State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 6, Chatham Sound and Prince Rupert, British Columbia

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In response to the Expert Panel of the World Class Tanker Safety System (WCTSS) report (Houston et al., 2013), the Government of Canada commissioned pilot studies aimed to help develop and implement oil spill response plans for high risk areas in Canadian coastal waters. The Centre for Offshore Oil, Gas, and Energy Research (COOGER) published a five-volume report in 2019 focused on providing a general overview of the environmental factors that may influence oil spill fate, behaviour and response in four port areas in Canadian waters (Ryan et al., 2019). As an extension of this initiative, the Government of Canada requested volumes for three additional areas of interest: Prince Rupert and Chatham Sound, British Columbia; Placentia Bay and St. John’s, Newfoundland and Labrador; and Iqaluit and Frobisher Bay, Nunavut.

This is the sixth volume of the eight-volume report. It contains information relevant to developing an area response plan for Chatham Sound and Prince Rupert, British Columbia.

RÉSUMÉ

MacIsaac, B.I., King, T.L., and Ortmann, A.C. 2023. State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 6, Chatham Sound and Prince Rupert, British Columbia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3252: vi + 32 p.

En réponse au rapport du Comité d'experts du Système de sécurité de classe mondiale pour les navires-citernes (SSCMNC) (Houston *et al.* 2013), le gouvernement du Canada a commandé des études pilotes visant à faciliter l'élaboration et la mise en œuvre des plans d'intervention en cas de déversement d'hydrocarbures dans les zones à risque élevé des eaux côtières canadiennes. En 2019, le Centre de recherche sur le pétrole, le gaz et autres sources d'énergie extracôtières a publié un rapport en cinq volumes visant à dresser un tableau général des facteurs environnementaux qui peuvent influer sur le devenir et le comportement des hydrocarbures et l'intervention en cas de déversement d'hydrocarbures dans quatre zones portuaires des eaux canadiennes (Ryan *et al.* 2019). Dans le prolongement de cette initiative, le gouvernement du Canada a demandé des volumes pour trois autres zones d'intérêt : Prince Rupert et le détroit de Chatham, en Colombie-Britannique; la baie Placentia et St. John's, à Terre-Neuve-et-Labrador; et Iqaluit et la baie Frobisher, au Nunavut.

Ce volume est le sixième des huit volumes du rapport. Il contient des renseignements utiles pour élaborer un plan d'intervention par secteur pour le détroit de Chatham et Prince Rupert, en Colombie-Britannique.

1 INTRODUCTION

In response to the Expert Panel of the World Class Tanker Safety System (WCTSS) report (Houston et al., 2013), the Government of Canada commissioned pilot studies aimed to help develop and implement oil spill response plans for high risk areas in Canadian coastal waters. The Centre for Offshore Oil, Gas, and Energy Research (COOGER) published a five-volume report in 2019 focused on providing a general overview of the environmental factors that may influence oil spill fate, behaviour and response in four port areas in Canadian waters (Ryan et al., 2019). The first Ryan et al. (2019) volume provides an introduction to petroleum products handled in Canadian waters, their physical and chemical properties, and the fate and behaviour in the event of a spill and response methods used to reduce environmental impact. The information provided in the introductory volume is relevant to any location, and meant to accompany subsequent volumes generated for other pilot areas. The four pilot areas in the Ryan et al. (2019) report include: 1. Saint John, including the Bay of Fundy; 2. Port Hawkesbury and Canso Strait; 3. St. Lawrence Seaway from Montreal to Anticosti; and 4. the Strait of Georgia, including the Juan de Fuca Strait. As an extension of this initiative, the Government of Canada requested volumes for three additional areas of interest:

- Prince Rupert and Chatham Sound, British Columbia
- Placentia Bay and St. John’s, Newfoundland and Labrador
- Iqaluit and Frobisher Bay, Nunavut

The focus of this volume is the Port of Prince Rupert, the 8th largest port in Canada and the second largest on the Canadian Pacific Coast (Statistics Canada, 2012; Lin and Fissel, 2018). In 2019, the Port of Prince Rupert transferred over 29 million tonnes of cargo and 79 thousand passengers at their facilities (Prince Rupert Port Authority, 2019). The Port includes a coal terminal (thermal coal and petroleum coke), liquid propane bulk terminal, grain terminal, wood pellet terminal, ship-to-rail container terminal and cruise ship facility (Prince Rupert Port Authority, 2019). There is ferry service between May and September connecting Prince Rupert to offshore islands throughout the North Coast (Hotte and Sumaila, 2014).

The Port of Prince Rupert has seen substantial growth and development in the last decade, promoting itself as a gateway connecting North American to Western Pacific markets (Prince Rupert Port Authority, 2019). There is public concern around the increase in vessel traffic that will result from future development, increasing the risk of petroleum spills in marine and estuarine waters of the North Coast (Johannessen et al., 2019). A better understanding of the environmental and biological impacts of increased vessel traffic is required and how petroleum will respond: its fate and behaviour in the event of a spill in the area (Johannessen et al., 2019). Vessels enroute to central and northern port facilities must navigate through several localized hazards, including but not limited to large swells and shallow banks in Dixon Entrance and Queen Charlotte Sound, and strong winds that change abruptly in Hecate Strait (Figure 1; Jacques, 1997). Tankers and vessels that travel into southern Chatham Sound must maneuver through dynamic estuarine flats that change in size and location with fluctuations in river discharge (Jacques, 1997; Northern Gateway Pipelines Inc., 2010).

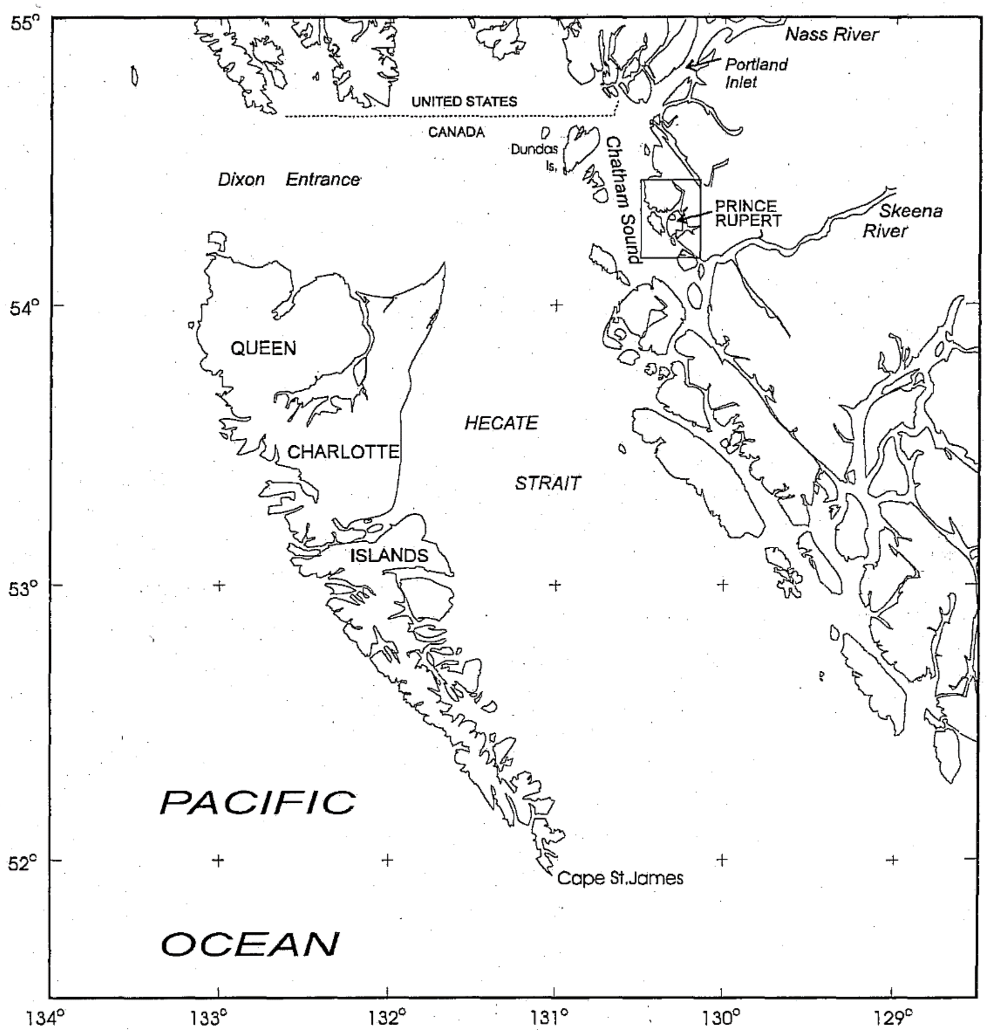

Figure 1. Map of northern British Columbia. Black box highlighting location of Prince Rupert (Stucchi and Orr, 1993)

2 GEOGRAPHY

2.1 LOCATION

The Port of Prince Rupert is located in Chatham Sound on the Pacific North Coast of Canada in British Columbia. Chatham Sound connects to the Pacific Ocean through a series of coastal seaways: Dixon Entrance and Hecate Strait (Figure 1; Thomson, 1981). Chatham Sound (Figure 2) is a semi-enclosed waterbody with limited open ocean influence and controlled primarily by estuarine processes from the two river systems that drain into it from the southeast (Skeena River) and the northeast (Nass River) (Thomson, 1981).

