State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 5, Strait of Georgia and the Juan de Fuca Strait, British Columbia

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State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 5, Strait of Georgia and the Juan de Fuca Strait, British Columbia

by

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Increasing Canadian oil production and tanker traffic elevates the risk of accidental oil spills in Canadian waters. In response, the Government of Canada announced the World Class Tanker Safety System and created the independent Tanker Safety Expert Panel to review Canada's ship-source oil spill preparedness and response. Using the panel's recommendations, the Government of Canada is establishing response plans for four pilot areas which have the highest tanker traffic in Canada: Saint John, NB, Port Hawkesbury and Canso Strait, NS, St. Lawrence Seaway, Qc, and the southern portion of British Columbia.

This is the fifth volume of a five volume report and contains information relevant to developing an area response plan for the Strait of Georgia and the Juan de Fuca Strait, British Columbia. The first volume of this report contains introductory information on oil products and spills and should accompany subsequent volumes.

RÉSUMÉ

Ryan, S.A., Wohlgeschaffen, G., Jahan, N., Niu, H., Ortmann, A.C., Brown, T.N., King, T.L., and Clyburne, J. 2019. State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 5, Strait of Georgia and the Juan de Fuca Strait, British Columbia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: viii + 47 p.

L'augmentation de la production de pétrole et du trafic de navires-citernes au Canada accroît le risque de déversements accidentels de produits pétroliers dans les eaux canadiennes. En réponse, le gouvernement du Canada a annoncé le Système de sécurité de classe mondiale pour les navires-citernes et créé le Comité d'experts sur la sécurité des navires-citernes pour examiner la préparation et l'intervention du Canada en cas de déversement de produits pétroliers provenant de navires. Suivant les recommandations du Comité, le gouvernement du Canada établit des plans d'intervention pour quatre zones pilotes où le trafic de navires-citernes est le plus élevé au Canada: Saint-Jean (Nouveau-Brunswick), Port Hawkesbury et le détroit de Canso (Nouvelle-Écosse), la Voie maritime du Saint-Laurent (Québec) et la partie sud de la Colombie-Britannique.

Le présent rapport est le cinquième volume d'un rapport de cinq volumes et renferme de l'information pertinente pour l'élaboration d'un plan d'intervention régional pour le détroit de Georgie et le détroit de Juan de Fuca, en Colombie-Britannique. Le premier volume du présent rapport contient des renseignements introductifs sur les produits pétroliers et les déversements et devrait accompagner les volumes suivants.

1 INTRODUCTION

In November 2013, the Expert Panel of the World Class Tanker Safety System (WCTSS) produced its first report (Houston et al. 2013). In response to the Panel's recommendations, the Government of Canada aims to develop and implement fitted oil spill response plans in the following four pilot areas:

- Saint John and Bay of Fundy, New Brunswick
- Port Hawkesbury-Canso Strait, Nova Scotia
- St. Lawrence Seaway, Montreal to Anticosti, Québec
- Strait of Georgia and the Juan de Fuca Strait, British Columbia

As part of this initiative, a five-volume report has been produced in order to provide a general review of factors that may influence oil spills and response in the four pilot areas. This report is intended to be practical in nature and not a detailed examination of the science of oil spills or specific scenarios that may be encountered.

Volume 1 of this report provides information that is common to the study as a whole, including oil products handled by the ports, oil spill fate and transport, fate and behaviour modelling of spilled oil, a synopsis of the methods currently employed in operational response, techniques used to monitor and track spills, and a glimpse of technologies under development. Four additional volumes provide information on the hydrography, oceanography, climate, case studies of spills, and, when available, spill modelling for each of the four selected pilot ports in the order listed above.

This volume focuses on the Port of Vancouver, the Straits of Georgia and Juan de Fuca, the Salish Sea, and waterways associated with them (Figure 1). Port Metro Vancouver is Canada's largest and busiest port and imports and exports fuel oil and gasoline through five terminals: Shellburn (Shell), Stanovan (Chevron), Westridge Marine Terminal (Kinder-Morgan), PetroCanada, and the Imperial Oil (IOCO) Terminal (Port Metro Vancouver 2012). In total, 1.7 million metric tons of gasoline and 1.4 million tons of fuel oil passed through the Port of Vancouver in 2006 (EnviroEmerg Consulting Services 2008). The Westridge Marine Terminal in Burnaby is the region's primary oil shipping terminal, loading crude oil onto tankers and importing refined oil products from barges. In addition to oil, there are also several petro-chemical plants, a sugar refinery, container shipping operations, and a log shipping facility located in Burrard Inlet (Demes et al. 2013).

2 GEOGRAPHY

2.1 LOCATION

The Port of Vancouver (Port Metro Vancouver) is located on the west coast of Canada just north of the Canada-US border in the city of Vancouver, British Columbia. Port facilities are situated in Burrard Inlet which opens into the Strait of Georgia. The identified study area includes Burrard Inlet, the Strait of Georgia, and the Juan de Fuca Strait, all of which connect to the Pacific Ocean (Figure 1).

Figure 1. Region of study, the Strait of Juan de Fuca to the Strait of Georgia

The Burrard Inlet is unique in terms of potential oil spill response operations due to its highly restrictive geography. In order to reach Westridge Marine Terminal from the Pacific, tankers must travel through the Juan de Fuca Strait, into the Strait of Georgia via Boundary Pass, along the deep water areas near Sturgeon Bank, and finally through Burrard Inlet, passing the Lions Gate and Second Narrows bridges. In addition to this, shallow waters in parts of the harbour limit tanker traffic to narrow tidal windows when water is deep enough to allow tanker traffic (Figure 2) (Demes et al. 2013).

The mouth of the Fraser River is located on the eastern shore of the Strait of Georgia just south of the Burrard Inlet, east of Sturgeon Bank. Outflow from the Fraser River plays a significant role in determining the hydrodynamics of the strait, in addition to hosting one of the largest commercial salmon fisheries in the world as well as a large recreational fishery (Stronach et al. 2006).

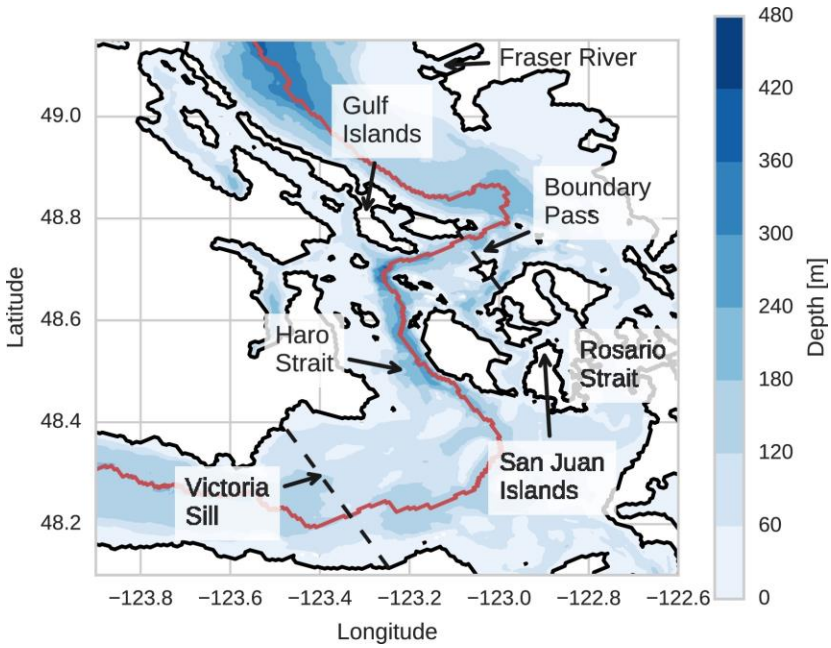

Figure 2. Bathymetry and geographic locations for the San Juan/Gulf Islands and surrounding area, the red line indicates the location of the deepest channel through the area (Soontiens and Allen 2017)

2.2 SHORELINES

Shorelines along the Port Vancouver study area range from highly developed urban areas to relatively untouched coastline. Satellite imagery in Figure 3 shows high levels of coastline development associated with the cities in the area, particularly Vancouver, while large stretches of coastline remain forested and minimally developed. ShoreZone high-resolution imaging and habitat classification for the Burrard Inlet suggests 42% sediment, 31.3% anthropogenic, 14% mixed rock and sediment, and 12.7 rocky shoreline (Coastal and Ocean Resources 2018). ShoreZone imaging and classification has been conducted for large areas of the Strait of Georgia – Juan de Fuca system by Coastal and Ocean Resources.

Figure 3. Satellite image of Vancouver study area (Google Maps)

Burrard Inlet is a complex system made up of six different sub-areas: the Outer Harbour and English Bay, False Creek, the Inner Harbour, Central Harbour, Port Moody Arm and Indian Arm (Figure 4). Other than lands surrounding Indian Arm, much of Burrard Inlet has been extensively developed for commercial, industrial, residential and recreational uses (Kostyniuke and Lin 2003). Rocky intertidal shoreline would be considered to be the most prevalent environment within the Burrard Inlet (Burrard Inlet Environmental Action Program 2010), but each of its sub-areas is distinct when it comes to shoreline development and geography.

Figure 4. Map of Burrard Inlet (Wikimedia Commons 2018)

The Outer Harbour is the largest sub-area within Burrard Inlet and is considered to be a transitional area between the Strait of Georgia and the remainder of Burrard Inlet. At low tide the southern shores of the Outer Harbour are predominantly made up of sand beaches. At the southwestern extent of the Harbour intertidal zones with sand and mudflats can be found with “benches” of soft sediment. Unlike its southern reaches, the northern shore of the Harbour is primarily rocky shoreline (Burrard Inlet Environmental Action Program 2011).

False Creek extends inland roughly 3.4km to the east from the Outer Harbour at English Bay and the shoreline has been converted into seawalls and public paths (Burrard Inlet Environmental Action Program 2011). The Inner Harbour of Burrard Inlet is considered to be the ~8.8km stretch between the First and Second Narrows. The shores are populated by marine and intermodal transport facilities including bulk and container terminals and road and rail infrastructure they rely upon (Burrard Inlet Environmental Action Program 2011). Burrard Inlet’s Central Harbour is ~7.8km long and shoreline development is much the same as the Inner Harbour, although its eastern reaches tend to be somewhat less developed. Port Moody Arm is the eastern most end of Burrard Inlet and is less developed than the Inner and Central Harbours, most of its shores fall within the City of Port Moody. Indian Arm is the least developed area of Burrard Inlet

and is primarily surrounded by steep mountain walls (Burrard Inlet Environmental Action Program 2011).

2.2.1 Coastal Resource Information Management System (CRIMS)

Detailed shoreline information collected by the Government of British Columbia and can be accessed through the Coastal Resource Information Management System (CRIMS) at the URL below.

https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/coast

3 HYDROGRAPHY

3.1 BATHYMETRY

3.1.1 Burrard Inlet

Burrard Inlet is considered to be waters east of Point Atkinson (Figure 5) (Levings and Samis 2001).

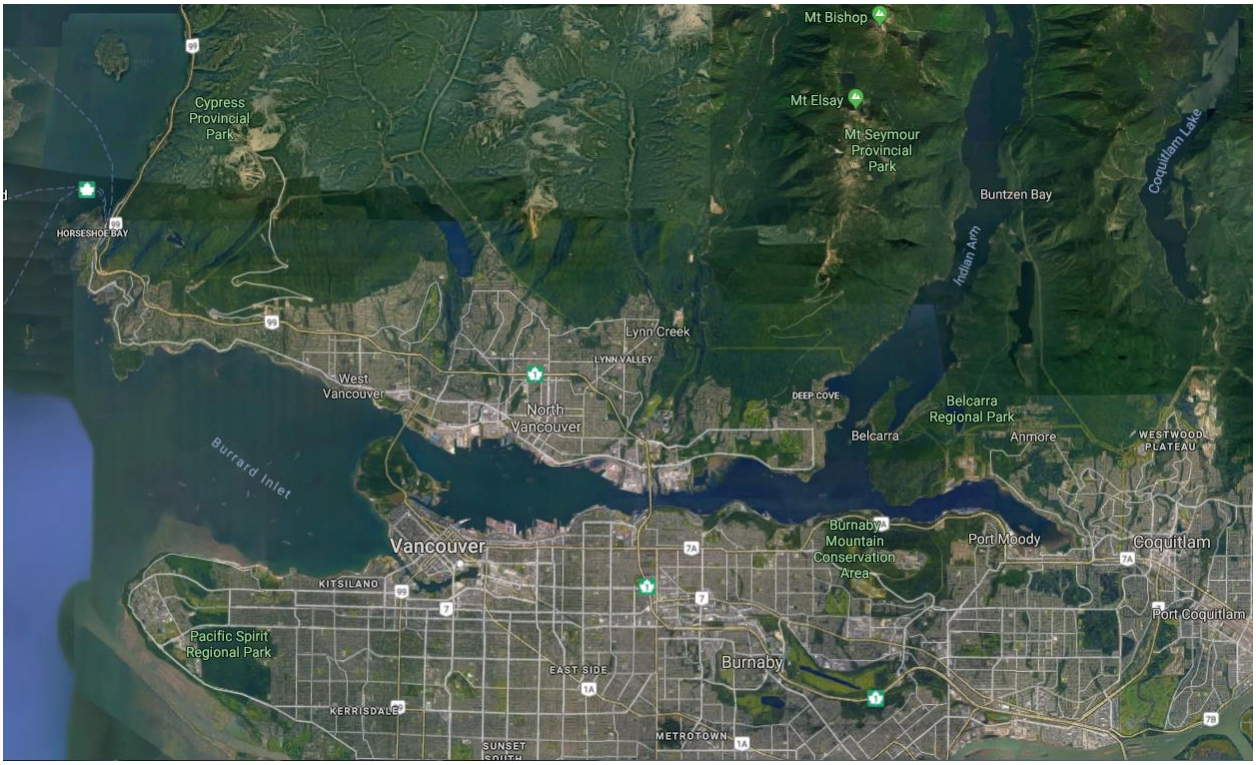

Figure 5. Burrard Inlet and Indian Arm (Google Maps)

Indian Arm is classified as a small fjord due to the fact that it is long, narrow, and bounded on both sides by mountain slopes which extend beneath the surface of the water. Indian Arm has a maximum depth of 220 m with a broad sill at its mouth that restricts the flow of salt water from Burrard Inlet (De Young 1986; Dunbar and Burling 1987; Haggarty 2001).

Burrard Inlet is unique in this area since it lacks a sill at its entrance and the surrounding lands are of moderate relief rather than a steep slope (Haggarty 2001). Despite not having a sill itself to restrict flow between the Strait of Georgia, the Burrard Inlet itself is quite shallow (<100m) and functions as a broad sill connecting Indian Arm (inland) to the Strait of Georgia. Within the inner portions of Burrard Inlet there are areas of relatively deep water (~65m) in the Inner and Central Harbours while water depths at First and Second Narrows are 15 and 19 m respectively (Figure 4). Due to these shallow areas it has been suggested that some fully loaded tankers leaving port through

the narrows would need to wait for a high-tide window of about 20 minutes in order to safely navigate out of the harbour, potentially leaving less than 2m of under-keel clearance (Demes et al. 2013). False Creek and Port Moody arm are relatively shallow sections of Burrard Inlet with depths of <8 m and <10m respectively.

3.1.2 Strait of Georgia

The Strait of Georgia is approximately 220 km long and runs northwest-to-southeast between Vancouver Island and mainland British Columbia. Being relatively narrow, the width of the Strait of Georgia varies from 25 to 55 km along its length. Average depth in the Strait of Georgia is 55 m with the deepest point being ~600 m (Akenhead 2013; Barrie et al. 2014; Thomson 1981). Large areas of the strait reach depths of between 300 and 400 m, although several shallow banks exist within the strait (Figure 6). The Strait of Georgia connects with Pacific Ocean through the San Juan and Gulf Islands and the Juan de Fuca Strait to the south and the long, narrow, and difficult to navigate Johnstone Strait to the north. Bottom topography through the San Juan and Gulf Islands is complex, and generally less than 100 m deep with the exception of two channels, Boundary Pass/Haro Strait (Figure 2) (Dewey and Tunnicliffe 2003).

