagrus schlegelii*), which are relatively resistant to disease and environmental change, were exposed in the laboratory to pH of 7.8 and 7.4 for eight weeks and showed significant atrophy throughout their microvilli in their small intestines. This reduced their ability to absorb nutrients and consequently affected growth and feeding efficiency. Likewise, an increase in pH can also disrupt the acid-base balance, ammonia excretion and ion-loss over the gills in fish, which can all have negative consequences on growth and productivity of fish (Wang *et al*., 2018).

For BC coastal waters, marine molluscs are the only taxonomic group for which the pH tolerance is well defined. Normal development of clam eggs occurred between pH 7.0 and 8.75 and oyster eggs between pH 6.75 and 8.75, which is within the normal pH range of BC marine waters (ENV, 2021a). However, as pH becomes more acidic over time, marine organisms will be affected differently. This will likely result in major shifts and thus impacts on food webs, which can affect fisheries in Burrard Inlet. The most sensitive to such changes are therefore aquatic organisms, with indirect impacts on humans if fisheries and food webs are negatively affected by such changes.

2.1.4 Suspended Solids and Turbidity

Total suspended solids (TSS) and turbidity are the most visible indicators of water quality. Suspended solids in marine waters are of both organic and inorganic origin and include, for example, silt and clay particles, algae, plankton, and decaying material. Turbidity is a measure of relative clarity of water and is caused by suspended solids and dissolved organic compounds.

Sources of Suspended Solids and Turbidity in Marine Waters

Suspended solids can come from terrestrial sources such as soil erosion, freshwater runoff, and wastewater discharges, as well as from marine sources including algal blooms and disturbed bottom sediments. Terrestrial activities including vegetation clearing, construction, mining, and agriculture can also contribute to high solid loads transported into inshore and nearshore marine environments. Human activities that lead to increased suspension of bottom sediments include commercial fishing, boat wakes, anchoring, and dredging, which can lead to TSS concentrations several orders of magnitude higher than the background marine environment. Specifically, the waves from large ships (freighters and cruise ships), tugboats and motor-powered recreational boats have shown to induce erosion and disturbance of shorelines and bottom sediments resulting in the creation of suspended sediments (Stevens and Ekermo, 2003; Guarnieri *et al.*, 2021). A study investigating wave climate in the Central Harbour of Burrard Inlet found that vessel wakes have significantly increased the wave energy relative to natural background levels (Kerr Wood Leidal, 2021). In addition to the waves created from boats, the sediment bed shear stress induced by propeller velocities mobilizes and re-suspends large amounts of sediment in ports (Guarnieri *et al.*, 2021). This was demonstrated by a study that performed numerical modelling to examine the hydrodynamics and related bottom sediment erosion induced by propellers in a port of Genoa, Italy. High particle concentrations are also observed because of riverine flood plumes and resuspension of bottom sediments caused by strong winds or tidal currents (CCME, 2002; Oelsner and Stets, 2019).

Effects of TSS and Turbidity on Aquatic Organisms

When suspended solids and turbidity exceed background levels, aquatic life can be negatively impacted. Major effects of turbidity and suspended solids in the marine environment include: the reduction of light penetration; increase in transport of nutrients and other compounds sorbed to the particles, including toxic pollutants; and absorption of heat energy, thereby raising water temperatures.

Phytoplankton are photosynthetic, meaning they harvest sunlight to convert carbon dioxide and water into chemical energy used in the metabolic processes of aquatic organisms. Much of the ocean life depends on phytoplankton and when light penetration is limited due to turbid conditions, the entire marine food chain is negatively affected. Macroalgae such as kelp and aquatic plants are also dependent on light penetration for their production and survival (CCME, 2002; Sigman and Hain, 2012).

Suspended solids exert several physical and biological effects on aquatic organisms and their habitats. Effects on invertebrates include abrasion, clogging of filtration mechanisms and respiration systems, and mortality from smothering and burial. Examples of physical effects on fish and their habitat include limited ability to select and capture prey, increased susceptibility to predators, gill abrasion and clogging, and reduced spawning habitat. Observed biological effects on aquatic organisms include disruptions in movement and migration, reduced ability to resist diseases, reduced hatching success, inhibited development, and reduced growth. Stress responses from turbidity and suspended solids vary with the duration and frequency of exposure as well as across species and with the developmental stage of individuals. Eggs and larvae tend to be less tolerant to solids than adult individuals. Fish in all life stages are the most sensitive aquatic organisms to changes in suspended sediment levels (Appleby and Scarratt, 1989; Kjelland *et al*., 2015; BC ENV, 2021c). Species that inhabit relatively clear water are generally less tolerant to increases in suspended solids than species that normally frequent waters that are high in solids.

2.2 Factors Influencing Physical Parameter Levels in Burrard Inlet

Some of the most important natural processes affecting water quality in Burrard Inlet are stratification, freshwater inputs, winds, tides, and currents. These processes impact diurnal changes, seasonal cycles of temperature, water quality parameters, and explain interannual (i.e., involving two or more years) variability in water quality. An introduction to the oceanography of Burrard Inlet, which is fundamental to water quality in Burrard Inlet, has been provided by Rao *et al*. (2019). A summary is provided below.

2.2.1 Stratification

Water stratifies into layers when there are differences in water density between the top and the bottom layers of the water column, resulting in the presence of a pycnocline (i.e., where the vertical density gradients are maximum).

The thermocline is the transition layer between the warmer, mixed water at the top of the water column and the cooler, deep water below (Figure B). If the salinity changes rapidly with depth, the zone is called the halocline zone (Figure C).

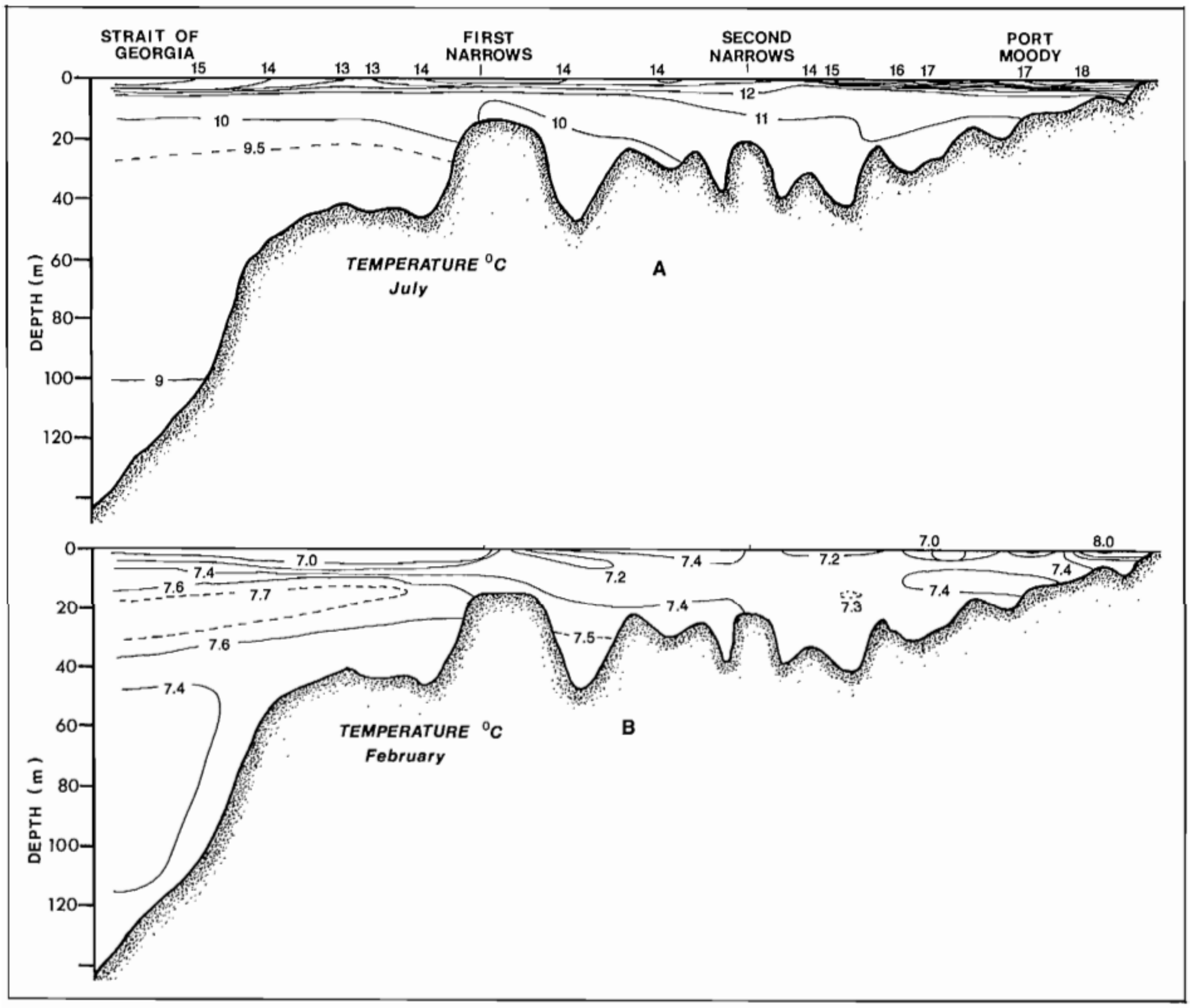


Figure B. Temperatures (°C) in mid-channel sections through Burrard Inlet: (A) July 7-9, 1966, (B) Feb. 15-18, 1962 (Thomson, 1981).

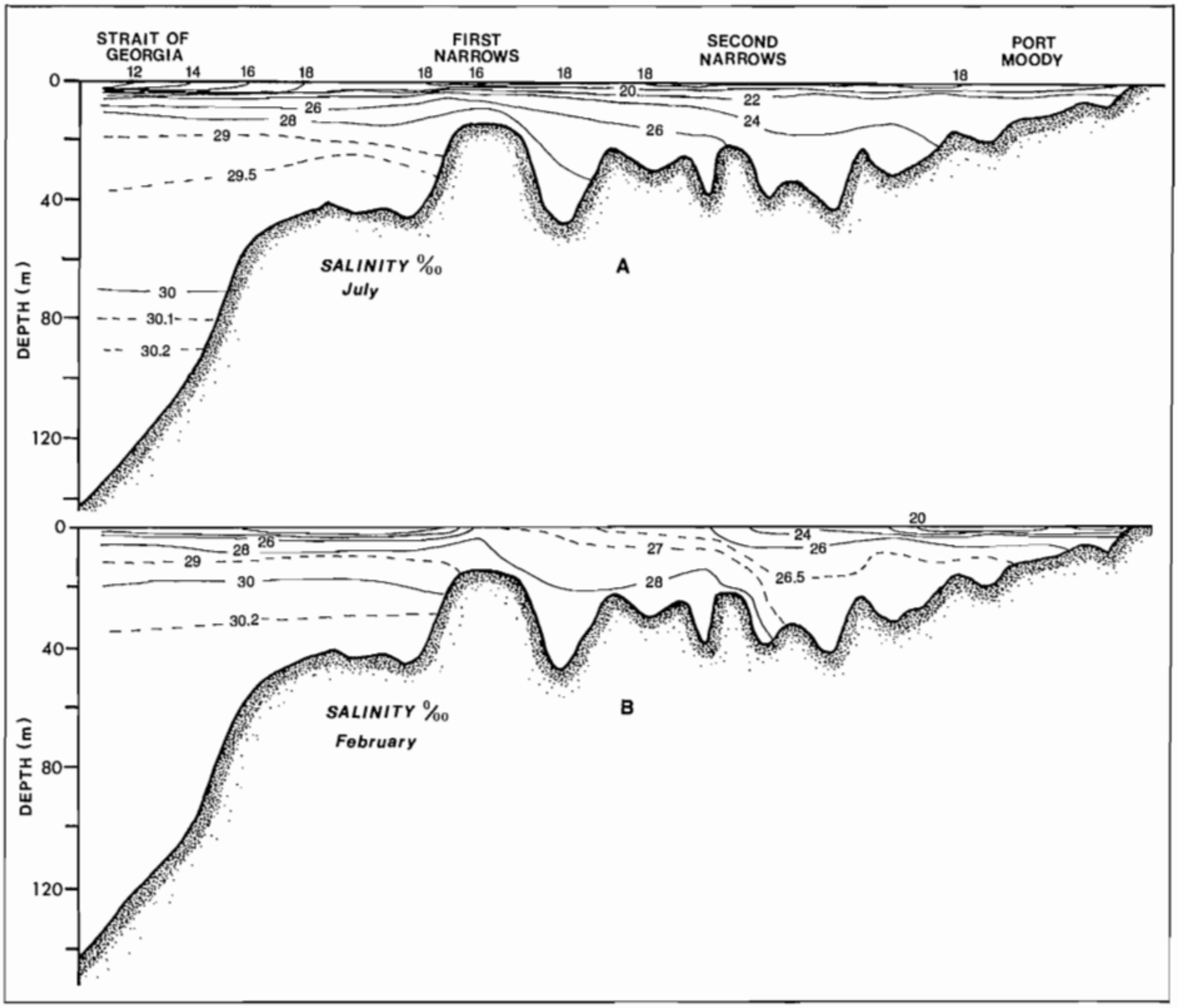


Figure C. Salinity (‰) in mid-channel sections through Burrard Inlet: (A) July 7-9, 1966, (B) Feb. 15-18, 1962 (Thomson, 1981).

As seen in Figure B and Figure C, stratification in Burrard Inlet is most pronounced during summer. Stratification restricts surface waters from mixing with water near the bottom, which can lead to oxygen deficiency in deeper waters and altered distribution of nutrients (Laffoley and Baxter, 2016). In Indian Arm, the surface layer with lower salinity is thin at 1-3 m in depth because of relatively small freshwater inputs, overlying a strong halocline between 3 and 5 m (Young and Pond, 1988).

2.2.2 Freshwater Inputs

Burrard Inlet receives considerable volumes of freshwater from the Fraser River through tidal movements, which is a major factor in controlling surface layer properties in Burrard Inlet (Figure D). Burrard Inlet is also fed with freshwater from over 100 streams and directly by precipitation. The major streams entering Burrard Inlet are Capilano River, Seymour River, Indian River, and water from the Upper Coquitlam River via the Buntzen Lake diversion from the Coquitlam Reservoir. Among the sub-basins in Burrard Inlet, waters in Outer Harbour are most influenced by the Fraser River, although intrusion through First Narrows can occur. A broad sill at the southern end of Indian Arm restricts exchange of water with the rest of Burrard Inlet, and freshwater inputs from Indian River and the

Coquitlam-Buntzen hydropower facilities are more important for water quality in Indian Arm than the Fraser River (Thomson 1981).

The flow of freshwater into Burrard Inlet has a bimodal cycle: a spring peak caused by the freshet, between April and June, and a fall to winter peak caused by runoff and regulated flows from the Coquitlam-Buntzen facilities. The highest rainfalls are seen from October through January, with a peak in November, while June through September receive the lowest amounts of rainfall.

In addition to seasonal changes in precipitation and runoff, climate patterns such as El Niño and La Niña may also affect the water quality of Burrard Inlet due to extreme fluctuations of dry and wet conditions.

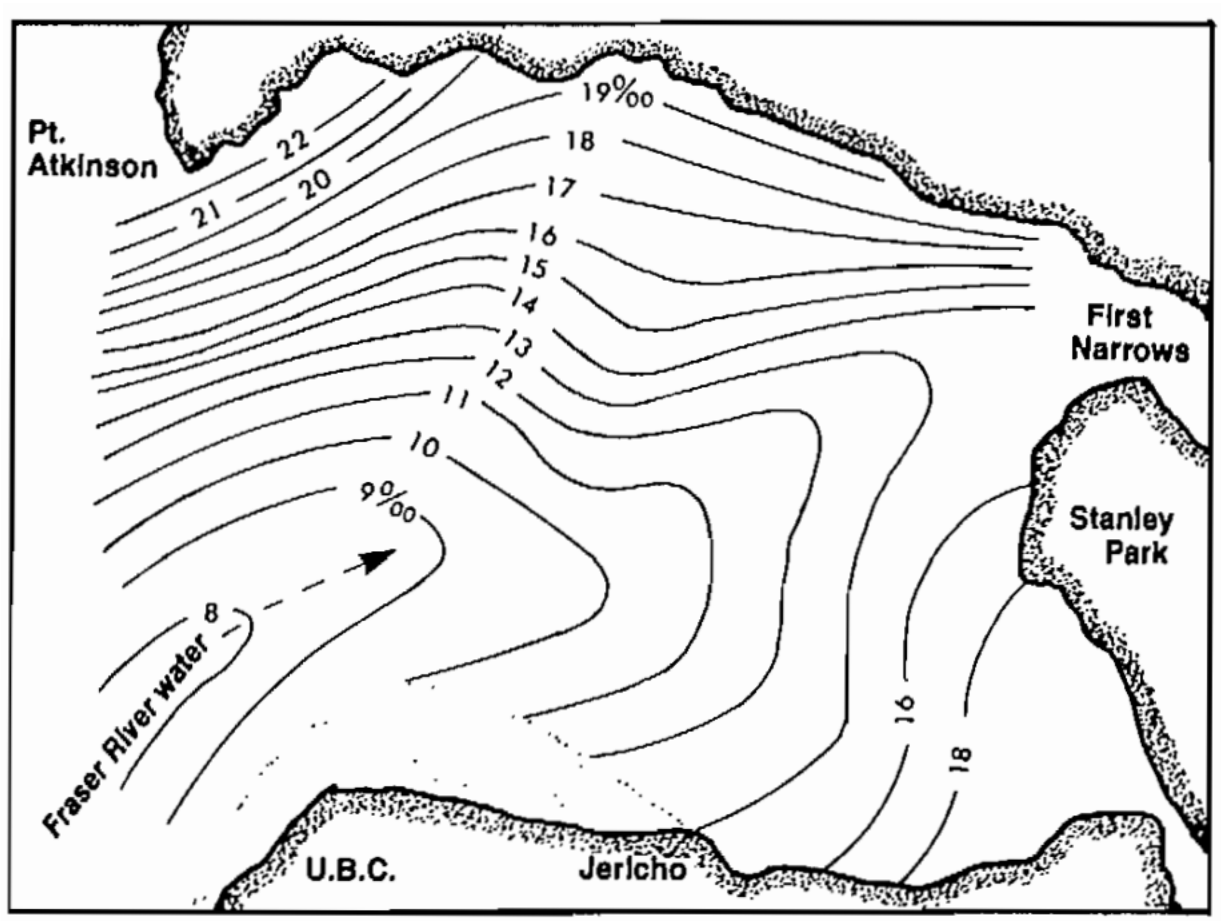


Figure D. Average summer surface salinity (ppt) in Burrard Inlet during large Fraser River runoff (Thomson 1981).