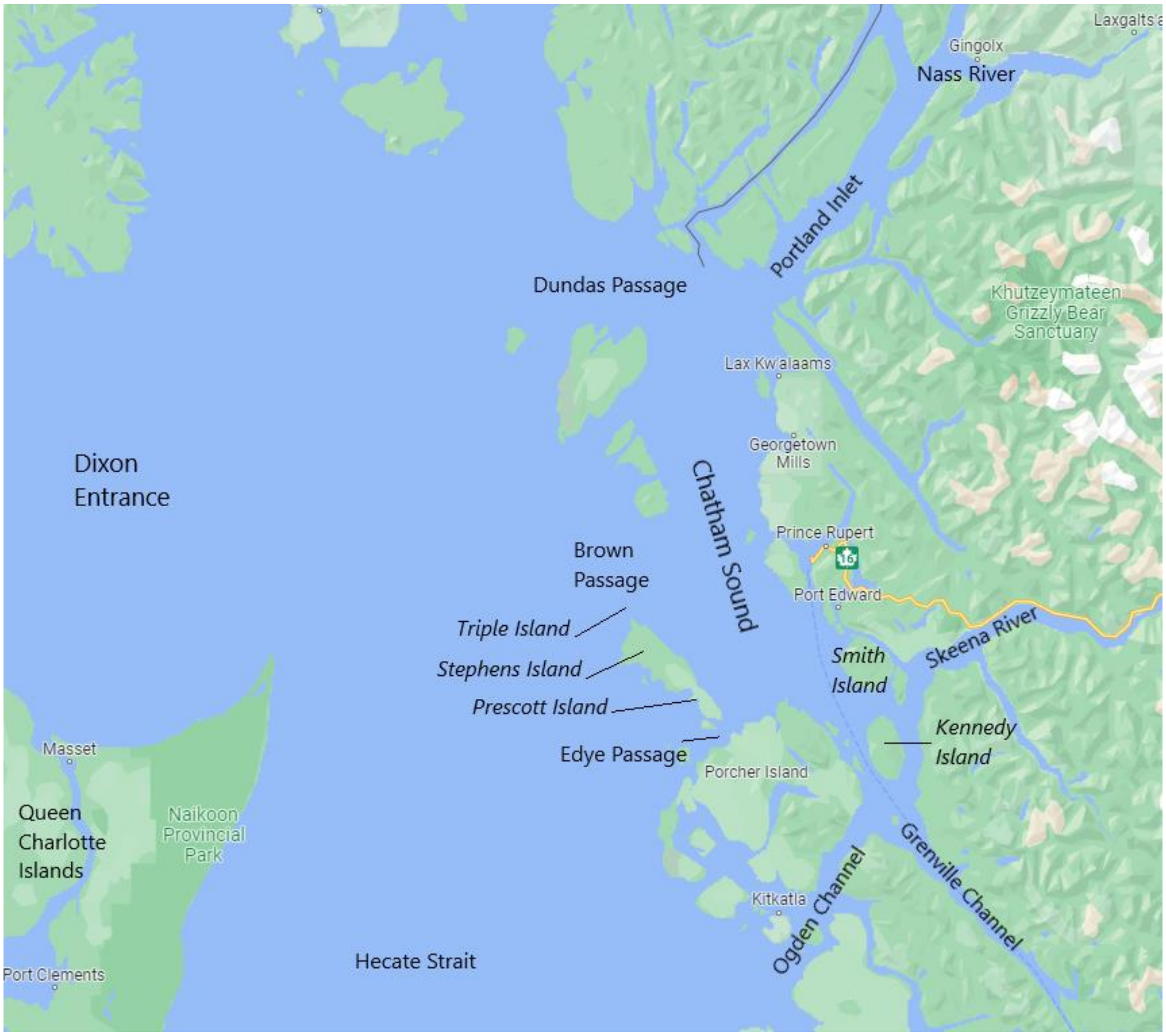

Figure 2. Chatham Sound, Prince Rupert and the names of surrounding passages and islands (modified from Google Maps, 2020)

The city of Prince Rupert (Figure 3) is situated on Kaien Island hugging closely to the mainland. The Port of Prince Rupert spreads out from the city limits into Chatham Sound and encompasses surrounding islands that have, over time, developed into shipping facilities (Thomson, 1981; Stucchi and Orr, 1993). Prince Rupert Port Authority's jurisdictional boundary includes a large portion of southeastern Chatham Sound (Figure 3). The Port of Prince Rupert consists of the Inner Harbour (City of Prince Rupert waterfront) and the Outer Harbour that extends out into Chatham Sound. The inland boundary encompasses Prince Rupert Harbour as far as the entrance to Tuck Inlet (Figure 3). The northern extent ends in Venn Passage between Digby Island and Tsimshian Peninsula (Figure 3). To the south the port boundary incorporates Ridley Island, Porpoise Harbour and Lelu Island, extending past Kitson Island toward Smith

Island (Figure 3). The southwest corner of the Prince Rupert Port Authority boundary is 54°08'36" N 130°26'47" W (Prince Rupert Port Authority, 2019). Surrounding the Prince Rupert Port Authority jurisdiction is a larger port boundary which extends out to all port anchorages and the pilot station at Triple Island (Figure 2; Prince Rupert Port Authority, 2019).

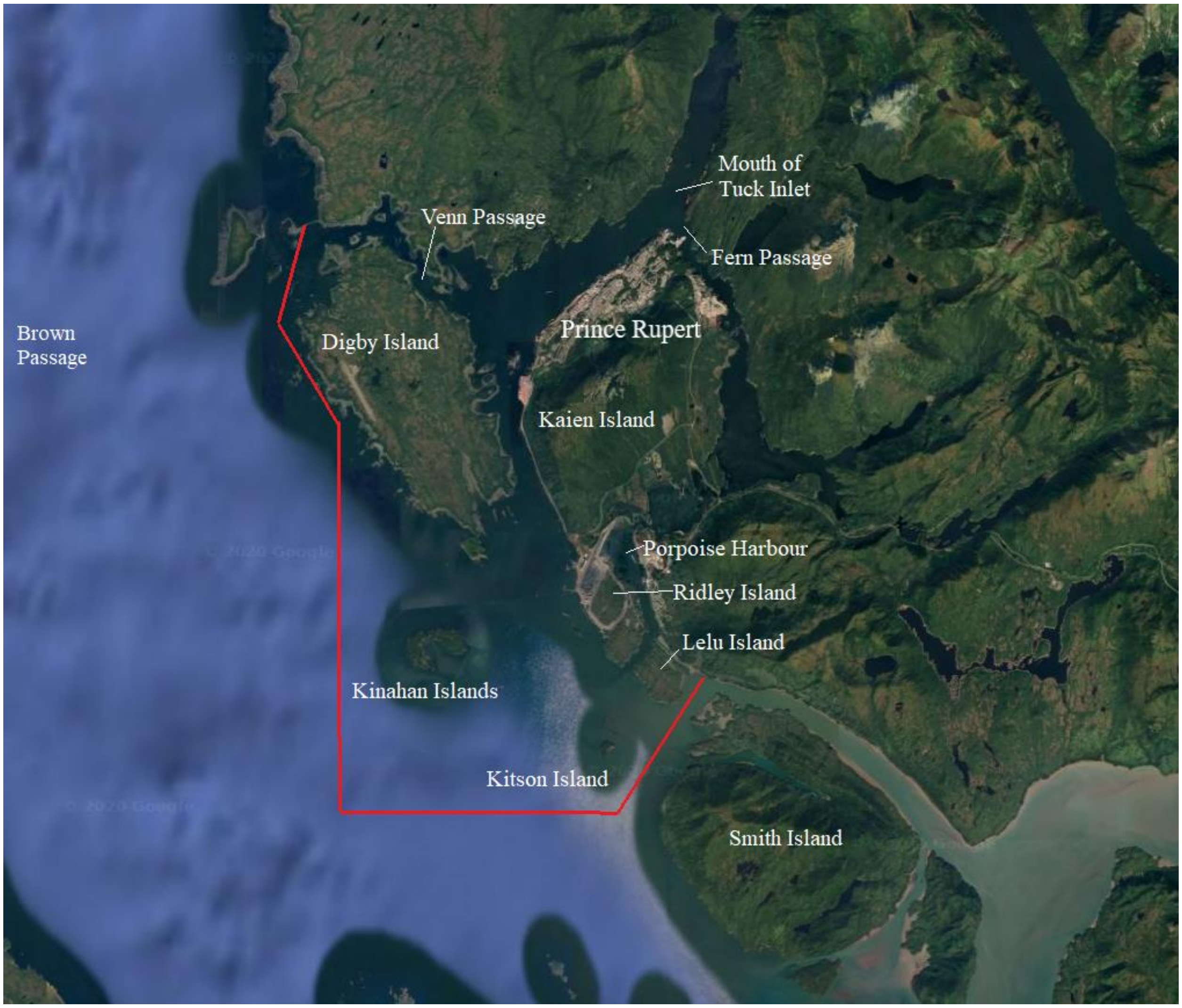

Figure 3. Approximate location of Prince Rupert Port Authority's jurisdictional boundary (red line) surrounding Prince Rupert Harbour (modified from Google Maps, 2020)

Vessels travelling to the Port of Prince Rupert approach from the north through Dixon Entrance or the south through Queen Charlotte Sound (Prince Rupert Port Authority, 2019). Both approaches pass through Hecate Strait and Brown Passage before reaching Chatham Sound. The southern entrance is used by many deep sea vessels approaching Prince Rupert, Kitimat and Stewart (Northern Gateway Pipelines Inc., 2010; Prince Rupert Port Authority, 2019). Prince Rupert Port Authority has no vessel size restrictions except for vessels anchoring in the inner Prince Rupert Harbour area where vessels cannot exceed 250 m in length (Prince Rupert Port

Authority, 2019). Anchoring policies change seasonally due to extreme southeast winds that can occur in the fall and winter months (Prince Rupert Port Authority, 2019).

2.2 SHORELINES

The Chatham Sound shoreline is made up of scattered islands, steep banks, low and ramped beaches, rock outcrops, muskegs and low-lying embayments (Thomson, 1981; Hall, 2008; Coastal and Ocean Resources, 2019). The region is backed by dramatic mountain terrain that closely hugs the coast (Thomson, 1981; Hall, 2008; Coastal and Ocean Resources, 2019). Development is scattered around the city of Prince Rupert and port facilities, and extends along the network of roads weaving between communities. Outside of the city the coastline is sparsely modified by anthropogenic structures (Coastal and Ocean Resources, 2020). At the mouth of Prince Rupert Harbour sits Digby Island (Figure 3) where the Prince Rupert Airport is located (Stucchi and Orr, 1993). Digby Island exhibits a more traditionally rocky shoreline on the outer coast and finer sediment dominates the inner shoreline (Coastal and Ocean Resources, 2020).

Coastal and Ocean Resources conducted a ShoreZone high resolution image and habitat classification for the North Coast of British Columbia as a part of a program that has classified over 45,000 km of coastline along the north pacific from Oregon to Alaska (Coastal and Ocean Resources, 2020). Coastal and Ocean Resources surveyed northern British Columbia in June 2014, June 2015 and July 2019 at low tides. Figure 4 visualizes the shoreline classification for Chatham Sound from the Coastal and Ocean Resources (2019) report. Chatham Sound is dominated by a mixture of rock/sediment (50.9%) and sediment (25.9%) (Coastal and Ocean Resources, 2019). The most common shoreline profile is ramped beaches and wide, low sloped beaches made up of gravel and fine sediment (Coastal and Ocean Resources, 2020). The remaining shoreline is mudflats, rock, riparian, anthropogenic structures, lagoon and current dominated shorelines. Approximately 80 km of coastline situated around the Skeena River is classified as estuarine (Coastal and Ocean Resources, 2020). A small percentage (3%) of the shoreline in Chatham Sound has some form of anthropogenic modification installed, which includes boat ramps, slips, landfills, bulkheads, riprap and wharf structures (Coastal and Ocean Resources, 2020). Approximately 75% of the shoreline on Kaien Island is highly modified (Coastal and Ocean Resources, 2020).