The majority of Haro Strait contains a deep channel between 180-250 m deep but has a shallow sill at its northern boundary which is about 60 m deep. A narrow and deep (250 m) passage runs through the still which is called Boundary Passage. This passage allows salt water to flow more easily into the upper reaches of the Strait of Georgia and also permits ship traffic through the strait. Rosario Strait is shallower than Haro strait at 60-70 m depth (Crean et al. 1988; Pawlowicz 2002; Thomson 1994).

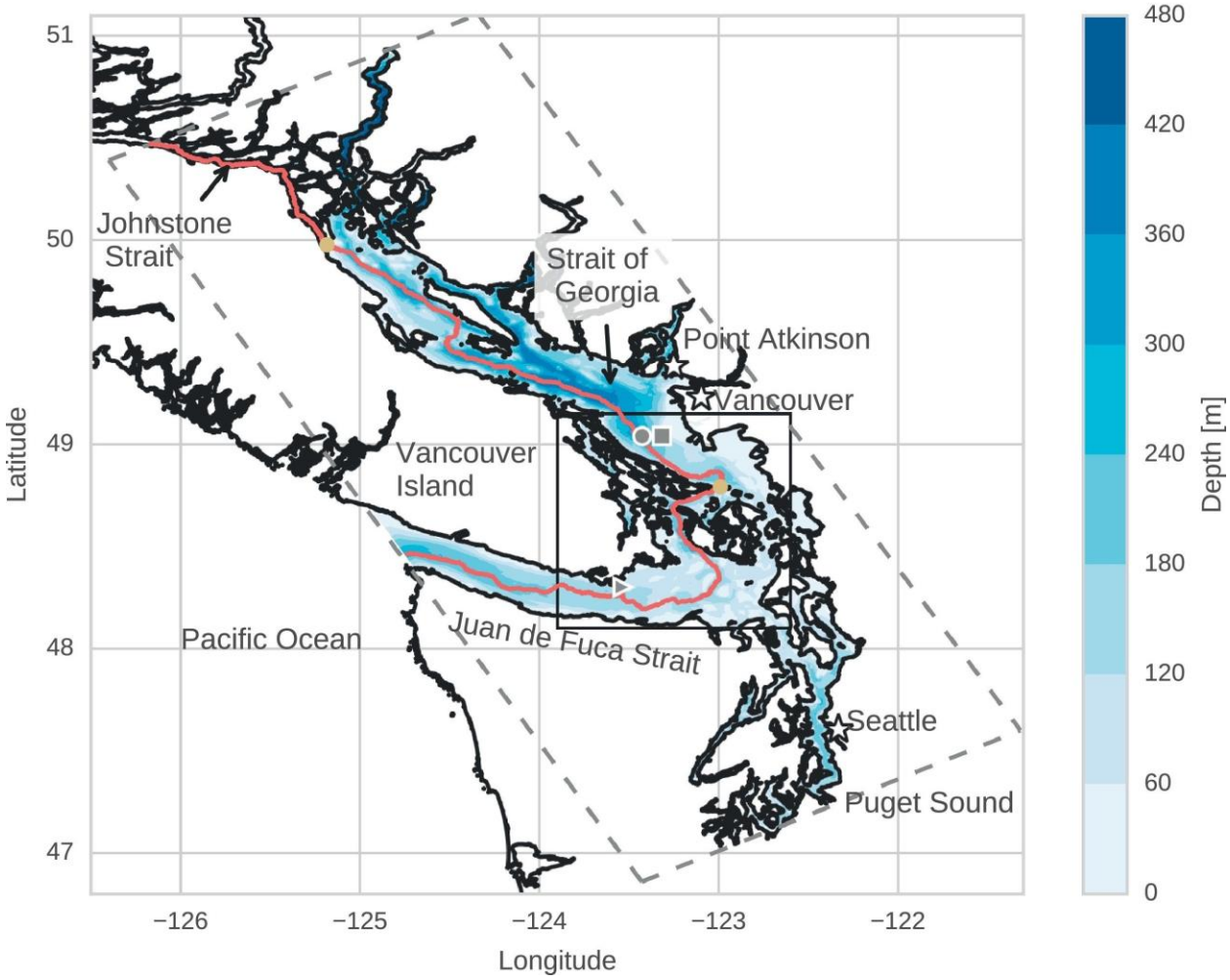

Figure 6. Bathymetry of the Strait of Georgia (Soontiens and Allen 2017)

3.1.3 Juan de Fuca Strait

The Juan de Fuca Strait is a submarine valley extending from the Pacific Ocean to Rosario Strait (Feely and Lamb 1979). The Juan de Fuca Strait is a long and narrow passage approximately 18-27 km wide and 130-160 km long located north of the Olympic Peninsula of Washington state, U.S., and south of Vancouver Island, British Columbia; it is the primary entrance to major Canadian and United States population centers located on the Strait of Georgia and Puget Sound (Cannon 1978; Thomson and Foreman 1998). At its western entrance from the Pacific, bottom depths range up to 275 m whereas at its eastern limit channel depths decrease to approximately 90 m. The Juan de Fuca Strait is made up of two main basins which are separated east-west by a narrow sill extending south from the city of Victoria, B.C. at around 60 m depth (Figure 2) (Crean 1988; Encyclopaedia Britannica 2018; Feely and Lamb 1979; Pawlowicz 2002).

3.2 CURRENTS

3.2.1 Burrard Inlet

Burrard Inlet is an estuarine system. Relatively fresh surface water generally flows out of the inlet over an inflowing layer of saline water from the Strait of Georgia (Davidson 1979), although fresher water from the Fraser River outflow enters at the surface at times (Thomson 1981). Circulation and water currents are largely driven by tidal forces with some influence from storm winds and outflow from the Seymour River (Fisheries and Oceans Canada 2012b; Nijman and Swain 1990). A high degree of mixing is known to occur as water passes through the shallow First and Second Narrows, which results in currents of 2-3m/s in these areas depending on tidal stage (Burrard Inlet Environmental Action Program 2011; Davidson 1979; Dunbar and Burling 1987; Fisheries and Oceans Canada 2012a; Stacey et al. 2002). Periods of high flow through the Narrows during incoming and outgoing tides create eddies on the down-current side of the narrows resulting in upwelling. The absolute location of these eddies change depending on the direction of flow through the narrows (Figure 7) (Haggarty 2001). Currents outside of the First and Second Narrows generally range between 0.25 and 0.5 m/s (Sutherland 2004). False Creek and Port Moody Arm both have very little freshwater input and have relatively low levels of circulation (Burrard Inlet Environmental Action Program 2011).

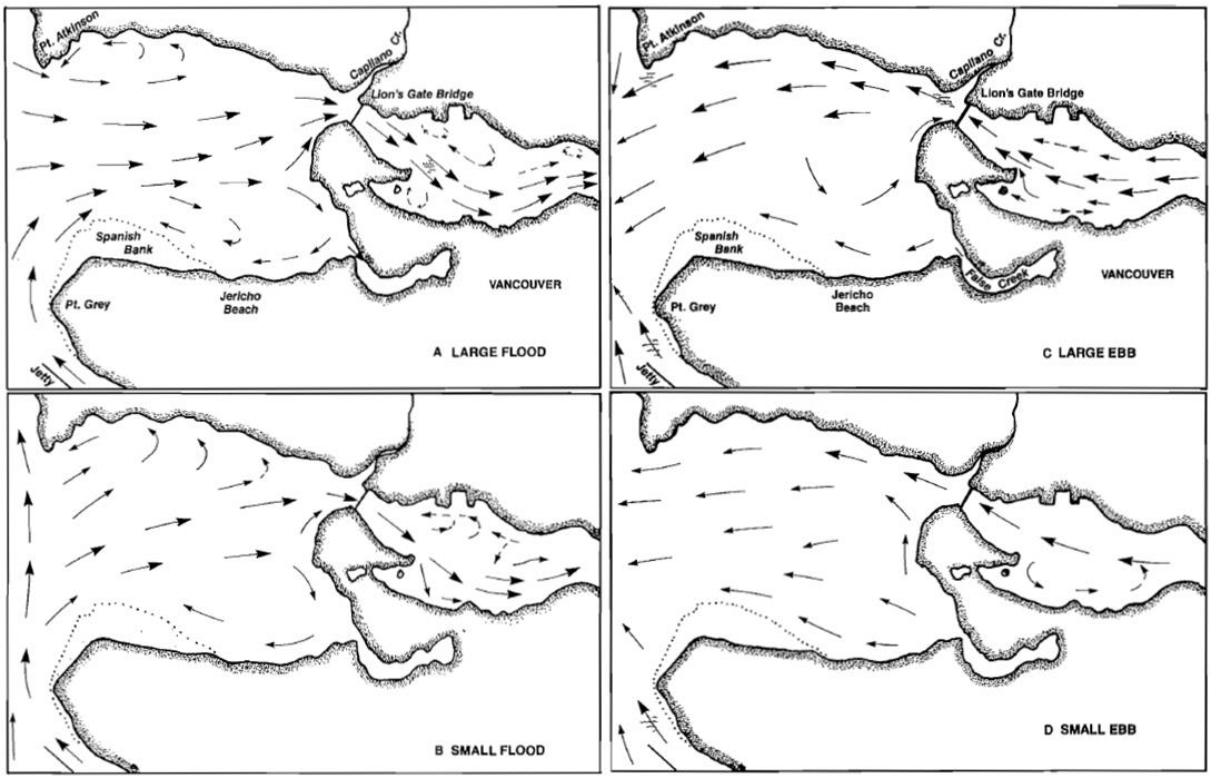

Figure 7. Tidal currents in Burrard Inlet; (A) large flood tide, (B) small flood tide, (C) large ebb tide, (D) small ebb tide (Thomson 1981).

3.2.2 Strait of Georgia

The Strait of Georgia has circulation patterns similar to those of a partially mixed estuary with moderately strong tidal currents, seasonal stratification and deep-water density intrusions during late summer and late winter (Crean and Ages 1971; Khangaonkar et al. 2017; Leblond 1983; Masson 2002; Thomson 1994). Although the Strait of Georgia is open on both its northern and southern end, the channel in the north is highly constricted meaning that most of the flow into and out of the strait occurs in the south through the San Juan and Gulf Islands, and ultimately the Juan de Fuca Strait. That said, it is estimated that upwards of 17% of freshwater in the Strait of Georgia exits through Johnson Strait in the north (Crean 1988; Khangaonkar et al. 2017). Freshwater input from the Fraser River results in estuarine circulation in the southern strait, resulting in a net outflow of low salinity water toward Juan de Fuca Strait in the upper water layer (<50m depth), and a net inflow of high salinity water lower in the water column (Barrie et al. 2005; Mosher and Thomson 2002). In addition to freshwater forcing, winds and tidal currents also have a major impact on circulation in the Strait of Georgia (Feely and Lamb 1979; Khangaonkar et al. 2017; Thomson 1994). Although their overall impact is large, currents generated from tidal activity in the Strait of Georgia are typically weak and often skewed by wind-generated currents, river runoff and internal tidal effects (Stronach et al. 2006). That said, tidal currents can be strong in the narrow passages of the San Juan and Gulf Islands in the southern Strait of Georgia and the mixing these currents cause plays an important role in controlling the flow of water through the Strait (Davenne and Masson 2001; Khangaonkar et al. 2017; Masson 2006). During the flood tide, water exiting the Fraser River is carried to the north due to a relatively strong north-flowing tidal stream present on the eastern side of the Strait of Georgia (Figure 8) (Thomson 1981). The velocity of the tidal stream generally ranges from 0.5 to 0.75 m/s. The outflow of the Fraser River at its mouth can reach upwards of 2.5m/s at low water while surface currents tend to be around 1m/s during slack water and vary depending on wind speed and direction (Thomson 1981). In the area of interaction between the Fraser River outflow and the tidal stream, a clockwise gyre can develop in the waters off Sturgeon Bank. During the ebbing tide, Fraser River outflow tends to follow its natural path to the southwest toward the Gulf Islands, and a counter-clockwise eddy may develop off of Sturgeon Bank (Davenne and Masson 2001; Khangaonkar et al. 2017).

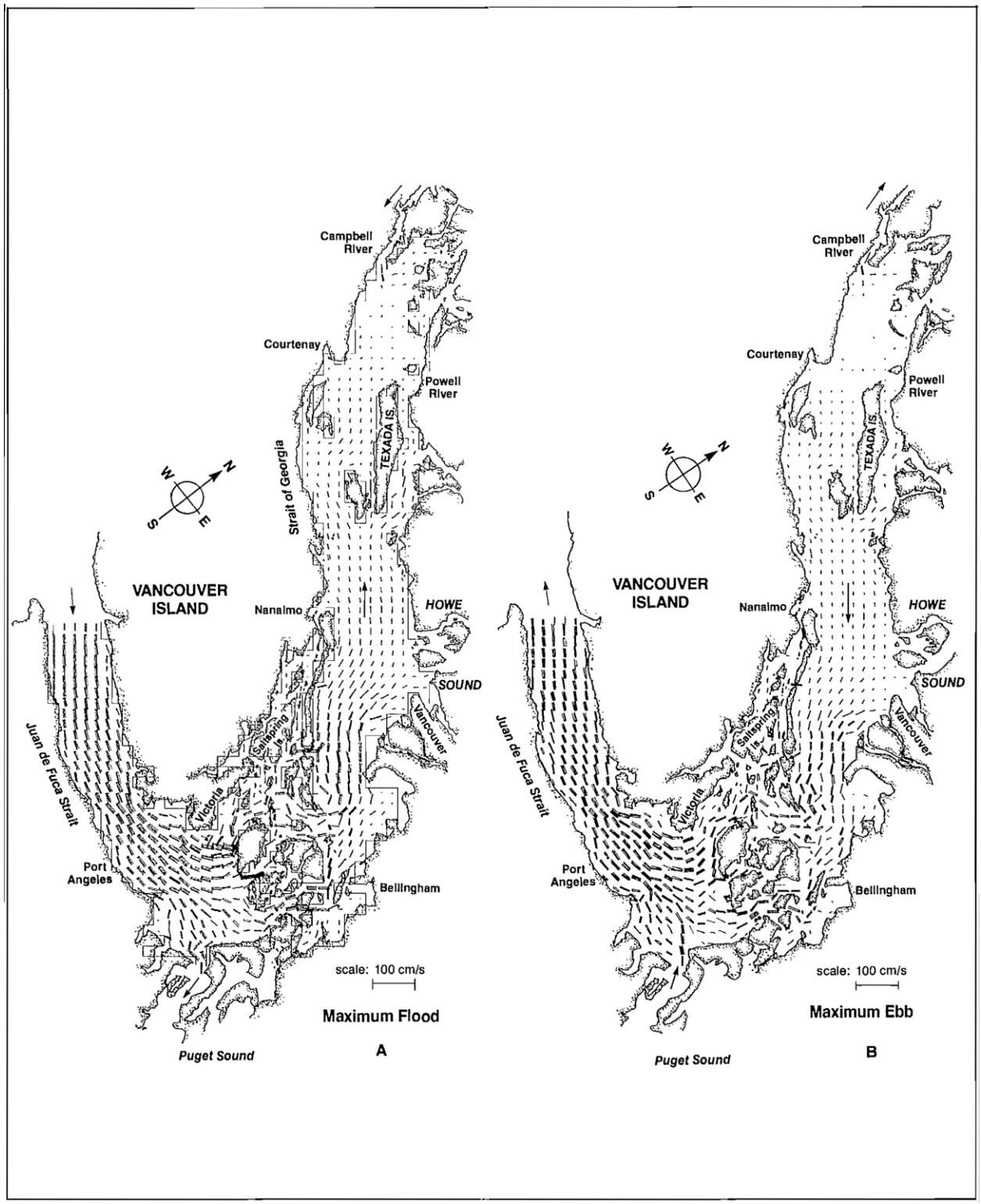

Figure 8. Tidal streams in the Strait of Georgia - Juan de Fuca Strait system at maximum flood (left) and ebb (right) tides. Large arrows represent the general direction of flow in an area and smaller lines represent angle and speed. Longer and/or thicker lines represent faster flow (Thomson 1981).