Freshwater inputs influence circulation, salinity, temperature, turbidity and sediment, nutrients, and ecology (e.g., reduction of primary production, entry of juvenile salmonids) in Burrard Inlet (Stockner and Cliff, 1979; Thomson, 1981; Macdonald and Chang, 1993; Swain *et al.*, 1998; Levings *et al.*, 2004). Freshwater is retained for about six months in the Inlet (Allen, 2017).

Water temperatures in Burrard Inlet, specifically in the Outer Harbour, are to a great extent directly affected by the temperature of waters discharged with the Fraser River. Between the years 1953 and 1998, mean summer temperatures in the Fraser River ranged from 15 to 19°C and increased at a rate of 0.022°C per year (Morrison, Quick and Foreman, 2002). Due to climate change, however, this temperature rate increase is predicted to be 0.066°C per year (total temperature increase of 1.9°C) between 2070-2099, resulting in increasing water temperatures in some parts of Burrard Inlet. Burrard Inlet's temperature is also affected when silt particles transported with the Fraser River absorb solar radiation, further increasing water temperatures. This is exasperated by the formation of a low-density brackish layer, which reduces mixing with the cold and salty bottom water.

Due to the quantity of freshwater inputs lowering the salinity of surface waters, Burrard Inlet is considered estuarine with brackish water. The lowest seawater salinities in Burrard Inlet are observed at the water surface and increase with depth, due to the lower density of freshwater compared to saltwater. Depending on the flow of the largest impacting freshwater source(s) and variations in precipitation, sub-basins of Burrard Inlet show different seasonal variations in salinities.

Also, turbidity in Burrard Inlet is largely affected by freshwater, mainly the silty waters of the Fraser River. The silty Fraser River plume can often be seen from both water and air (Figure E). The size of the plume ranges from nearly zero in midwinter to as much as 1400 km^2 during freshet (April through June) when both flow and turbidity are highest (Pawlowicz et al., 2017). Turbidity in Indian Arm, on the other hand, is less affected by intruding turbid seawater, and more by river-borne inorganic material, and events such as debris flows from stream and river (Buchanan, 1966).

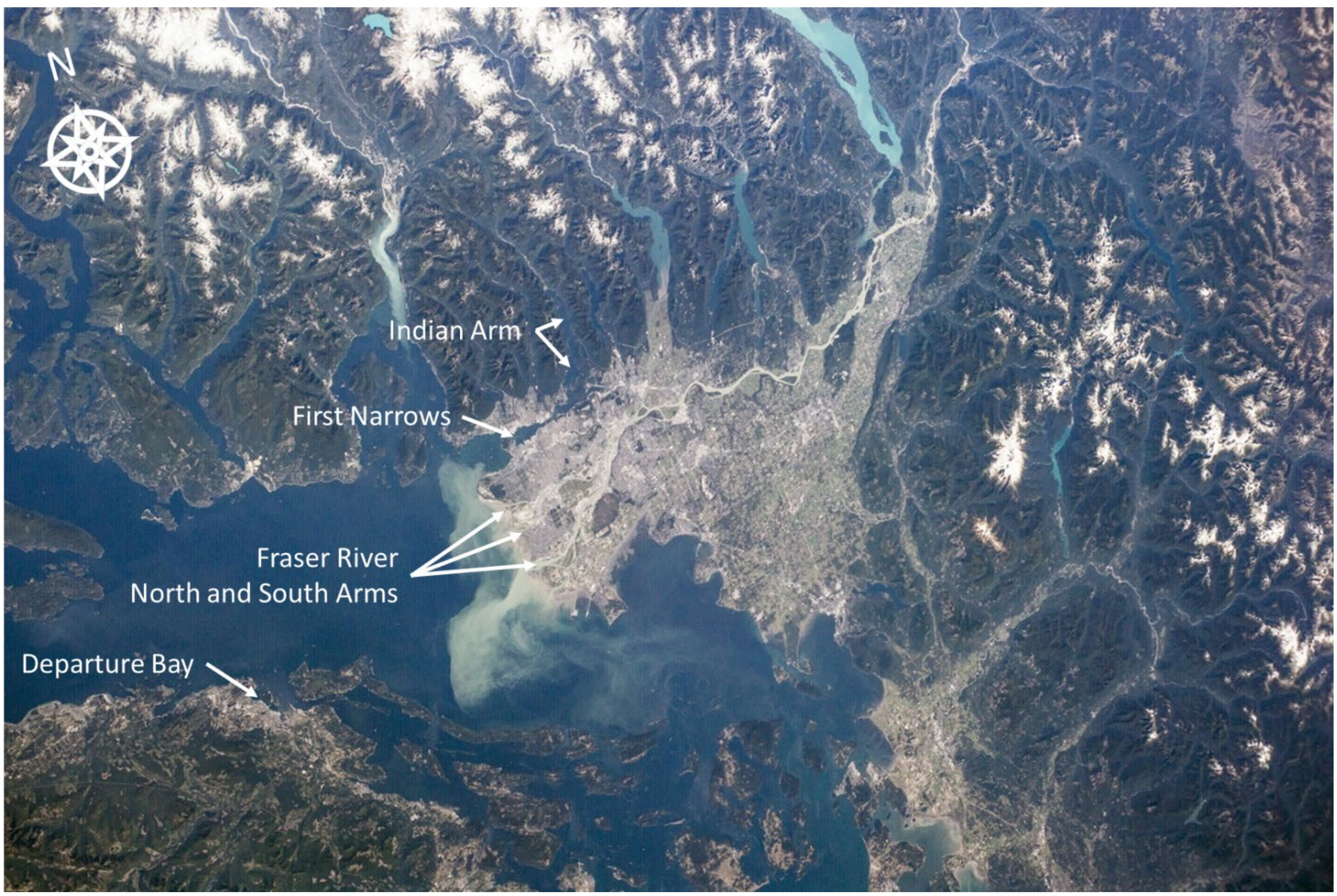


Figure E. Plume from the Fraser River extending throughout the southern reaches of the Strait of Georgia. The photograph was taken on September 6, 2014, by an astronaut on the International Space Station. https://earthobservatory.nasa.gov/images/85028/plume-from-the-fraser-river

2.2.3 Winds and Tides

The North Shore mountains lead to predominating east-west winds in Burrard Inlet, where easterly winds tend to drive surface water to the Inlet's seaward entrance. Tidal effects have great impact on water quality in estuaries like Burrard Inlet with relatively shallow areas: as tidal energy increases, mixing of the water column increases which distributes water constituents such as DO, particles, and nutrients in the water column of the estuary. Tidal changes also affect shallow beaches, mainly in Outer Harbour, leading to re-suspension of bottom sediments and increased turbidity. Diurnal and semi-diurnal tides entering and exiting the Inlet create eddies and upwellings in Inner and Central Harbours (Li and Hodgins, 2004), with tides averaging 3.3 m daily (Levings *et al.*, 2004). Tidal effects together with the constrictions at First and Second Narrows create a significant flushing action in Burrard Inlet with peak velocities at approximately 2 m/s at both Narrows.

The oceanography of Indian Arm differs considerably from the other sub-basins of Burrard Inlet as it is a fjord, characterized by deep water with mean depth of 120 m and a maximum depth of 218 m. There is a broad sill at the southern end of Indian Arm, which restricts exchange of salt water with the rest of Burrard Inlet. Variations in spring-neap tides over the sill control much of the salinity and density of waters in Indian Arm (Thomson, 1981). During spring tides or high runoff periods, dense waters outside Indian Arm are well mixed, with density sufficiently reduced to prevent deep water renewal in Indian Arm. During neap tides, tidal mixing is less intense and bottom waters in Burrard Inlet are denser, resulting in increased water renewal. Deep water in Indian Arm is renewed on average every three years (Stacey and Pond, 2005). Renewal leads to a saw-toothed shape in long-term (years) time series of water properties, which is common to many fjords (**Error! Reference source not found.**). After renewal, water properties show a steady decrease or increase over time, depending on the sign of the vertical gradient, until the next renewal cycle begins (Young and Pond, 1988).

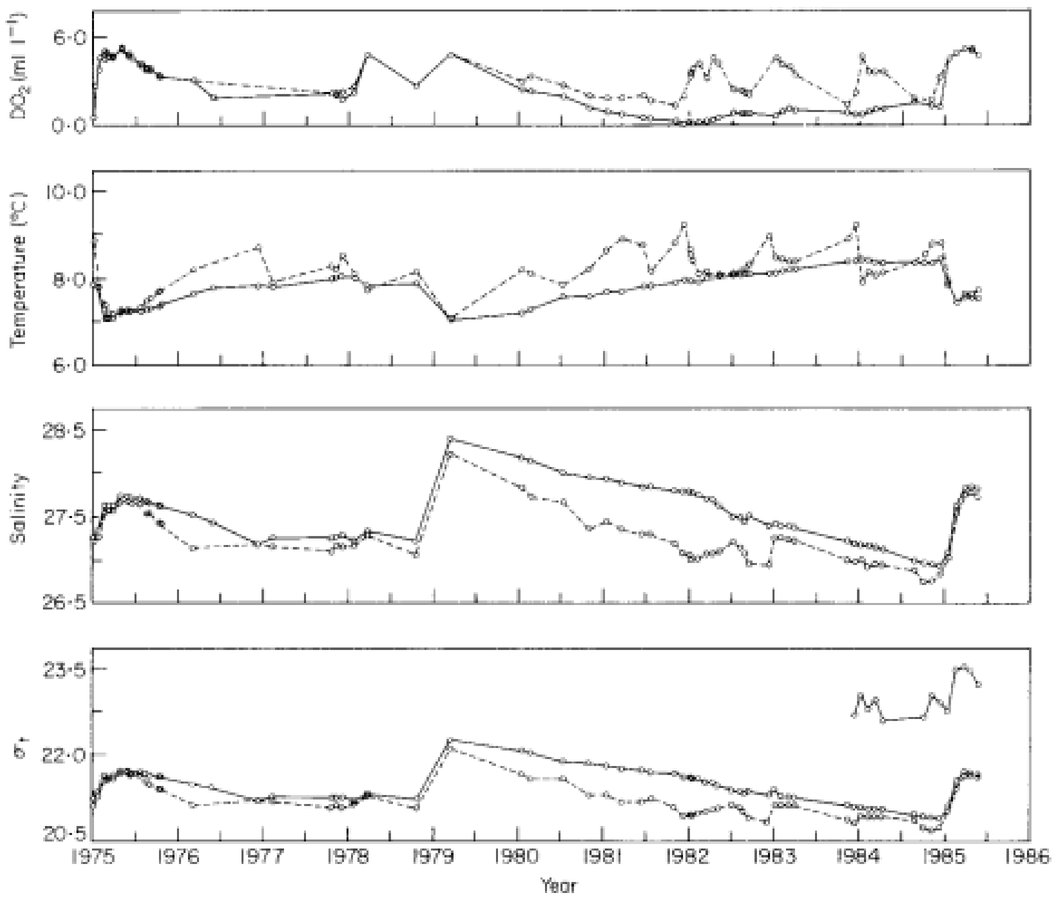


Figure F. Time series of dissolved oxygen concentration (DO₂), temperature, salinity, and density (σ) at Station 23 in Indian Arm in the years 1975 to 1985. Solid lines represent data at 200 m, and dashed lines at 100 m (from Young and Pond, 1988)*. Note: Station 23 has a similar location as the current monitoring station #4, see Figure G.*

2.2.4 Currents

The ocean has a complex circulation system where currents move water around the globe. Ocean currents are driven by surface winds, Earth's rotation, tides, temperature, and salinity (i.e., density, gradients). Thermohaline circulation is controlled by horizontal differences in temperature and salinity and is often called the Global Ocean Conveyor Belt because of its general impacts on oceanic circulation. Important features of the thermohaline circulation are deep water formation, upwelling and near-surface currents, leading to a slow replacement of surface water with water rising from deeper depths (Rahmstorf, 2013). Upwelling is one type of circulation that is important for the ocean's biota across all trophic levels as it brings cold, nutrient-rich, and oxygen-poor water toward the ocean surface while pushing warmer, less dense water downward. Along the west coast of British Columbia up- and downwelling are driven by wind and show seasonal trends: in spring, there is a shift from predominantly downwelling winter conditions to predominantly upwelling-favourable conditions in summer, referred to as the Spring Transition (Boldt, Leonard and Chandler, 2019). Due to high rates of upwelling from the Pacific Ocean, bringing nutrient-rich but oxygen-poor water closer to the coast, the Salish Sea is naturally slightly more acidic than other waters and has areas with naturally hypoxic conditions (US EPA, 2017). The upwelled water in the Salish Sea has high CO_2 concentrations relative to upwelled water in other parts of the world due to the North Pacific being the dead end of ocean circulation. The water has been accumulating CO_2, among other nutrients, for hundreds of years before it reaches the Salish Sea (Sarmiento and Gruber, 2006).

2.2.5 Anthropogenic Causes to Changes in Physical Parameters

Global climate change is the major anthropogenic factor impacting physical parameters of ocean waters. The main impacts of climate change to physical parameters include:

- Most of the excess heat due to human-caused global warming is absorbed by the oceans, leading to increased water temperatures.
- Global models predict that DO levels of marine waters will continue to decline as ocean temperatures rise and less oxygen can be dissolved in water. Global warming also leads to earlier thermal stratification onset, and longer and more intense thermal stratification, associated with an increase in hypoxic areas.
- The main reason for ocean acidification is the rise in atmospheric CO_2 concentrations, caused by burning of fossil fuels.
- Climate predictions have suggested a reduced seawater salinity in the future due to increases in precipitation and polar and glacial melt.

Some effects of climate change have already been observed in Pacific marine ecosystems, such as changes in the food web and responses by Pacific salmon caused by increased temperatures in offshore and coastal waters (Boldt, Leonard and Chandler, 2019).

Coastal waters like Burrard Inlet may also be impacted by local anthropogenic activities related to land use and development. Identified anthropogenic discharges to Burrard Inlet are reported in Rao *et al.* (2019). Potential causes to thermal pollution in Burrard Inlet are heated municipal wastewater effluents, cooling water from industries, and stormwater. Vegetation removal and exposed land lead to heated surfaces and hence heated stormwater runoff. Further, impoundment of rivers and streams for hydropower generation or drinking water supply can potentially alter the thermal regime of receiving waters (BC Ministry of Environment Lands and Parks, 2001). Anthropogenic sources that may give rise to sudden and transient changes in salinity include salt-laden stormwater and industrial discharges. Stormwater, erosion, industrial and municipal wastewater emissions, and spills may contribute to acidic sediments, nutrients, and acidic chemicals to Burrard Inlet, leading to coastal acidification (US EPA, 2018; Hall *et al.*, 2020). Potential nutrient-rich emissions in Burrard Inlet, which may cause local hypoxia and acidification, are municipal and industrial wastewater discharges, fertilizer runoff and animal waste, failing septic systems, and degradation of natural nutrients in local watersheds (US EPA, 2017). Soil disturbing activities and sewage discharges are potential sources of suspended solids in Burrard Inlet. In addition, boat wakes, dredging, and in-water construction activities (i.e., construction and expansions of new piers and terminals) can all lead to increased suspension of bottom sediments. Potential local anthropogenic sources of salinity changes are water from impoundments, diluting wastewater discharges and stormwater outfalls contaminated with road salts (Smyth and Elliott, 2016).

2.3 1990 Provisional Water Quality Objectives for Physical Parameters

The 1990 WQOs for DO, pH, TSS, and turbidity in Burrard Inlet marine water are summarized in Table 1. There were no WQOs set in 1990 for salinity or temperature in Burrard Inlet marine water.

Table 1: 1990 Provisional Water Quality Objectives for Physical Parameters

Sub-basin	False Creek	Outer Harbour	Inner Harbour	Central Harbour	Port Moody Arm	Indian Arm
Dissolved oxygen	6.5 mg/L minimum					
pH	N/A			6.5-8.5	N/A	
Suspended solids	10 mg/L maximum increase					N/A
Turbidity	5 NTU maximum increase					N/A

3. WATER QUALITY ASSESSMENT

3.1 Benchmarks Used in this Assessment

Benchmarks were used to screen available data for potential acute and chronic effects and to inform the derivation of proposed objectives for physical parameters in Burrard Inlet. Based on the literature, aquatic life is the value most sensitive to changes in physical parameters in marine water. Existing BC Water Quality Guidelines (WQGs) (BC ENV, 2023, 2021d) and Washington State Water Quality Standards for Surface Waters for marine and/or estuarine aquatic life (DOE, 2021) were used as screening benchmarks for the data assessment of physical water quality parameters and are summarized in Table 2, all of which are more recent than the 1990 WQOs for Burrard Inlet.

