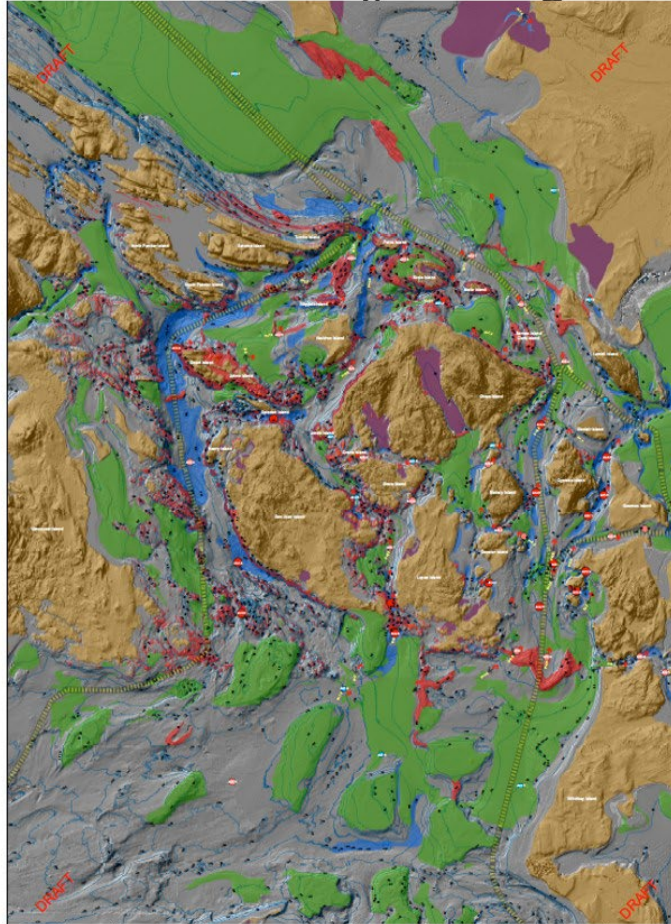

Oil Spill Assessment Maps of the Central Salish Sea
– Marine Seafloor & Coastal Habitats of Concern –
A Tool for Oil Spill Mitigation within the San Juan Archipelago,
San Juan County, Washington



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Tombolo Mapping Lab, Orcas Island
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Oil Spill Assessment Maps of the Central Salish Sea – Marine Seafloor & Coastal Habitats of Concern – A Tool for Oil Spill Mitigation within the San Juan Archipelago, San Juan County, Washington

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ABSTRACT

The potential for oil spills within the San Juan Archipelago of the central Salish Sea has been an increasing concern for some time. Within this region the spectacular islands, coastline, and underwater environment has drawn tourists, fisher people, residents, and researchers from around the world to play, live, and study here. The diverse biological resource of the region provides sustenance for many of the islanders and supports a valuable tourist industry for whale watching; salmon, crab, and shrimp fishing; and underwater diving – all of which can be adversely impacted from an oil spill.

The present plans to ship more hydrocarbon products including diluted bitumen (dilbit) from transfer sites located along the coastline of mainland British Columbia, Canada has the potential to increase tanker vessel traffic seven-fold through the San Juan Archipelago ([Seattle Times, June 22, 2019](#)). This, along with other types of marine traffic such as cruise ships, tug-and-tow barges, articulated tank barges, bulk carriers, freighters, and general cargo shipping will increase the risk of a collision, grounding, or other events that may lead to a significant oil spill. To date, the central Salish Sea region is only marginally prepared for an oil spill tracking, containment, and recovery action. Thus, a need exists to stage equipment for the mitigation of an oil spill event if critical marine habitats are to be protected.

To strategically locate or assemble any mitigation apparatus for a rapid response to an oil spill, a map showing critical marine habitats is a necessity. Such a map should highlight the most critical habitats along the marine transportation corridors (primarily Rosario and Haro straits, and

Guemes Channel) as well as the relatively isolated sounds and bays including Padilla, Samish, and Fidalgo bays that could act as depot centers for oil accumulation. This report addresses that need and usefulness for such a map, as no longer can it be said that what lies beneath the sea's surface is "out-of-sight", and thus "out-of-mind". This means that this study is critical to the development of realistic Natural Resources Damage Assessment (NRDA) settlements and can be used to inform developments of future Geographic Response Plans (GRPs).