The San Juan and Gulf Islands in the southern region of the Strait of Georgia serves as a boundary between the Strait off Georgia and the Juan de Fuca Strait. Due to the complex nature of the islands and the presence of sills, the flow of water in this area is highly restricted (Masson 2002). The Haro Strait and Boundary Pass is the main route for the exchange of water through the Gulf Islands (Figure 9). Despite being referred to as a sill, Boundary Pass itself has a narrow and deep (250m) channel which allows the flow of water between the Juan de Fuca and Strait of Georgia and facilitates estuarine circulation patterns where relatively fresh water flows on top of a deeper salt water layer (Crean 1988). The impact of Boundary Pass on water currents becomes apparent as currents in the area are always strong, well-mixed, and tend to align with the channel during the tidal cycle (Davenne and Masson 2001; Johannessen et al. 2006). Tidal currents north of the Gulf Islands near Roberts Bank are typically between 0.5 and 1.0m/s while currents nearer to Boundary Pass at Saturna Island reach up to 1.5-2.0m/s (Figure 9)(Thomson 1981).

Figure 9. San Juan and Gulf Islands (Pfly 2018)

3.2.3 Juan de Fuca Strait

Currents in the western region of the Juan de Fuca Strait are dominated by oceanic processes from the Pacific while the eastern region of the Strait is more complex, governed by wind, estuarine influences, and intense tidal currents (Figure 8) related to tidal passages located in the San Juan and Gulf Islands (Feely and Lamb 1979; Thomson 1981; Thomson et al. 2007). The 60m deep Victoria sill is located in the eastern Juan de Fuca Strait and extends south from the city of Victoria, B.C. (Figure 2), all the way across the strait, limiting deep-water flow in the area (Crean 1988; Thomson et al. 2007). The speed of currents in the Juan de Fuca Strait typically increase from west to east with those in the east representing a fairly significant navigational hazard with strong rip currents in many areas around Victoria and the San Juan Gulf Islands (Holbrook et al. 1980; Thomson 1981). Currents in the Rosario Strait can reach 3.6m/s during peak tides (Thomson 1981) (Figure 9). Due to its long and narrow profile, the direction of water flow through the Strait tends to follow its east-west orientation with little circular flow between tidal cycles; the exception being in the San Juan and Gulf Islands where currents align with the various passages and channels through the area. Estuarine circulation occurs in the Juan de Fuca Strait with relatively warm/fresh surface water flowing westward over inflowing cold and more saline water ~90% of the time in the summer months and ~55% of the time in winter, although surface salinity tends to remain above 28 ppt for most of the year (Thomson et al. 2007).

3.3 TIDES

3.3.1 Burrard Inlet

Tides in Burrard Inlet are mixed, mainly semi-diurnal with a mean tidal range in of 3.3m and a maximum tidal range of approximately 5m (Demes et al. 2013; Haggarty 2001; Sutherland 2004). The tidal range increases only 0.03 m from the entrance of Burrard Inlet to the inland section at Port Moody Arm, but high tide is delayed by roughly 30 min. in Port Moody Arm relative to the inner Harbour (Demes et al. 2013; Haggarty 2001).

3.3.2 Strait of Georgia

Tides in the Strait of Georgia are mixed and mainly semi-diurnal with mean tidal range of approximately 2m - 3.35m (Thomson 1981). Tidal water enters the Strait of Georgia through the Juan de Fuca Strait and is reflected back again when it reaches the highly constricted northern end of the Strait. This south-reflected tidal energy interacts with the northward tidal energy producing a standing wave in the Strait of Georgia. Due to the presence of this standing wave, water levels in the Strait of Georgia rise and fall in unison every ~12 h, 25 min and tidal range tends to increase from south to north (Figure 10) (Thomson 1981).

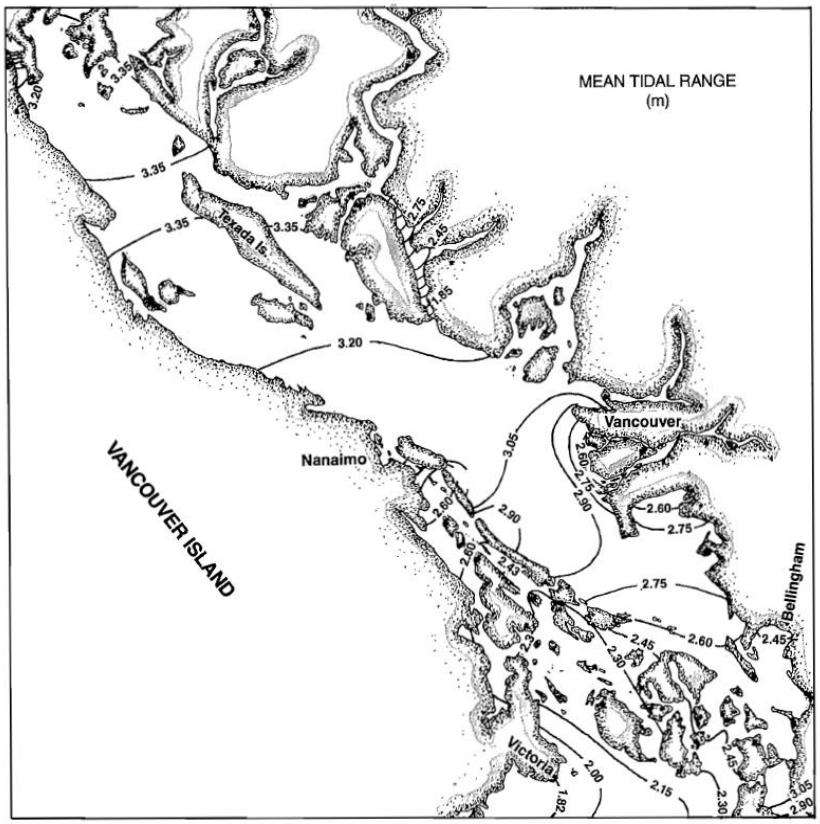

Figure 10. Lines of equal mean tidal range in Strait of Georgia (Thomson 1981).

The tidal range in the Strait of Georgia varies on a roughly biweekly cycle due to changes in declination and phase of the moon. Spring tides occur in the Strait of Georgia every 15 days, roughly 26 h after the new or full moon, compared to a delay of ~15 h after the new or full moon in the eastern Juan de Fuca Strait. Maximum tidal ranges occur during the summer and winter solstices while minimum ranges occur during the spring and autumn equinoxes (Thomson 1981).

The flow of water in the lower Fraser River (below Chilliwack at low river flow, and below Mission at high river flow) is dictated in part by tidal influences from the Strait of Georgia (Swain and Holms 1985). Similar to the Strait, the lower Fraser experiences mixed, mainly semidiurnal tides but tidal range in the river tends to decrease upstream with increased freshwater flow and the tidal cycle is delayed by the shallowness of the river (Figure 11) (Thomson 1981).

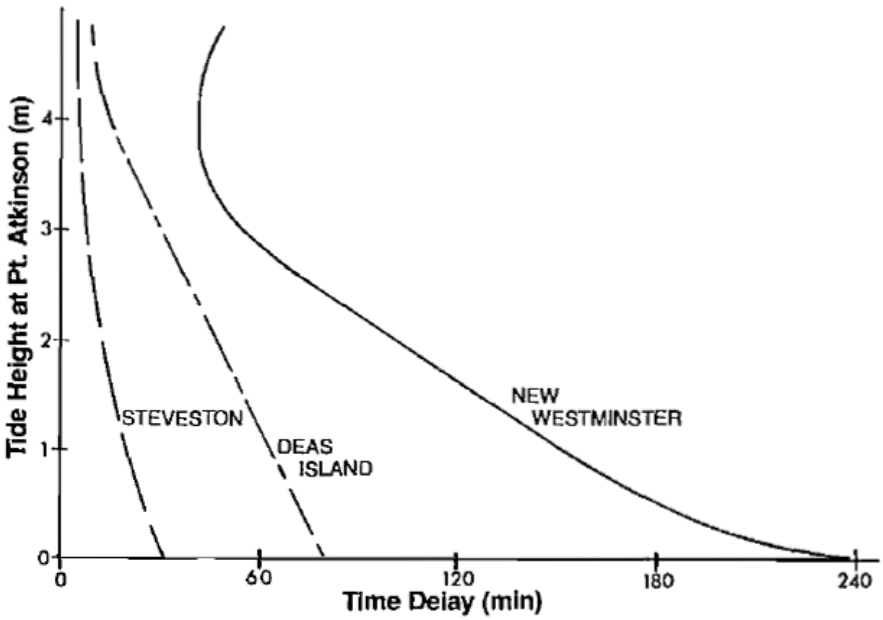

Figure 11. Tidal heights and time differences Fraser River (Thomson 1981)

3.3.3 Juan de Fuca Strait

Much like the rest of the Georgia-Fuca system, tides in the Juan de Fuca Strait are primarily mixed and semi-diurnal although in some eastern sections of the Strait the influence of the diurnal tidal cycle outweighs the semi-diurnal cycle (Crean 1988; Thomson 1981). From the entrance of the Juan de Fuca Strait to the vicinity of Race Rocks, the tides are mixed, mainly semi-diurnal while from Race Rocks east they become mixed, mainly diurnal. The diurnal tidal cycle is so strong near Victoria that the tide becomes fully diurnal, having only one high and low water each day, for around 20 days each month (Thomson 1981). Tidal range within the Juan de Fuca Strait is highest at the western Pacific entrance of the Strait through to the city of Victoria and increases eastward toward the San Juan and Gulf Islands (Figure 12). The tidal range within the Juan de Fuca Strait also tends to be greater on the US side of the Strait than it is on the Canadian side (EBA Engineering Consultants Ltd. 2013). Typical tidal range in the western Juan de Fuca Strait varies from 2.0m for mean tides and 3.2m for large tides (Fisheries and Oceans Canada 2012b). Further east in the Rosario Strait, typical tidal range varies from 2.6m for mean tides and 3.9m for large tides with storm surge potentially increasing these values (Fisheries and Oceans Canada 2012b).

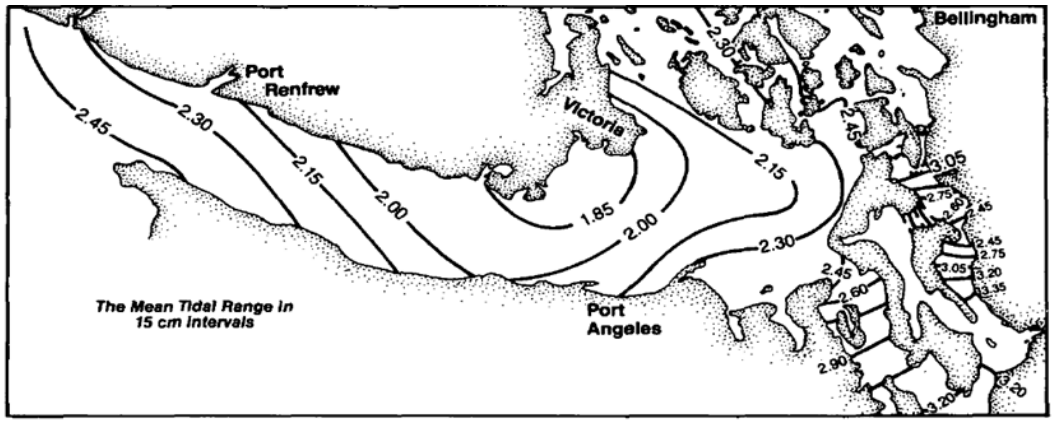

Figure 12. Mean tidal range in Juan de Fuca Strait (m) (Thomson 1981).

3.4 WATERSHED

3.4.1 <u>Burrard Inlet</u>

Burrard Inlet has 190 kilometres of marine foreshore and a drainage basin of approximately 98,000 hectares (Jacques Whitford AXYS Ltd. 2008). Direct freshwater input originates primarily from the Indian River in Indian Arm, the Seymour River (monthly mean discharge of 3.8 m^3/s to 24.9 m^3/s) in the Inner Harbour, and the Capilano River (5.7 m^3/s to 42.8 m^3/s) located in the Outer Harbour, however, outflow from these rivers rarely exceed 1% of the outflow from the Fraser River which reaches the Harbour via the Strait of Georgia (Davidson 1979; Demes et al. 2013; Haggarty 2001).

In addition to river outflow, Burrard Inlet has many permitted discharges made up of municipal and industrial effluents and unpermitted combined sewer outflows. The two largest permitted outflows are from Burrard Thermal, a gas-fired electrical generator, and Lion's Gate Waste Water Treatment Plant; these operations release up to 1,700,000 m^3/day of cooling water into Port Moody Arm and 102,000 m^3/day of primary treated sewage near First Narrows, respectively (Burrard Inlet Environmental Action Program 1997; Levings and Samis 2001). For reference, one of the largest of the unpermitted outflows is at Clark Drive which discharges, on average, 20,800,000 m^3/year of mixed storm water and untreated domestic sewage.

Sediments in Burrard Inlet range from fine mud in deposition areas such as Port Moody Arm, to coarse cobble and gravel at First and Second Narrows, and on river deltas such as the mouth of Capilano River. Dredging is needed at First Narrows to maintain the navigational channel, indicating net deposition at that location. Sedimentation rates in Burrard Inlet (Vancouver Harbour, Indian Arm, Port Moody Arm) range from 0.4 to 1 cm (Johannessen et al. 2003; Pedersen and Waters 1989) and dredging of deep-sea berths is periodically needed in this area (Levings and Samis 2001).

3.4.2 Strait of Georgia

The central region of the Strait of Georgia is dominated by runoff from the Fraser River which account for approximately 75% of the total freshwater runoff into the Strait (Johannessen et al. 2003; Thomson 1981). The watershed for the Fraser River covers an area of about 250,000 km^2 which accounts for roughly 25% of the total land area of British Columbia, and all but ~30% of the river's discharge empties into the Strait of Georgia (Cartwright 2003; Kostaschuk and Luternauer 2004; Thomson 1981). Average discharge from the Fraser River is around 3,475m^3/s, but freshwater output from the Fraser varies seasonally with rates up to and sometimes exceeding 11,000 m^3/s from June to mid-July and lower flows of around 1,000 m^3/s by mid-March (Halverson and Pawlowicz 2008; Masson and Cummins 2004; Swain and Holms 1985; Thomson 1981). Although the specific location of the plume of the Fraser River is primarily determined by wind velocities, during periods of high river discharge a 1-10m thick layer of silt-laden brackish water extends well into and covers wide areas of the Strait of Georgia (Figure 13) (Pawlowicz et al. 2017). During periods of low flow, the brackish water intrusion remains relatively close to shore. Boundaries between the light, brownish coloured brackish water and the darker salt water are usually very obvious unless wave conditions are very rough (Pawlowicz et al. 2017; Thomson 1981). Generally speaking, freshwater from the Fraser River water flows into the southern Strait of Georgia, through the Haro Strait (becoming well mixed by the strong tidal currents), into the Juan de Fuca Strait, and out to the Pacific (Barrie et al. 2005; Harrison et al. 1994; Johannessen et al. 2006; Thomson 1994).