Table 2: Screening Benchmarks for Physical Parameters in Water Used in this Assessment

Parameter	Screening Benchmark	Value	Reference
Temperature	Maximum ± 1 °C change from natural ambient background. Hourly rate of change up to 0.5 °C. The natural temperature cycle characteristic of the site should not be altered in amplitude or frequency by human activities.	Marine and estuarine aquatic life	ENV 2001
	Highest 1-day maximum: Extraordinary Quality[1] = 13 °C. Excellent Quality[2] = 16 °C. Good Quality[3] = 19 °C. Fair Quality[4] = 22 °C.	Marine and estuarine aquatic life	DOE 2021
Salinity	**Long-term:** maximum ± 10% change in concentration (NaCl or equivalent) **Short-term:** 24-hour change in salinity should not exceed 1 if natural salinity is 0 to 3.5; 2 if natural salinity is 3.5 to 13.5; and 4 if natural salinity is 13.5 to 35.	Estuarine aquatic life	ENV 2021d (DOE 1972)
Dissolved oxygen	**All life stages other than buried embryo/alevin**: Minimum 30-day mean: 8 mg/L Instantaneous minimum: 5 mg/L	Marine and estuarine aquatic life	ENV 1997
pH	Unrestricted change within 7.0 to 8.7	Marine aquatic life	ENV 2021a
	Extraordinary Quality: Must be within the range of 7.0 to 8.5 with a human-caused variation within the above range of less than 0.2.	Marine aquatic life	DOE 2021

Parameter	Screening Benchmark	Value	Reference
	Excellent Quality: Must be within the range of 7.0 to 8.5 with a human-caused variation within the above range of less than 0.5. **Good Quality:** Same as 'Excellent Quality'. **Fair Quality:** Must be within the range of 6.5 to 9.0 with a human-caused variation within the above range of less than 0.5.		
Total suspended solids	**Clear Waters[5]:** Maximum change from background of 25 mg/L at any one time for a duration of 24 h. Maximum change from background of 5 mg/L at any one time for a duration of 30 d. **Turbid Waters[5]:** Maximum change from background of 10 mg/L at any time when background is 25 - 100 mg/L Maximum change from background of 10% when background is >100 mg/L at any time	Aquatic life - fresh, marine, estuarine	ENV 2021d&e
Turbidity	**Clear Waters:** Maximum change from background of 8 NTU at any one time for a duration of 24 h Maximum change from background of 2 NTU at any one time for a duration of 30 d **Turbid Waters:** Maximum change from background of 5 NTU at any time when background is 8 - 50 NTU Maximum change from background of 10% when background is >50 NTU at any time	Aquatic life - fresh, marine, estuarine	ENV 2021b&c

1 Extraordinary Water Quality: Water quality of this use class shall markedly and uniformly exceed the requirements for all uses including, but not limited to, salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.
2 Excellent Water Quality: Water quality of this use class shall meet or exceed the requirements for all uses including, but not limited to, salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.
3 Good Water Quality: Water quality of this use class shall meet or exceed the requirements for most uses including, but not limited to, salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning/
4 Fair Water Quality: Water quality of this use class shall meet or exceed the requirements for selected and essential uses including, but not limited to, salmonid and other fish migration.
5 The terms clear flow period and turbid flow period are used to describe the portion of the hydrograph when suspended sediment concentrations are low (i.e., < 25 mg/L) and relatively elevated (i.e., ≥ 25 mg/L), respectively.

The BC WQG for water temperature is based on the fact that many biological processes in marine organisms are sensitive to temperature changes and the maximum allowable variation from natural ambient background of ± 1°C is proposed to minimize human-caused impacts on marine resources (BC ENV 2001). The maximum allowable hourly change of ± 0.5°C is proposed to minimize the impact of sudden and human-caused temperature variations. Site-specific diurnal, seasonal, and interannual water temperature regimes are intended to be maintained with implementation of the guideline (CCME, 1999a). The Washington water quality standards were developed for the protection of all indigenous fish and non-fish aquatic species (DOE, 2021). The protection categories can be found in the footnote of Table 2.

The BC WQG for salinity (maximum ± 10% change) is designed to avoid, or limit human-caused variation in salinity with the purpose to protect fish and other marine animals (BC ENV, 2021c). The 24-hour maximum allowable change in salinity was developed to protect the most sensitive species of aquatic tender leaves and stems from plasmolysis, i.e., contraction of the cell due to exposure to a hypertonic solution and resulting in death of the plants (US EPA, 1976).

The BC WQG for an instantaneous minimum concentration of DO (5 mg/L) is protective against severe stress and established lethal limits for juvenile/adult life stages of the most sensitive species (BC ENV, 2023). The instantaneous minimum can be exceeded for short periods if the exceeding concentration is above that which could result in serious impairment or lethality. The 30-day mean objective (8 mg/L) is most protective for early life stages, because it limits concentrations below the mean and hence is protective of the short-duration and sensitive stages of development. The 30-day mean objective is above reported responses to hypoxia and growth impairment for salmonids. The BC guidelines are mainly based on salmonid research as there is a general lack of available data on DO requirements of marine organisms in Canadian waters.

The BC WQG also suggests DO guidelines to protect sensitive early life stages of salmonids (BC ENV, 2023. These apply to interstitial spawning in gravel (buried embryo) as well as further developmental stages occurring in the water column. As buried salmonid embryos or alevins are not found in marine waters, the more conservative DO guidelines for early life stages were not used as benchmarks in this assessment.

The BC WQG for pH is based on the pH tolerance for development and survival of marine molluscan larvae observed in BC waters (BC ENV, 2023). Molluscs are the only taxonomic group for which there are data on the effects of pH in the marine environment. The pH of marine and estuarine waters should fall within the range 7.0 to 8.7 unless it is a result of natural processes. Unrestricted change in pH due to human activities within the specified range may not be protective of organisms with narrow pH tolerances. To reduce the potential impacts on these organisms, the Washington standards also include a limit on induced pH changes (0.2-0.5) within the allowable range (DOE, 2021).

The BC WQG for TSS is based on the change in suspended sediment concentration that causes a response in the most sensitive group of aquatic organisms (BC ENV,2023). As the biotic, physical, and chemical conditions of aquatic ecosystems are diverse, the recommended objectives should be compared to natural background levels. At TSS concentrations exceeding 25 mg/L, small variations in TSS from background levels are likely to cause reversible behavioural and sublethal effects on fish. The long-term exposure objective for TSS is based on extrapolation from a short-term concentration-duration-response curve. The turbidity objectives have then been extrapolated from the TSS guideline, assuming a general TSS to turbidity correlation of 3 to 1 (CCME, 1999b).

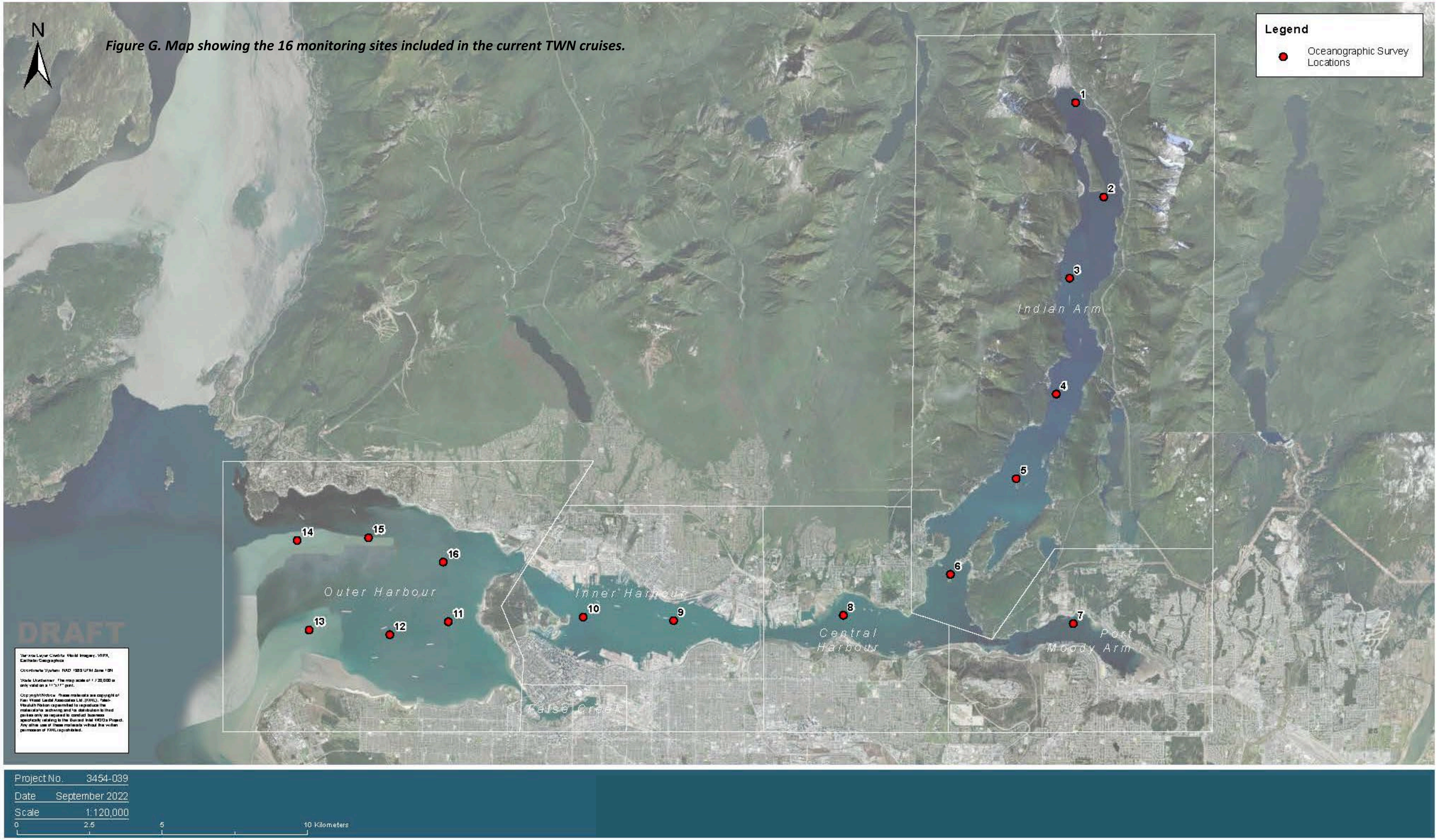
3.2 Data Sources

To assess the current status of physical water quality parameters in Burrard Inlet, sensor-based data collected during cruises performed by TWN in 2018-2020, with technical and data management support from Ocean Networks Canada (ONC), were used. Although other datasets containing physical parameters sampling data may exist, TWN datasets were found to be the best available data for assessing the current status of physical parameters within Burrard Inlet within the constraints of the project. The dataset is considered to be the best available because of the high spatial resolution (16 sites), collection frequency (biweekly to monthly), and consistency (since early 2019). Both TWN science and western science were considered in program design, site selection, implementation, and data collection. Data collected during the TWN cruises include conductivity, temperature, pressure, oxygen saturation (expressed as a percentage but converted to the DO concentration [mg/L] for the purpose of comparing to benchmarks expressed as concentrations), turbidity, and fluorescence (Chlorophyll-a)[7] at 16 sites across all sub-basins of Burrard Inlet except False Creek. These include six sites in Indian Arm; one in Port Moody Arm; one in Central Harbour; two in Inner Harbour; and six in Outer Harbour (see Figure G). Since early 2019, the conductivity, temperature, and depth (CTD) surveys have been consistent at all sites, performed biweekly from spring to early fall (from April through September), and monthly through fall and winter from October through March). During the cruises, water quality was measured continuously throughout the water column, from the water surface to approximately 3 m above the seafloor. In addition to the CTD casts, discrete water samples have been collected, using a Niskin water sampler system, at the water surface and at 5 m above the sea floor to measure dissolved inorganic carbon, nutrients species (phosphate, nitrate, silicate), alkalinity, δ18O (a measure of the ratio of the stable oxygen isotopes ^{18}O and ^{16}O), as well as surface plankton samples for taxonomical analysis.

The physical circulation and oxygen dynamics in Burrard Inlet have been well described by research performed by DFO and at the University of British Columbia (Gilmartin, 1962; Davidson, 1979; Stacey and Pond, 2005). However, major data gaps exist with respect to the biogeochemistry of the inlet, including ocean acidification, nutrient concentrations, and phytoplankton abundance and distribution. Additionally, descriptions of physical water properties within Indian Arm were made when the Buntzen Power Plant contributed approximately 40% of the annual freshwater input to the basin; with changes in the power plant's water usage, this number has decreased, and a new set of physical data was needed. The TWN data collection initiative, which also includes a TWN/ONC seafloor observatory[8], will update physical oceanographic data for the inlet and provide the first complete set of biogeochemical data in the inlet.

[7] Instrument used was AML Plus-X with conductivity, temperature, pressures, dissolved oxygen, turbidity, and fluorescence (chlorophyll-a) sensors.
[8] Includes monitoring of conductivity, temperature, pressures, dissolved oxygen, turbidity, fluorescence (Chlorophyll-a and CDOM) using an AML Metrec-X; currents using a RDI 600 kHz ADCP; pH using a SeaBird SeaFET and dissolved oxygen using a Pro-Oceanus.

Figure G. Map showing the 16 monitoring sites included in the current TWN cruises.



Total suspended solids were not included in the TWN monitoring program, as TSS determination requires filtration and the TWN monitoring was performed using sensors. Also, pH data were not collected by TWN because of the inherent difficulty in monitoring seawater pH with available sensors, leading to issues with precision and accuracy. These measurement difficulties arise from the need for frequent calibrations of sensors if used in marine waters due to high ionic strength, varying temperatures, and changing pressure (Clarke *et al.*, 2015). Instead, pH in marine waters can be derived from data on inorganic carbon as pH in marine waters is mostly dictated by the carbonate system. Water samples have been collected by TWN for the purpose of determining inorganic carbon and related parameters, but results were not available at the time of writing. pH data have been collected by other monitoring programs and organizations using sensors; however, it is not known whether collected data have been verified with measurements determined using discrete bottle samples and therefore were not deemed reliable for the current assessment.

3.3 Assessment Results

Physical water quality data collected by TWN are assessed separately for each sub-basin of Burrard Inlet, because of the different conditions and factors influencing water quality and physical parameters in the sub-basins, e.g., tides, waves, and mixing. Variations in data have been summarized separately for each season and at different depths for each monitored sub-basin. Seasons are meteorological: winter is December – February (inclusive), spring is March – May, summer is June – August, and fall is September – November. Depth layers were determined for each sub-basin CTD profile plots (Appendix A) and defined by the points where temperature and salinity change (Table 3).

Table 3. Depth delineations for each sub-basin in Burrard Inlet.

Depth Layer	Outer Harbour	Inner Harbour	Central Harbour	Port Moody	Indian Arm
Surface (m)	0-8	0-5	0-5	0-4	0-5
Mid (m)	8-60	5-20	5-18	4-11	5-75
Bottom (m)	60-88	20-34	18-34		75-180

Ranges of salinity, temperature, DO, and turbidity at surface, mid-, and bottom depth layers in different seasons are discussed for each sub-basin in the sections below.

In addition to the recent, and relatively short-term, data collected by TWN, historical data collected by e.g., Fisheries and Oceans Canada (DFO) and other researchers, have been reviewed to get a better understanding of long-term time trends in physical parameters.

3.3.1 Water Temperature

Water temperatures in Burrard Inlet generally follow the same seasonal patterns as salinity, and generally dictate density differences in the water column.

In spring, summer and fall, water temperatures are warmer at the surface and decrease with depth in all sub-basins (Table 4). The highest surface temperatures are observed in Port Moody followed by Indian Arm. The thermocline is shallow in all sub-basins and summer water temperatures start decreasing considerably at 5 m depth, with the Port Moody sub-basin being an exception because of its shallow depth. Summer water temperatures become uniformly cold below 20 m depth and generally vary by less than 1°C in all sub-basins.

Central and Inner Harbours show the most uniform water temperatures with depth in summer, compared to other sub-basins (Table 4). The comparably uniform temperatures observed in Central and Inner Harbours are due to lower freshwater impacts and more intense mixing. While the largest differences in water temperatures between surface and bottom layers are observed in summer, winter water temperatures in all sub-basins are rather uniform at all depths. In winter, surface waters are generally slightly colder than deeper waters due to heat loss to the atmosphere (Thomson, 1981).

Among the sub-basins, water temperatures in Outer Harbour are most affected by the Fraser River. The northern shore of Burrard Inlet generally shows lower surface water temperatures in summer (details not shown in Table 4) because the warmer waters from the Fraser River rarely reach the northern shore, and cold and well-mixed waters from the vicinity of First Narrows help keep temperatures cool (Thomson, 1981). Conversely, the brackish layer from the Fraser River helps keep temperatures higher on the southern shore. Consequently, summer surface temperatures in Outer Harbour vary more than summer variations in other sub-basins (Table 4).