INTRODUCTION

Accidental spill of oil into the marine environment is of considerable concern today as much of the world's crude oil is transported to refineries by ships from their points of origin or terrestrial trans-shipment facilities. The Salish Sea is the maritime gateway to Pacific Rim countries ([WDOE, 1997](#)). While this work focuses on the marine environment that could potentially be impacted from submerged oil spilled within the Salish Sea, we spend time here describing the known and reported physical environment; the types of oil readily being shipped and how they are obtained; the fates, behavior, and potential impacts of non-floating oil; and some of the mechanisms available to increase awareness of the Salish Sea environment. To accomplish this, we draw heavily upon the excellent reporting on the consequences of oil spills and shipping that have previously been reported by [Environment Canada \(2013\)](#); [Green et al. \(2016\)](#); [Jonannessen et al. \(2019\)](#); [McWhinnie, et al. \(2021\)](#); [Mullan \(2017\)](#); the United States National Academies of Sciences, Engineering, and Medicine ([NASEM, 2016](#)); and Washington State Department of Ecology ([WDOE, 2019](#)).

Physiography

The Salish Sea is a marginal urban estuarine body that is composed of the Georgia Basin, Gulf Islands, and northern Juan de Fuca Strait areas of British Columbia, Canada, and the San Juan Archipelago, southern Strait of Juan de Fuca, and the Puget Sound areas of Washington State,