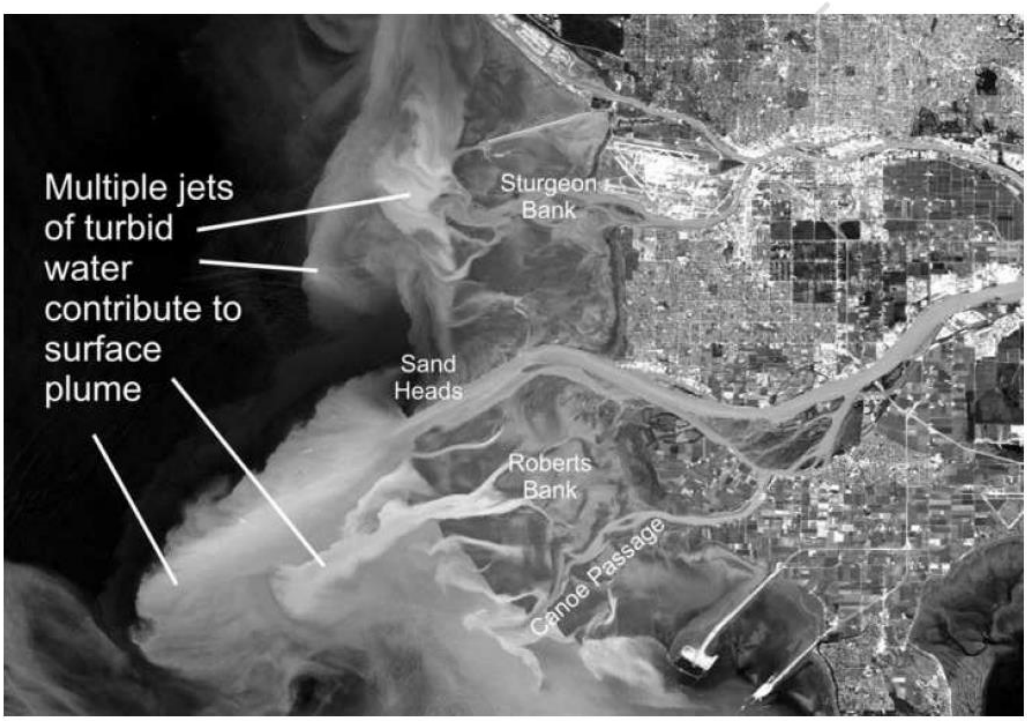

Figure 13. Landsat image of Fraser Delta and turbid surface plume, July 30, 2000 (Hill et al. 2008).

Approximately 230,000 m^3 of sediment are carried into the Strait of Georgia each year by the Fraser River which amounts to 65-80% of the particulate matter entering the Strait (Emergency Management B.C. 2012; Johannessen et al. 2003). Sedimentary processes at the mouth of the Fraser River are controlled by river discharge, sediment load, tidal influences, and the degree of saltwater intrusion into the river (Johannessen et al. 2006; Johannessen et al. 2005; Kostaschuk and Luternauer 2004; Pawlowicz et al. 2017). Sediments carried by waters flowing from the Fraser River consist of both fine grained, muddy sediment that is suspended in the water column, and coarser sandy material that is transported along the bottom. Suspended sediment load in the Fraser tends to follow trends in discharge, but peaks slightly earlier during periods of high flow (Kostaschuk and Luternauer 2004; Pawlowicz et al. 2017). As the plume from the Fraser River pushes into the Strait of Georgia coarse sediments tend to settle rapidly and are carried down-slope by submarine currents while fine grain sediments can be carried throughout the Strait by wind and tidal currents (Evoy et al. 1993; Hart et al. 1992; Kostaschuk and Luternauer 2004).

3.4.3 Juan de Fuca Strait

With a drainage area of only 7,420 km^2 the Juan de Fuca Strait has relatively little direct freshwater inflow and is in large part dominated by discharge from the Fraser River flowing in from the Strait of Georgia (Grant and Ross 2002).

While sediment loads in the Juan de Fuca strait are relatively low compared to the Strait of Georgia, surface water in the Juan de Fuca Strait is most turbid in the winter and very clear in late summer/early fall (Johannessen et al. 2006). It is believed that sediments found in surface water of the western Juan de Fuca Strait during the winter are a result of water from the Columbia River moving northward along the coast of Washington State rather than input from within the Strait (Macdonald and Pedersen 1991).

3.5 SALINITY AND WATER TEMPERATURE

3.5.1 Burrard Inlet

The salinity and temperature of water within Burrard Inlet is highly dependent on local and regional freshwater inputs, more specifically, conditions in the Strait of Georgia, influx of water from the Fraser River, winds, and tides (Davidson 1979; Nijman and Swain 1990; Thomson 1981). Generally speaking, surface water salinity in Burrard Inlet ranges from 20-25 ppt during the winter to between 10 and 20 ppt in the summer months depending on the influence of the Fraser River plume (Figure 14) (Davidson 1979; Demes et al. 2013). Salinities in the outer harbour trend higher to the north as you get further away from the mouth of the Fraser River, while the highest surface salinities within Burrard Inlet tend to be found in areas surrounding the narrows due to high levels

of mixing in those areas (Figure 15). The surface layer outside of the narrows tends to be fairly heavily stratified with both a thermocline and halocline present between 5 and 10m water depth (Davidson 1979; Demes et al. 2013). Salinity in the deeper waters of the Harbour (>10m) is fairly uniform at 29-30 ppt (Davidson 1979; Nijman and Swain 1990).

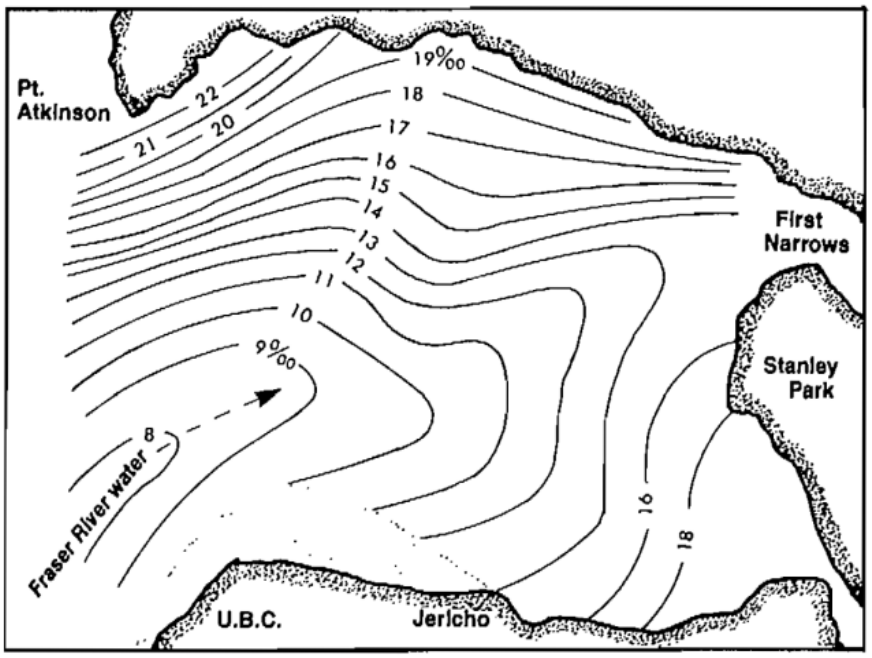

Figure 14. Average summer surface salinity (ppt) in Burrard Inlet during large Fraser River runoff (Thomson 1981).

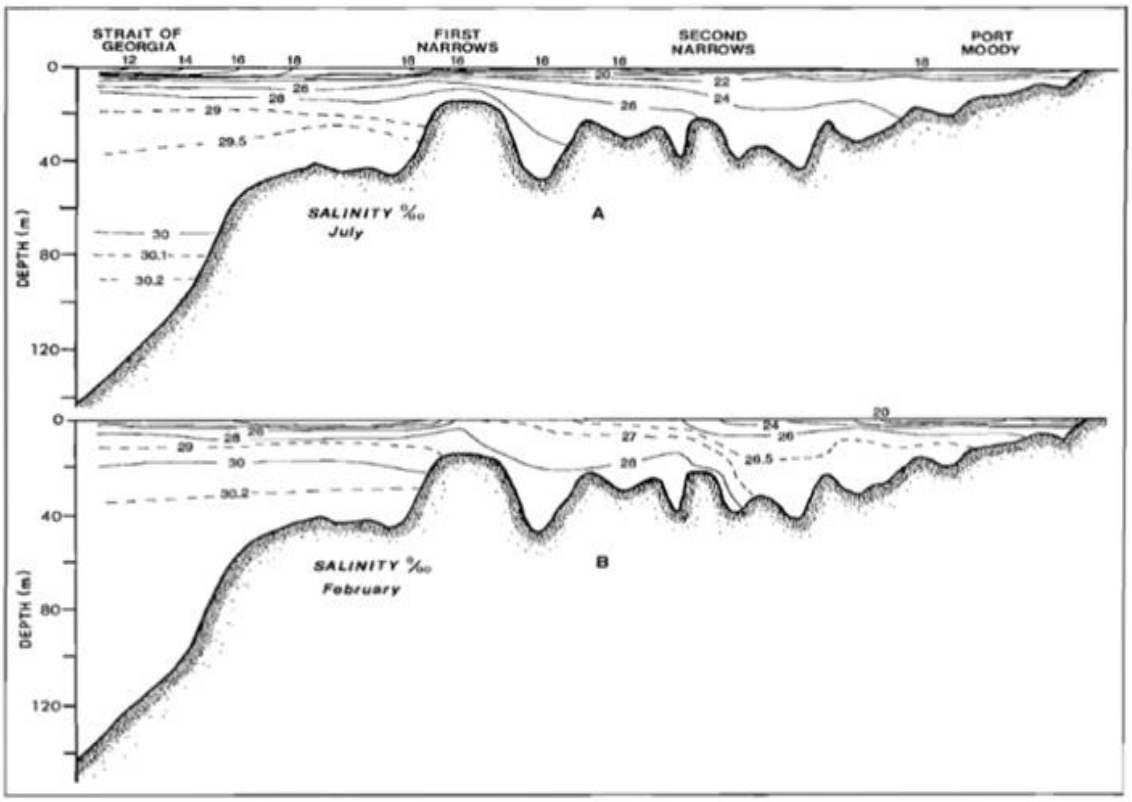

Figure 15. Salinity (ppt) in mid-channel sections through Burrard Inlet: (A) July 7-9, 1966, (B) Feb. 15-18, 1962 (Thomson 1981).

The temperature of surface waters in Burrard Inlet tend to be highest from July to early August and can reach up to 20ºC with surface waters approaching air temperatures during times of low winds (Davidson 1979; Thomson 1981). High levels of vertical mixing at First and Second Narrows result in relatively cold (<15ºC) summer surface temperatures around these areas (Figure 16) (Thomson 1981). Outside of the narrows, a shallow thermocline can result in a drop of 5-10ºC in the top 5m of water, with bottom water temperatures normally between 10ºC and 15ºC (Davidson 1979; Thomson 1981). Temperatures during the winter months tend to be uniformly cold throughout the water column and range between 5 and 8ºC (Davidson 1979; Demes et al. 2013; Thomson 1981).

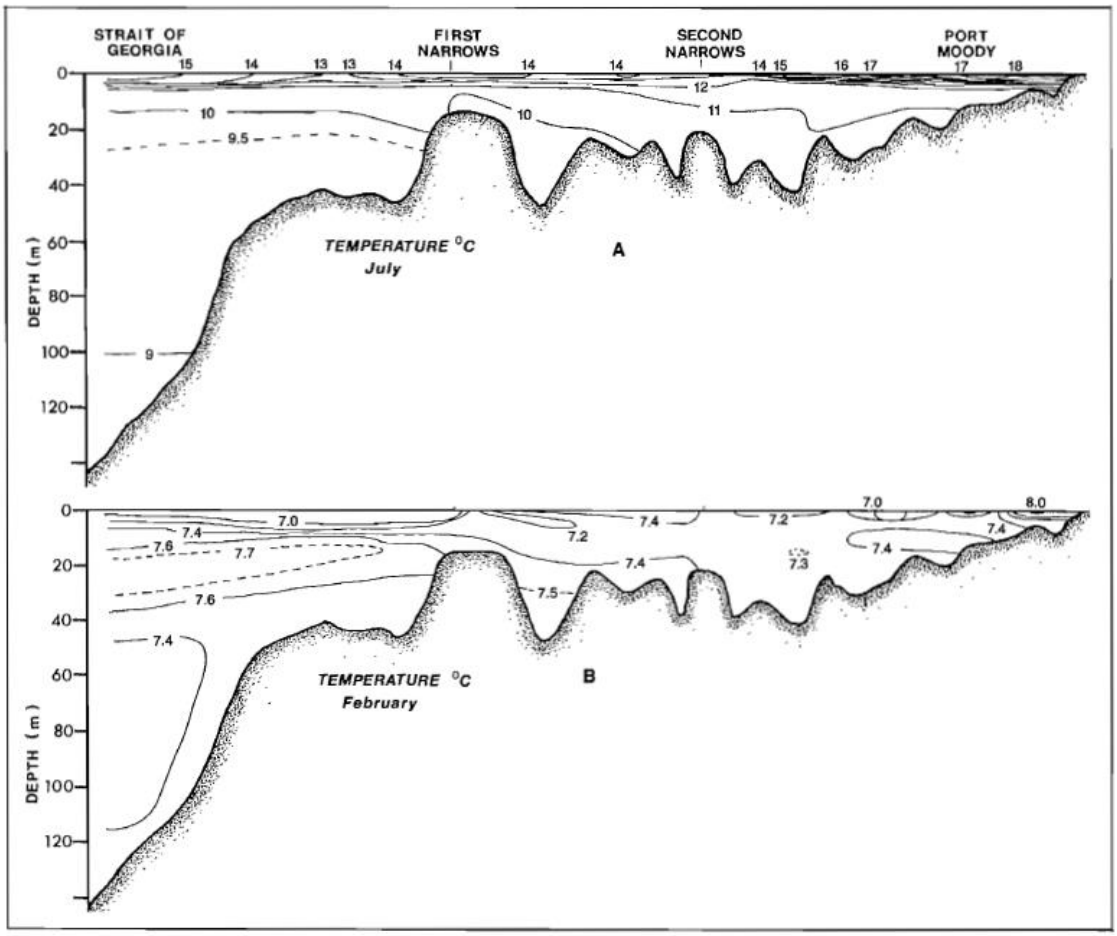

Figure 16. Temperatures in mid-channel sections through Burrard Inlet: (A) July 7-9, 1966, (B) Feb. 15-18, 1962 (Thomson 1981).

3.5.2 <u>Strait of Georgia</u>

Outside of the Gulf Islands where high levels of mixing dominate, the Strait of Georgia is highly stratified due to the large freshwater input from numerous rivers flowing into the Strait, the largest of which being the Fraser River (Crean et al. 1988; Feely and Lamb 1979; Stronach et al. 2006; Thomson 1981). Tidal saltwater intrusion from the Pacific by way of the Juan de Fuca Strait to the south drives the estuarine circulation pattern found in the Strait of Georgia (Waldichuk 1957). The deep water layer in the Strait of Georgia (>50m) is quite stable with salinities ~30.5ppt in summer and ~31ppt in winter, but the surface water layer is highly variable (Figure 17) (Thomson 1981). During the winter months (December-April) when river runoff is low, salinities in the upper water layer of the Strait (<50m) range between 27-29.5ppt, increasing slightly with depth, while areas directly affected by the Fraser River have somewhat lower salinities of ~15ppt (Crean et al. 1988; Stronach et al. 2006; Thomson 1981). During periods of high freshwater discharge in the Fraser River (particularly the late-May freshet) most of the central and southern Strait can be covered by layer of brackish water a few meters deep with a

salinity of <15 PSU (Crean et al. 1988; Halverson and Pawlowicz 2008; Stronach et al. 2006; Thomson 1981). Discharge from the Fraser River tends to decrease by August and salinities in the Strait of Georgia gradually increase once again. During this time of year salinity varies considerably, primarily with distance from the mouth of the Fraser River, but also very localized areas of low salinity can be found near other small rivers than empty into the Strait (Halverson and Pawlowicz 2008; Thomson 1981). Salinity among the Gulf Islands, in Haro Strait in particular, tends not to drop below 25-26 ppt in summer due to high levels of mixing (Thomson 1981).