The long-term time series (1951-2000) of deep-water data collected in Indian Arm by DFO showed large variations in temperatures with a saw-tooth renewal cycle, similar to salinity (DFO, 2009). Like other deep inlets, Indian Arm exhibited large variations, approximately ±3°C, in its deep-water temperatures during the monitoring period. The lowest deep-water temperatures were observed at time of renewal, together with the highest deep-water salinities, followed by a warming period extending over several years. In the first half of the time series (1950s to 1970s), deep-water temperatures after renewal (i.e., the lowest temperatures) were in the range 6.0-6.5 °C, while the coldest temperatures post-1980 increased by 1.5 °C to 7.5-8.0 °C.

Another long-term DFO data collection of daily sea surface temperature and salinity observations has been performed at Departure Bay (Pacific Biological Station) since 1914 (DFO, 2021). Departure Bay is relatively far from Burrard Inlet (other side of the Salish Sea) but is the closest station in the Strait of Georgia with long-term water quality data. Observations are made daily using seawater collected in a bucket lowered into the surface water at or near the daytime high tide. The long-term data series of average monthly seawater temperatures at Departure Bay indicate that water temperatures have increased over this past century (DFO, 2021). The largest increases in water temperatures at Departure Bay have been observed during the colder months, with a peak change in average temperatures for January at 0.01°C per year. During summer months, the temperature increases have been less than 0.004°C per year.

The BC ENV-derived benchmark dictates that temperature changes "should not exceed ± 1°C from natural ambient background" and that "the natural temperature cycle characteristic of the site should not be altered in amplitude or frequency by human activities". However, water temperatures in Burrard Inlet show large variations over the year, making it difficult to define a "natural ambient background" temperature with the existing data (Table 4). It is also not known if or how much of the observed changes in water temperatures are caused by human activities, or are due to natural variations caused by e.g., tides and seasonal changes. The long-term data collected by DFO show, however, that water temperatures in deep waters of Indian Arm have increased by more than 1°C between the 1980s and 2000s compared to the years between the 1950s to 1970s and may be due to global climate change.

Compared to the Water Quality Standards for Surface Waters of the State of Washington, observed maximum water temperatures in Burrard Inlet (Table 4) reach "extraordinary" (≤ 13°C) or "excellent" (13-16°C) quality in all sub-basins in fall, winter, and spring. The only exception is found in the surface waters of Indian Arm in spring, where temperatures occasionally reach over 16°C and are classified as "good quality" waters. During summer, maximum surface temperatures in Indian Arm, Port Moody, and

Outer Harbour fall into the most impaired temperature category and are classified as “fair” (≥ 19°C), while surface temperatures in Central Harbour and Inner Harbour are of “good” quality (16-19°C).

Table 4. Seasonal ranges (averages) of surface, mid depth, and deep-water temperature (°C) in Burrard Inlet sub-basins. Data collected by TWN cruises in 2018-2020. Data is categorized by season: Winter (December to February), Spring (March to May), Summer (June to August), and Fall (September to November). Depth delineations are defined in Table 3.

Depth Layer	Outer Harbour	Inner Harbour	Central Harbour	Port Moody	Indian Arm
Winter					
Surface	6.7 - 9.8 (8.3)	7.4 - 9.5 (8.4)	6.2 - 9.5 (8.3)	6.2 - 9.6 (8.0)	5.1 - 11.4 (8.3)
Mid	7.8 - 10.1 (9.1)	7.5 - 9.6 (8.5)	7.5 - 9.5 (8.6)	7.3 - 9.7 (8.6)	7.6 - 12.0 (9.6)
Bottom	8.4 - 9.7 (9.1)	7.9 - 9.5 (8.6)	7.6 - 9.5 (8.6)		8.0 - 10.1 (8.7)
Spring					
Surface	7.2 - 14.2 (9.7)	7.5 - 12.9 (9.6)	7.7 - 10.7 (9.6)	7.9 - 12.9 (9.6)	7.8 - 17.7 (10.2)
Mid	7.2 - 12.9 (8.7)	7.6 - 11.8 (9.0)	7.7 - 9.5 (8.7)	7.7 - 9.8 (8.6)	7.7 - 13.4 (8.5)
Bottom	8.0 - 10.2 (8.5)	7.7 - 8.9 (8.5)	7.7 - 9.2 (8.6)		7.7 - 8.9 (8.1)
Summer					
Surface	10.6 - 20.7 (15.2)	12.4 - 16.9 (15.1)	12.7 - 16.5 (14.9)	15.1 - 20.6 (17.7)	13.6 - 20.9 (16.4)
Mid	9.2 - 13.9 (10.8)	10.3 - 15.8 (13.1)	12.1 - 15.2 (13.8)	14.4 - 16.0 (15.1)	7.9 - 16.2 (11.5)
Bottom	9.2 - 10.3 (9.9)	10.3 - 11.9 (11.5)	11.7 - 13.9 (13.1)		7.9 - 8.6 (8.1)
Fall					
Surface	7.6 - 16.8 (11.3)	10.4 - 13.8 (11.5)	8.5 - 15.2 (11.6)	8.2 - 13.7 (11.2)	8.0 - 15.9 (12.3)
Mid	8.1 - 13.4 (10.6)	10.4 - 13.5 (11.3)	9.5 - 15.6 (11.4)	9.9 - 13.2 (11.2)	8.3 - 13.9 (11.8)
Bottom	9.3 - 10.9 (10.3)	10.4 - 13.2 (11.0)	9.5 - 12.0 (11.1)		8.1 - 10.1 (8.6)

3.3.2 Salinity

The average global ocean salinity is 35, while salinity in Burrard Inlet typically ranges between 15 and 30 (Table 5), where the upper limit is closer to the salinity of Strait of Georgia.

Seasonal salinity trends in Outer Harbour are usually different from the other sub-basins because of the impacts from the Fraser River plume. This plume occasionally enters through the First Narrows during favourable winds and tide conditions and can in some cases also affect Inner Harbour salinity. In winter, a decrease in freshwater from the Fraser River and an intensified mixing by winter winds leads to comparably higher salinities in Outer Harbour (Thomson, 1981), which was observed during the TWN cruises (Table 5). During freshet, the salinity in Outer Harbour decrease, usually reaching the lowest levels in the beginning of summer. In other sub-basins, where local streams have a higher impact on water quality, the lowest surface salinities are generally observed during fall, winter, and spring, coinciding with the highest rainfall, while summer salinities are usually higher due to reduced rainfall. Surface salinities increase towards the seaward entrance of Burrard Inlet, with Inner and Outer Harbour becoming increasingly salty because of their exchange with water from the Strait of Georgia (Table 5). Surface salinities in Indian Arm in all seasons show the largest variations, followed by salinities in the Port Moody sub-basin.

The highest salinities are observed at the bottom layer of all sub-basins, with the highest salinities generally occurring in Outer Harbour, where bottom salinities can reach 30 or more during all seasons (Table 5). Salinities generally show low variations in the deep waters of all sub-basins. The Port Moody sub-basin shows relatively narrow ranges in salinity throughout the water column, because of its shallow depth and well mixed waters.

Long-term, deep-water salinity data from Indian Arm were collected annually by DFO between 1951 and 2000 (DFO, 2009). The long time series of data allowed for calculations of anomalies, defined as the departure of the annually averaged deep-water property (e.g., salinity, temperature, DO) from the mean of the time series. For Indian Arm, salinity did not show an overall trend or anomalies over the almost 50-year span in DFO data. The deep-water renewal cycle in Indian Arm is quasi-periodic and the long-term data series have revealed a saw-tooth renewal cycle with relatively high deep-water salinity at times of renewal, followed by one to three years of decline in salinity (also shown in Figure FFigure F). Recorded minimum and maximum salinities were approximately 26 and 28.5, respectively, at depths between 100 and 300 m.

Another long-term DFO data collection of daily sea surface salinity observations has been performed at Departure Bay (shown in Figure E), outside Burrard Inlet in the Strait of Georgia, since 1914 (DFO, 2021). The long-term data series of monthly averages show that surface salinities at Departure Bay have generally decreased from September through June and increased in July and August. The changes are generally very small, less than ±0.02 per year, with the largest changes observed for the months March through May.

In Burrard Inlet, where the natural salinity is > 13.5, BC's working WQGs prescribe that the 24-hour change in salinity should not exceed 4, and that the long-term change in concentration (NaCl or equivalent) should not exceed ± 10%. Salinity monitoring in Burrard Inlet has not been designed to detect short-term changes (within 24 h) and the existing data (Table 5) cannot be assessed using the short-term working WQGs.

Table 5. Seasonal ranges (averages) of surface, mid depth, and deep-water salinity (no unit) in Burrard Inlet sub-basins. Data collected by TWN cruises in 2018-2020. Data is categorized by season: Winter (December to February), Spring (March to May), Summer (June to August), and Fall (September to November). Depth delineations are defined in Table 3.

Depth Layer	Outer Harbour	Inner Harbour	Central Harbour	Port Moody	Indian Arm
Winter					
Surface	20.6 - 29.8 (26.8)	22.7 - 27.8 (25.8)	1.7 - 27.3 (23.1)	15.2 - 26.5 (23.4)	3.0 - 27.1 (21.2)
Mid	23.1 - 30.6 (29.6)	22.8 - 29.5 (26.8)	22.2 - 27.6 (26.0)	21.9 - 27.1 (25.2)	20.3 - 27.5 (26.8)
Bottom	29.9 - 30.8 (30.4)	27.4 - 29.1 (28.3)	22.8 - 27.8 (26.5)		26.9 - 27.6 (27.3)
Spring					
Surface	16.9 - 29.3 (25.3)	23.3 - 28.2 (26.8)	23.7 - 27.2 (25.6)	21.3 - 26.8 (25.2)	5.9 - 27.3 (24.1)
Mid	24.9 - 30.4 (29.7)	25.8 - 29.1 (27.9)	26.3 - 27.8 (27.1)	25.8 - 27.3 (26.6)	24.7 - 28.0 (27.3)
Bottom	30.1 - 30.5 (30.2)	28.6 - 29.3 (29.0)	26.7 - 27.9 (27.4)		27.6 - 27.9 (27.7)
Summer					
Surface	11.0 - 29.2 (21.7)	20.1 - 26.1 (23.5)	22.0 - 26.2 (24.5)	21.3 - 26.1 (24.0)	17.4 - 26.1 (23.8)
Mid	25.8 - 30.4 (29.5)	23.4 - 29.1 (26.5)	23.2 - 26.8 (25.2)	23.0 - 25.8 (25.3)	22.5 - 27.6 (26.3)
Bottom	29.9 - 30.5 (30.3)	28.0 - 29.2 (28.9)	25.6 - 26.9 (26.4)		27.4 - 27.7 (27.6)
Fall					
Surface	18.2 - 29.0 (25.0)	22.9 - 28.1 (26.2)	19.0 - 26.9 (25.3)	18.2 - 26.4 (23.8)	10.8 - 26.8 (23.4)
Mid	24.1 - 30.5 (29.3)	23.2 - 29.0 (27.1)	25.2 - 27.1 (26.3)	24.4 - 26.9 (25.8)	20.3 - 27.4 (26.6)
Bottom	26.2 - 30.8 (29.9)	27.6 - 29.1 (28.3)	25.8 - 27.2 (26.7)		27.0 - 27.6 (27.5)

3.3.3 Dissolved Oxygen

Burrard Inlet is generally characterized by a relatively high DO content. Surface DO concentrations reach a peak in spring in all sub-basins, after which DO declines over the year, with the lowest surface DO concentrations usually found in fall (Table 6). The high DO concentrations observed during the productive seasons (spring and summer) are due to high oxygen production by phytoplankton through photosynthesis. As marine production increases in spring and summer, respiration also increases, leading to consumption of DO. Increasing water temperatures during summer also leads to decreasing DO levels, due to lower gas solubility and increased rate of decomposition of organic matter. In all Burrard Inlet sub-basins, peak and average DO concentrations are generally lower during summer than in spring (Table 6).

Production during spring can lead to surface oxygen concentrations as high as 15 mg/L in Indian Arm and Port Moody, followed by 14 mg/L in Outer Harbour and 13 mg/L in Central Harbour (Table 6). However, primary production is not only affecting surface waters, as the highest DO levels are observed at all depths in all sub-basins during spring except for the waters of Inner Harbour, which have the lowest surface DO levels among all sub-basins in spring. In summer, the lowest surface oxygen concentrations are observed in Central Harbour and Port Moody, which may be due to high water temperatures (Port Moody, Table 5) and/or oxygen-demanding activities, combined with lower oxygenation through winds (both sub-basins). In fall and winter, surface oxygen levels show relatively low variations between sub-basins, although higher oxygenation through winds may explain the comparatively higher DO concentrations in Outer Harbour.

DO concentration decreases with depth due to limited light to support photosynthesis and lower oxygenation through winds and tides. At the same time, oxygen is removed from deeper waters through respiration of organisms, and the decomposition of organic material by bacteria. Decomposition is assumed to account for decreasing deep-water DO concentrations from May through November. Oxygen minimums usually occur in October when the high productivity season ends (Davidson, 1979). In the following months, physical processes account for the observed changes in deep-water DO levels. The lowest DO levels are found in Indian Arm and Outer Harbour, the deepest sub-basin of Burrard Inlet, during fall (Table 6). Hypoxic conditions are reached in both the mid- and bottom layers of Indian Arm during fall and winter, and in spring near-hypoxic conditions are observed.

During the long-term (1951-2000) DFO water monitoring in Indian Arm, very low DO concentrations were observed at times, although with no corresponding time trend (DFO, 2009). DFO oxygen observations varied greatly between 0 and 6.5 mg/L at depths exceeding 100 m, which was also observed during the TWN cruises (Table 6). The greatest deep-water DO levels were observed at time of renewal, followed by a rapid decrease to near-zero concentrations, i.e., anoxic conditions. Another study of deep-water renewal in Indian Arm found higher DO levels at shallow depths before renewal occurred, while DO levels were higher at deeper depths right after renewal occurred, showing that low-oxygen water was displaced upwards by the inflow of cold, oxygen-rich water (Young and Pond, 1988). Surrounding areas such as the waters of Strait of Georgia and Puget Sound have also shown a declining trend in DO concentrations between 2010-2019 and 2000-2019, respectively (US EPA, 2017).

DO concentrations below the 5 mg/L minimum instantaneous benchmark for protection of all life stages other than buried embryo/alevin (BC ENV, 2023) were observed during the TWN cruises in Indian Arm and Outer Harbour during all seasons (Table 6). Concentrations below this benchmark were generally observed in the mid- and bottom layers of these sub-basins, although surface concentrations in Indian Arm in fall and winter occasionally fall below 5 mg/L. In Port Moody, Central Harbour, and Inner Harbour, concentrations below this benchmark were not observed during TWN cruises. The long-term benchmark (30-day mean) of 8 mg/L (BC ENV, 2023) was met in the surface waters of all sub-basins in Burrard Inlet during spring and summer (Table 6). In deeper layers during spring and summer and in all layers during fall and winter, average concentrations typically fell below 8 mg/L in all sub-basins, with some exceptions.

Table 6. Seasonal ranges (averages) of surface, mid depth, and deep-water DO concentration (mg/L) in Burrard Inlet sub-basins. Data collected during TWN cruises in 2018-2020. Data is categorized by season: Winter (December to February), Spring (March to May), Summer (June to August), and Fall (September to November). Depth delineations are defined in Table 3.

Depth Layer	Outer Harbour	Inner Harbour	Central Harbour	Port Moody	Indian Arm
Winter					
Surface	5.9 - 8.6 (7.4)	5.4 - 7.7 (7.1)	5.9 - 8.5 (7.2)	5.7 - 8.6 (7.1)	4.8 - 11 (7.2)
Mid	4.3 - 7.6 (6.1)	5.3 - 7.7 (6.8)	5.6 - 7.8 (6.7)	5.0 - 7.4 (6.3)	2.6 - 7.8 (4.9)
Bottom	4.3 - 6.8 (5.7)	5.6 - 7.4 (6.7)	5.5 - 7.5 (6.5)		2.0 - 6.1 (3.6)
Spring					
Surface	5.9 - 14 (9.1)	7.4 - 10 (8.8)	9.2 - 13 (11)	8.3 - 15 (12)	7.4 - 15 (12)
Mid	3.9 - 11 (6.8)	6.6 - 9.7 (8.1)	7.9 - 11 (9.2)	7.9 - 12.7 (11)	3.1 - 14 (7.5)
Bottom	3.8 - 6.7 (6.2)	6.8 - 8.4 (7.2)	7.6 - 9.4 (8.3)		3.0 - 7.6 (5.8)
Summer					
Surface	6.7 - 12 (9.1)	7.4 - 10 (8.4)	7.7 - 8.8 (8.1)	7.1 - 9.0 (8.2)	7.9 - 12 (9.9)
Mid	4.8 - 8.7 (6.5)	6.0 - 9.6 (7.3)	6.8 - 8.6 (7.5)	6.0 - 8.0 (7.3)	3.7 - 12 (6.8)
Bottom	4.6 - 5.8 (5.4)	5.6 - 7.2 (6.2)	6.5 - 7.6 (7.0)		4.4 - 5.7 (5.8)
Fall					
Surface	5.6 - 8.9 (7.1)	5.8 - 7.1 (6.2)	5.7 - 7.2 (6.4)	5.2 - 9.7 (7.0)	4.1 - 10 (6.7)
Mid	4.0 - 7.4 (5.0)	5.4 - 6.7 (5.9)	5.4 - 6.9 (6.0)	4.6 - 7.3 (5.7)	2.7 - 7.8 (4.7)
Bottom	3.9 - 5.0 (4.3)	5.2 - 6.0 (5.7)	5.4 - 6.2 (5.9)		2.2 - 4.7 (3.6)

3.3.4 pH

pH was not monitored during the TWN cruises, but data have been collected from Burrard Inlet in other monitoring programs. Existing pH data from the Inlet are very limited, however. Existing pH data were found through www.waterproperties.ca, managed by the Ocean Sciences Division (OSD) of DFO in Sidney, BC. Among the sub-basins of Burrard Inlet, the Water Properties database only contains pH data collected from Outer Harbour by OSD. During the years 2018 through 2020, DFO performed several programs in Outer Harbour where pH data were collected, including the OSD Winter Cruise, the Strait of Georgia Water Properties Survey, and the Vancouver Harbour Water Properties Survey. Data were collected through CTD casts. During some cruises performed in 2019 at the west end of Outer Harbour, water was collected in bottles in combination with CTD casts. The accuracy of pH data found in the Water Properties database is unknown, and summary data in Table 7 have therefore not been manipulated in any way (e.g., rounded).