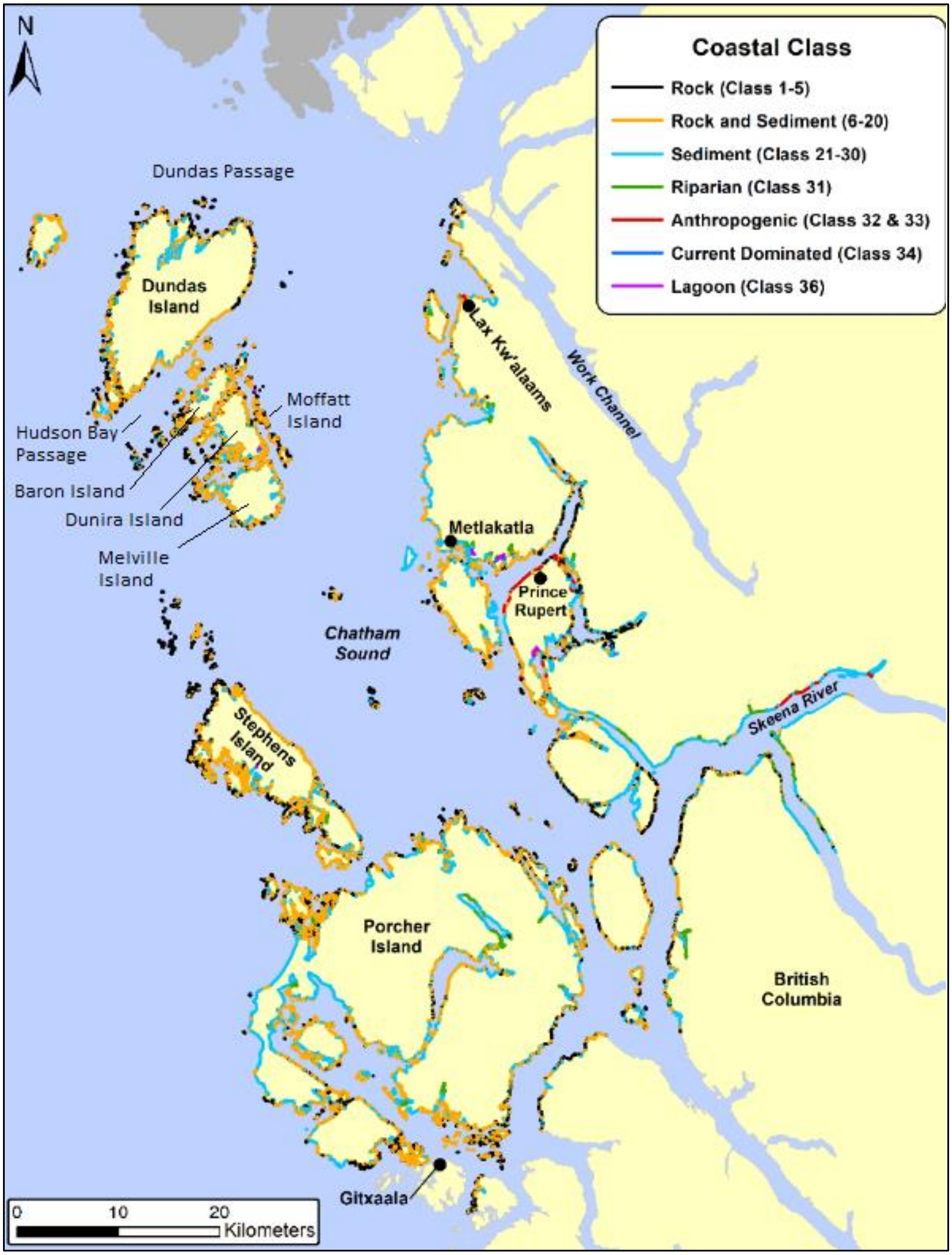

Figure 4. Shoreline classification for Chatham Sound (modified from Coastal and Ocean Resources, 2020)

3 HYDROGRAPHY

3.1 BATHYMETRY IN CHATHAM SOUND

Chatham Sound is a semi-enclosed (15,500 km^2) basin flanked by the mainland to the east and the Pacific Ocean to the west through Dixon Entrance and Hecate Strait (Trites, 1952; Lin and Fissel, 2018; Lin et al., 2018). A series of narrow channels and large passages connect Chatham Sound to Dixon Entrance and Hecate Strait. Dundas and Brown Passage located in the north and central west region of the Sound are the largest and deepest passages connecting Chatham Sound to the outer seaway (Lin and Fissel, 2018; Lin et al., 2018). Openings in the south are shallow and narrow, limiting the water exchange between southern Chatham Sound and the Pacific Ocean (Lin and Fissel, 2018).

Chatham Sound is approximately 70 km north to south and 12 to 25 km east to west (Trites, 1952; Lin and Fissel, 2018; Lin et al., 2018). The average depth in the Sound is 200 m, with deeper areas reaching more than 600 m in the northeast (Lin and Fissel, 2018). The Sound is shallower (100 m or less) in the south than the north, mainly due to Skeena River discharge carrying a high sediment load, creating a series of banks and rills that shift in size, shape and location when there is a change in river discharge volume, speed and direction (Jacques, 1997; Lin and Fissel, 2018; Lin et al., 2018). Depending on the time of year, a large estuarine plume is present and can extend as far as 30 km from the mouth of the river (Thomson, 1981; Lin and Fissel, 2018). The dynamic nature of estuarine environments like the Skeena River make southern Chatham Sound a difficult water body to navigate (Jacques, 1997).

3.1.1 ***<u>Prince Rupert Harbour (Inner Harbour)</u>***

Prince Rupert Harbour is a long, narrow channel that separates Kaien Island and Tsimshian Peninsula and connects to Tuck Inlet roughly 20 km upstream to the northeast (Stucchi and Orr, 1993; Prince Rupert Port Authority, 2019). Vessels entering Prince Rupert inner Harbour must navigate through a channel between Kaien Island and Digby Island that is approximately 600 m wide, 5 km long and 45m deep (Stucchi and Orr, 1993). Figure 5 shows the depth profile for Prince Rupert Harbour between the mouth and Tuck Inlet (location shown in Figure 3; Stucchi and Orr, 1993). There are smaller passages connected to Prince Rupert Harbour from the north (Venn Passage) and the east (Fern Passage) but they are not suitable for large transport vessels (Thomson, 1981). The entrance to Prince Rupert Harbour is 457 m wide and 35 - 40 m deep with no prominent sill (Stucchi and Orr, 1993). Depths throughout Prince Rupert Harbour are between 40 - 60 m and 90 m near the waterfront as a result of dredging practices (Stucchi and Orr, 1993).

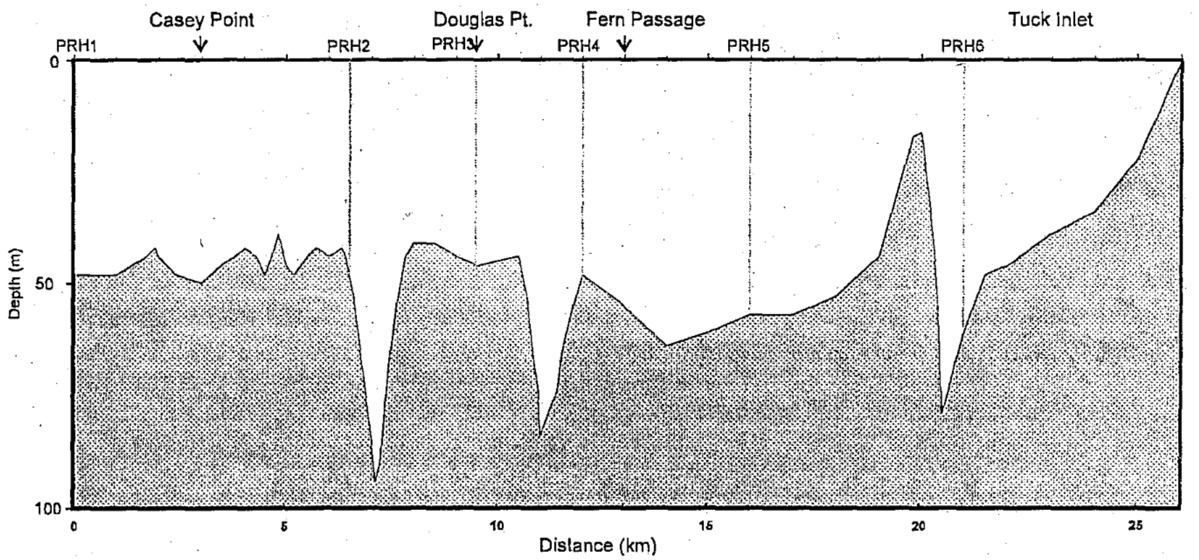

Figure 5. Depth profile of Prince Rupert Harbour from the mouth to Tuck Inlet (Stucchi and Orr, 1993)

3.2 CIRCULATION AND CURRENTS IN CHATHAM SOUND

The movement of water within Chatham Sound is influenced by tidal fluctuations, river discharge and seasonal wind-driven currents (Lin and Fissel, 2018). Large volumes of water pass through Dundas and Brown Passages (Lin and Fissel, 2018). Smaller channels restrict water exchange into the Sound resulting in turbulence (Lin and Fissel, 2018). Tidal currents are strong in Chatham Sound, particularly in the southern and western portion (Lin and Fissel, 2018). The deeper channels of northern Chatham Sound have a strong subsurface tidal current and a much weaker surface tidal current (Lin and Fissel, 2018). Shallow areas around eastern Dundas Island, Moffatt Island and Melville Island (Figure 4) experience weak surface tidal currents.

Non-tidal currents in Chatham Sound are strongly correlated with Skeena River discharge; circulation and non-tidal current speed and direction change seasonally as the discharge volume rises and falls (Trites, 1956; Thomson, 1981; Lin and Fissel, 2018). For most of the year, currents primarily flow to the northwest (Fine and Masson, 2015). During normal conditions (non freshet), approximately 30% of Skeena River outflow passes through Brown and Bell Passage and the narrower Edye Passage, Ogden and Grenville Channels in southern Chatham Sound, identified in Figure 2 (Trites, 1952). The remaining outflow (~ 70%) from the Skeena River moves northward along the eastern side of Chatham Sound to join Nass River outflow through Dundas Passage and Hudson Bay Passage (Figure 4; Trites, 1952). During freshet conditions, between late May to June, the flow of freshwater into the Sound is three to four times the average (Trites, 1956; Lin and Fissel, 2018). Due to the large volume of freshwater being discharged, there is no distinct path taken by the discharge. Fresh water leaves Chatham

Sound through all the channels, with the greatest efflux through Dundas Passage. The influx of fresh water creates large cells of low-salinity water within the Sound (Trites, 1956). The Nass River outflow extends farther into Chatham Sound during freshet conditions, reaching Melville Island at the northern entrance of Brown Passage (Trites, 1956; Lin and Fissel, 2018). Trites (1952) stated that the influx of Nass River water during freshet conditions might block Skeena River outflow in the North, diverting some of Skeena River's outflow during freshet through other channels.

The dominant, northward flow of southern Chatham Sound surface waters is the result of prevailing southerly and southeasterly winds (Lin and Fissel, 2018). The Coriolis Effect directs the northward circulation towards the eastern side of Chatham Sound (Lin and Fissel, 2018). During the fall and winter months the Sound is susceptible to periods of high winds that can generate strong surface currents (Lin and Fissel, 2018). The Prince Rupert Port Authority anchoring policies change seasonally in order to account for strong wind events in the fall and winter (Prince Rupert Port Authority, 2019). In the summer, the prevailing winds shift northwest and although the wind speed is generally lighter than those experienced in the fall and winter months, the change in wind direction alters the dominant surface current direction (Lin and Fissel, 2018).

3.2.1 ***Prince Rupert Harbour***

Currents are aligned with the axis of Prince Rupert's Harbour entrance, alternating ebb and flood in the northeast and southwest direction (Stucchi and Orr, 1993). Currents entering Prince Rupert Harbour flow between Digby and Kaien Islands and can reach 1.5 ms^{-1} (Stucchi and Orr, 1993). Surface mean flow is directed out of the harbour to the southwest at 0.05 - 0.15 ms^{-1}, with highs of 0.25 ms^{-1} (Stucchi and Orr, 1993). Results from Stucchi and Orr (1993) are based on a 63-day survey that took place in the summer of 1992. Narrow passages on the eastern side of Kaien Island complicate water flow in Prince Rupert Harbour, entering perpendicular to the harbour's main flow (Thomson, 1981; Lin and Fissel, 2018). The water that enters the harbour through the small channels create turbulent conditions up to 1 ms^{-1} (Stucchi and Orr, 1993).

Tidal currents are fast and play an important role in water circulation in Prince Rupert Harbour (Stucchi and Orr, 1993). Tera Planning Ltd. (1993) reported a tidal current of 0.8 ms^{-1} to the north during flood tides and 1.28 ms^{-1} to the south during ebb tides. At 17 m, the mean tidal current was 0.19 ms^{-1} moving out of the harbour in the southwest direction (Stucchi and Orr, 1993).