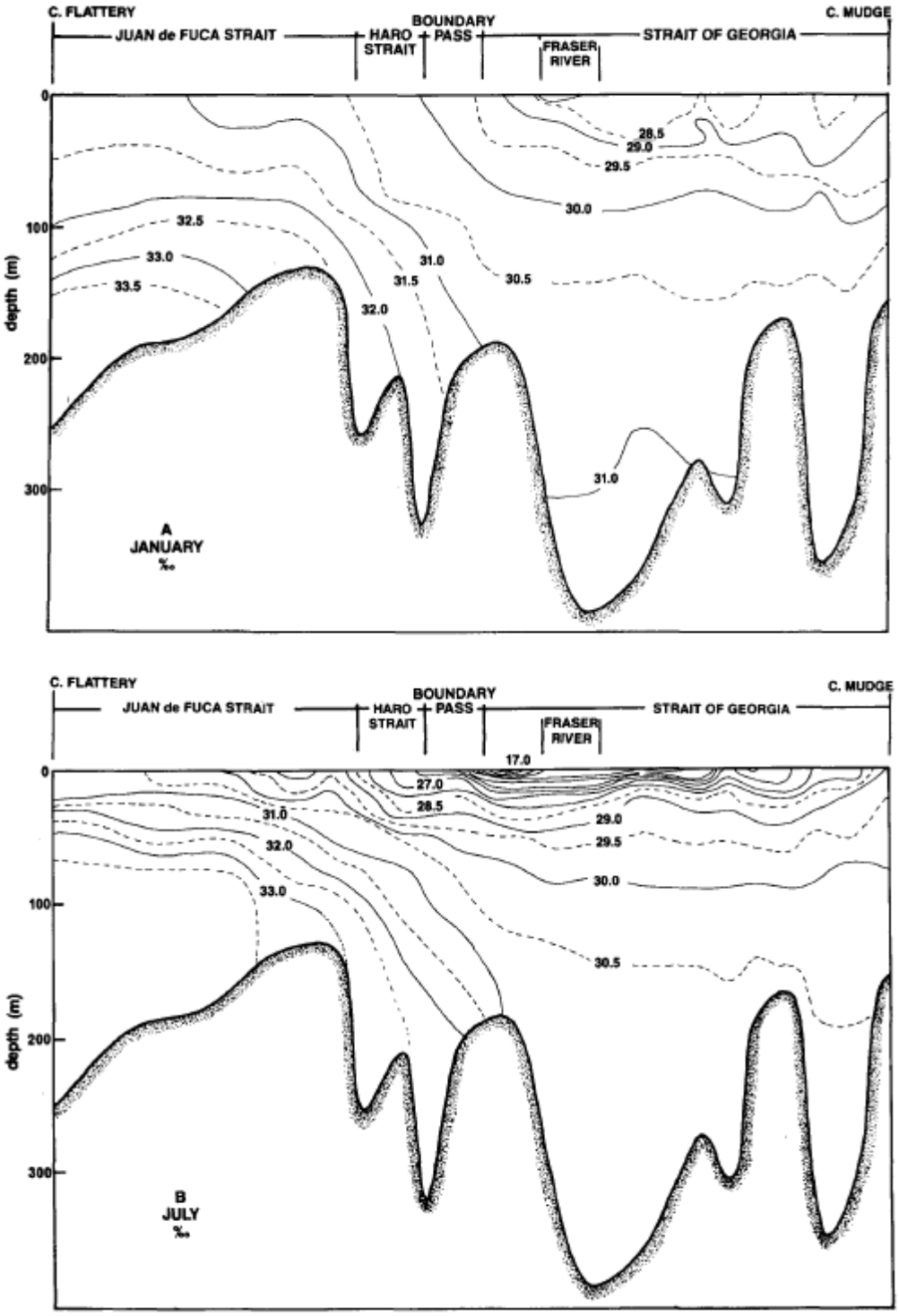

Figure 17. Salinity along channel sections from the western end Juan de Fuca Strait to northern end of the Strait of Georgia: (A) January1968, (B) July 1968 (Thomson 1981).

Much like salinity, outside of the generally well-mixed Gulf Islands, temperatures in the deeper water (>50m) of the Strait of Georgia are fairly consistent all year long, between 8 and 10°C, while surface temperatures are much more variable (Figure 18) (Thomson 1981). Water temperatures in the surface layer (<50m) warm from 5-6°C in winter up to ~15°C in May, and higher in summer, when stratification can permit further warming. Seawater in some areas can exceed 20°C in July. Water temperatures remain around 10°C throughout the summer in tidally-mixed areas such as the Gulf Islands (Thomson 1981).

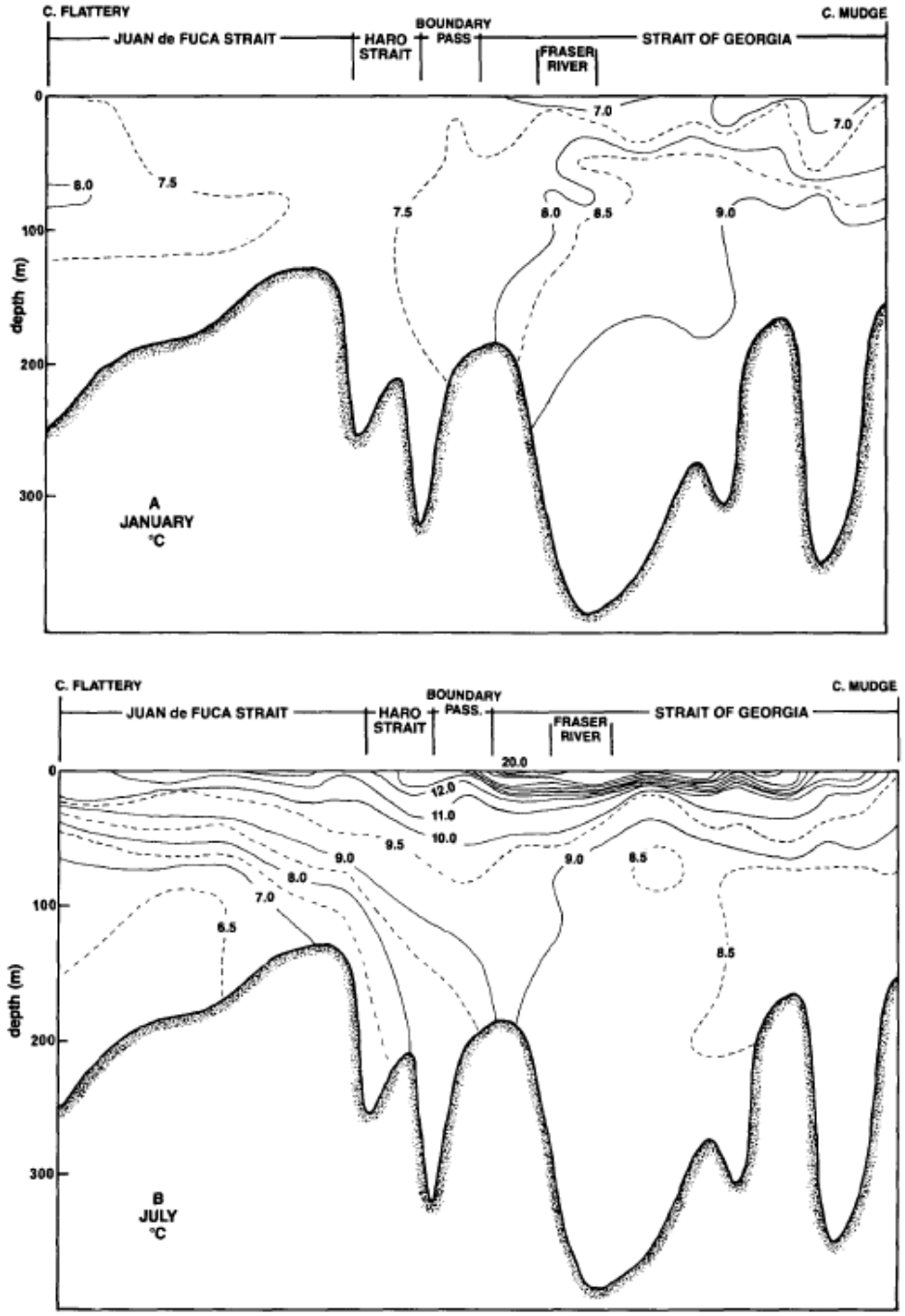

Figure 18. Temperature along channel sections from the western end of the Juan de Fuca Strait to the northern end of the Strait of Georgia: (A) January 1968, (B) July 1968 (Thomson 1981).

3.5.3 <u>Juan de Fuca Strait</u>

In Juan de Fuca Strait, brackish water flowing in from the Strait of Georgia drives estuarine circulation, with seaward flowing brackish water at the surface, and high

salinity water returning at depth (Masson and Cummins 2000; Thomson et al. 2007). While this estuarine activity does have some impact on the Juan De Fuca Strait as a whole, the eastern regions of the Strait are most affected (Masson and Cummins 2000). During the winter months, surface salinity in the strait is generally around 30-31ppt, while during the summer months, runoff from the Fraser River entering through the Haro Strait can lead to surface salinities between 28 and 30ppt in the eastern Juan de Fuca. Deepwater salinity in the Juan de Fuca Strait remains greater than 30ppt throughout the year with bottom water at the Pacific entrance reaching 33.5 ppt in summer (Thomson 1981).

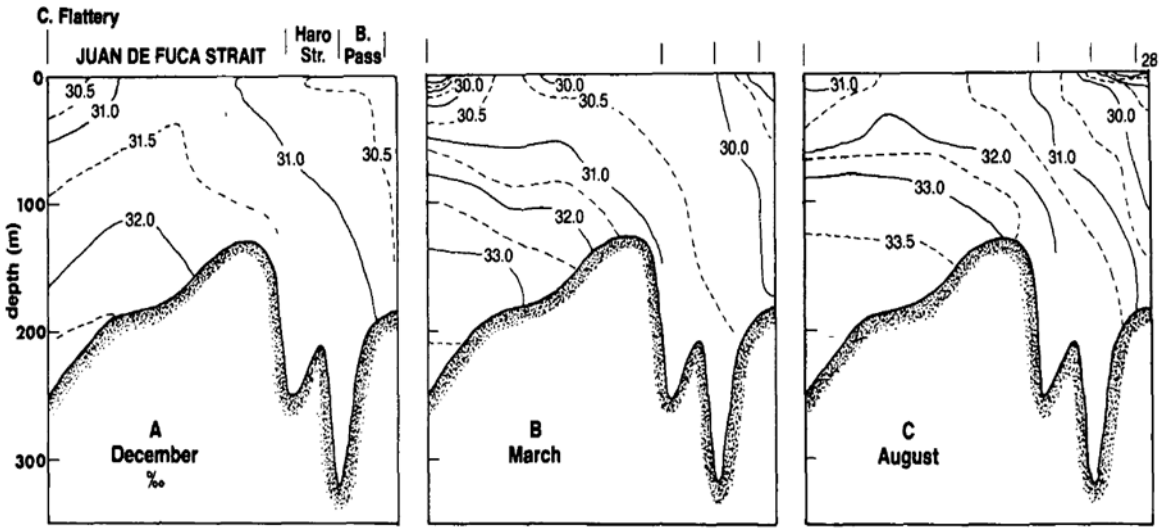

Figure 19. Mid-channel salinity (ppt) from the western Juan de Fuca Strait to Haro Strait; (A) December 1967, (B) March 1968, and (C), and August 1968 (Thomson 1981).

Water in the Juan de Fuca Strait remains cold year around with the exception of a few protected bays and harbours. Direct exposure to the relatively cold waters of the Pacific to the west, and strong tidal mixing in the San Juan and Gulf Islands to the east makes heat retention difficult; regardless of season or depth, water temperatures are rarely warmer than 13°C (Figure 18) (Thomson 1981). At certain times during the winter months, cooling of surface waters due to low air temperatures can result in lower water temperatures in eastern regions of the Strait relative to the west, but rarely would this occurrence result in a difference of more than a 1-2°C (Figure 20) (Thomson 1981).

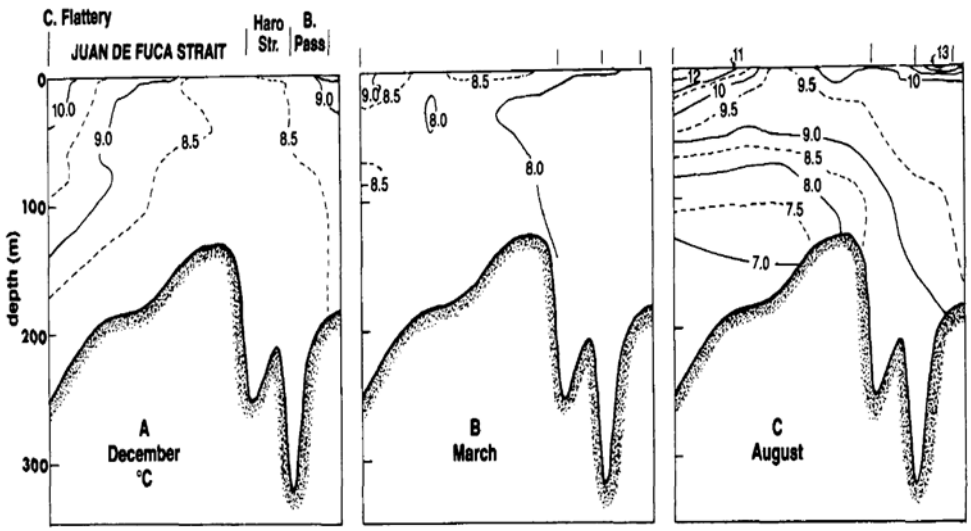

Figure 20. Mid-channel water temperature (ºC) from the western Juan de Fuca Strait to Haro Strait; (A) December 1967, (B) March 1968, and (C) August 1968 (Thomson 1981).

4 CLIMATE

4.1 AIR TEMPERATURE & PRECIPITATION

The area surrounding Vancouver and the Georgia-Fuca system is considered to be one of the warmest and mildest climates in Canada (Davenne and Masson 2001). The southern Strait of Georgia region receives ~600mm of precipitation per year whereas more northern areas of the region receive upwards of 3,000mm per year. Compared to the rest of Canada, average monthly temperatures vary only a small amount throughout the year with mean temperatures between 12 and 18˚C in July, and an average temperature range of 2-6˚C in January (Davenne and Masson 2001; Davidson 1979). Relatively warm winter air and water temperatures mean there is no sea ice in the area (Davenne and Masson 2001). Figure 21 shows mean temperature and precipitation for 1981 to 2010 at Vancouver International Airport; while absolute precipitation may vary slightly around the Inlet, trends in precipitation and temperature are representative of the area surrounding Burrard Inlet (Davidson 1979; Environment Canada 2018).

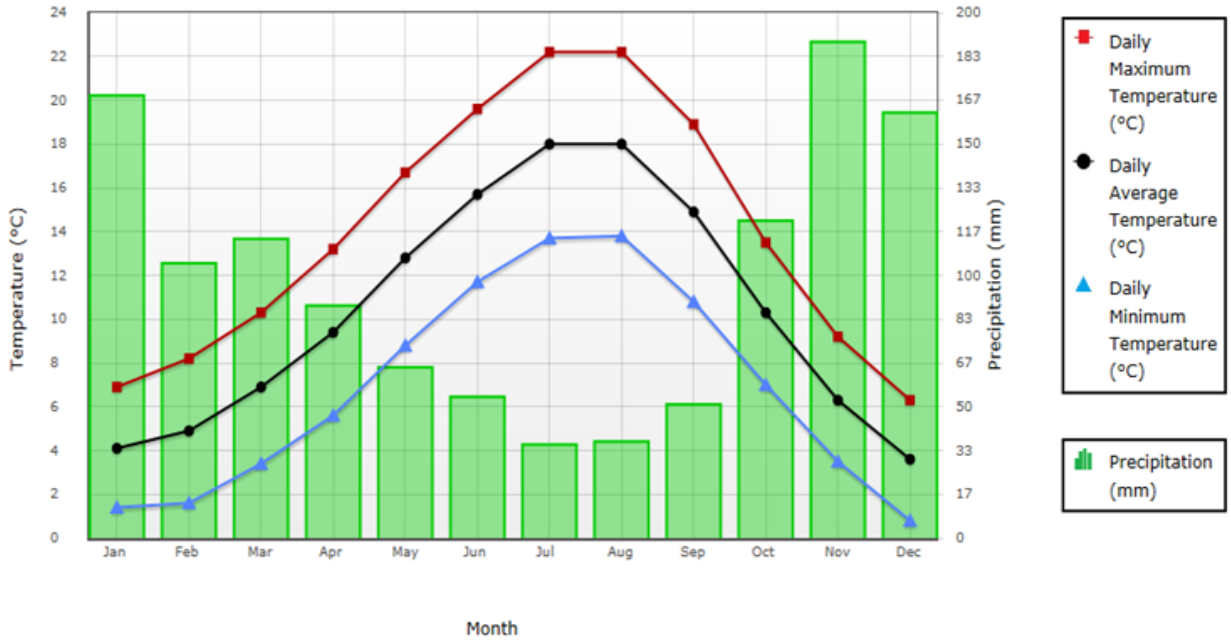

Figure 21. Temperature and precipitation chart for 1981 to 2010 Canadian climate normals at Vancouver International Airport (Environment Canada 2018).