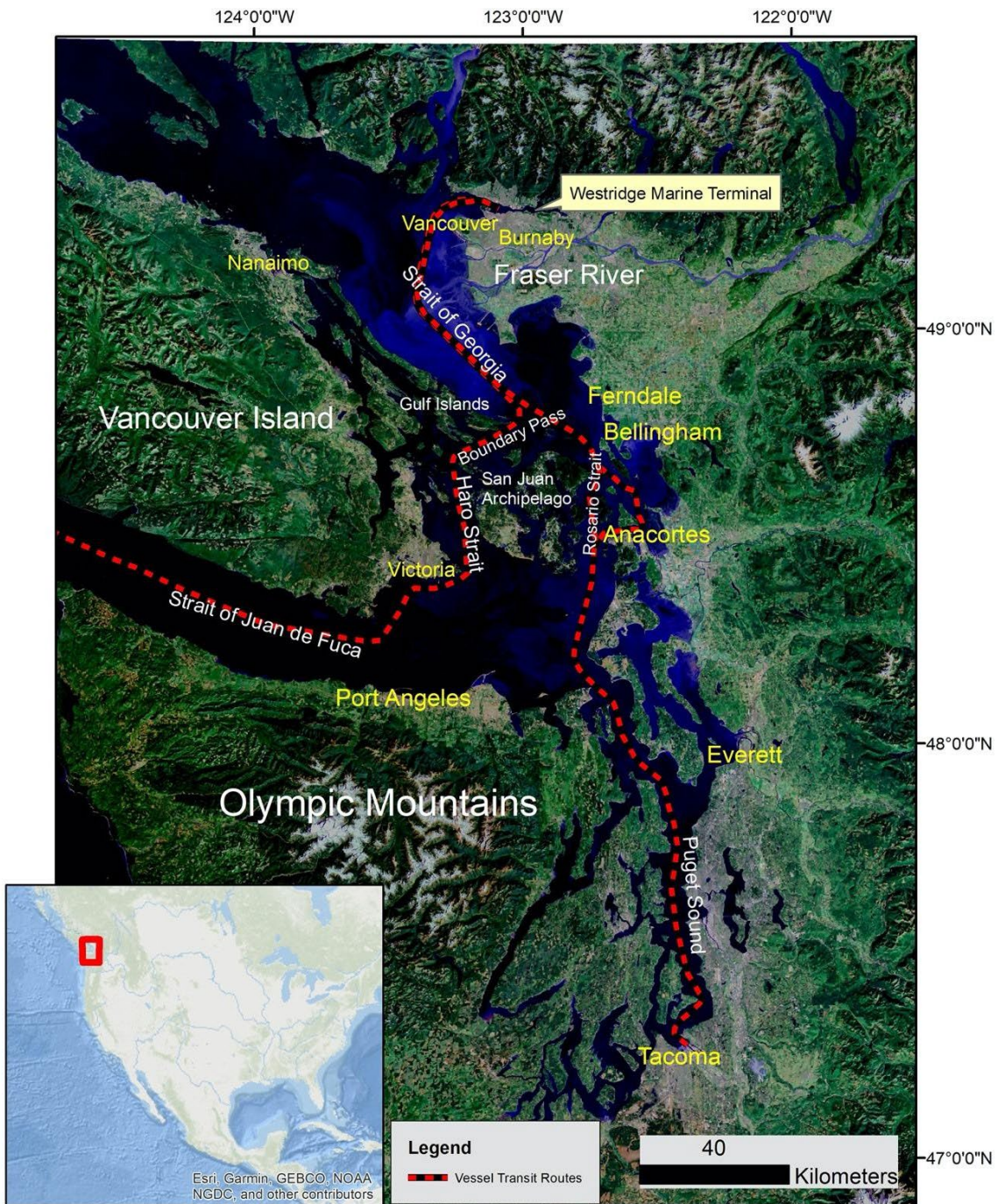


Figure 1. Index map of the central Salish Sea region where dilbit will be transported through two major straits, Haro and Rosario straits connected to the Pacific Ocean by the Strait of Juan de Fuca. Oil loaded at Westridge Terminal at Burnaby, located at Burrard Inlet. Other shipments take place between Anacortes and Tacoma.