Near-bottom currents are slower than those at the surface and tend to travel in the opposite direction to surface currents, heading northward at 20 m and 30 m depths (Thomson, 1981; Tera Planning Ltd., 1993). Near-bottom circulation occurs through advection, replacing bottom waters over approximately a 12-day cycle (Stucchi and Orr, 1993). AES Ltd (1977) conducted a short water property study in Prince Rupert Harbour, from July 4 to July 15, 1977. Vertical current meters stationed 0.8 m from the bottom revealed the presence of periodic tidal currents reaching approximately 0.22 ms^{-1}.

3.2.2. ***Circulation outside Chatham Sound***

Outside of Chatham Sound, during normal conditions, the tidal currents move clockwise, changing in speed and direction every 12.5 hours between northeast (flood) and southwest (ebb) (Thomson, 1981). Near-bottom currents in Hecate Strait and Queen Charlotte Sound are weaker and tend to travel in different directions from near-surface currents (Thomson, 1981).

3.3 TIDES

The tides in Chatham Sound are mixed semidiurnal, with two high and two low water levels a day (Thomson, 1981; Stucchi and Orr, 1993). Tides propagate northward, arriving on the north coast an hour later than in southern British Columbia (Thomson, 1981). As tides move through the North Coast, they amplify, weaving among islands and through narrow channels (Thomson, 1981). At the mouth of Dixon Entrance and Queen Charlotte Sound, the tidal range is 2.4 m, increasing to 3.0 m in Hecate Strait and further increasing as it progresses towards the mainland (Thomson, 1981). The tidal range is 3.7 m in outer Chatham Sound, and 4.9 m in Prince Rupert's inner harbour (Thomson, 1981; Akenhead, 1992; Stucchi and Orr, 1993). At the Port of Prince Rupert's Ridley Terminal, the mean highest high water level is 6.1 m and mean lowest low water level is 1.2 m (Prince Rupert Port Authority, 2019). The tidal range fluctuates with the declination and phases of the moon (M_2 tidal constituent) and accounts for most of the tidal amplification between spring and neap tides in Chatham Sound (Lin and Fissel, 2018). Stuchhi and Orr (1993) measured the M_2 constituent in the Port of Prince Rupert to be 1.94 m. A strong tidal current was noted by Lin and Fissel (2018) as the flow narrows into the inner harbour of Prince Rupert between Digby Island and Kaien Island. Large tidal currents in western Chatham Sound represent the water exchange through Browns Passage (Lin and Fissel, 2018). There is a strong surface, subsurface and near bottom tidal current noted along the northern boundary of Browns Passage that hugs the coast of Melville Island (Lin and Fissel, 2018). The bathymetry in southern Chatham Sound compresses the flow resulting in larger and stronger tidal currents.

3.4 WATERSHED

The Nass and Skeena Rivers are the two main watersheds that discharge into the North Coast region. Both of these river systems flow into Chatham Sound; Nass River from the north and Skeena River from the south (Thomson, 1981; Stucchi and Orr, 1993). The Skeena River has a 42,300 km^2 catchment area and is the largest river draining into the North Coast, accounting for one quarter of the total volume of water in Chatham Sound (Lui et al., 2016; Lin and Fissel, 2018). The Skeena River has two high outflow periods occurring in the spring and fall. River discharge is the lowest in the winter before starting to increase in May and peaking in June (Lin and Fissel, 2018). Outflow decreases over the summer before increasing for a short period in the fall (Lui et al., 2016). The Skeena River's annual average discharge is 1760 m^3s^{-1} with the largest annual peak flow reaching more than 3000 m^3s^{-1} (Lin and Fissel, 2018). This discharge is significantly larger than the Nass River (annual outflow of 780 m^3s^{-1}, with a peak of 2200 m^3s^{-1}; Lin and Fissel, 2018). Outflows can cause turbulent currents and friction that re-suspends sediments (Lin and Fissel, 2018).

There is no major discharge flowing directly into Prince Rupert Harbour. Kaien Island is a small (225 km^2) island with only two creeks (Hays and Morse Creek) flowing into the harbour (Stucchi and Orr, 1993). Average annual freshwater flow into the harbour is approximately 22.5 m^3s^{-1} not including anthropogenic sources (Stucchi and Orr, 1993).

3.5 SALINITY AND WATER TEMPERATURE

There are few longstanding monitoring stations on the North Coast, limiting the number of historical datasets available (Irvine and Crawford, 2011); however, the available long-term data showed that the 30-year ocean temperature average between 1971 and 2000 was 0.1°C cooler than the average between 1981 and 2010 (Irvine and Crawford, 2011). Figure 6 shows average sea-surface temperatures surrounding the northern British Columbia coast during the (a) summer and (b) winter (Irvine and Crawford, 2011). Sea-surface temperatures tend to be more uniform in the winter (3.7 °C to 8.7 °C) than in the summer (9 °C to 19 °C). Cooler temperatures generally occur in areas that restrict flow and areas where strong tidal mixing takes place.

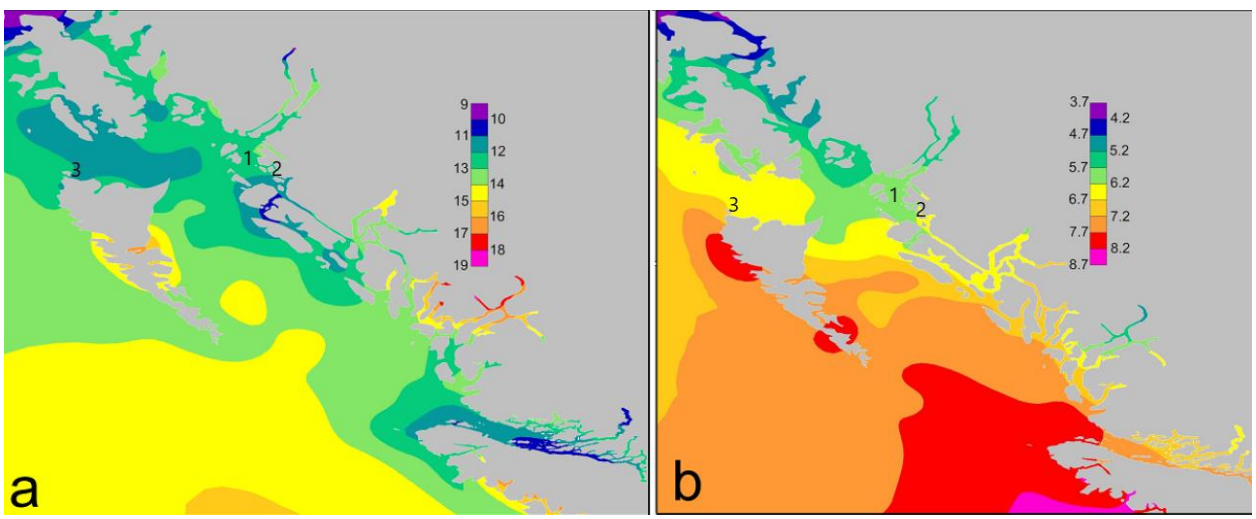

Figure 6. Average sea surface temperatures in northern British Columbia in a) summer and b) winter in degrees Celsius. Location of (1) Chatham Sound, (2) Prince Rupert and (3) Langara Island (modified from Irvine and Crawford, 2011)

Fluctuating, seasonal river discharge influences salinity and plays a larger role than temperature in determining density and circulation in parts of northern British Columbia (Thomson, 1981). There are three persistent surface salinity regimes within the North Coast of British Columbia (Crean, 1967): 1) low salinity in Chatham Sound, Clarence Strait, northern Dixon Entrance; 2) moderate salinity within the inner reaches of Hecate Strait and Dixon Entrance; and 3) higher salinity around the mouth of Dixon Entrance, northern Hecate Strait and Queen Charlotte

Sound, where open ocean interaction is most prevalent (Crean, 1967). Generally, surface salinity decreases closer to the mainland with an annual range of 28-32 (Thomson, 1981; Lin and Fissel, 2018). Figure 7 illustrates the salinity gradient by comparing the average ocean surface salinity measurements for the summer and winter (Irvine and Crawford., 2011). Surface salinity is more uniform during the winter and higher salinity waters push farther inland than in the summer.

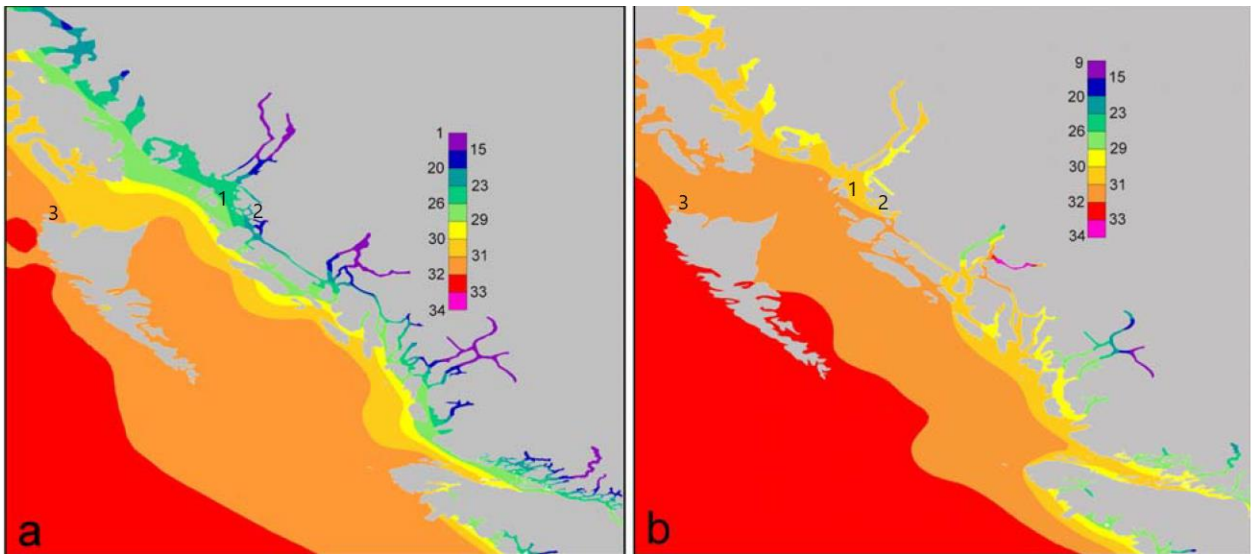

Figure 7. Average surface salinity in northern British Columbia in a) summer b) and winter measured on the practical salinity scale. Location of (1) Chatham Sound, (2) Prince Rupert and (3) Langara Island (modified from Irvine and Crawford, 2011)

There is a noticeable difference in salinity over the North Coast during spring freshet, especially for Chatham Sound and the inner extent of Dixon Entrance (Thomson, 1981). There is a persistent halocline in Dixon Entrance that varies in depth seasonally, becoming shallower and more intense in the summer, a common characteristic for coastal waters dominated by river discharge (Thomson, 1981; Jacques, 1997). There have been changes in salinity around Langara Island, located off the northwest coast of Graham Island (Irvine and Crawford, 2011). The decrease started in the 1970s amounting to almost 1g of salt/kg of seawater (parts per thousand) and may be attributed to the Aleutian Low expanding over the north coast, shifting winter patterns and wind-driven currents (Irvine and Crawford, 2011).