Table 7. pH data collected between 2018 and 2020 during DFO monitoring cruises in Outer Harbour.

Location	Number of Cruises (collected in)	Collection Method; Instrumentation	Depths	Reported pH range
Approx. 49.315, -123.174 Just west of First Narrows/Stanley Park	6 cruises (winter, spring, and fall)	CTD (5) and bottle (1); Sea-Bird CTD, SBE-911plus, Rosette sampler	2 – 36 m	7.705 – 8.822
Approx. 49.325, -123.233 North shore of Outer Harbour	5 cruises (winter, spring, and fall)	CTD; Sea-Bird CTD, SBE-911plus	2 – 62 m	7.679 – 8.800
Approx. 49.297, -123.233 North of Spanish Banks	4 cruises (winter and spring)	CTD; Sea-Bird, SBE-911plus	2.5 – 64 m	7.698 – 8.803
Approx. 49.315, -123.265 West end of Outer Harbour	10 cruises (winter, spring, and fall)	CTD (5) and bottles (5); Sea-Bird CTD, SBE-911plus, Rosette sampler	2 – 110 m	8.069 – 8.855

Observed pH ranges in Outer Harbour are above the lower limit of the BC-based benchmark "unrestricted change within 7.0 to 8.7" (BC ENV, 2023), but observations above 8.7 (pH ≤ 8.9) occurred at all monitored locations, with the highest pH levels observed at the westernmost monitoring station (Table 7). At all stations, the highest pH levels were found closer to the water surface. Because of the limited data, estimations of average or median pH levels at different depths was not possible. The marine data within the BC ENV SEAM database had an average pH of 7.8 across BC marine waters (standard deviation at 0.2, based on 434 observations), with minimum and maximum pH at 7.1 and 8.6, respectively (BC ENV, 2021a).

The Washington Water Quality Standard prescribes human-caused variation of pH to range less than ± 0.2 to be classified as water of "extraordinary quality", while other categorisation prescribes changes less than ± 0.5 (DOE, 2021). The existing pH data do not allow for assessing human-caused changes versus natural variations. Human-caused changes are difficult to monitor as they are likely caused by spills and other transient discharges. In addition, human-caused pH changes due to climate change (increased carbon dioxide concentrations) occur over a long time, and because of lack of historical pH data, the potential impacts of climate change on Burrard Inlet pH level are currently unknown.

3.3.5 Total Suspended Solids

Suspended solids were not monitored during the TWN cruises, but surface concentrations of suspended particulate matter (SPM) from the Fraser River plume were estimated at ≤ 10 mg/L (Pawlowicz *et al*., 2017) using satellite imagery, with the highest concentrations near the Inlet entrance. The satellite imagery revealed a narrow tongue of the plume with SPM concentrations around 3 mg/L curving around Point Grey into Burrard Inlet.

3.3.6 Turbidity

Among the sub-basins in Burrard Inlet, turbidity in Outer Harbour is most influenced by the Fraser River. The average surface turbidity levels in Outer Harbour in spring and summer are higher than the fall and winter turbidity levels (Table 8) because the discharge from the Fraser River declines.

In addition to the Fraser River, turbidity in the waters of the Outer, Inner, and Central Harbours is also affected by other freshwater sources, stormwater discharges, combined sewer overflows, industrial effluents, dredging activities, boat wakes, and commercial and recreational anchorages (see maps in Rao *et al.*, 2019). At First Narrows, the Lions Gate Wastewater Treatment Plant outfall may also contribute to turbidity, and the shallow beaches in Outer Harbour may lead to increased turbidity as bottom sediments are re-suspended during tidal changes. In Inner and Central Harbours, higher turbidity levels are generally found in the mid- and bottom layers of the water column (Table 8), likely because of re-suspension of bottom sediments due to freight, recreational and cruise ship movement. At these mid- to bottom depths, other anthropogenic activities like anchoring and anchor dragging can also cause physical disturbances, as can discharges of waste streams at greater depths. Disposal at sea at Point Grey may potentially also affect water quality in sub-basins of Burrard Inlet, specifically in the Outer Harbour.

Commercial boat traffic is expected to have comparably lower effect on turbidity in Indian Arm than Outer and Inner Harbours, due to fewer anchorage sites. The surface waters of Indian Arm show the largest variations in turbidity during periods of high rainfall and runoff, i.e., fall and winter (Table 8). In spring and summer, turbidity is rather homogeneous throughout the entire water column due to lower rainfall and decreased transport of material with runoff. During all seasons, except winter, and at all depths, Indian Arm shows the lowest average turbidity levels of all sub-basins. The maximum turbidity observed in surface waters of Indian Arm in the winter (510 NTU) appears to be an outlier, potentially due to equipment issues or a pulse of river-borne material, as the median turbidity for the season is considerably lower at 0.22 NTU (not shown in Table 8).

Potential turbidity sources in the Port Moody sub-basin are freshwater runoff, stormwater outfalls, dredging, and commercial and recreational boat traffic and anchorages (Rao *et al.*, 2019). In Port Moody, the maximum turbidity levels generally show small fluctuations in all seasons except winter Table 8). In spring and summer, turbidity is homogenous throughout the water column due to the sub-basin's moderate depths (maximum 17 m) and well mixed waters.

Studies performed across the sub-basins of Burrard Inlet from the early 1970s to early 1980s showed turbidity levels ranging from below 1 NTU to 38 NTU (mean value close to 2 NTU), with the highest values found in Port Moody Arm (Nijman and Swain, 1990). Data collected during the TWN cruises show that turbidity levels in Burrard Inlet are generally below 8 NTU, with exceptions in Indian Arm during the fall and winter and Outer Harbour in winter (Table 8). The maximum turbidity reading in Outer Harbour during winter may be an outlier as the average winter turbidity levels are lower than in spring and summer, where the Fraser River is assumed to have a larger effect on turbidity in Outer Harbour. According to BC's approved WQGs (BC ENV, 2021a), "clear water" conditions prevail when suspended sediment concentrations are low below 8 NTU (i.e., < 25 mg/L); hence, the general turbidity conditions found in all sub-basins could be defined as "clear waters" (Table 8). The short- and long-term benchmarks for aquatic life prescribe turbidity changes from the background should be ≤ 8 NTU and ≤ 2 NTU, respectively, in clear waters (BC ENV, 2023). Existing data, collected during the TWN cruises, cannot be assessed against the short-term benchmark as monitoring was not performed with the purpose to measure turbidity changes within a 24 h period. When comparing turbidity data to the long-term benchmark, however, data from Indian Arm (winter and fall), Port Moody (winter), and Outer Harbour (all seasons) show larger variations than the ±2 NTU benchmark (Table 8). With the existing data, it is not possible to determine how much of the variation is due to natural variations versus anthropogenic changes.

Table 8. Seasonal ranges (averages) of surface, mid depth, and deep-water turbidity (NTU) in Burrard Inlet sub-basins. Data collected by TWN cruises in 2018-2020. Data is categorized by season: Winter (December to February), Spring (March to May), Summer (June to August), and Fall (September to November). Depth delineations are defined in Table 3.

Depth Layer	Outer Harbour	Inner Harbour	Central Harbour	Port Moody	Indian Arm
Winter					
Surface	0.4 - 9.6 (1.1)	0.47 - 1.7 (0.97)	0.24 - 1.6 (0.83)	0.50 - 7.8 (2.3)	0.02 – 510* (3.94)
Mid	0.09 - 2.2 (0.72)	0.50 - 1.8 (1.0)	0.3 - 2.5 (0.93)	0.30 - 6.9 (1.5)	0.01 - 1.5 (0.33)
Bottom	0.2 - 1.8 (0.81)	0.50 - 1.8 (1.0)	0.4 - 2.9 (1.2)		0.05 - 1.5 (0.28)
Spring					
Surface	0.78 - 2.7 (1.5)	0.72 - 1.6 (1.1)	0.50 - 1.1 (0.79)	0.80 - 1.2 (1.0)	0.28 - 1.8 (0.82)
Mid	0.17 - 2.3 (0.97)	0.80 - 1.5 (1.2)	0.56 - 1.2 (0.86)	0.80 - 1.2 (1.0)	0.14 - 1.7 (0.48)
Bottom	0.36 - 1.2 (0.73)	1.0 - 1.4 (1.3)	0.70 - 1.2 (1.0)		0.11 - 1.1 (0.22)
Summer					
Surface	0.48 - 3.8 (2.0)	0.56 - 1.5 (1.1)	0.49 - 1.2 (0.74)	0.85 - 1.2 (1.0)	0.17 - 2.0 (0.46)
Mid	0.38 - 3.2 (1.0)	0.56 - 1.4 (1.0)	0.40 - 1.2 (0.75)	0.70 - 1.2 (1.0)	0.05 - 1.2 (0.24)
Bottom	0.36 - 1.3 (0.70)	0.70 - 1.3 (0.93)	0.60 - 1.3 (0.93)		0.14 - 0.46 (0.22)
Fall					
Surface	0.05 - 7.0 (0.83)	0.43 - 1.1 (0.64)	0.20 - 0.90 (0.51)	0.25 - 1.4 (0.54)	0.01 - 31 (0.43)
Mid	0.01 - 2.4 (0.52)	0.40 - 1.5 (0.76)	0.32 - 0.92 (0.59)	0.31 - 1.3 (0.55)	0 - 17 (0.22)
Bottom	0.26 - 2.1 (0.59)	0.60 - 1.5 (1.1)	0.43 - 1.1 (0.74)		0.08 - 0.82 (0.18)
* Assumed outlier as median turbidity in surface water during winter is 0.22 NTU.					

3.4 Knowledge Gaps and Research Needs

- The Salish Sea, including the Strait of Georgia and Strait of Juan de Fuca, is well researched, with data collected through, for example, the Strait of Georgia Ecosystem Research Initiative, the Institute of Ocean Sciences at DFO, by the Pacific Salmon Foundation, and by researchers from UBC's Institute for the Oceans and Fisheries. In comparison, Burrard Inlet is not as well-studied as the Strait of Georgia and Juan de Fuca Strait, and Burrard Inlet is generally only summarily mentioned.
- Among all Burrard Inlet sub-basins, Indian Arm is the most researched. There is, however, insufficient data for all sub-basins to draw conclusions on pre-contact baseline water quality conditions and long-term trends in data. The current work of TWN, DFO and other current conditions program will fill some of these gaps.

- CTD data were not collected from False Creek during the TWN cruises and there is a general lack of physical parameter data from the sub-basin.
- There is a general lack of historical data, with pH and TSS data being the most limited, and analyses of long-term trends in physical parameters, for example effects caused by climate change, have not been possible to perform. The lack of historical and current data also limits the potential to assess baseline conditions from which change can be measured.
- The effects of changes in physical parameters have primarily been studied in freshwater species; the risks for marine species are less known. A particular knowledge gap is the requirements for forage fish embryos.

4. PROPOSED OBJECTIVES FOR PHYSICAL PARAMETERS IN BURRARD INLET

4.1 Proposed Objectives

Proposed WQOs for physical parameters are presented in Table 9.

Table 9: Proposed Water Quality Objectives for physical parameters in marine water

Sub-basin	False Creek	Outer Harbour	Inner Harbour	Central Harbour	Port Moody Arm	Indian Arm
Temperature in Marine Water	No further increase in temperature; the natural temperature cycle[1] characteristic of the site should not be altered in amplitude or frequency by human activities.					
Salinity in Estuarine and Marine Water	No change in concentration (NaCl or equivalent) from the expected natural level[1] at that time and depth					
Dissolved Oxygen in Marine Water[2]	8 mg/L 30-day mean[3] 5 mg/L instantaneous minimum					
pH in Marine Water	7.7 to 8.8[4]					
Total Suspended Solids in Marine Water	No increase from the expected natural levels in the ambient background, defined by best available data[5] as: 10 mg/L					
Turbidity in Marine Water	No increase from the expected natural levels in the ambient background, defined by best available data[5] as: < 1 NTU[6]					

[1] Data are unavailable to conclusively define "natural" levels; until additional information becomes available, monitoring results can be compared to current conditions as described in Table 4 and Table 5. See section 4 for further details. The WQOs are intended to not exacerbate the ongoing effects of climate change.
[2] In cases where natural DO concentrations do not meet the criteria, no statistically significant reduction below natural levels should be permitted.
[3] A mean should be calculated from 5-in-30 sampling (i.e., five samples taken over 30 days).
[4] To be refined when data are available for additional sub-basins and/or more sensitive species.
[5] See Appendix B for details on how background was determined. Although other datasets may exist, the datasets used for determining the background (i.e., data available in ENV's Environmental Monitoring System database) were found to be the 'best available data' within the constraints of the project. As more data becomes available, the background concentration may be revisited.
[6] For comparison to the background, a mean should be calculated from 5-in-30 sampling (i.e., five samples taken over 30 days).

4.2 Rationale

The terms “natural” and “background” are particularly complex with respect to physical parameters. TWN defines background, or baseline, conditions in Tsleil-Waututh territory as conditions prior to European contact (e.g. Taft et al. 2022). According to the protocol for deriving BC Water Quality Guidelines:

> For substances that occur naturally, it can become important to distinguish between the concentration that is due to natural causes (i.e. the natural background concentration) and the concentration that is due, at least in part, to anthropogenic activities. The natural background concentration of naturally occurring substances is a very site-specific matter…. (ENV 2019)

Washington State Water Quality Standards provide the following definition:

> “Natural conditions” or “natural background levels” means surface water quality that was present before any human-caused pollution. When estimating natural conditions in the headwaters of a disturbed watershed it may be necessary to use the less disturbed conditions of a neighboring or similar watershed as a reference condition. (State of Washington 2022)

Levels of marine and estuarine physical parameters can show large natural variations due to factors such as location, season, depth, and climate conditions. In addition, all physical parameters are affected by global climate change, for which local measures may have limited effect. Several of the proposed objectives in Table 9 are therefore expressed relative to expected natural levels in the ambient background, with the intention to limit the negative impacts on physical parameters from local sources. As a result of this approach, specific objectives were not proposed for each sub-basin; however, monitoring results can in some cases be compared to current conditions.

A WQO for water temperature of no increase or alteration is proposed to minimize human-caused impacts on the identified values in Burrard Inlet, in recognition of global climate change. Long-term data collected in deep waters of Indian Arm indicate that the temperature increase from natural ambient background may already have exceeded the BC WQG of ± 1°C (DFO, 2009). Some degree of continued warming due to global climate change will occur and is dependant on the degree and response of global action. In an attempt to keep the rate of warming to a minimum in Burrard Inlet, local anthropogenic effects on water temperature should be eliminated. To identify trends in temperature, long time series of data are required and are currently missing for most waters of Burrard Inlet.

The WQO proposed for salinity is consistent with the approach to the WQO for temperature, in that natural concentrations should not be further altered by human activities. Long time data series are required to identify trends in salinity and are currently missing for Burrard Inlet.

The WQOs for DO are proposed to be consistent with the most conservative of the BC approved WQGs for DO, for the protection of marine aquatic life (BC ENV, 2023) as the guidelines are believed to be protective of species and life stages found in Burrard Inlet for which data are available. Existing data (Table 6) show that DO concentrations in the waters of Burrard Inlet repeatedly fall below the proposed WQOs (8 mg/L 30-day mean and 5 mg/L instantaneous minimum). In cases where natural DO concentrations do not meet the criteria, no statistically significant reduction below natural levels should be permitted (BC Ministry of Environment Lands and Parks, 1997).

The BC approved WQG for pH for the protection of marine aquatic life (BC ENV, 2023) of unrestricted change between 7.0-8.7 is based on observed effects on the most sensitive species, molluscan larvae. This WQG is not proposed as the WQO for Burrard Inlet for three reasons: 1) monitoring of current conditions in Outer Harbour indicate that pH in Burrard Inlet may range from 7.7 to 8.8 (Table 7), 2) measured pH in a less impacted reference area (Desolation Sound) has ranged from 8.2 to 8.3 (BWP and ENV, 2005a) and 3) ocean acidification is a globally recognized anthropogenic phenomenon (e.g., UNESCO, 2021). The allowable range may be refined when ambient pH ranges have been determined in all sub-basins of Burrard Inlet, and when there is more information about the impacts of changes in pH on marine aquatic life.

The BC approved WQGs for TSS and turbidity (BC ENV, 2023) were not adopted as WQOs for Burrard Inlet because of the historical and ongoing cumulative anthropogenic impacts on Burrard Inlet including, among others, provincially authorized discharges into Burrard Inlet. Existing turbidity data from Burrard Inlet sub-basins indicate that the maximum allowed increase as per the BC WQGs has been exceeded at times (Table 8), although it is not known whether the changes are natural variations or caused by point sources. The proposed TSS and turbidity WQOs (no increase from the expected natural levels in the ambient background, defined by best available data for TSS as: 10 mg/L and < 1 NTU for turbidity), reflect the guiding principles of protecting water values, rather than allowing impact (Rao *et al*., 2019). This conservative approach does not allow for further change and decline in water quality as such changes would not support the overall goal of the Burrard Inlet Action Plan. A similar approach has been applied by the Government of Alaska, which indicates no measurable increase in concentrations above natural conditions (Alaska, 1979).