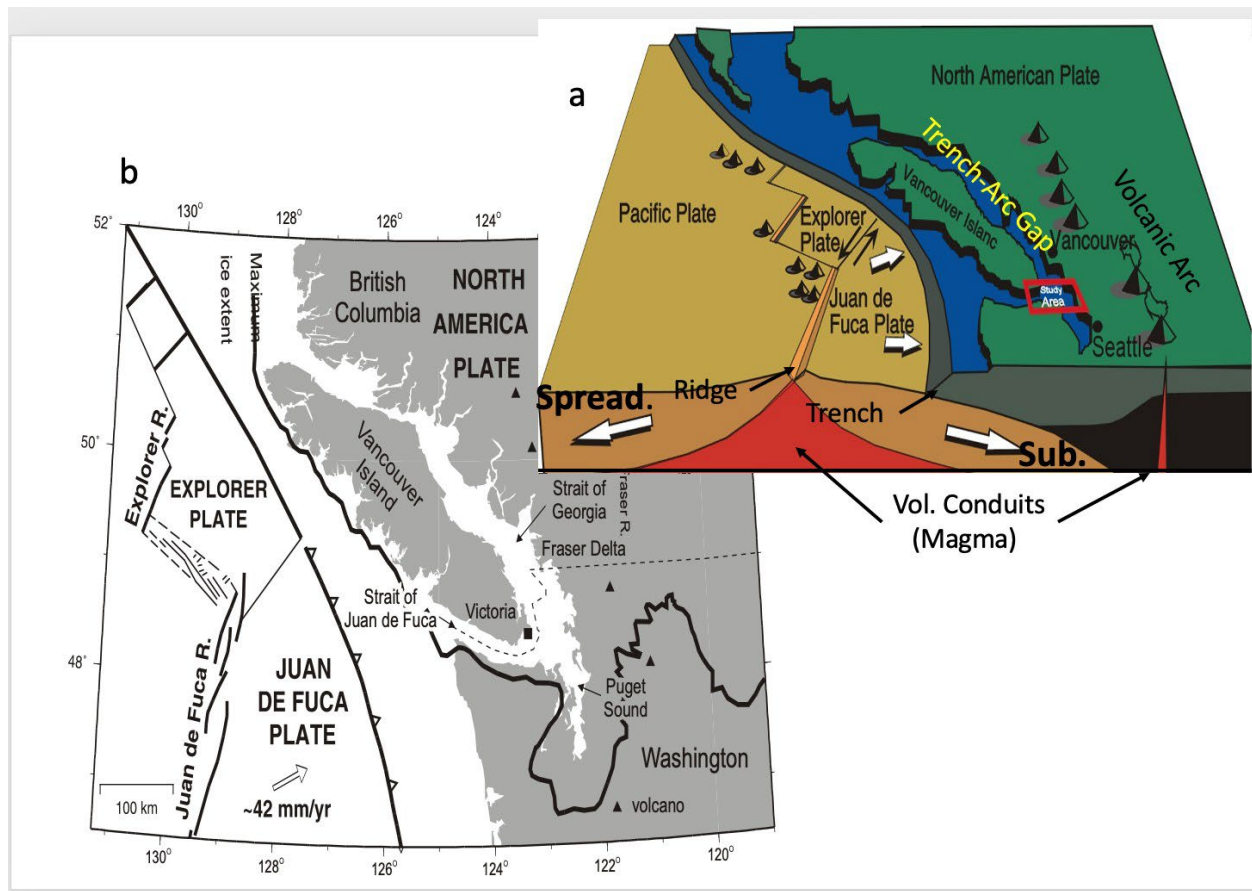


Figure 2. Regional geologic setting: a) tectonic map illustrating the plated tectonic processes active within the region, consisting of subduction (Sub.), spreading (Spread.) from the oceanic ridges, and the position of the Salish Sea within the Trench-Arc gap (forearc) of the Cascadia Subduction Zone, and b) the extent of the last glacial advanced covering the area where glaciated sculptured bedrock and covered the landscape with glacial deposits. Sub. – subduction, Spread = spreading.

USA (Fig. 1). As an urban ocean its aquatic environment is influenced by processes taking place within its terrestrial drainage sheds, coastal areas, and nearshore seafloors by both natural and anthropogenic influences. The physiography of the region is the creation of a major global tectonic process resulting with the oceanic Juan de Fuca and Explorer plates, remnants of the Farallon Plate, subducting (moving down) beneath the continental North American Plate (Fig. 2a). This ongoing process creates a seismically active region of tectonic deformation with the Salish Sea essentially filling the forearc region of the Cascadia subduction zone, generally located within the trench-arc gap (Riddihough et al., 1991). This deformation has been sculptured into deep fiords, sounds, and bays by the last major glacial advance (Fig. 2b) that receded approximately 10,000 years ago leaving a spectacularly diverse geography enjoyed today by residents of, and visitors to, the region.

Mullan (2017) notes that the Salish Sea covers approximately 18,000 km² (6,950 mi²), a region consisting of three major physiographic basins: Strait of Juan de Fuca (~4,400 km² [1,700 mi²], with a max. depth of ~250 m [820 ft.]), Strait of Georgia (~6,400 km² [2,471], with a max. depth of ~400 m [1,312 ft.]), and Puget Sound (~2,500 km² [965 mi²], with a max. depth of ~280 m [919 ft.]). A sinuous coastline of approximately 7,500 km (4,460 mi) long and hundreds of islands including the San Juan Archipelago and inter-island passages covering an area of approximately 4,700 km² (1,815 mi²) bounds the Salish Sea (Mullan, 2017). The Salish Sea is the name that has been more recently adopted for this entire body of water, in honor of the Coast Salish peoples of the Pacific Northwest (both First Nations and Native Americans), who have inhabited this region for several thousand years, and whose descendants still depend on its waters for sustenance. Some indigenous people call the sea “whulge” meaning “the water we know” or simply “salt water” (Bates et al., 1994; Mullan, 2017; Scigleano and Thompson, 2003).

The three major basins (Strait of Juan de Fuca, Strait of Georgia, Puget Sound) of the central Salish Sea are connected by tidal straits (Fig. 1), Haro-Boundary Pass and Rosario straits (Mullan, 2017). Mullan (2017) reports that a tidal strait is defined as elongate passageway connecting wide marine basins, and that: “In straits, tidal current dominance may result from convergence and amplification of flow due to channel geometry (e.g., Anastas et al., 2006; Dalrymple, 2010; Longhitano, 2013; Longhitano and Steel, 2016; Pugh, 1987)”. Haro Strait is the deepest (~413 m, 1,356 ft.) subtidal flow conduit between the Strait of Georgia and the open Pacific Ocean through the connection of the Juan de Fuca Strait with depths exceeding 375 m (1,130 ft.). Rosario Strait is the next deepest and secondary subtidal flow conduit with a 160 m (525 ft.) maximum depth (Mullan, 2017).