Based on ocean colour analysis, the concentrations of suspended particles, chlorophyll and phytoplankton are higher in the surface waters of Dixon Entrance during freshet (Lazin et al., 2017; Johannessen et al., 2019). *In situ* measurements taken in Dixon Entrance in August 2018 recorded concentrations of 8 mg/L, compared to <4 mg/L year round in Hecate Strait (Lazin et al., 2017).

3.5.1 ***Chatham Sound***

The sea surface temperature range is small throughout Chatham Sound except during freshet conditions. For most of the year, the surface temperature range in the Sound is 6 - 8 °C (Lin and Fissel, 2018). The temperature range in northern Chatham Sound is narrower and more uniform, with deep water temperatures reflecting the exchange through Dixon Entrance (Lin and Fissel, 2018). During the summer months the shallow waters that hug the coastline are warmer than the surrounding Sound, between 13 - 14 °C (Figure 6; Irvine and Crawford, 2011). The sea surface temperature from June to August is typically 6 - 16 °C, with lower but more uniform temperatures throughout the water column on the western side of the Sound (Lin and Fissel, 2018). Figure 6 shows that the average sea surface temperature in southern Chatham Sound is slightly cooler in the summer compared to northern waters, by approximately 1-2 °C (Irvine and Crawford, 2011). The highest temperature reading at Tuck Island Prince Rupert Port Authority's Marine Environmental Water Quality (MEWQ) Station occurred in August 2015 measuring 13°C (Lui et al., 2016), consistent with Irvine and Crawford (2011).

The freshwater content of Chatham Sound exceeds the rest of British Columbia's North Coast (Lin and Fissel, 2018). In general, there is a salinity gradient in the Sound that decreases from west to east, with a higher salinity content on the west side linked to the interaction with Pacific Ocean waters (Thomson, 1981; Jacque, 1997; Lin and Fissel, 2018). Salinity is generally higher in the winter and lower in the spring and summer. The Nass River has less effect on salinity in Chatham Sound than the Skeena River (Lin and Fissel, 2018). Trites (1956) determined that surface salinity in Chatham Sound never drops below 20, even during the May freshet. However, just outside the boundaries of Chatham Sound in Portland Inlet, salinity as low as 11 was observed in the top 5 m of Portland Canal, near the mouth of the Nass River, in June 2020 (personal communication, Sophia Johannessen). Southern Chatham Sound has a higher surface salinity during the winter (January – May) and fall (September – December) as saltier water is driven inland by the strong southerly winds (Irvine and Crawford, 2011; Lin and Fissel, 2018). Low salinity follows the Skeena River outflow, extending northwards beyond Digby Island (Lin and Fissel, 2018).

The Prince Rupert Port Authority MEWQ monitoring program tracks impacts from port operations. MEWQ measurements taken over May 19 - 21, 2015, recorded surface salinities between 23.5 and 26.5 (Lui et al., 2016). In August 2018 the salinity was 19 - 31 (Johannessen et al., 2019). Skeena River discharge during peak flow influences surface salinity throughout Chatham Sound, as illustrated at the Tuck Island Station, where surface salinity in June 2015 during peak flow measured 21, while salinity at 20 m measured 29 (Lui et al., 2016).

Water quality is influenced by river discharge, wind mixing and erosion, which increases suspended sediment concentrations. A plume of sediment-rich water is notable in satellite images of southern Chatham Sound and can extend 30 km towards Ridley Island (Lin and Fissel, 2018). Surface particle concentrations of 6.5 - 11.3 mg/L were recorded in August 2018 (Johannessen et al., 2019). The Prince Rupert Port Authority MEWQ program conducted water quality sampling four times a year at multiple locations between 2013 - 2014. Average total suspended solids for surface and deep water was 4.9 mg/L (Lui et al., 2016). Around Ridley Island, the optical depth can be less than 1 m (Lin and Fissel, 2018).

3.5.2 ***Prince Rupert Harbour***

The characteristics of water in Prince Rupert Harbour are largely influenced by Skeena River discharge although the Harbour itself does not directly receive high volumes of runoff. Stucchi and Orr (1993) noted a variation in salinity and temperature during spring and neap tides, experiencing lower salinity shortly after spring tides when the temperature is higher, and higher salinity during neap tides when temperatures are lower (Stucchi and Orr, 1993).

Surface salinity in the harbour decreases closer to the mouth, with a range of 20 - 25 (Stucchi and Orr, 1993). Salinity in the inner harbour does not appear to go below 20 (Stucchi and Orr, 1993). Subsurface waters must mix considerably before entering the harbour. The vertical structure of the water column in the inner harbour lacks a defined thermocline and halocline (Stucchi and Orr, 1993). The channel between Digby Island and Kaien Island acts as a barrier restricting high salinity water from entering Prince Rupert Harbour, although there is evidence of active mixing within the narrow entrance (Stucchi and Orr 1993). Circulation between surface and subsurface waters in the harbour may occur through horizontal advection within the water column. It appears to take approximately 12 days to exchange the water at the bottom of the harbour (Stucchi and Orr, 1993).

4 CLIMATE

4.1 AIR TEMPERATURE AND PRECIPITATION

British Columbia's North Coast has a mild, humid climate. The region is influenced by large pressure systems, the Aleutian Low in the winter and North Pacific High in the summer. These large pressure systems alter the precipitation, temperature, wind direction and speed in the region (Thomson, 1981; Juszko et al., 1988; Hall, 2008). Figure 8 shows mean temperature and precipitation at Prince Rupert Airport from 1981 to 2010 (Environment Canada, 2019). Daily average temperature ranges from 2.4 to 17 ^{o}C annually, with considerable fluctuation throughout the seasons. For example, the air temperature in Chatham Sound in the winter ranges from -24 to +18 ^{o}C and +1 to +28 ^{o}C in the summer (Tera Planning Ltd., 1993). Cold Arctic pressure systems can bring extreme temperatures which can result in heavy rainstorms during winter months. A similar but reverse effect occurs during the summer months when warm, dry continental pressure systems advance from the mainland.

Chatham Sound receives its highest annual rainfall in October (Environment Canada, 2019). The city of Prince Rupert is considered one of the cloudiest and wettest places in Canada (Northern Gateway Pipeline Inc., 2010). The annual mean precipitation between 1981-2010 was approximately 2619.2 mm (Figure 8; Environment Canada, 2019). Most precipitation falls as rain, with few snowfall events (Tera Planning Ltd., 1993). Snowfall events do occur, totalling approximately 142 cm between November and April, when cold air can become trapped under a warm, moist air mass (Northern Gateway Pipeline Inc., 2010).

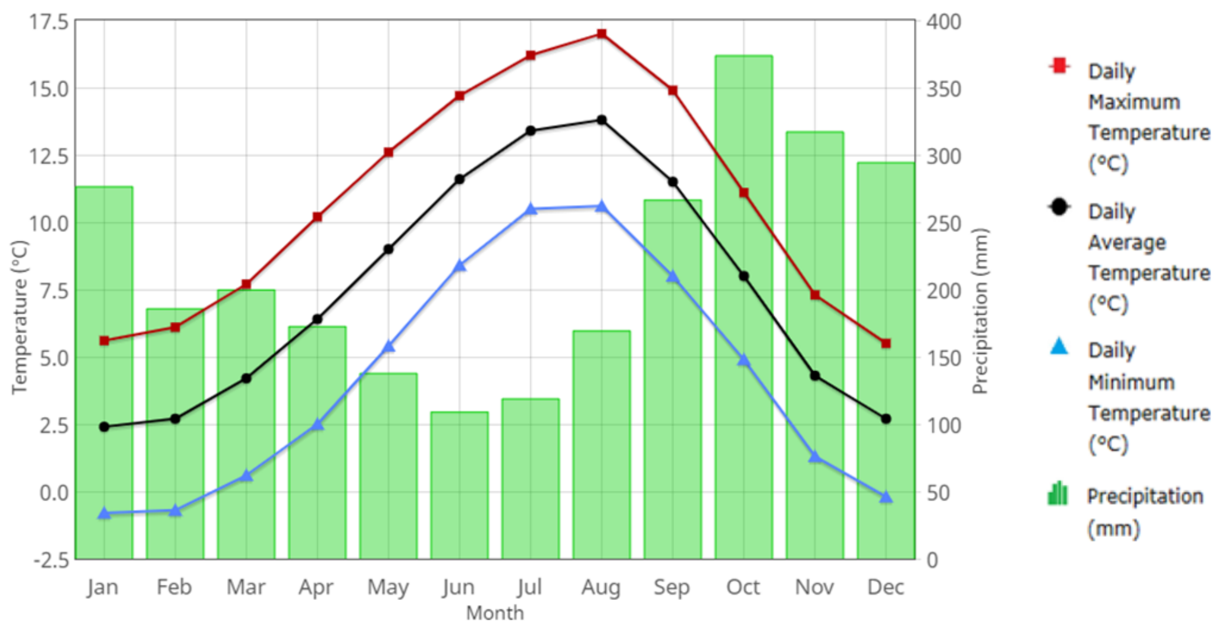

Figure 8. Temperature and precipitation chart for 1981 – 2010 Canadian climate normals at Prince Rupert Airport (Environment Canada, 2019)

4.2 WIND AND WAVES

Seasonal fluctuations from the Aleutian Low and North Pacific High pressure systems introduce considerable variability to the winds on the North Coast (Thomson, 1981; Hall, 2008). Prince Rupert Airport, on Digby Island can be difficult to access due to a combination of winds, low clouds, fog and rain (Klock and Mullock, 2001). For most of the year the wind direction is dominated by a south to southeast flow with speeds less than 12 ms^{-1} (Lin and Fissel, 2018). Northern Chatham Sound also experiences strong northeast winds (24 - 30 ms^{-1}). Wind speeds can exceed 30 ms^{-1} from the east to southeast between the fall and winter months (Lin and Fissel, 2018). By late summer, anti-cyclonic flow from the west and northwest typically result in clearer skies, minimal precipitation and calmer wind conditions (Thomson, 1981; Fine and Masson, 2015; Stucchi and Orr, 1993). In the winter, pressure can drop offshore, moving colder air from the interior down the coast (Thomson, 1981; Lin and Fissel, 2018). This Arctic outflow transports strong, cold winds (up to 25 ms^{-1}) from the northeast, increasing wave height and creating snowfall conditions that reduce visibility (Thomson, 1981; Lin and Fissel, 2018).

Wind conditions are important for generating surface and upper layer currents and circulation within Chatham Sound (Lin and Fissel, 2018). Occasionally, large swells can enter Chatham Sound through Dundas Passage in the north. Coastal and Ocean Resources (2020) analyzed biological wave exposure in Chatham Sound (Figure 9) and determined approximately 87% of the shoreline is classified as very protected to semi-protected. Large waves typically dissipate before reaching eastern Chatham Sound but can reach far inland if the wind direction is favourable.

A wave rider buoy was stationed 2 km west of Prince Rupert Harbour between September 1972 to June 1973 at a depth of 90 m (Thomson, 1981). The buoy was deployed in a fairly sheltered area so the results would not represent the wave conditions for the entire Sound. Wave heights were observed to be less than 1 m from the south with 2 - 5 second periods (Thomson, 1981). Only 10% of observed wave heights were over 1 m, but significant wave heights were over 3 m (Thomson, 1981). Low swells occurred 20% of the time with periods of 8 - 10 seconds (Thomson, 1981). Low-lying Digby Island at the entrance to Prince Rupert Harbour provides little protection from strong gusts that occur periodically during fall and winter months (Akenhead, 1992; Stucchi and Orr, 1993; Klock and Mullock, 2001).