The background levels for TSS and turbidity are based on an analysis of current condition data available in ENV's Environmental Monitoring System (EMS) database from 1985-1995 for TSS and turbidity in Burrard Inlet. Details are provided in Appendix B. The ENV datasets were considered 'best available data' within the constraints of the project because of adequate sample counts (736 sample points for TSS and 415 for turbidity), and due to consistency in the individuals/organization conducting the sampling, locations of the monitoring, and presence of no large spatial or temporal gaps. It is proposed to use these WQOs until more information becomes available about the acute and chronic levels of turbidity or TSS that would impact the most sensitive aquatic species; literature on this is currently limited.

5. MONITORING RECOMMENDATIONS

Monitoring recommendations help refine existing monitoring programs and inform future assessments to determine whether the objectives for physical parameters are attained. Continuous funding to carry out the recommended monitoring activities listed below is one of the most important aspects of gaining consistent and reliable monitoring data over time. The following are recommendations for future physical parameter monitoring in Burrard Inlet:

- Continue the TWN cruises to collect high resolution physical parameter data across all sub-basins of Burrard Inlet. Include False Creek in the monitoring program as well as monitoring of pH and TSS in all sub-basins and at a range of depths.
- Continue other ongoing monitoring programs, e.g., performed by DFO, to build on the existing database and allow for establishing ambient background levels of physical parameters as well as assessment of trends over time.
- Monitor around known discharge points, e.g., industrial discharges, wastewater discharges, stormwater outfalls, marinas, and anchorages, where transient and/or local changes in physical

parameters may occur[9]. In addition, require increased compliance with discharge permits and improve enforcement of non-compliances.

- Monitor at a frequency sufficient to record patterns of ambient diurnal and human-induced variations, to allow for attainment monitoring of WQOs that prescribe a maximum human-caused change in physical parameters, as well as allowable hourly or daily changes.
- Increase our understanding of potential adverse effects on marine biota occurring in Burrard Inlet by conducting long-term toxicity assessments using environmentally relevant levels of physical parameters.
- Further study the effects of cumulative current and future ship/boat wakes in combination with propeller-induced jets and their effects on sediment resuspension.

6. MANAGEMENT OPTIONS

Variations in physical parameters in Burrard Inlet are, to a considerable extent, natural or caused by a changing climate that is a result of global anthropogenic factors. External factors cannot be fully managed on a local or regional level; however, physical parameters are also affected by local activities, such as wastewater and stormwater discharges, industrial effluents, dredging, disposal at sea, anchorage, and boat traffic, which can be managed to mitigate and reduce their impacts.

The following are recommendations to reduce the anthropogenic impacts on physical parameters in Burrard Inlet:

- Implement stormwater management in urban areas to mitigate surface runoff, erosion and flooding. Stormwater discharge transports material from land to water, such as acidic sediments, nutrients, and solids from land, that may affect physical parameters. Increased vegetative cover and enhanced stormwater infiltration may reduce the water temperature of stormwater as well as reduce peak flows of stormwater, leading to reduced erosion and hence reduced TSS and turbidity concentrations in receiving waters.
- Remove unneeded dams and impoundments to keep waters that flow into Burrard Inlet from heating up during the summer months. During the replacement of any critical dam infrastructure, alternative solutions or technological improvements need to be assessed to reduce the water temperatures prior to reaching the Inlet.
- Improve sanitary and industrial wastewater treatment to further reduce levels of organic material and hence, biological oxygen demand[10] and nutrients that may reduce DO levels in wastewater released into Burrard Inlet.
- Limit or mitigate industrial discharges that may lead to increased water temperature, pH changes, reduced oxygen, or increased turbidity.
- Reduce vessel wakes to decrease the effects of sediment re-suspension, and possible remobilization of solids into the water column.
- Evaluate all dredging and in-water construction activities with the purpose of avoiding or limiting harmful impacts. Ensure adequate compliance and enforcement to mitigate sediment

[9] Many of the discharge points are presented in the maps associated with Rao et al. (2019), and also viewable in the interactive map, produced by TWN in 2022, [Selected Impacts of Colonial Development in Burrard Inlet](https://twn.maps.arcgis.com/apps/webappviewer/index.html?id=3fc2979e988e429eae1a5ff0a91d6ae6#): https://twn.maps.arcgis.com/apps/webappviewer/index.html?id=3fc2979e988e429eae1a5ff0a91d6ae6#

[10] Biological oxygen demand (BOD) is a measure of the amount of oxygen required by aerobic bacteria to decompose organic matter from water. Sanitary wastewater typically contains high BOD levels, and therefore requires large amounts of oxygen to decompose.

plumes to the extent possible during dredging and construction to reduce TSS and turbidity concentrations.

- The ocean's potential to mitigate climate change is often overlooked. Protecting and restoring ocean habitats such as eelgrass and salt marshes in Burrard Inlet, as well as their associated food webs, can sequester carbon dioxide from the atmosphere.
- Enforce the federal Fisheries Act to regulate stormwater discharges. Under the Act, discharge of deleterious substances is prohibited, unless specifically authorized. Stormwater that would negatively impact fish and their habitat can be considered a deleterious substance.

The following initiatives that address physical water quality parameters are already in progress:

- Develop and implement Integrated Stormwater Management Plans (ISMPs) for all developed watersheds that flow into Burrard Inlet. The ISMPs address erosion, drainage, flooding, stream health and remediation of any potential water quality issues within watersheds.
- Metro Vancouver is currently building the North Shore Wastewater Treatment Plant, a new treatment facility that will provide tertiary treatment and improve the quality of the treated wastewater released into the Burrard Inlet. Decommissioning the existing Lions Gate Wastewater Treatment Plant, currently providing primary treatment, will begin in the mid-2020s.

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APPENDIX A: CTD PLOTS – TWN CRUISES

Data collected during the TWN cruises were prepared and summarized by DFO staff and are shown in the CTD plots, Figures A1 to A5. For each sub-basin, seasonal ranges and means are presented for the parameters salinity (no unit), oxygen saturation (%), temperature (°C) and turbidity (NTU). Note that the monitored water depth ranges differ between sub-basins. During the cruises, water quality was measured continuously throughout the water column, from the water surface to approximately 3 m above the seafloor.

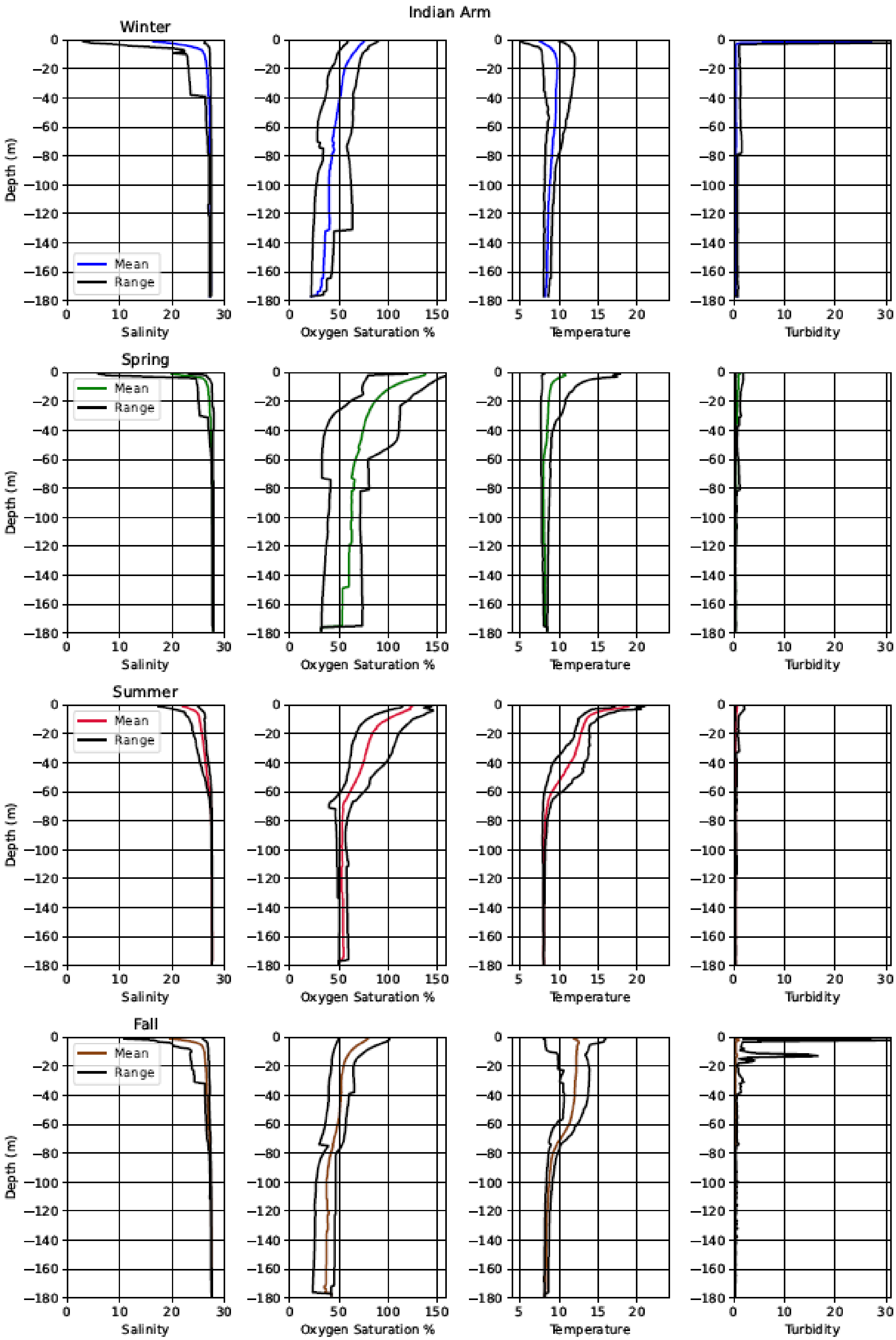

Figure A1. Seasonal ranges (black lines) and means (coloured lines) of salinity (-), oxygen saturation (%), temperature (°C) and turbidity (NTU) at different depths in Indian Arm.

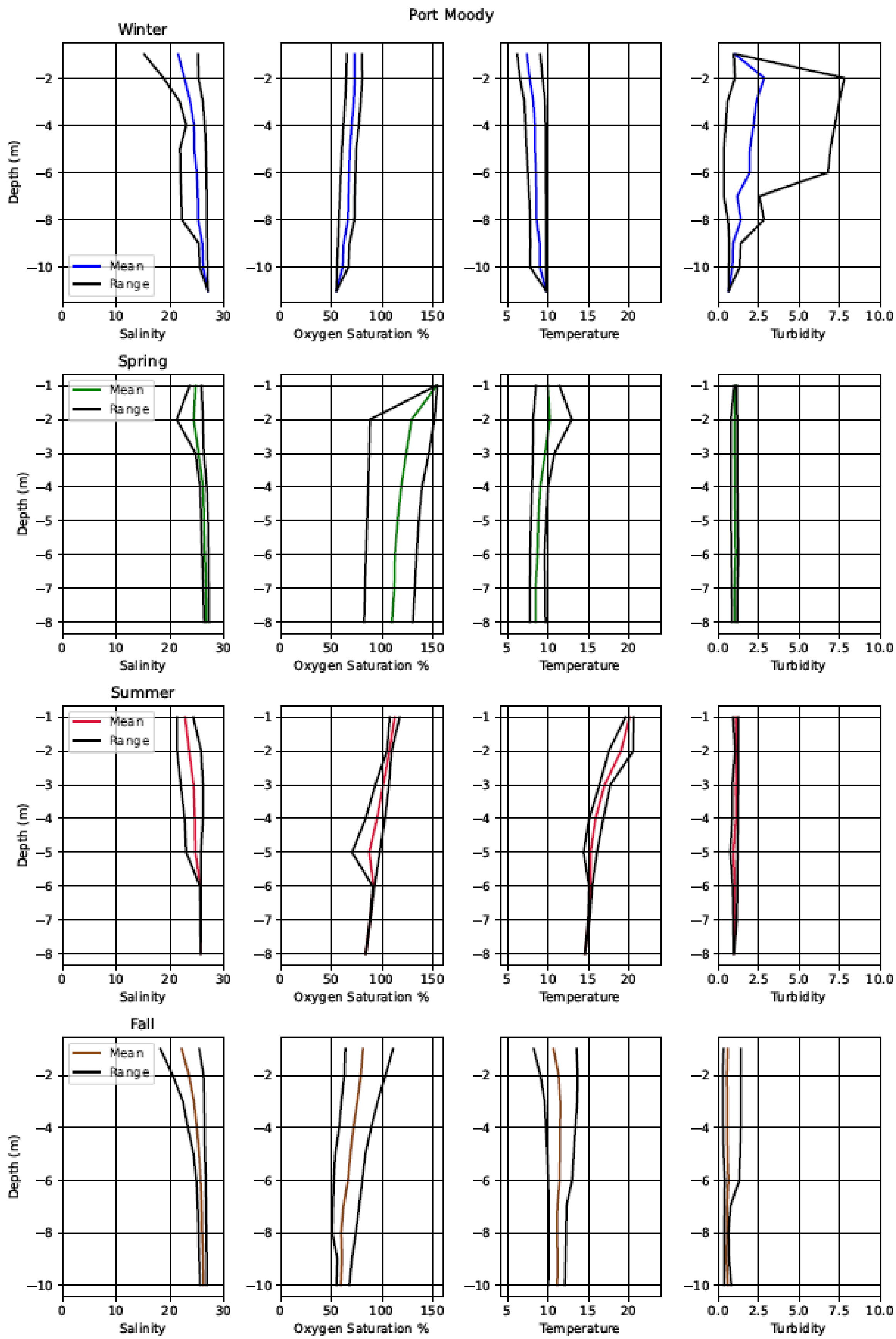

Figure A2. Seasonal ranges (black lines) and means (coloured lines) of salinity (-), oxygen saturation (%), temperature (°C) and turbidity (NTU) at different depths in Port Moody Arm.

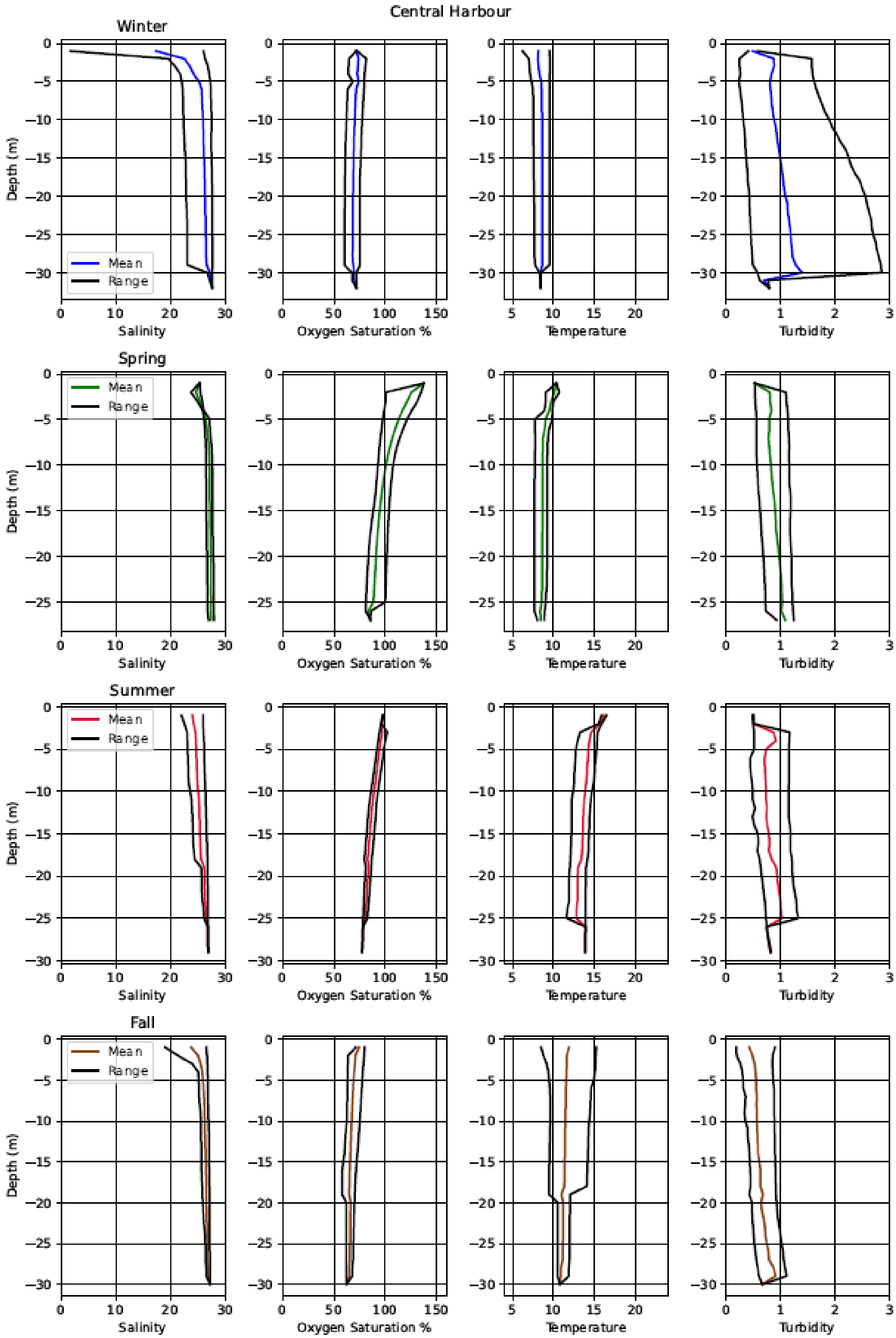

Figure A3. Seasonal ranges (black lines) and means (coloured lines) of salinity (-), oxygen saturation (%), temperature (°C) and turbidity (NTU) at different depths in Central Harbour.