4.2 WIND AND WAVES

4.2.1 Burrard Inlet

The Vancouver area receives westerly winds from the Strait of Georgia, easterly winds from Howe Sound and the Fraser Valley, and southerly winds from Juan de Fuca Strait. Winds from the east occur most frequently, but the relatively uncommon strong westerlies tend to be most dangerous winds in the Burrard Inlet (Environment Canada

2015). In this area, 98% of wind speeds are less than 3.5 m/s (12.6 km/h), and 78% of wind speeds are less than 2.0 m/s (7.2 km/h). Winds blow mostly from the East and the West, and the frequency from the East (27% of the time) is higher than from the west (13% of the time). Wind speeds greater than 12.6 km/h occur mostly from the east, southeast, and west (Golder Associates Ltd. 2012). Wind maxima occur mostly from the west in the winter and from the southeast and east in the summer (EBA Engineering Consultants Ltd. 2013; Golder Associates Ltd. 2012).

4.2.2 Strait of Georgia

Due to the seasonal migration of the Aleutian Low and North Pacific High pressure zones, winds in the Strait of Georgia can be quite dynamic and vary considerably throughout the year (EBA Engineering Consultants Ltd. 2013). Winds from the southeast predominate through the winter months in much of the Strait of Georgia while winds emanating from the northwest are more prevalent in summer. A year-round small-scale enclosed anti-clockwise wind pattern dominates the San Juan and Gulf Islands area to the south (Figure 22) (Feely and Lamb 1979). Frontal systems moving through the area result in short-term deviations from this pattern and differences in local topography within the Strait also have a noticeable effect on winds, particularly in the southern half of the Strait where the orientation of channels tends to determine wind direction (EBA Engineering Consultants Ltd. 2013). Winds are strongest during the winter when northwesterlies develop behind cold fronts moving over the mainland. However, these strong northwesterlies have also been known to occur on occasion during the summer months without much prior indication. Winter outflow winds up to and exceeding 20m/s also occur on occasion in the Strait of Georgia, particularly in the area of Howe Sound, when northerly outflow winds converge with easterly outflows from the Fraser Valley (EBA Engineering Consultants Ltd. 2013).

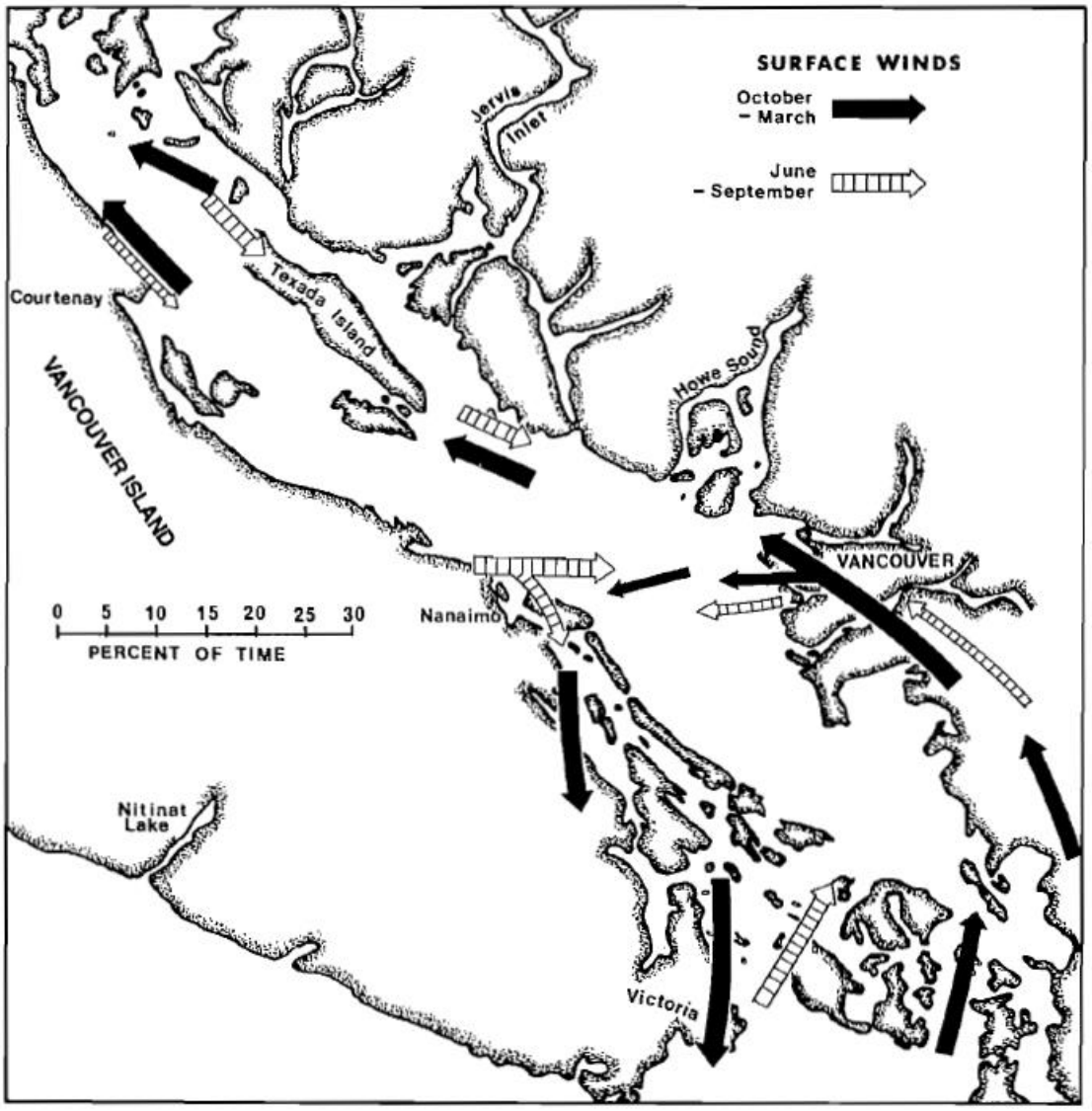

Figure 22. Dominant surface wind patterns over Strait of Georgia in winter (solid arrows) and summer (hatched arrows). Thick arrows correspond to speeds 4.5-9 m/s, thin arrows less than 4.5 m/s. Comparison of length of arrow to scale on left yields frequency of occurrence of particular wind (Thomson 1981).

Waves resulting from wind currents in the Strait of Georgia are highly variable depending on their location within the strait, but generally follow the direction of the predominant winds: southeast in winter and northwest in summer in northern areas of the strait, and a more complex counterclockwise wind system governed by channels and passes in the San Juan and Gulf Islands (Figure 22). A study conducted near Sand Heads over 26 months between 1974 and 1976 shows that 39% of significant wave heights are above 0.33m and 4% of significant wave heights are above 1m. These waves, however, are frequently modified due to reflection, refraction, and diffraction in shallow waters (Thomson 1981). Waves moving toward the shore can also steepen

dramatically when currents flow in the opposite direction; such conditions are frequently found near the north arm of the Fraser River where dangerous rips have been observed during periods of high river discharge and also during the ebb tide (Jonsson 1990; Stronach et al. 2006; Thomson 1981). In this area, wave height has been known to double in a matter of a few hours during the transition from slack to ebb tide (Komen et al. 1994). In the southern Strait of Georgia, waves also tend to interact with tidal currents in an erratic manner within the narrow channels of the San Juan and Gulf Islands, often posing severe hazards to ships travelling through the area (EBA Engineering Consultants Ltd. 2013). Having said that, the main shipping channels through the San Juan and Gulf Islands, Haro Strait, Boundry Pass, and Rosario Strait, are all sheltered and have a small fetch, meaning wind-generated waves tend not to be a significant factor in these areas (EBA Engineering Consultants Ltd. 2013).

4.2.3 Juan de Fuca Strait

Although winds in the Juan de Fuca Strait are largely generated by the same processes as those in the Strait of Georgia, the effects of the Olympic Mountains tend to shift the winds to primarily easterly in winter and westerly in the summer (Figure 23) (Thomson 1981). Similar to the Strait of Georgia, winds are strongest during the winter months, averaging just over 10 m/s during this time, with the strongest winds generally being found to the west of the Strait (Feely and Lamb 1979; Thomson 1981). During the winter, winds greater than 15m/s are observed 10-15 days per month in winter compared to only 1-2 days per month in summer (Thomson 1981).

Two important factors influencing winds in the Juan de Fuca that aren't associated with the broader oceanic wind regime are polar outbreaks in winter and the sea breeze in summer (Thomson 1981). Polar outbreaks which result in strong easterly winds are common in winter when skies are clear and temperatures are near freezing due to the formation of a high pressure region over Washington State (Thomson 1981). In summer, moderate winds build along the Strait as the warming of the land during the day draws cooler air inland from the ocean which combines with westerly oceanic winds to cause an increase in wind speed to the east. Although significant, the prominence of these summer winds is less intense than the effects of the polar outbreaks in winter (Thomson 1981).

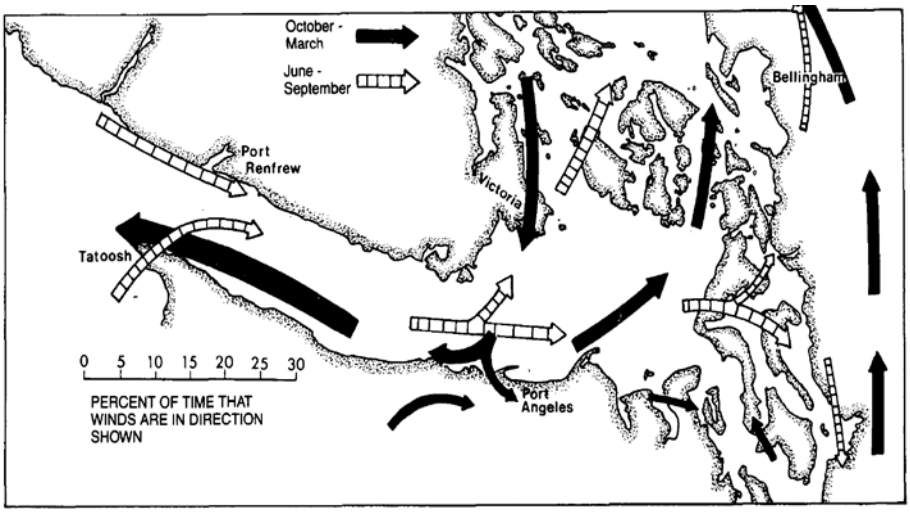

Figure 23. Dominant surface wind patterns over Juan de Fuca Strait in winter (solid arrows) and summer (hatched arrows). Thick arrows correspond to speeds over 9m/s; medium arrows 4.5-9m/s, and thin arrows less than 4.5 m/s. Comparison of length of arrow to scale on left yields frequency of occurrence of particular wind (Thomson 1981).

Waves in the Juan de Fuca Strait are a combination of waves generated by local winds and large swells coming in from the Pacific. Waves are generally largest at the mouth of the Strait where it meets the Pacific (Thomson 1981). Due to the ocean swell, wave action tends to be intense throughout, and long waves are able to penetrate deep into the Juan de Fuca with no wind energy required (Thomson 1981). At its mouth, influence from the Pacific results in wave heights that exceed 6 m at least 10% of the time in winter and 3 m about 10% of the time in summer with swell height steadily decreasing as they travel further east, into the Strait (Thomson 1981). Excluding the ocean swell, with fully developed seas under sustained 10 m/s winds in Juan de Fuca Strait, significant wave heights of 1.5 m and probable maximum heights of 2.7 m could be expected. That said, under normal conditions, waves are not typically larger than 2 m (Thomson 1981).

Wave roses included in EBA Engineering Consultants Ltd. (2013) from the western end of the Juan de Fuca Strait (Neah Bay) show that waves originating from the Pacific tend to dominate the area while waves coming from the east or elsewhere play only a minor role. Wave roses for the eastern Strait (New Dungeness) near Victoria are also dominated by waves from the west, but during the summer months there is a more significant presence of waves coming from the east (EBA Engineering Consultants Ltd. 2013).

5 PAST OIL SPILLS

The Transportation Safety Board of Canada (TSBC) maintains a database of air, marine, rail, and pipeline incidents and accidents, collectively called occurrences, and publishes annual reports with statistics (Transportation Safety Board of Canada 2018). The marine occurrences database contains information on the vessels involved, cargo, location, reported pollution and more. As reporting requirements have changed over time the number of marine occurrences entered into the database per year has increased. The most recent update of TSBC reporting requirements was 2014 (Transportation Safety Board of Canada 2014), and data for many more occurrences are available from that time onward. Statistics have been compiled here for occurrences of interest for the entire span of the database (1975-2018) and on an annual average basis for full years since the new reporting requirements (2015-2017).

Statistics for four different types of marine occurrences have been compiled: 1) occurrences involving cargo vessels, either tankers or barges, that transport petroleum products; 2) occurrences in which pollution was reported or any type of cargo was lost overboard; 3) occurrences in which petroleum products were reported spilled on board or into the water; and 4) occurrences in which vessels were sunk, capsized or otherwise seriously damaged beyond repair, and expected to release fuel into the environment.

Statistics for the Strait of Juan de Fuca, Strait of Georgia and the Port of Vancouver were compiled by filtering for occurrences in the province of BC or in international waters, within the latitudinal range of 48°N to 49.5°N, and within the longitudinal range of 122.6°W to 124.7°W. This corresponds to the Strait of Georgia as far north as the Port of Vancouver and the Strait of Juan de Fuca as far west as the entrance to the Pacific, which roughly corresponds to the shipping lane to the Port of Vancouver. See Table 1 for statistics.

Table 1. Transportation Safety Board incident and accident occurrences in the Port of Vancouver Shipping Lane

Occurrences involving…	All years (1975-2018)	Annual Average (2015-2017)
All occurrences	2060	167.3
Petroleum cargo vessels	18	1.7
Pollution or cargo lost overboard	129	11.0
Petroleum spills onboard or overboard	28	6.3
Vessels sunk, capsized or destroyed	52	2.7

Three of the categories from Table 1, occurrences involving pollution, petroleum and vessel loss, have significant overlap. However, cargo vessels carrying petroleum products have not been involved in any occurrences of the other three categories. The median volume of petroleum spilled per occurrence from 2015-2017 was 40 litres. The amount spilled from 1975-2018 was 10,000-20,000 litres of F-76 petroleum distillates spilled from the HMCS Calgary into the Strait of Georgia in 2018 (Kines 2018;

Pawson 2018). Another significant spill was in 2016 when a barge with 40,000 litres of diesel oil on board broke loose from its mooring and ran aground spilling about 25,000 litres into Esquimalt Harbour (Laanela 2016). Five other occurrences from 2014 to 2018 involved spills of petroleum products greater than 1000 litres, including the Marathassa spill in 2015.

Most of the vessels lost in 1975-2018 were either fishing boats (26) or tugs (18). The amount of fuel on board these vessels is not consistently recorded in the database, but they are relatively small vessels with median lengths of 12.5 and 11.4 meters for fishing boats and tugs, respectively. TSBC statistics have shown a decreasing trend in accidents involving both fishing and non-fishing vessels from 2007 onward (Transportation Safety Board of Canada 2017). Two of the remaining incidents involved BC Ferries vessels damaged but not sunk, and several pleasure craft and small passenger vessels which sunk. In one occurrence from 2001, the “Destiny 1”, a 32m charter vessel, caught fire near Granville Island and was subsequently towed to the outer harbour where it sank. The accident report states that the vessel was later beached and then salvaged.