Dixon Entrance, Hecate Strait and Queen Charlotte Sound, experience some of the most extreme wind and wave conditions, particularly between November and February (Thomson, 1981; Foreman et al., 2005). Within the exposed seaway, waters are mixed by strong winds, allowing surface waters to circulate down to the near-bottom (Crawford and Thomson, 1991; Wright et al., 2017). During the winter months, storm events occur frequently (every 2 - 3 days) with monthly mean wind speeds reaching 22 ms^{-1} (Foreman et al., 2005; Cherniawsky and Crawford, 1996). The annual mean wind speed in Queen Charlotte Sound and Hecate Strait exceeds 10 ms^{-1} (Foreman et al., 2005). Waves in the region are high, with an annual mean wave height of 2.5 m at the mouth of Queen Charlotte Sound and 1.5 m in Dixon Entrance (Foreman et al., 2005). An October storm event in 1968 recorded swells reaching 20 m in Hecate Strait around *Shell Drill Rig SEDCO 135F* (Thomson, 1981). Reports from the event recount one swell close to 30 m, reaching the main deck of the drill rig platform (Thomson, 1981). Hecate Strait is considered a dangerous body of water, experiencing extreme changes in winds over short periods of time (Thomson, 1981; Environment Canada, 2015).

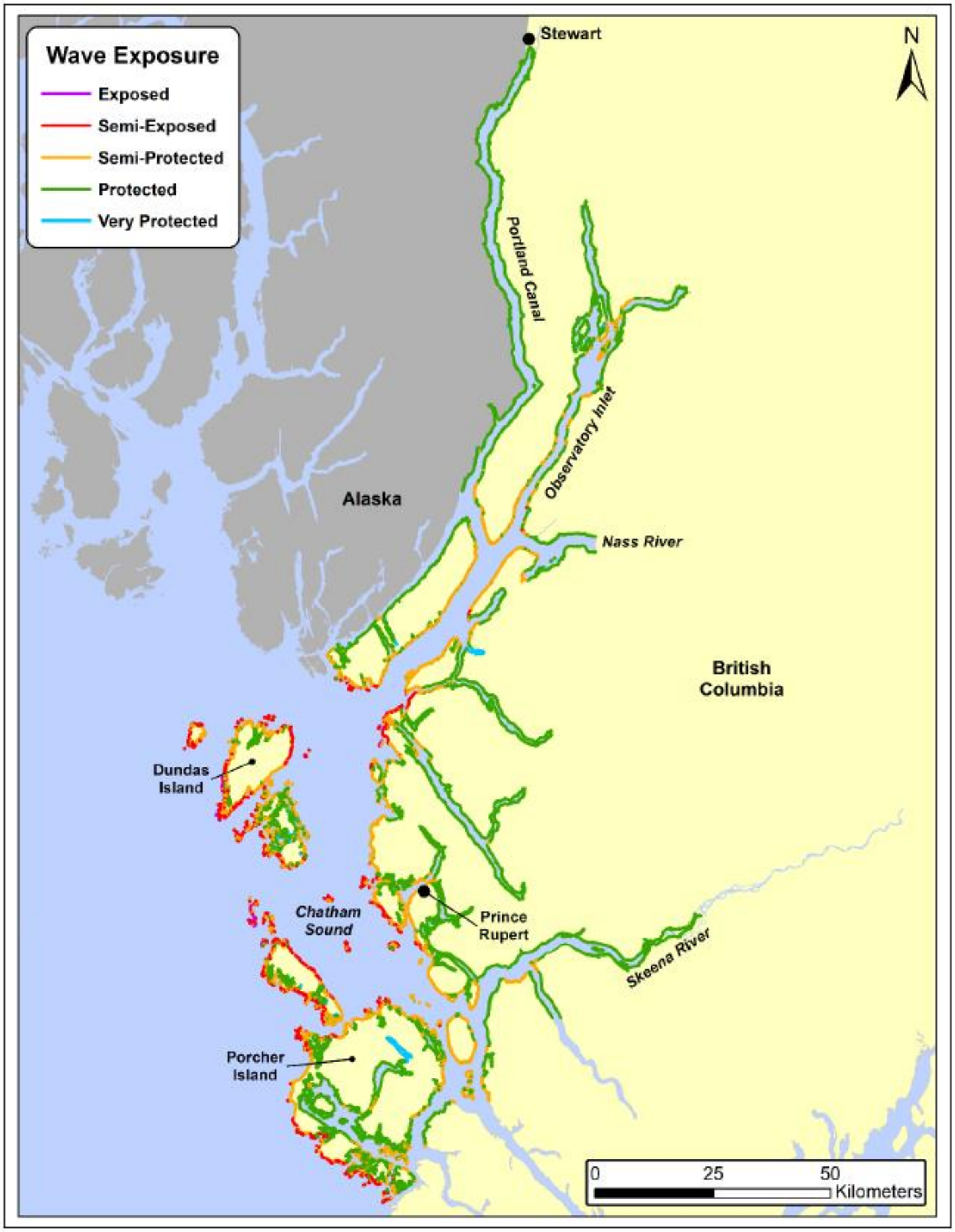

Figure 9. Biological wave exposure in the North Coast, including Chatham Sound (Coastal and Ocean Resources, 2020)

5 PAST OIL SPILLS

5.1 OIL TANKER MORATORIUM ACT

A moratorium was put in place for the North Coast between 1972-2006 restricting the size of oil tankers that can enter Hecate Strait, Dixon Entrance and Queen Charlotte Sound (Government of Canada, 2019; Living Oceans Society, 2011). This moratorium was enacted because of the potential environmental impacts of an oil spill and further extended to include offshore oil and gas exploration in the region. Two events occurred on the Pacific North Coast that solidified public support for the moratorium, Nestucca Barge spill in Gray's Harbour (Washington) in 1988 and the 1989 Exxon Valdez oil spill in Prince William Sound (Alaska). In September 2019, the Government of Canada enacted a new Oil Tanker Moratorium Act which prohibits oil tankers carrying more than 12,500 metric tons of crude and persistent oils from stopping or unloading at marine ports on the North Coast of British Columbia. This act only prohibits persistent oils and oils that do not break down or evaporate quickly, including bitumen and diluted bitumen. The moratorium does not include refined or non-persistent oils such as LNG, naphtha, gasoline, propane and others (Government of Canada, 2019).

5.2 TRANSPORTATION SAFETY BOARD OF CANADA (TSBC) DATABASE

The TSBC maintains a database of air, marine, rail and pipeline incidents and accidents, collectively called 'occurrences.' The marine occurrence database dates back to 1975 and contains information including vessel type, location, incident summary, cargo involved and reported pollution. Reporting requirements and marine navigation has changed since the database was created in 1975, leading to an increase in the number of occurrences entered into the database. The most recent update of TSBC reporting requirements was 2014, and data for many more occurrences are available from that time onward. In this report, statistics have been compiled for marine occurrences of interest for the entire span of the database (1975 – 2019) and on an annual average basis (2015 - 2018) for full years since the new reporting requirements (Transportation Safety Board of Canada, 2014). The database only includes marine occurrence reports up to September 4th, 2019.

Marine occurrences were classified into four different types of events: 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; 4) occurrences in which vessels were sunk, capsized or otherwise seriously damaged beyond repair, and expected to release fuel into the environment.

The following statistics look at occurrences within an area 53.00^{o}N to 55.00^{o}N and 129.50^{o}W to 133.00^{o}W, which includes parts of Dixon Entrance, Hecate Strait and Queen Charlotte Sound, corresponding with the main transport routes to the Port of Prince Rupert.

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

Occurrences involving…	All Years (1975 - 2019)	Annual Averages (2015 - 2018)
All occurrences	890	60.7
Petroleum cargo vessels	3	0.5
Pollution or cargo lost overboard	19	2.5
Petroleum spills onboard or overboard	13	1.0
Vessels sunk, capsized or destroyed	49	1.5

A high percentage (92%) of occurrences reported inside the area of interest did not fall into designated categories. These accidents included workplace safety incidents or infractions, technological failures and near misses. Minor incidents, such as dragged anchors, make up 60 of the reported occurrences. Over half (494) of the 890 occurrences involved fishing vessels. Out of the 494 accidents involving fishing vessels, 24 were lost at sea.

Large transport vessels, including bulk carriers, container vessels and barges make up 119 of the 890 occurrences in this region, the majority of which were transporting dry and non-dangerous goods. Only three occurrences involved tankers carrying petroleum products and none of them reported petroleum pollution. Cargo was lost overboard and pollution occurred onboard or overboard in 17 occurrences, 13 of which reported a petroleum spill. Minor pollution was reported in most of the 13 petroleum spills, but did not provide an estimate of petroleum lost. Of the 13 petroleum spills, eight reported petroleum lost overboard. Six of the petroleum spill occurrences involved fishing vessels with limited fuel capacity. Only three of 13 occurrences provided details on the volume of petroleum spilled. One of the occurrences resulted in a fishing vessel sinking with approximately 30 L of fuel on board. Another fishing vessel sank outside of Langara Island, releasing approximately 1500 L of diesel fuel. An event in October 2018 involved a pilot boat which released 2000 L of marine diesel between Prince Rupert and Triple Islands in Chatham Sound.

It is important to note that there are inconsistencies in the TSBC dataset. Information is missing that is important in analyzing the extent of petroleum pollution and historical response performance. For example, an accident report from September 8, 2008 made no mention of petroleum products on board when *West Island 395* came loose from the mooring buoy. The Ship-source Oil Pollution Fund 2018-2019 annual incident report stated that the barge had approximately 18,000 L of gasoline and 15,000 L of diesel onboard during the incident (Government of Canada, 2019).

There are notable oil spill events that took place within the North Coast region just outside the area of interest but along the same transportation route vessels take to reach Prince Rupert. On March 2, 2008 the 40 m tug *Sea Voyager* ran aground close to a functioning lighthouse during calm seas, releasing approximately 49,000 L of diesel lube oil into the water. The tug was carrying 56,000 L of diesel, 6,800 L of oil and 1,200 L of hydraulic oil (Living Oceans Society, 2011).

On October 13th 2016, the tugboat *Nathan E. Stewart* and petroleum barge *DBL 55* ran aground at the entrance of Seaforth Channel, south of Prince Rupert. The tug sustained damage and released approximately 110,000 L of diesel fuel into the environment. The tug was carrying 226,837 L of diesel fuel, 2,419 L of lube oil, 2,082 L of hydraulic oil, 2,082 L of gear oil and 3,668 L of "dirty bilge" (Government of Canada, 2019). The majority of the cargo was offloaded onto the barge as the tug sank in 9 m of water (Government of Canada, 2019). The barge *DBL 55* was not carrying any cargo at the time. The event highlighted some issues in prevention and response measures. Weather conditions allowed the spill to spread quickly and the *Nathan E. Stewart* was not adequately prepared to contain the spill with the amount of booms on board. The location of the occurrence was a 20 hour boat ride from Western Canadian Marine Response Corporation headquarters in Prince Rupert. Due to the long commute, the skimmer did not arrive in time to remove the oil slick. At the time of the event, the *Nathan E. Stewart* was exempted from the Pacific Pilotage Authority mandate and did not have a Canadian pilot on board to help navigate the area.

6 MODELLING

6.1 CIRCULATION MODELLING

Most circulation models for the North Coast encompass large areas and as a result of poor spatial resolution, Chatham Sound has not been well represented (Lin and Fissel, 2018). Notwithstanding, oceanographic measurements have been taken periodically in Chatham Sound over the years with the first tide gauge measurement recorded in 1903 at the Port of Prince Rupert, and temperature and salinity recordings as far back as the 1930s (Lin and Fissel, 2018). Trites (1956) was the first to conduct a full oceanographic study of the entire extent of Chatham Sound. The results of Trites' (1956) study confirm how influential Skeena River discharge is on circulation patterns in Chatham Sound.