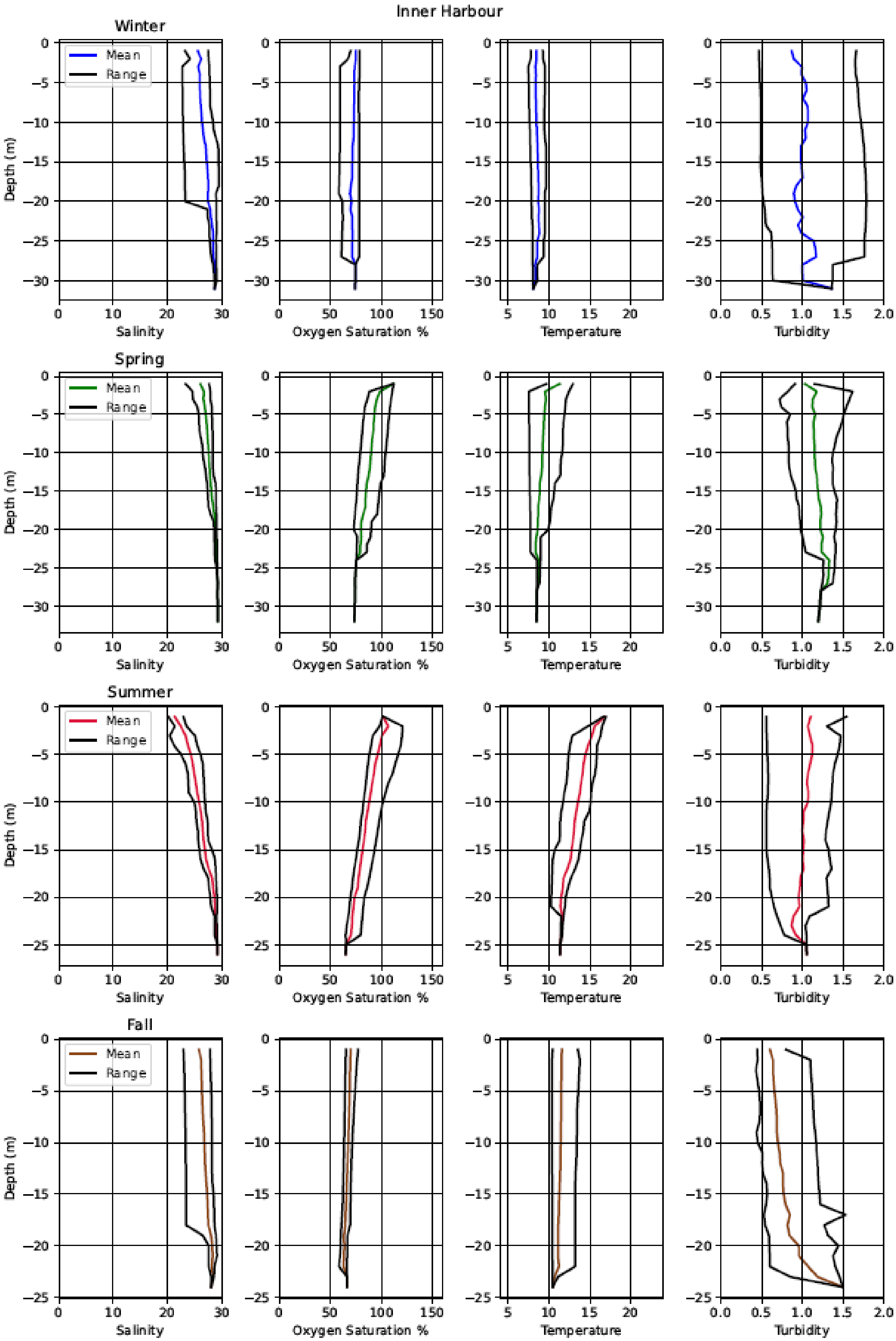

Figure A4. Seasonal ranges (black lines) and means (coloured lines) of salinity (-), oxygen saturation (%), temperature (°C) and turbidity (NTU) at different depths in Inner Harbour.

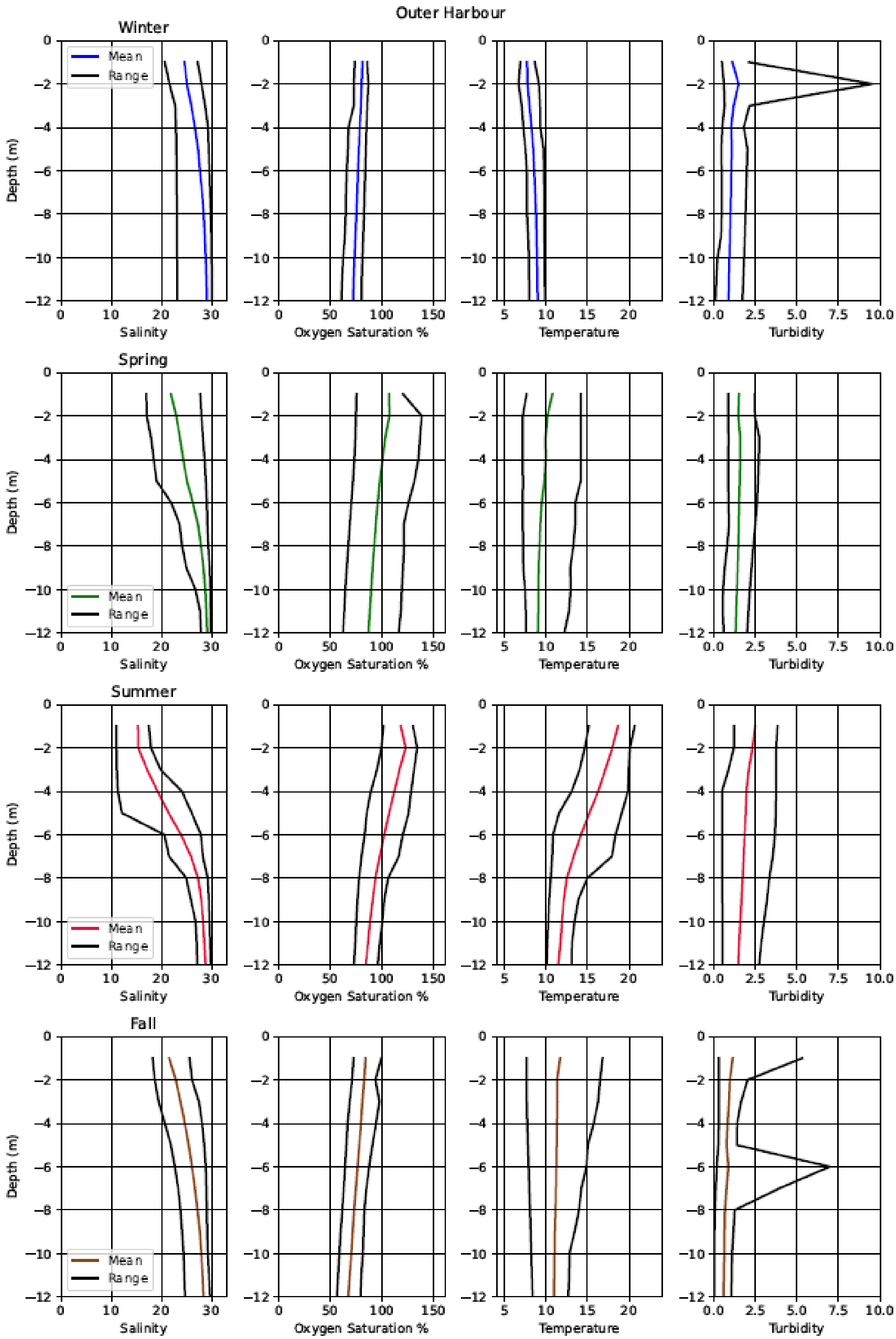

Figure A5. Seasonal ranges (black lines) and means (coloured lines) of salinity (-), oxygen saturation (%), temperature (°C) and turbidity (NTU) at different depths in Outer Harbour.

APPENDIX B: DERIVATION OF BACKGROUND CONCENTRATIONS FOR TSS AND TURBIDITY

Defining background concentrations for TSS and turbidity in Burrard Inlet is challenging; the majority of the Inlet is influenced by input sources that have the potential to impact these parameters. Additionally, consideration should be given to the natural fluctuations of these parameters in marine waters due to tides, wave action, currents, and algal blooms. Thus, available historical data for TSS and turbidity in the Burrard Inlet was assessed for appropriateness to be applied as the background concentration for these parameters.

An ambient dataset with adequate sample counts for TSS and turbidity is available in ENV's Environmental Monitoring System (EMS) database for all sub-basins of the Burrard Inlet from 1974 to present. A 10-year subset from 1985 to 1995 was selected for this assessment due to consistency in the individuals conducting the sampling, locations of the monitoring, and presence of no large spatial or temporal gaps. Note that the EMS data have not be categorized based on sample collection depth as this information is not available.

Total Suspended Solids

The average TSS concentration from 1985 to 1995 for the entire Burrard Inlet was 9.6 mg/L (Table B1). Average TSS in the six sub-basins of the Burrard Inlet ranged from 7.8 mg/L in Indian Arm to 10.4 mg/L in Inner Harbour but did not significantly differ from each other (i.e., TSS did not vary significantly based on sub-basin) (ANOVA; F_5=1.88; p=0.096).

Table B1. TSS (mg/L) for Burrard Inlet by sub-basin for the years 1985 to 1995.

Sub-basin	Min	Max	Average with standard deviation	Sample Count
Indian Arm	1	36	7.8 ± 6.5	44
Port Moody	2	43	10.2 ± 7.6	108
Central Harbour	1	35	9.2 ± 6.2	141
Inner Harbour	1	39	10.4 ± 7.4	236
Outer Harbour	2	31	9.2 ± 5.3	103
False Creek	2	27	8.9 ± 5.5	104
Entire Burrard Inlet	**1**	**43**	**9.6 ± 6.7**	**736**

TSS often varies due to seasonal variations in rainfall or stream inputs (e.g., TSS is often high during freshet). To examine potential seasonal differences in TSS, data were grouped by Winter (December to February), Spring (March to May), Summer (June to August), and Fall (September to November). TSS varied slightly among seasons, with averages for the entire Burrard Inlet ranging from 8.9 mg/L in the fall to 10.4 mg/L in the spring (Table B2) but did not significantly differ from each other (ANOVA; F_5=2.36; p=0.070).

Table B2. TSS (mg/L) Burrard Inlet average concentrations from 1985 to 1995.

Sub-basin	Winter	Spring	Summer	Fall
Indian Arm	6.6	8.9	8.5	7.1
Port Moody	8.4	10.2	11.9	10.6
Central Harbour	8.4	9.6	12	7.4
Inner Harbour	9.7	13	9.0	8.7
Outer Harbour	9.2	8.2	8.8	10.5
False Creek	10.4	8.6	7.9	8.6
Entire Burrard Inlet	**9.0**	**10.4**	**9.9**	**8.9**

Additionally, to determine if TSS varied with depth, the available data was graphed after removing TSS results that were at surface level (i.e., 0 m) (Figure B1). A decreasing trend was not observed until below 15 m and no distinct pattern was observed for shallower results; therefore, depth was not considered further.

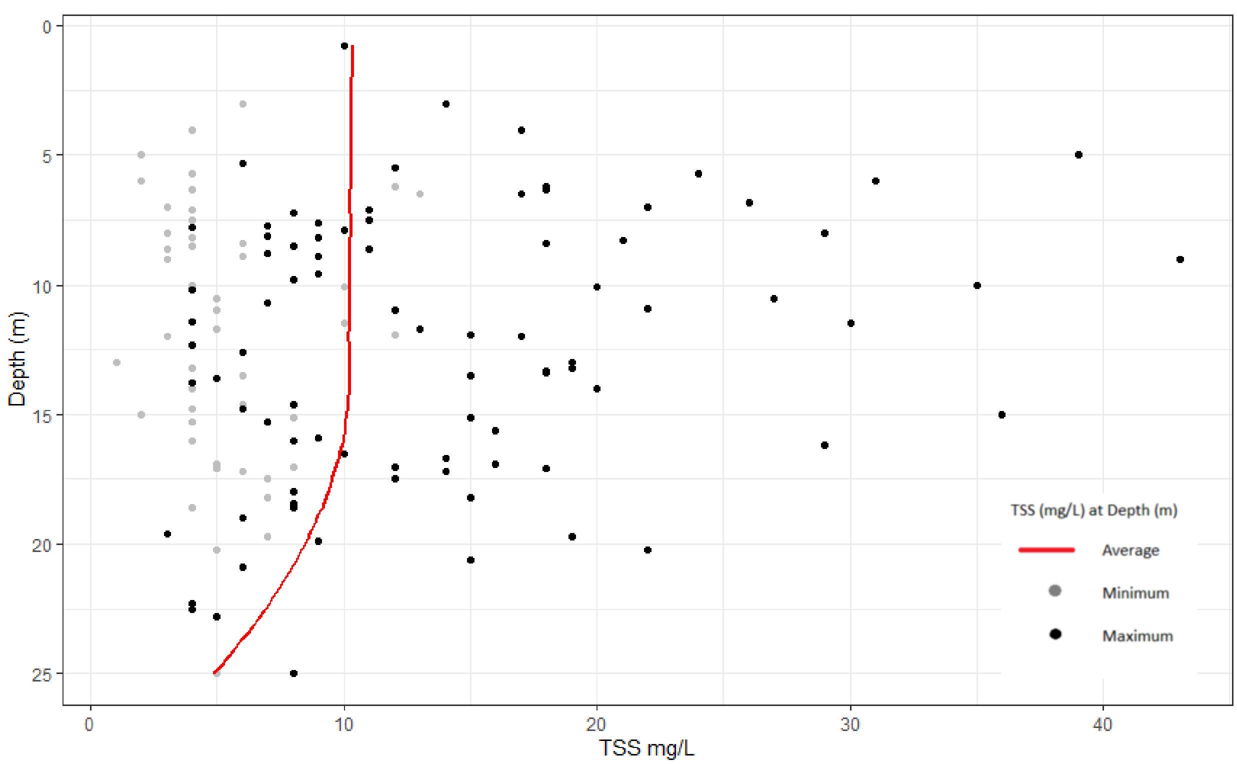

Figure B1. TSS (mg/L) and depth (m) in Burrard Inlet from 1985-1995. No distinct pattern was observed.

To be useful for estimating a background concentration the data should not have an upward or downward trend through time. A Mann-Kendall[11] Test was used to identify if any of the sub-basins

[11] A Seasonal Kendall test was not applied as the data did not have a consistent frequency for each season per year.

showed a temporal trend. No sub-basin showed an upward or downward trend in TSS concentration from 1985 to 1995 (Figure B2).

In summary, TSS in Burrard Inlet did not vary significantly by sub-basin or season. In addition, no temporal trend in TSS concentration was found in any of the sub-basins. This supports applying a single TSS concentration derived by an average across the entire inlet and all seasons. This yields a background concentration of 9.6 mg/L, which for ease of application is rounded up to 10 mg/L.

Use of a nearby less-impacted waterbody can also be applied to determine background levels (ENV, 2021e; State of Washington, 2022; USEPA, 2003). The nearby waterbodies of Desolation Sound and Okeover Inlet are less developed than Burrard Inlet and comparing the TSS in these waterbodies to Burrard Inlet can help to see if the derived background concentration of 10 mg/L is much different from a less developed condition.

TSS data collected in Desolation Sound and Okeover Inlet in July 2002 and 2003 are available in EMS (BWP and ENV, 2005ab). TSS results for Desolation Sound/Okeover Inlet ranged from 1 to 15 mg/L (Table B3). While the Desolation Sound/Okeover Inlet dataset was limited to two sampling events in July 2002 and 2003, the average results of the Burrard Inlet summer data (9.9 mg/L) and the proposed background concentrations (10 mg/L) are both within the range of the Okeover Inlet data (Figure B3).

Although the Burrard Inlet TSS data from 1985 to 1995 was captured in a time when Burrard Inlet was already developed, the similarity of this data to the minimally developed Desolation Sound/Okeover Inlet supports the use of the historical Burrard Inlet data to define a background concentration for TSS.

In conclusion, a background TSS concentration of 10 mg/L is considered appropriate for Burrard Inlet.