The following are a collection of some of the more noteworthy spills that have occurred in this area for which documentation was obtained during our review of the literature.

5.1 WESTRIDGE OIL SPILL

On July 24, 2007 approximately 224,000 L of crude oil was released following a pipeline rupture during construction work on the Barnett Highway in Burnaby, BC (Jacques Whitford Stantec AXYS Ltd. 2009). Approximately 100,000 L of that oil was discharged into the inner Burrard Inlet near Kask Creek through the storm drain system and affected ~1,200 m of shoreline. An estimated 6,000 L of oil was not recovered during cleanup efforts and was presumed that at least some of that oil entered the water column of Burrard Inlet (Jacques Whitford Stantec AXYS Ltd. 2009). Monitoring of PAHs in sediment along the shoreline of the spill area is ongoing (Bull and Freyman 2013).

5.2 WESTWOOD ANETT OIL SPILL

On August 5th, 2006 the general cargo ship Westwood Anette drifted into a pylon and punctured its day-tank during high wind conditions releasing 243 barrels of IFO 380 fuel oil into Howe Sound and the adjacent Squamish Estuary which are located directly to the north of Burrard Inlet. Response efforts included skimming and other techniques, but attention was paid to using strategies what would not cause more harm than good when remediating the sensitive marsh area (EnviroEmerg Consulting Services 2008).

5.3 NESTUCCA OIL SPILL

In the midst of a storm on the night of December 22, 1988, the barge Nestucca collided with its tug off the northern pacific coast of Washington after its tow cable broke (Pacific States/British Columbia Oil Spill Task Force 2011). In total, 231,000 gallons of Bunker C were spilled. Although this spill did not occur in the Port of Vancouver study area, by December 31, oil had reached the entrance to Juan de Fuca Strait, and by January 15 some oil had washed up on the Canadian side of the strait (Pacific States/British Columbia Oil Spill Task Force, 2011). Ebbesmeyer et al. (1991) estimate the speed of the drifting oil to be 9 nautical miles per day (19 cm/s) into the Juan de Fuca Strait.

5.4 WORLD BOND OIL SPILL

On June 4th 1972 a filling flange failed on an oil tanker (World Bond) while it was unloading at the Atlantic Richfield refinery in Cherry Point, Washington. In total, 13,000 gallons of crude oil were spilled and reached Canadian shores in the Juan de Fuca Strait during the height of a particularly large herring spawn (Pacific States/British Columbia Oil Spill Task Force 2011).

5.5 ANACORTES OIL SPILL

On April 26, 1971, ~230,000 gallons of No. 2 diesel was spilled at the Texaco refinery near Anacortes in the San Juan Islands (Ebbesmeyer et al. 1979). The slick from the spill traveled southward through Rosario Strait, reaching Smith Island, some 38 km downstream in the Juan de Fuca Strait, the same day. Efforts to contain the spill were largely ineffective; there is no documentation of the long-term movement of the slick as it travelled through the Juan de Fuca Strait (Thomson 1994).

5.6 M/V ANDRE GOMES

On July 4, 2006, the bulk carrier M/V Andre Gomes spilled 200 gallons of Bunker C fuel oil into the Burrard Inlet (Ross 2006). After one day of skimming, Shoreline Cleanup Assessment Team (SCAT) teams estimated that an 800 m by 0.5 m of shoreline was oiled in 4 segments near Chevron on the south side of Burrard Inlet, and Vancouver Pile Driver, Lynnwood Marina and Rempel Bros on the north side of the Inlet (Figure 24).

Over the span of three weeks following the spill, shoreline restoration measures included manual scraping, brushing, and washing of oiled surfaces, including the use of chemical oil dispersants to assist with these tasks (Figure 25). Oil absorbing boom and pompoms were also deployed at the water line in order to catch any oil washed back to the water from the shoreline (Ross 2006).

Figure 24. Oiled shoreline following the M/V Andre Gomes spill before shoreline cleanup (Ross 2006)

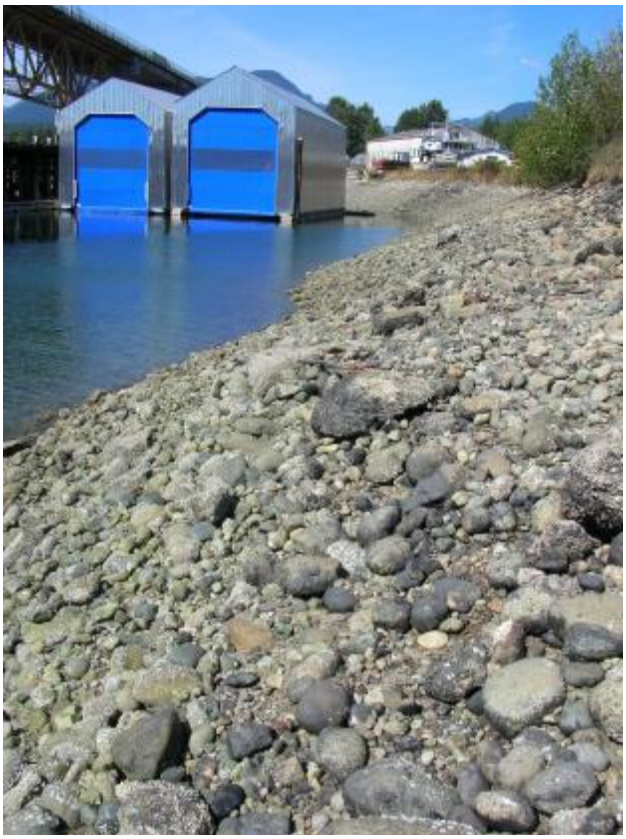

Figure 25. Oiled shoreline following the M/V Andre Gomes spill after shoreline cleanup (Ross 2006)

5.7 M/V MARATHASSA OIL SPILL

On April 8, 2015, an estimated 2,800 litres of intermediate fuel oil (IFO-380) leaked from a cargo vessel (M/V Marathassa) while it was anchored in the outer harbour of Burrard Inlet (Butler 2015). Once the spill was detected, absorbent boom was deployed around the ship to prevent further contamination, and water skimming began to recover oil that had already been spilled. In total, it is estimated that 1400L of oil was recovered using skimmer equipment (Butler 2015). In addition to this, several National Aerial Surveillance Flights (NASP) were conducted during the response effort in order to estimate the extent of the spill. It was estimated that by the afternoon of the following day only 5.9 L of oil was remaining on the surface of the water (Butler 2015).

Despite these efforts, some of the spilled oil formed globs and were carried to beaches in the area. Following the survey of over 85 km of shoreline by a Shoreline Cleanup Assessment Technique (SCAT) team it was determined that the majority of the shoreline contamination took place near the west side of Stanley Park, North Vancouver, and West Vancouver (Wootton 2015).

A hind cast spill modelling exercise was conducted by Zhong et al. (2018) using a three-dimensional high resolution hydrodynamic model called the Finite-Volume Community

Ocean Model (FVCOM) that fed into the Oil Spill Contingency and Response (OSCAR) model. In this exercise, forty numerical simulations were run using varied release time, discharge duration, wind forcing, and recovery action parameters. It was found that the OSCAR spill model was effective in simulating oil mass balance, and trajectories (), and various weathering processes such as spreading, drifting, natural dispersion, chemical dispersion, evaporation, stranding, dissolution, adsorption, settling, emulsification and biodegradation (Zhong et al. 2018).

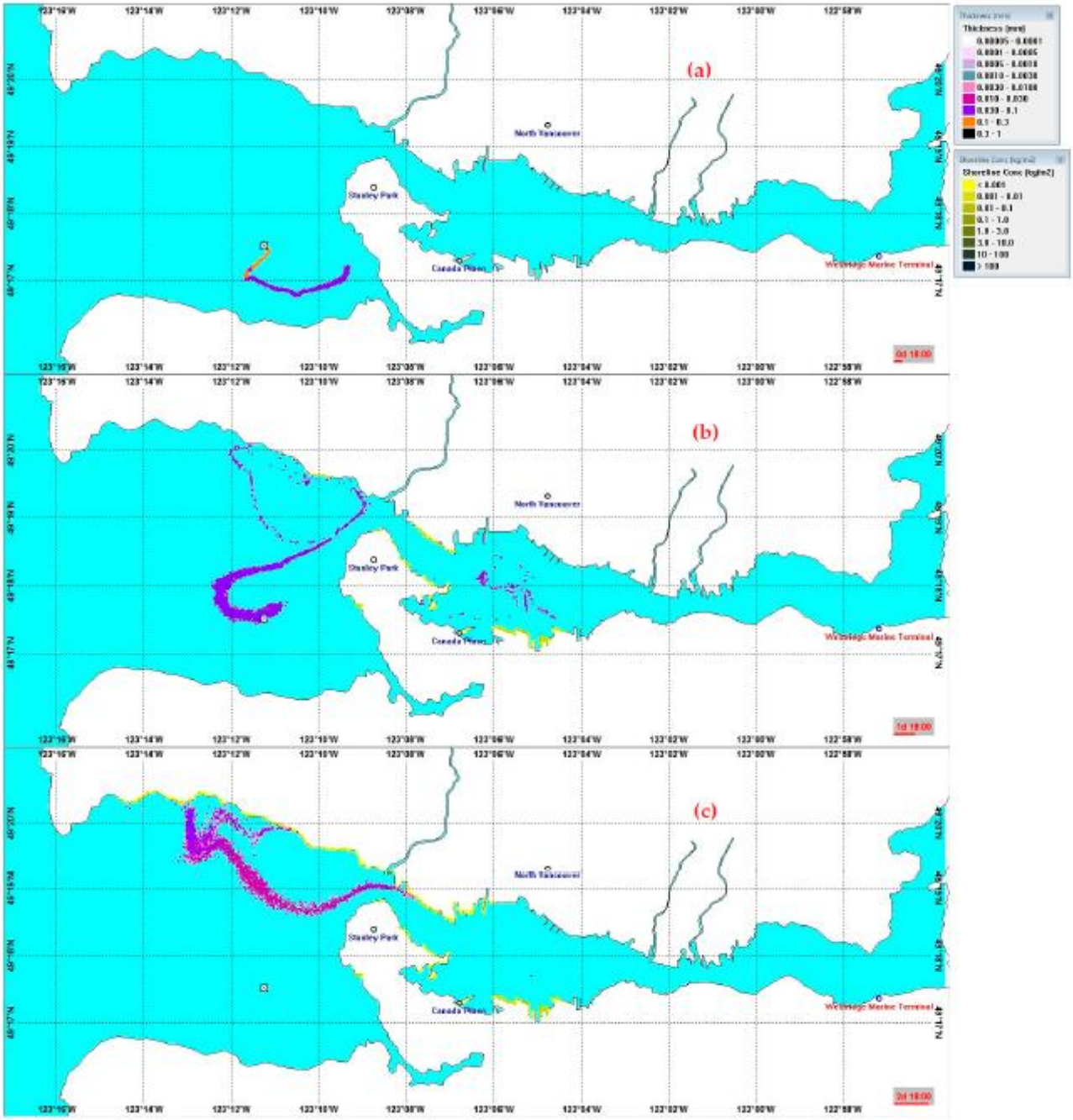

Figure 26. Example output of the Oil Spill Contingency and Response (OSCAR) oil spill model for the M/V Marathassa spill in Vancouver, BC. These simulations show the progression of a 22 hour continuous spill at the 18h (top), 1d 18h (middle), and 2d 18h (bottom) time points (Zhong et al. 2018).

6 CONCLUSIONS

The area surrounding the Port of Vancouver has the mildest climate in Canada. Vancouver experiences only occasional snow and ice during the winter. In addition to relatively mild temperatures, the area also is known for high levels of precipitation.

Port Metro Vancouver is Canada's largest and busiest port with 1.7 million metric tons of gasoline and 1.4 million tons of fuel oil passing through in 2006: much of that activity takes place within Burrard Inlet. Although the Burrard Inlet connects to the Strait of Georgia which itself is relatively large, it is long, fairly narrow, and highly sheltered from the Pacific Ocean. Mixing within the inner reaches of the Inlet is limited by two narrows which restrict the exchange of water. Although the outer Harbour mixes readily with the Strait of Georgia, due to its sheltered nature, the exchange of water between the Strait of Georgia and the Pacific Ocean is limited and must pass through or by a series of interconnected waterways which span the border between the U.S. and Canada; San Juan and Gulf Islands, Puget Sound, and the Juan de Fuca Strait.

The vast majority of interaction between the Strait of Georgia and the Pacific happens through the Juan de Fuca Strait to the south. Bridging the gap between the Strait of Georgia and the Juan de Fuca are the San Juan and Gulf Islands which are essentially a matrix of small islands and narrow channels flowing between them. The two primary channels through the islands are the Rosario Strait and Haro Strait/Boundary Pass with Haro Strait being the deeper and more heavily travelled route. Due to the highly restricted flow through the San Juan and Gulf Islands, currents can be very strong and somewhat variable depending on the weather and tides, making safe navigation a challenge, particularly during intense weather events.

The Strait of Georgia and connected waterways are also highly impacted by sediment laden freshwater flow from the Fraser River which can reach 11,000 m^3/s in early summer. Due to this high level of freshwater input and the relatively low mixing between the Strait of Georgia and the Pacific Ocean, a thick layer of relatively turbid brackish water can develop over wide areas of the Strait during periods of high river flow.

7 REFERENCES

Akenhead, S.A. 2013. An Introduction to the Strait of Georgia. Alexander Department of Geography, Vancouver Island University.

Barrie , J.V., Hetherington, R., Macleod, R., and 2014. Pacific margin, C.s.p.a.c.h.o.g., tectonism, oceanography and sea-level change. Chapter 22, p.305-313. [In Continental Shelves of the world. Their evolution during the last glacio-eustatic cycle. Edited by F.L.Chiocci and A.R. Chivas. 2014. Pacific margin, Canada shelf physiography: a complex history of glaciation, tectonism, oceanography and sea-level change. Continental Shelves of the world. Their evolution during the last glacio-eustatic cycle. Geological Society of London, London. pp. 305-313.

Barrie, J.V., Hill, P.R., Conway, K.W., Iwanowska, K., and Picard, K. 2005. Environmental marine geoscience 4: Georgia Basin: Seabed features and marine geohazards. Geosci Can **32**(4): 145-156. Available from <Go to ISI>://WOS:000241134800001 [accessed.

Bull, J., and Freyman, L. 2013. Status of Water Quality Objectives Attainment in Burrard Inlet and Tributaries 1990 to 2010. Ministry of Environment Environmental Protection South Region, B.C.

Burrard Inlet Environmental Action Program. 1997. Burrard Inlet point source discharge inventory.

Burrard Inlet Environmental Action Program. 2010. Burrard Inlet Tracking Report.

Burrard Inlet Environmental Action Program. 2011. Consolidated Environmental Management Plan for Burrard Inlet.

Butler, J. 2015. Independent Review of the M/V Marathassa Fuel Oil Spill Environmental Response Operation. http://www.ccg-gcc.gc.ca/independent-review-Marathassa-oil-spill-ER-operation.

Cannon, G.A. 1978. Circulation in the Strait of Juan de Fuca. NOAA Technical Report **399**(29).

Cartwright, D.S. 2003. Multibeam bathymetric Surveys in the Fraser River Delta, Managings Service acoustic refraction issues. M. Eng. Report, Geodesy and Geomatics.

Coastal and Ocean Resources. 2018. ShoreZone Habitat Mapping Summary Report - Burrard Inlet Survey Area.

Crean. 1988. Numerical simulation of oceanographic processes in the waters between Vancouver Island and the mainland. Oceanography and Marine Biology, An Annual Review **26**: 11-142.