Lin and Fissel (2018) created a high resolution 3D finite-difference model using the Coastal Circulation Model for Sediment transport (COCIRM-SED) to better capture the tidal and wind-driven currents in Chatham Sound. The model covers Chatham Sound and Brown Passage extending 86 km north to south and 47 km east to west. The main forcings selected for the model were winds and tides; however, freshwater discharge is also represented. The model incorporated historical oceanography, verified by CHS DFO tidal/current datasets and superimposed on satellite imagery. The model was verified using historical datasets and the surface circulation results were found to be in good agreement with these observations. The model showed that near-surface waters on the eastern side are dominated by river discharge from Skeena River and have a lower salinity than the western side of Chatham Sound. Southern Chatham Sound is dominated by large tidal currents, with near-surface waters hugging the eastern side as they circulate northward. The study confirms a correlation between non-tidal current speeds and discharge volume from Skeena River, addressing some of the seasonal variation in flow and the gradient of decreasing salinity from west to east. The band of lower salinity surface waters is more prominent during summer freshet months, stretching up the coast following the direction of the current (Lin and Fissel, 2018). The western side of Chatham Sound is influenced by the high salinity waters of Hecate Strait. For much of the western side of Chatham Sound, non-tidal currents are dominated by wind forcing. Historical datasets may not properly represent deep currents and near-bottom circulation within Chatham Sound, so further study using modern equipment and methods should be done.

6.2 OIL BEHAVIOUR AND TRANSPORT

6.2.1 ***Environmental Sensitivity Index (ESI) and Oil Residence Index (ORI) for Chatham Sound***

The ShoreZone coastal benthic habitat mapping system uses visual and expert interpretation of images, aerial video and low altitude still images to create a searchable geographic database of intertidal and nearshore habitat. As a part of the Coastal and Ocean Resources ShoreZone study, a ground survey was conducted along the North Coast. This included monitoring coastal habitat and shoreline morphology in Chatham Sound to determine an Environmental Sensitivity Index (ESI) and Oil Residence Index (ORI) to help assess shoreline sensitivity in the event of an oil spill. There is an updated version of the ESI and ORI results on the Coastal and Ocean Resources website[1] that provides a full assessment of British Columbia's North Coast.

The ESI was developed by NOAA (Peterson et al., 2002) to rank shoreline sensitivity to oil spills based on wave exposure and substrate in the high, mid and low intertidal zone. Figure 10 shows that the areas of Chatham Sound most sensitive to oil spills are sheltered tidal flats, rocky and rubble shores, mixed gravel and sand beaches and other areas of high permeability (Coastal and Ocean Resources, 2020). Table 2 provides the definition of each of the categories mentioned in the ESI map (Figure 10). The majority (57.2%) of shoreline in Chatham Sound falls within the high and very high sensitivity range which includes the intertidal flats in southern Chatham Sound (Figure 11; Coastal and Ocean Resource, 2019; Coastal and Ocean Resources, 2020). Approximately 32% of the shoreline is ranked as having low sensitivity to oil (Coastal and Ocean Resources, 2020).

The Oil Residence Index (ORI) is based on wave exposure, sediment texture and abundance. Low wave exposure areas comprised of high mobility substrate result in a long to medium-long oil residence timeframe (Figure 12). The ORI indicates that 75% of the shoreline examined in this study has a high oil residence time of months to years (Coastal and Ocean Resources, 2019). Shorter residence times (days and weeks) are reported in areas of Chatham Sound that are made of up harder, cohesive shoreline substrate or experience greater wave action.

[1] Coastal and Ocean Resources: Coastal & Ocean Resources (CORI) | Marine Environmental Consultants (coastalandoceans.com)

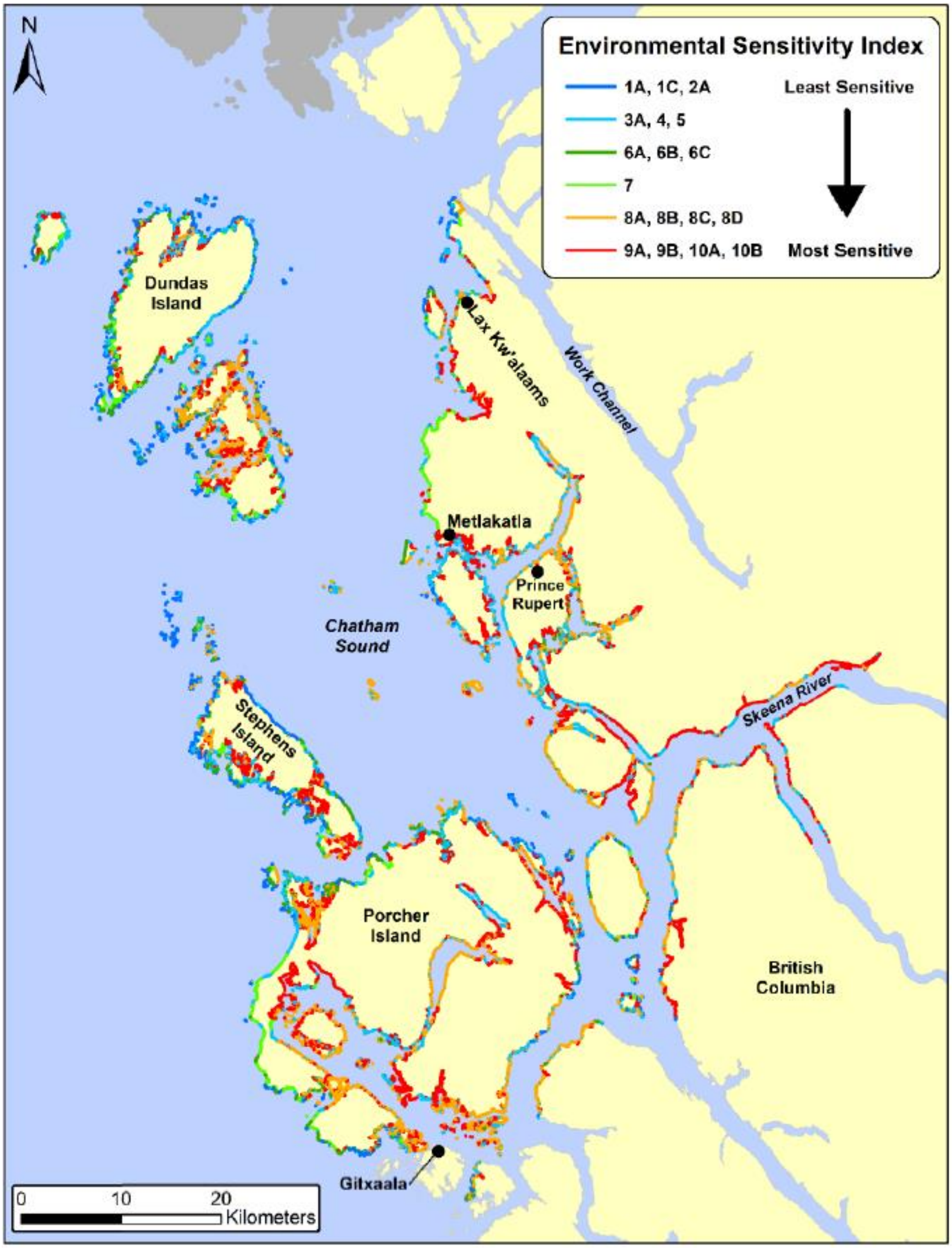

Figure 10. Environmental sensitivity index classifying shorelines by least-to-most sensitive to oil spills based on wave climate, composition and permeability (Coastal and Ocean Resources, 2020)

Table 2. Summary of ESI coastal classes for the Prince Rupert survey area (Coastal and Ocean Resources (2020) adaptation of Peterson et al. (2002))

Environmental Sensitivity Index (ESI)	
No.	Description
1A	Exposed rocky shores; exposed rock banks
1C	Exposed rock cliffs with boulder talus base
2A	Exposed wave-cut platforms in bedrock, mud, or clay
3A	Fine to medium grain sand beaches
4	Coarse-grained sand beaches
5	Mixed sand and gravel beaches
6A	Gravel beaches (granules and pebbles)
6B	Gravel beaches (cobbles and boulders)
6C	Rip rap
7	Exposed tidal flats
8A	Sheltered scarps in bedrock, mud, or clay; sheltered rocky shores (impermeable)
8B	Sheltered, solid, man-made structures; sheltered rocky shores (permeable)
8C	Sheltered rip rap
8D	Sheltered rocky rubble shores
9A	Sheltered tidal flats
9B	Vegetated low banks
10A	Salt and brackish water marshes
10B	Freshwater marshes

Figure 11. Intertidal flats around the mouth of Skeena River in southern Chatham Sound (Coastal and Ocean Resources, 2019)

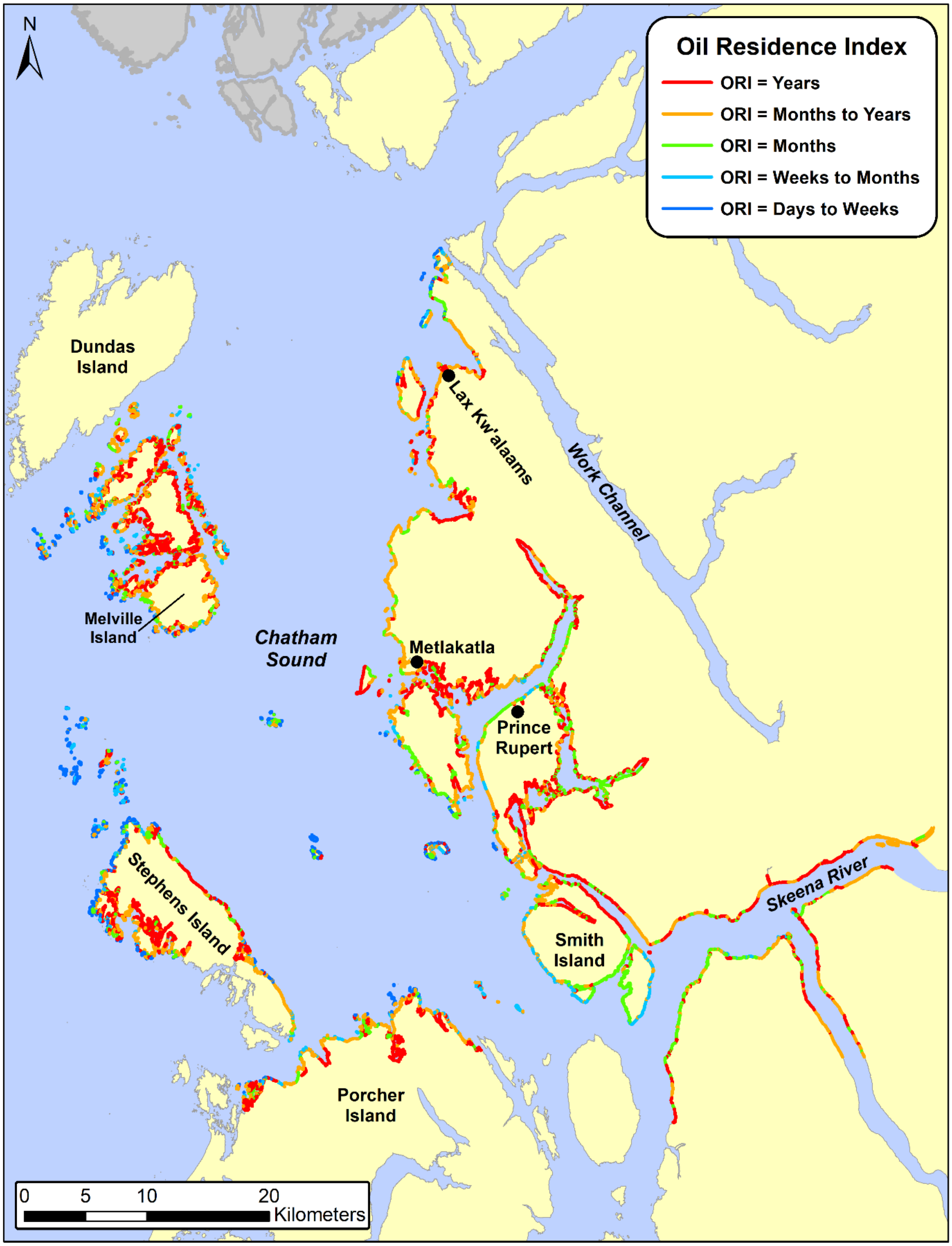

Figure 12. Oil Residence Index for Chatham Sound (Coastal and Ocean Resources, 2020)