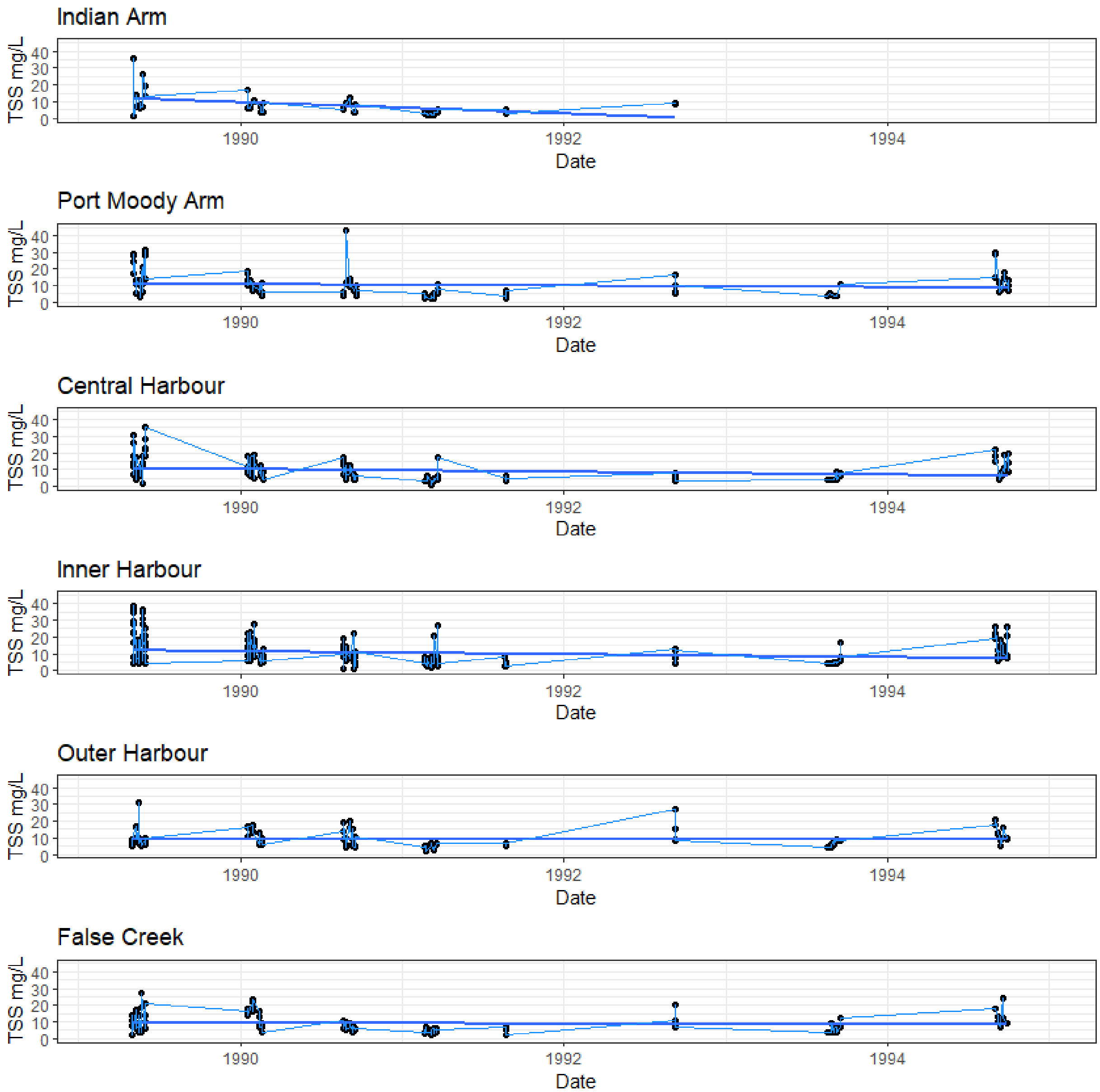

Figure B2. TSS (mg/L) for each sub-basin in the Burrard Inlet from 1985-1995. No significant temporal trends were observed.

Table B3. TSS (mg/L) for Desolation Sound/Okeover Inlet in July 2002/03 and Burrard Inlet summer results for the years 1985 to 1995.

Waterbody	Min	Max	Average with standard deviation	Count
Desolation Sound	1	9	5.5 ± 2.4	26
Okeover Inlet	3	15	7.8 ± 3.2	18
Overall	**1**	**15**	**6.5 ± 3.0**	**44**
Burrard Inlet (Summer)	1	43	9.9 ± 7.6	129

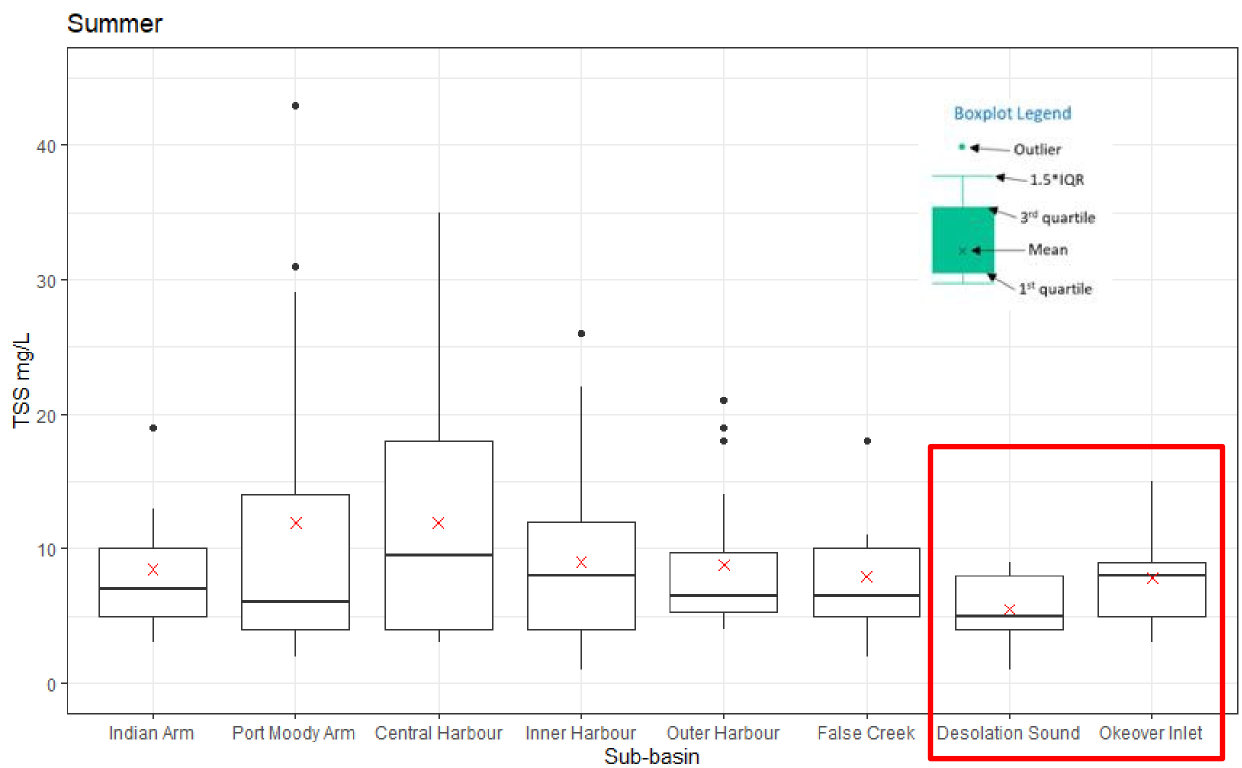

Figure B3. TSS in summer for Burrard Inlet sub-basins and Desolation Sound/Okeover Inlet.

Turbidity

Average turbidity from 1985 to 1995 for the entire Burrard Inlet was 1.2 NTU (Table B4). The average turbidity in each of the six sub-basins ranged from 0.6 NTU in Indian Arm to 1.5 NTU in False Creek and Port Moody. Turbidity was found to vary significantly between sub-basins (ANOVA; F_5=5.190; p=0.000125).

Table B4. Turbidity (NTU) for Burrard Inlet by sub-basin for the years 1985 to 1995.

Sub-basin	Min	Max	Average with standard deviation	Sample Count
Indian Arm	0.3	1	0.6 ± 0.2	21
Port Moody	0.1	10	1.5 ± 1.6	60
Central Harbour	0.1	4	0.7 ± 0.5	82
Inner Harbour	0.1	8	1.2 ± 1.4	133
Outer Harbour	0.1	5	1.3 ± 0.9	59
False Creek	0.2	9	1.5 ± 1.4	60
Entire Burrard Inlet	**0.1**	**10**	**1.2 ± 1.2**	**415**

Similar to TSS, turbidity often varies due to seasonal variations in rainfall or stream inputs and data were grouped to examine potential seasonal differences. Turbidity was found to vary significantly between seasons, with averages for the entire Burrard Inlet ranging from 0.8 NTU in the fall to 1.6 NTU in the winter (Table B5) (ANOVA; F_5=11.001; p=5.81e-07).

Table B5. Turbidity (NTU) Burrard Inlet average concentrations from 1985 to 1995.

Sub-basin	Winter	Spring	Summer	Fall
Indian Arm	0.7	0.6	0.6	0.6
Port Moody	2.2	1.6	1.2	1.0
Central Harbour	0.9	0.9	0.7	0.6
Inner Harbour	1.6	1.6	0.9	0.7
Outer Harbour	1.7	1.8	1.3	0.7
Entire Burrard Inlet	**1.6**	**1.5**	**1.0**	**0.8**

To determine if turbidity varied with depth, available data were graphed after removing turbidity results that were at surface (i.e., 0 m) (Figure B4). Similar to TSS, a decreasing trend was not observed until below 15 m and no distinct pattern was observed for shallower results; therefore, depth was not considered further.

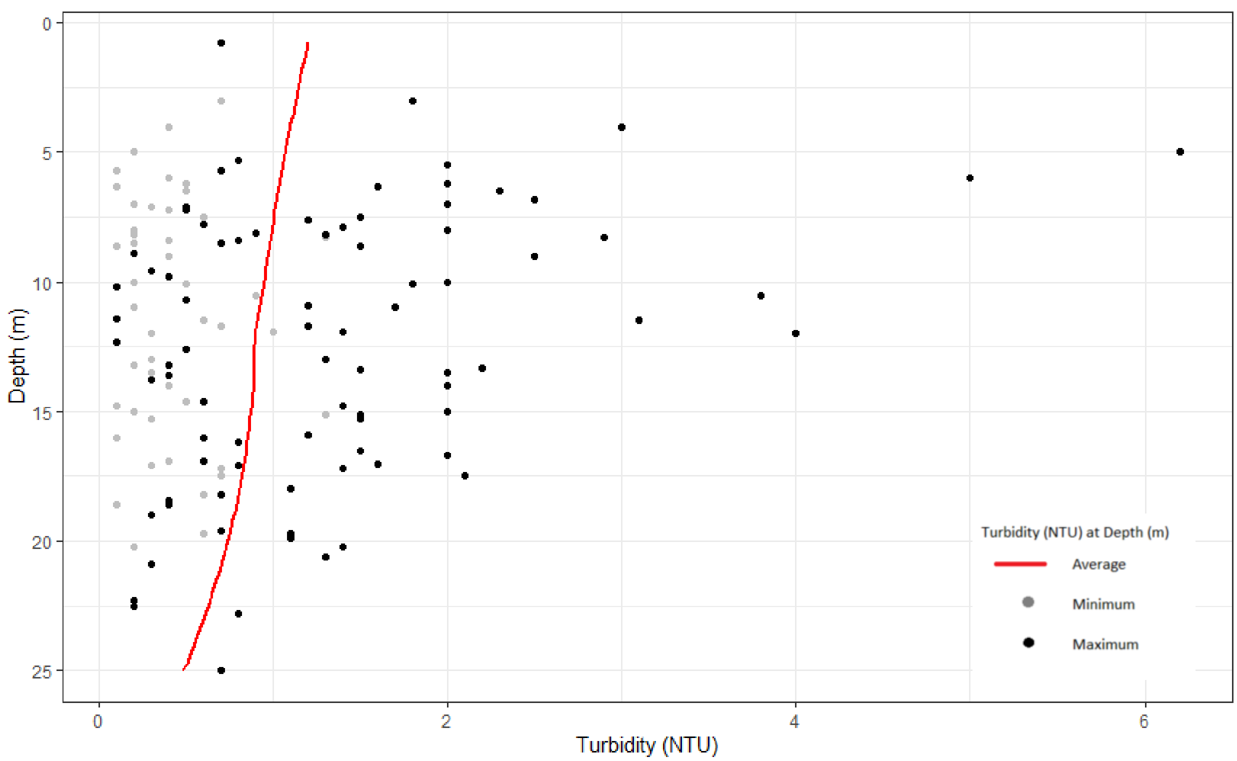

Figure B4. Turbidity (NTU) and depth (m) in Burrard Inlet from 1985-1995. No distinct pattern was observed.

To be useful for estimating a background concentration the data should not have an upward or downward trend through time. A Mann-Kendall[12] Test was used to identify if any of the sub-basins showed a temporal trend. For most sub-basins, except for Port Moody Arm, there was no trend present

[12] A Seasonal Kendall test was not applied as the data did not have a consistent frequency for each season per year.

in the data (Figure B5). For Port Moody Arm there was an overall slight downward trend observed in the data; however, the data was still considered acceptable for estimating a background.

Turbidity data in EMS from Desolation Sound and Okeover Inlet was not available for comparison (as was done for TSS).

Turbidity in Burrard Inlet was found to vary significantly by sub-basin and season; however, the accuracy of the meter used in the field to measure turbidity and laboratory precision of determining turbidity results needs to be considered. Multiple factors can affect turbidity results including sampling technique, calibration and verification methodology, and limitations of the equipment or analysis.

The average turbidity results (when rounded) for spring and winter were 2 NTU for Outer Harbour, False Creek, Inner Harbour, and Port Moody Arm. For all other seasons and sub-basins, the average turbidity results (when rounded) were 1 NTU. Based on confidence in accuracy of turbidity measurements (for reasons presented above), an overall value of 1 NTU is considered appropriate as a background value for turbidity for the entire Burrard Inlet.

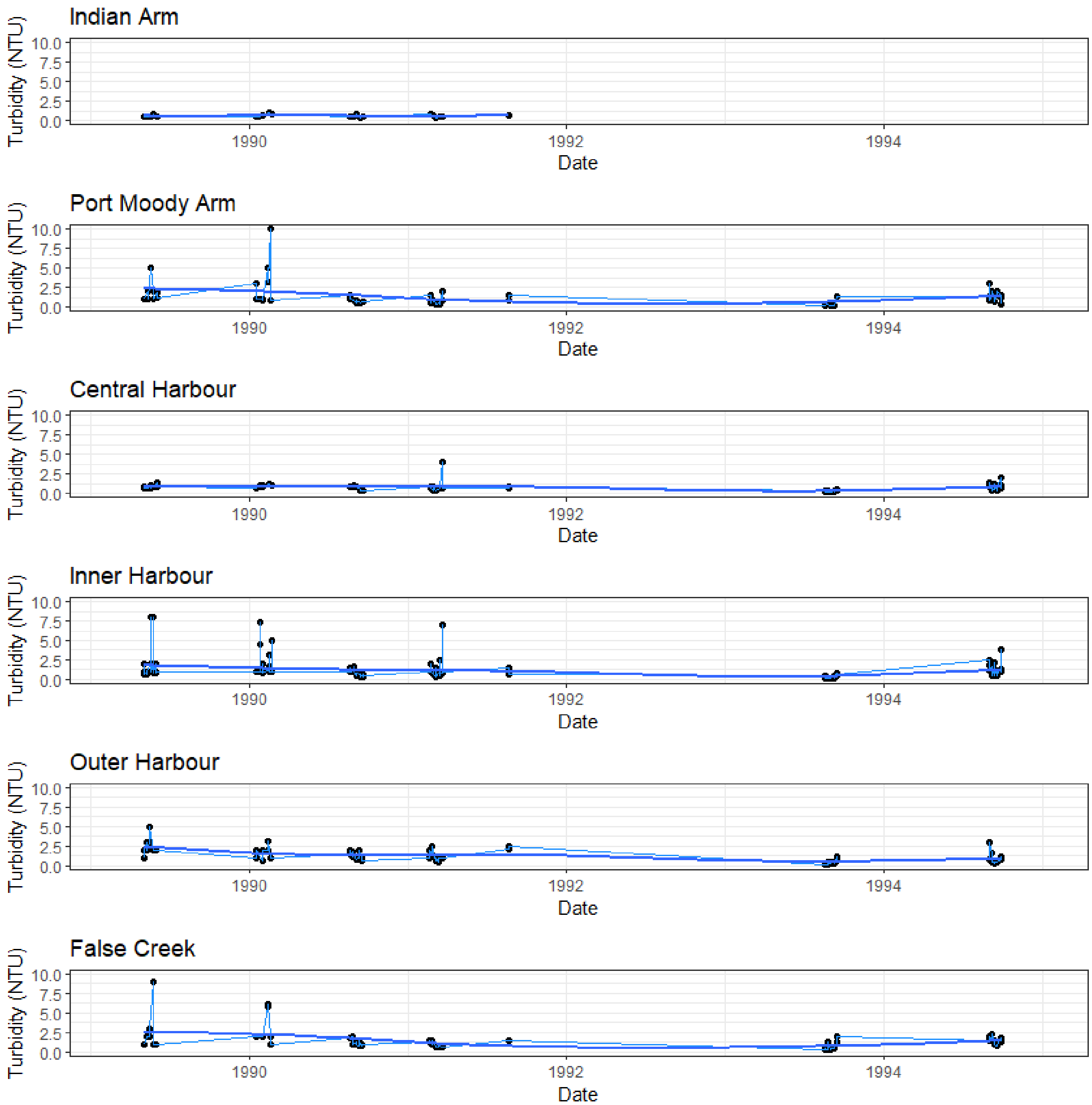

Figure B5. Turbidity (NTU) for each sub-basin in the Burrard Inlet from 1985-1995. No significant temporal trends were observed with the exception of a slight downward trend in Port Moody Arm.