Major metropolises are located within the Salish Sea and consist of Vancouver and Victoria, BC, Canada, Bellingham, greater Seattle, Tacoma, and Olympia, WA, USA, with the two largest ports on the west coast of the US located in Seattle/Tacoma and Vancouver, B.C. areas (Fig. 1), home to over 8 million people (SeaDoc Society, 2020), as well as to hundreds of marine species including mammals, birds, fish, and invertebrates, all of which feed down the food chain (Gaydos et al., 2008; Gaydos and Person, 2011; McWhinnie et al., 2021; WDOE, 2019). These

cities and ports along with a multitude of small towns and villages clustered around the urban ocean act as receiving and transshipment points for western Canada and northwestern US. This highly populated region along with its commercial shipping centers produces anthropogenic pressures to the marine environment that is potentially detrimental to the health of the Salish Sea. Commodities such as oil and grain that are produced in the interior of western North America are often shipped from ports along the mainland of the Salish Sea.

Oil Types

While oil comes in many varieties and grades, in this study we classify the oils of concern for the central Salish Sea into two basic types: floating (non-persistent) and non-floating or sinkable (persistent) oils (clearseas.org). "Nonpersistent or group 1 oil" are a petroleum-based oil, such as gasoline, kerosene, diesel, liquified natural gas (LNG), or jet fuel, which evaporates relatively quickly. At the time of shipment, such oil consists of hydrocarbon fractions of which at least 50% by volume distills at a temperature of 340°C (645°F), and at least ninety-five percent by volume distills at a temperature of 370°C (700°F). Also, a nonpetroleum oil with a specific gravity less than 0.8 is considered as nonpersistent (Clearseas.org; [WAC 173-182-030](#) (32), p. 7).

Persistent oils or "Nonfloating oil" means those oils that exhibit qualities that could potentially cause the oils to submerge or sink such as the oil characteristics, weathering, environmental factors, or how they were discharged. Examples of these types of oils include, but are not limited to, diluted bitumen (dilbit), Group V Residual Fuel Oils (GPVRFO), Low American Petroleum Institute Oil (LAPIO), heavy fuel oil (HFO), decant, crude, asphalt, and asphalt products ([WAC 173-182-030](#) (31), p. 7; clearseas.org).

Non-persistent oils spread easily, evaporate, disperse, and dissolve while persistent oils also spread but emulsify and interact with particles (sediment, organics) in the water ([King et al., 2015](#); [Lee et al., 2012](#)). Since persistent oils sink, they are often discounted for mitigation as they are generally "out-of-sight", thus "out-of-mind". We, therefore, in this study focus on the behavior and fate of persistent oils as they have as much adverse impact potential to sub-tidal benthic habitats as non-persistent oils have on tidal and coastal habitats.

Bitumen is a dense, highly viscous petroleum product often incorporated in sand and clay deposits and have been variously called “bitumen sands”, “oil sands”, “tar sands”, and “asphaltum” (Green et al., 2016; Gosselin et al., 2010). Raw bitumen is semi-liquid at room temperatures and too viscous to transport through pipelines. Dilbit refers to the chemically diluted, highly viscous bitumen that has been treated for transport in unheated pipelines (Crosby et al., 2013). Dilution of the heavy oil is made through the addition of lighter constituents (Fig. 3), either of condensate or synthetic crude (synbit) to form dilbit (Environment Canada, 2013). Other common names for dilbit are “synbit”, “dilsynbit”, and “railbit” (NASEM, 2016).

Most global oil sands deposits are located >1,000 km (621 mi) from a coastline (Green et al., 2016) and thus requires transportation to coastal trans-shipment points by pipeline or rail. Transportation to, and storage at coasts along with marine transport of dilbit has furthered debate about the ecological, economical, and social hazards and opportunities created by extraction of this commodity (Green et al., 2016; Palen et al., 2014). In addition, this drilling industry affects climate change through methods of extraction, refining, transport, and combustion (Green, et al., 2016). Levine et al. (2014) reported that production of oil sands, or tar sands, in North America increased 46% since 2008 with the increase of hydraulic fracturing (“fracking”) of less permeable rocks such as shale.