Crean, P.B., and Ages, A.B. 1971. Oceanographic records from twelve cruises in the Strait of Georgia and Juan de Fuca Strait, 1968. Department of Energy, Mines, and Resources, Marine Research Sciences Branch.

Crean, P.B., Murty, T.S., and Stronach, J.A. 1988. Numerical-Simulation of Oceanographic Processes in the Waters between Vancouver-Island and the Mainland. Oceanogr Mar Biol **26**: 11-142. Available from <Go to ISI>://WOS:A1988Q990100001 [accessed.

Davenne, E., and Masson, D. 2001. Water Properties in the Strait of Georgia and Juan de Fuca. Institute of Ocean Science, F.a.O. Canada, Sidney, B.C.

Davidson, L.W. 1979. Physical oceanography of Burrard Inlet and Indian Arm. University of British Columbia, Vancouver, B.C.

De Young, B. 1986. The Circulation and Internal Tide of Indian Arm. University of British Columbia, Vancouver, B.C.

Demes, K., Piscitelli, M., Chang, S., Stone, J., Quayle, M., and Denise, W., D. 2013. Economic and Biophysical Impacts of Oil Tanker Spills Relevant to Vancourver, Canada, A literature Review. UBC Biodiversity Research Centre, University of British Columbia.

Dewey, R., and Tunnicliffe, V. VENUS: Future Science on a Coastal Mid-depth Observatory. *In* 3rd Int. Workshop on Scientific Use of Submarine Cables and Related Technologies. 2003. pp. 232-233.

Dunbar, D.S., and Burling, R.W. 1987. A Numerical-Model of Stratified Circulation in Indian Arm, British-Columbia. J Geophys Res-Oceans **92**(C12): 13075-13105. doi:DOI 10.1029/JC092iC12p13075.

EBA Engineering Consultants Ltd. 2013. Meteorological and Oceanographic data relevant to the proposed Westridge Terminal Shipping Expansion.

Ebbesmeyer, C.C., Cox, J.M., Helseth, J.M., Hinchey, L., and Thomson, D.W. 1979. Dynamics of Port Angeles Harbor and approaches. EPA-60017-79-252.

Ebbesmeyer, C.C., Cayan, D.R., McLain, D.R., Nichols, F.H., Peterson, D.H., and Redmond, K.T. 1976 step in the Pacific climate: forty environmental changes between 1968-1975 and 1977-1984. *In* Pacific climate (PACLIM) workshop. 1991. *Edited by* J.L. Betancourt and V.L. Tharp.

Emergency Management B.C. 2012. Fraser River Sediment Management Program. Government of B.C.

Encyclopaedia Britannica. 2018. Juan de Fuca Strait. Available from https://www.britannica.com/place/Juan-de-Fuca-Strait2018].

EnviroEmerg Consulting Services. 2008. Major marine vessel casualty risk and response preparedness in British Columbia. Vancouver, B.C.

Environment Canada. 2015. National marine weather guide – British Columbia regional guide.

Environment Canada. 2018. Canadian Climate Normals 1981-2010 Station Data. Available from http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&txtStationName=vancouver&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=889&dispBack=02018].

Evoy, R.W., Moslow, T.F., Patterson, R.T., and Luternauer, J.L. 1993. Patterns and Variability in Sediment Accumulation Rates, Fraser-River Delta Foreslope, British-Columbia, Canada. Geo-Mar Lett **13**(4): 212-218. doi:Doi 10.1007/Bf01207750.

Feely, R.A., and Lamb, M.F. 1979. A study of the dispersal of suspended sediment from the Fraser and Skagit River into Northern Puget Sound using Landsat Imagery. U.S. Environmental Protection Agency.

Fisheries and Oceans Canada. 2012a. Canadian Tide and Current Tables. Volume 6 – Discovery Passage and West Coast of Vancouver Island.

Fisheries and Oceans Canada. 2012b. Canadian Tide and Current Tables, Volume 5 - Juan de Fuca Strait and Strait of Georgia.

Golder Associates Ltd. 2012. Harbourside Waterfront. Sea Level Rise Food Management Plan. C. Properties.

Grant, S.C.H., and Ross, P.S. 2002. Southern Resident Killer Whales at Risk: Toxic Chemicals in the British Columbia and Washington Environment. Can. Tech. Rep. Fish. Aquat. Sci. **2412**: 111.

Haggarty, D.R. 2001. An Evaluation of Fish Habitat in Burrard Inlet. University of Victoria, Victoria, B.C.

Halverson, M.J., and Pawlowicz, R. 2008. Estuarine forcing of a river plume by river flow and tides. J Geophys Res-Oceans **113**(C9). doi:Artn C09033 10.1029/2008jc004844.

Harrison, P.J., Mackas, D.L., Frost, B.W., Macdonald, R.W., and Crecelius, E.A. An Assessment of Nutrients, Plankton and Some Pollutants in the Water Column of Juan de Fuca Strait, Strait of Georgia and Puget Sound, and Their Transboundary Transport. *In* BC/Washington Symposium on the Marine Environment 1994. *Edited by* R.C.H. Wilson and R.J. Beamish and F. Aitkens and J. Bell. Canadian Technical Report of Fisheries and Aquatic Sciences. pp. 36-98.

Hart, B.S., Prior, D.B., Barrie, J.V., Currie, R.G., and Luternauer, J.L. 1992. A River Mouth Submarine Channel and Failure Complex, Fraser Delta, Canada. Sediment Geol **81**(1-2): 73-87. doi:Doi 10.1016/0037-0738(92)90057-X.

Hill, P.R., Conway, K., Lintern, D.G., Meule, S., Picard, K., and Barrie, J.V. 2008. Sedimentary processes and sediment dispersal in the southern Strait of Georgia, BC, Canada. Mar Environ Res **66**: S39-S48. doi:10.1016/j.marenvres.2008.09.003.

Holbrook, J.R.M., R. D., Kachel, D.G., Wright, C., and 1980. Circulation in the Strait of Juan de Fuca: Recent Oceanographic Observations in the Eastern Basin, p.N.T.R.E.-P. 1980. Circulation in the Strait of Juan de Fuca: Recent Oceanographic Observations in the Eastern Basin. NOAA Technical Report ERL 412-PMEL 33: 21.

Houston, G., Gaudreau, R., and Sinclair, M. 2013. A Review of Canada's Ship-source Oil Spill Preparedness and Response Regime: Setting the course for the future. Tanker Safety Panel Secretariat 978-1-100-54627-8, Ottawa, ON.

Jacques Whitford AXYS Ltd. 2008. Burrard Inlet Environmental Indicators Report Public Consultation Document.

Jacques Whitford Stantec AXYS Ltd. 2009. Long Term Monitoring Program: Foreshore Environment, Westridge Hydrocarbon Accidental Release.

Johannessen, S.C., Macdonald, R.W., and Paton, D.W. 2003. A sediment and organic carbon budget for the greater Strait of Georgia. Estuar Coast Shelf S **56**(3-4): 845-860. doi:10.1016/S0272-7714(02)00303-7.

Johannessen, S.C., Masson, D., and Macdonald, R.W. 2006. Distribution and cycling of suspended particles inferred from transmissivity in the Strait of Georgia, Haro Strait and Juan de Fuca Strait. Atmosphere-Ocean **44**(1): 17-27. doi:DOI 10.3137/ao.440102.

Johannessen, S.C., O'Brien, M.C., Denman, K.L., and Macdonald, R.W. 2005. Seasonal and spatial variations in the source and transport of sinking particles in the Strait of Georgia, British Columbia, Canada. Mar Geol **216**(1-2): 59-77. doi:10.1016/j.margeo.2005.01.004.

Jonsson, I.G. 1990. Wave Current Interactions. *In* The Sea. *Edited by* B. Le Mehauté and D.M. Hanes. Harvard University Press.

Khangaonkar, T., Long, W., and Xu, W.W. 2017. Assessment of circulation and inter-basin transport in the Salish Sea including Johnstone Strait and Discovery Islands pathways. Ocean Model **109**: 11-32. doi:10.1016/j.ocemod.2016.11.004.

Kines, L. 2018. Less fuel spilled from HMCS Calgary than first reported. *In* Times Colonist, https://www.timescolonist.com/news/local/less-fuel-spilled-from-hmcs-calgary-than-first-reported-1.23186928.

Komen , G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., and Janssen, P.A.E.M. 1994. Dynamics and Modelling of Ocean Waves. Cambridge University Press. pp. 532.

Kostaschuk, R.A., and Luternauer, J.L. 2004. Sedimentary processes and their environmental significance : Lower main channel, Fraser river estuary. *In* Issues of an Urban Estuary. *Edited by* B.J. Groutx and D.C. Mosher and J.L. Luternauer and D.E. Bilderback. Geology Survey of Canada. pp. 81-92.

Kostyniuke, S., and Lin, L. 2003. A Review of Burrard Inlet Effluent Discharges.

Laanela, M. 2016. Esquimalt fuel spill leaves fishing, beaches closed nearly 4 months later. *In* CBC News, https://www.cbc.ca/news/canada/british-columbia/equimalt-fuel-spill-1.3742537.

Leblond, P.H. 1983. The Strait of Georgia - Functional-Anatomy of a Coastal Sea. Can J Fish Aquat Sci **40**(7): 1033-1063. doi:DOI 10.1139/f83-128.

Levings, C.D., and Samis, S. 2001. Environmental Assessment of Vancouver Harbour Data Report for the PICES Practical Workshop. *In* PICES Practical Workshop. *Edited by* C.M. Stehr and T. Horiguchi.

Macdonald, R.W., and Pedersen, T.F. 1991. Geochemistry of Sediments of the Western Canadian Continental-Shelf. Cont Shelf Res **11**(8-10): 717-735. doi:Doi 10.1016/0278-4343(91)90076-I.

Masson, D. 2002. Deep water renewal in the Strait of Georgia. Estuar Coast Shelf S **54**(1): 115-126. doi:10.1006/ecss.2001.0833.

Masson, D. 2006. Seasonal water mass analysis for the Straits of Juan de Fuca and Georgia. Atmosphere-Ocean **44**(1): 1-15. doi:DOI 10.3137/ao.440101.

Masson, D., and Cummins, P.F. 2000. Fortnightly modulation of the estuarine circulation in Juan de Fuca Strait. J Mar Res **58**(3): 439-463. doi:Doi 10.1357/002224000321511106.

Masson, D., and Cummins, P.F. 2004. Observations and modeling of seasonal variability in the Straits of Georgia and Juan de Fuca. J Mar Res **62**(4): 491-516. doi:Doi 10.1357/0022240041850075.

Mosher, D.C., and Thomson, R.E. 2002. The Foreslope Hills: large-scale, fine-grained sediment waves in the Strait of Georgia, British Columbia. Mar Geol **192**(1-3): 275-295. doi:Pii S0025-3227(02)00559-5

Doi 10.1016/S0025-3227(02)00559-5.

Nijman, R., and Swain, L.G. 1990. Ambient water Quality objectives for Burrard Inlet Coquitlam-Pitt River area. M.o.E.B. Columbia.

Pacific States/British Columbia Oil Spill Task Force. 2011. The Stakeholder Workgroup Review of Planning and Response Capabilities for a Marine Oil Spill on the U.S./Canadian Transboundary Areas of the Pacific Coast Project.

Pawlowicz, R. 2002. Observations and linear analysis of sill-generated internal tides and estuarine flow in Haro Strait. J Geophys Res-Oceans **107**(C6). doi:Artn 3056 10.1029/2000jc000504.

Pawlowicz, R., Di Costanzo, R., Halverson, M., Devred, E., and Johannessen, S. 2017. Advection, Surface Area, and Sediment Load of the Fraser River Plume Under Variable Wind and River Forcing. Atmosphere-Ocean **55**(4): 293-313. doi:10.1080/07055900.2017.1389689.

Pawson, C. 2018. Canadian navy ship spills 30,000 litres of fuel in Strait of Georgia. *In* CBC News, https://www.cbc.ca/news/canada/british-columbia/hmcs-calgary-fuel-spill-1.4551467.

Pedersen , T.F., and Waters, R.D. 1989. Assessment of the enrichment of cadmium and other metals in the sediments of Port Moody and Indian Arm, British Columbia. Environment Canada.

Pfly. 2018. Gulf Islands map 2. https://en.wikipedia.org/wiki/Gulf_Islands#/media/File:Gulf_Islands_map_2.png.

Port Metro Vancouver. 2012. Moving Goods Through Marine Ports in Metro Vancouver.

Ross, P. 2006. Personal Communication: M/V Andre Gomes Bunker C Spill.

Soontiens, N., and Allen, S.E. 2017. Modelling sensitivities to mixing and advection in a sill-basin estuarine system. Ocean Model **112**: 17-32. doi:10.1016/j.ocemod.2017.02.008.

Stacey, M.W., Pieters, R., and Pond, S. 2002. The simulation of deep water exchange in a fjord: Indian Arm, British Columbia, Canada. J Phys Oceanogr **32**(10): 2753-2765. doi:Doi 10.1175/1520-0485(2002)032<2753:Tsodwe>2.0.Co;2.

Stronach, J., Zaremba, L., Wong, M., Neil, L., and McLennan, N. 2006. Wave and Current Forecast System for the Mouth of the Fraser River. *In* 9th International Workshop on Wave Hindcasting & Forecasting, Victoria, B.C.

Sutherland, D. 2004. Water Quality Objectives Attainment Monitoring in Burrard Inlet in 2002. B.C. Ministry of Water, Land and Air Protection, Environmental Quality Section.

Swain, L.G., and Holms, G.B. 1985. Ambient water quality assessment and objectives for the Fraser River Sus-Basin from Kanaka Creek to the mouth. B.C. Ministry of Environment, Water Management Branch.

Thomson, R.E. 1981. Oceanography of the British Columbia Coast. Canadian Special Publication of Fisheries and Aquatic Sciences **56**.

Thomson, R.E. Physical oceanography of the Strait of Georgia–Puget Sound–Juan de Fuca Strait system. *In* BC/Washington Symposium on the Marine Environment. 1994. *Edited by* R.C.H. Wilson and R.J. Beamish and F. Aitkens and J. Bell. Canadian Technical Report of Fisheries and Aquatic Sciences. pp. 36-98.

Thomson, R.E., and Foreman, M.G.G. 1998. Basin areas and volumes for coastal southwest British Columbia and Northwest Washington. Can. Tech. Rep. Fish. Aquat. Sci. **196**: 17.

Thomson, R.E., Mihaly, S.F., and Kulikov, E.A. 2007. Estuarine versus transient flow regimes in Juan de Fuca Strait. J Geophys Res-Oceans **112**(C9). doi:Artn C09022
10.1029/2006jc003925.

Transportation Safety Board of Canada. 2014. Canadian Transportation Accident Investigation and Safety Board Act. *In* Transportation Safety Board Regulations. *Edited by* G.o. Canada, http://laws-lois.justice.gc.ca/eng/regulations/SOR-2014-37/FullText.html.

Transportation Safety Board of Canada. 2017. Statistical Summary: Marine Occurrences 2017. Government of Canada, http://www.tsb.gc.ca/eng/stats/marine/2017/ssem-ssmo-2017.asp.

Transportation Safety Board of Canada. 2018. TSB Accident Statistics. http://www.tsb.gc.ca/eng/stats/.

Waldichuk, M. 1957. Physical Oceanography of the Strait of Georgia, British-Columbia. J Fish Res Board Can **14**(3): 321-486. doi:DOI 10.1139/f57-013.

Wikimedia Commons, t.f.m.r. 2018. Burrard-Inlet-map-en.svg. https://commons.wikimedia.org/w/index.php?title=File:Burrard-Inlet-map-en.svg&oldid=293136388.

Wootton, B. 2015. M/V Marathassa Fuel Spill Environmental Impact Assessment. Hemmera Envirochem Inc., Burnaby, BC, Canada.

Zhong, X.M., Niu, H.B., Wu, Y.S., Hannah, C., Li, S.H., and King, T. 2018. A Modeling Study on the Oil Spill of M/V Marathassa in Vancouver Harbour. J Mar Sci Eng **6**(3). doi:ARTN 106
10.3390/jmse6030106.