6.2.2 *Oil spill Trajectory on the Northern British Columbia Coast: Numerical Simulations*

Fine and Masson (2015) conducted a numerical simulation focused on potential oil spill distribution along eastern Hecate Strait, a main route for large vessels travelling to and from ports in northern and central British Columbia. The study focused on the southwest coastline of Banks Island, near Morseby National Park and Naiboon Provincial Park, an area designated as ecologically and biologically significant.

The simulation was created using the Regional Ocean Modelling System (ROMS) and Larval TRANSport Lagrangian model (LTRANS) particle tracking software. Hindcast models were completed from 1998 to 2007 to understand oil particle distribution for a 10-year period. The simulation released 20 droplets every five days at each model grid cell within the top vertical layer and monitored them for 15 days to visualize distribution. Over the 10 year simulation period the model released 5,624,000 particles. Oil droplets were given neutral buoyancy to look at movement both vertically and horizontally. The simulation used random walk behaviour to represent turbulent diffusion and advection by ocean currents.

The simulation indicated that the distribution of oil spilled along eastern Hecate Strait will vary significantly depending on the time of year as shown in Figure 13. During the fall and winter months the wind direction is predominantly toward the north and northeast. The majority of oil would move northward along the shoreline and up towards northern British Columbia into Chatham Sound, southern Alaska and Dixon Entrance. By spring, freshwater discharge shifts patterns and oil distribution would move away from the shoreline but still largely northward. Wind patterns are more variable during the summer months, therefore oil particles were more widespread, evenly distributed and moving predominantly offshore.

A simulation visualizing the spread of oil particles within the water column shows that vertical distribution also varies seasonally. Vertical distribution reaches below 35 m during the winter, but only 10 m in the summer. The spring and fall were considered transitional periods with vertical distributions 15-25 m.

Throughout the 10-year simulation, most oil particles remained within 50 km of the spill source with most of the oil moving northward close to the shoreline. This represents the mean distribution of droplets. There were years in which winds causing upwelling tended to dominate, such as 1999 and 2006. In those years, a high percentage (over 50%) of oil particles spread further outside the source area.

As noted in the Fine and Masson (2015) paper, this simulation does not take into account different types of petroleum products or their chemical composition, nor the weathering processes that alter viscosity and density, and therefore fate and behaviour. The simulation was created to capture the general transport trend of released oil particles. It does show that there is a high likelihood for oil spilled in southeastern Hecate Strait to reach remote coastal shorelines, with a greater likelihood of reaching Moresby Island in the summer. An oil spill occurring in the winter has an increased probability of reaching remote shorelines northward towards southern Alaska.

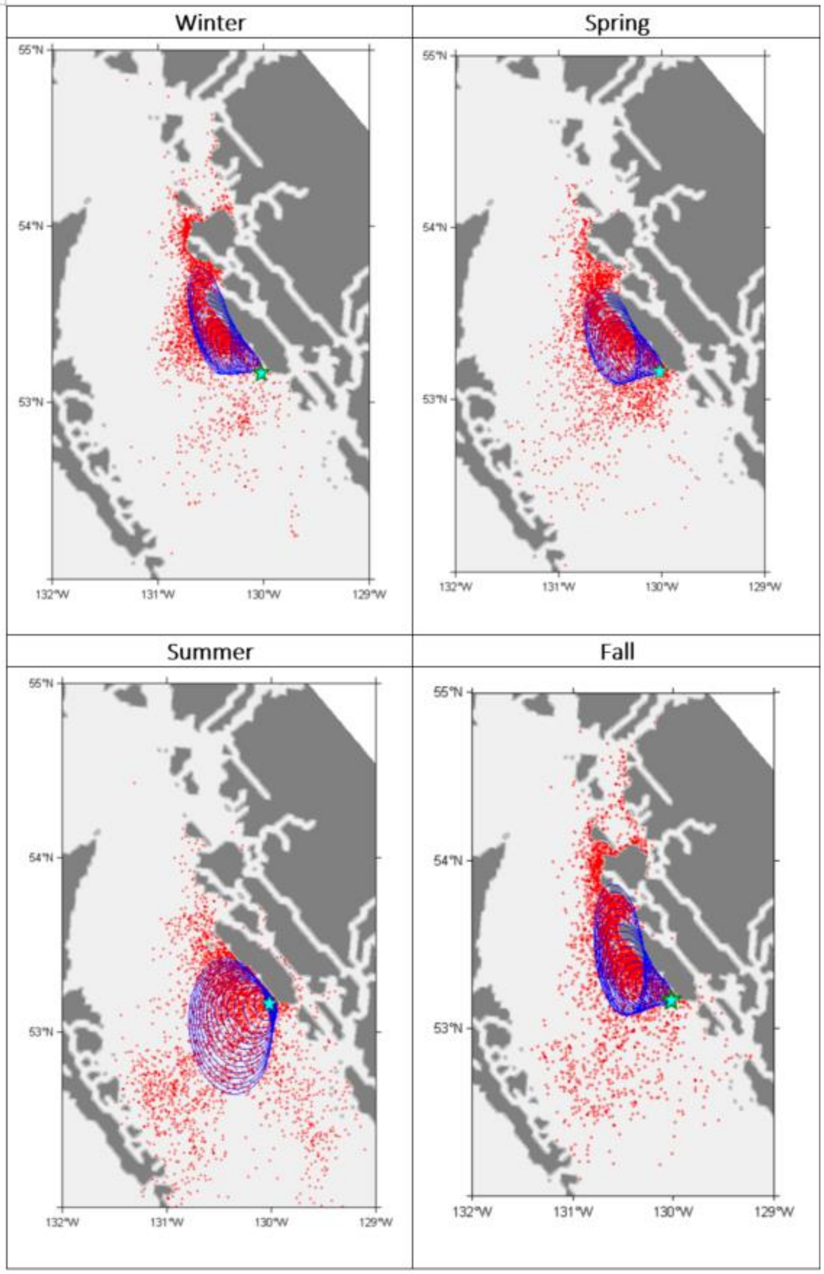

Figure 13. Model simulation of oil spill droplet distribution 15 days after release from single point (star) at different times of the year (Fine and Masson, 2015)

6.2.3 ***Fate of Diluted Bitumen in the coastal waters of British Columbia***

A preliminary assessment of the likely fate and behaviour of spilled dilbit in northern and central British Columbia has been done, which focused on Access Western Blend (AWB) and Cold Lake Blend (CLB) (Johannessen et al., 2019). To determine fate and behaviour within the context of northern and central British Columbia, Johannessen et al. (2019) completed a review of present and historical oceanographic data for Chatham Sound. Suspended particle concentration, surface salinity and temperature data were also collected for high risk and high priority areas in the region.

Based on density alone, they concluded that dilbit would be unlikely to sink anywhere in Chatham Sound. However, strong wave conditions can submerge dilbit and other types of petroleum products below the surface (O'Laughlin et al., 2017). Oil submerged by wave conditions may re-surface when the conditions diminish or they may remain below the surface if there is a consistent and strong vertical movement caused by down-welling or tidal convergence (Johannessen et al., 2019). Highly weathered dilbit would have an increased likelihood of sinking in some areas of central and northern British Columbia that have a salinity <14, such as around the mouth of a river during freshet, over shallow mudflats and within sheltered inlets after heavy rain.

Fresh dilbit has a lower density than freshwater and seawater, becoming increasingly denser as the lighter properties break down and evaporate. A wave tank experiment at the Bedford Institute of Oceanography was conducted to understand the weathering process of dilbit blends AWB and CLB in seawater (King et al., 2014; Government of Canada, 2013). The study determined that AWB and CLB reach maximum density after 13 days before the remaining components start to break down and density begins to decrease. Another weathering study determined that AWB exceeded the density of freshwater after six days (SL Ross Environmental Research Ltd., 2012; Government of Canada, 2013).

7 CONCLUSION

The Port of Prince Rupert is located in northern British Columbia. The climate is mild and humid with an annual temperature range between -24 to +28 ˚C (Environment Canada, 2019). For ten months of the year, the dominant wind direction is from the southeast (Fine and Masson 2015). Seasonal shifts in wind patterns in the fall and winter can produce dangerous wind and wave conditions for vessels navigating through Chatham Sound (Stucchi and Orr, 1993; Klock and Mullock, 2001). The Port of Prince Rupert changes anchoring procedures seasonally to address this shift in conditions (Prince Rupert Port Authority, 2019). The area is also susceptible to intense storm events in winter and large swells in the outer seaways of the North Coast (Lin and Fissel, 2018). These factors will make it difficult to provide suitable equipment in the event of a spill and delay their availability (Johannessen et al., 2019). Northern British Columbia is largely remote with scattered, isolated communities and little infrastructure, which adds to the complexity of recovery procedures and methods used in the event of an oil spill. Much of the region is disconnected from the response centre in Prince Rupert, where support and resources are located.

The shoreline of Chatham Sound is comprised mainly of medium and small grain sediment substrate (Coastal and Ocean Resources, 2020). The orientation and profile shelters much of the shoreline from strong oceanic wave exposure and as a result of these characteristics, large areas of Chatham Sound have an oil residence time of months to years (Coastal and Ocean Resources, 2020). There are some areas of the Sound that are exposed to open ocean waves (AECOM, 2011). Chatham Sound has a strong, northward, surface current hugging the eastern shoreline, except during summer months when the winds shift surface currents to the offshore (Lin and Fissel, 2018). If oil was to spill within Chatham Sound it would likely reach the shoreline.

Based on density alone, petroleum, particularly dilbit, would likely not sink in Chatham Sound. However, turbulent conditions, such as strong waves or tidal convergence can carry oil underwater (Johannessen et al., 2019). Surface salinity in the Sound has been measured at 14-20 ppt during freshet conditions (Trites, 1956). The salinity is higher on the western side of the Sound (Thomson, 1981; Lin et al., 2018; Lin and Fissel, 2018). There is limited consistent data available for the North Coast and Chatham Sound to provide a fully accurate depiction of the hydrography of the area (Lin and Fissel, 2018; Johannessen et al., 2019) and this adds to the difficulty in predicting the fate of a diluted bitumen spill.

8 ACKNOWLEDGEMENTS

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