Even though Washington State does not have a natural petroleum source, it is a major refining center with crude oil shipped in by tankers from Valdez, Alaska as well as in pipelines and rail cars from interior US and Canada with tankers from British Columbia delivering oil to Washington refineries for nearly the past 50 years (WDOE, 1997). Prior to 1950 oil refineries did not exist in Washington State and little crude oil (also called “black oil”) was transported into the region. Mobil Oil and Trans-Mountain Pipeline Company first brought in crude from Canada to be refined at the Mobil Oil refinery constructed in 1954 (later owned by Tosco) at Anacortes, Shell Oil refinery built in Anacortes in 1955, US Oil refinery (now Par Pacific) built in 1957 in Tacoma, and Texaco refinery built in Anacortes in 1958. In 1971 ARCO built a refinery at Cherry Point near Ferndale, which increased tanker traffic and increased production far above the state’s consumption. The state has the fifth largest refining capacity in the US (WDOE, 1997).

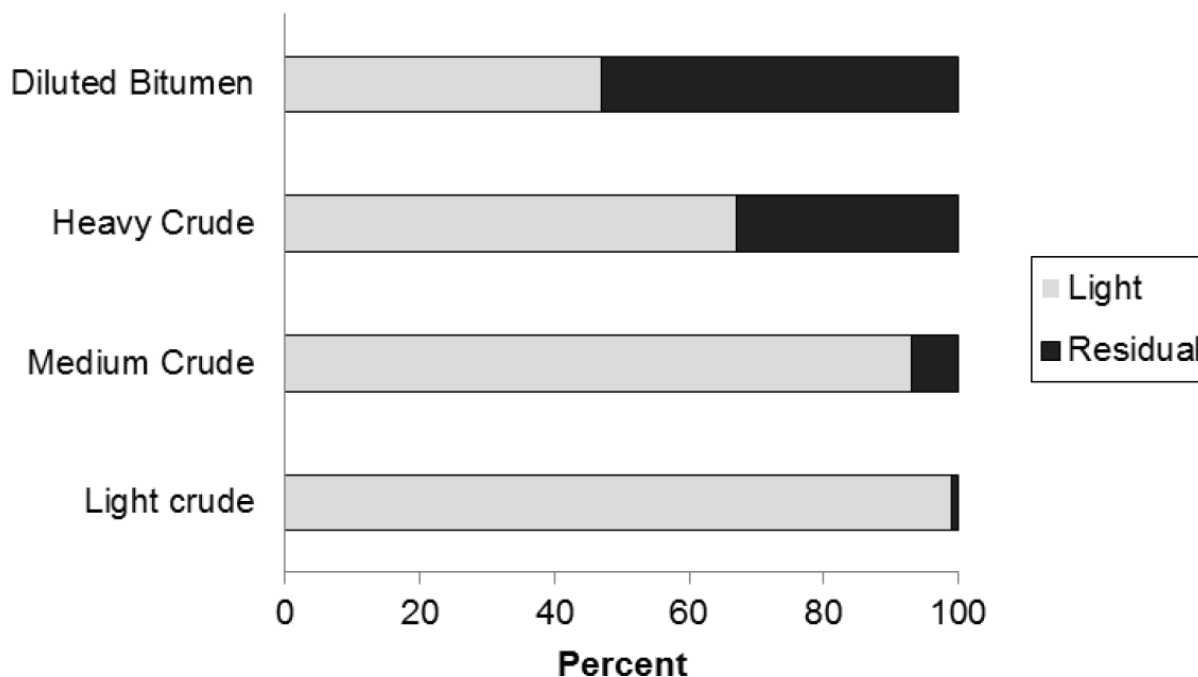


Figure 3. Relative proportions of light versus heavier residual components in crude oils. Note diluted bitumen contains the largest amount of heavy oil. After [NASEM \(2016\)](#); original sources: [Environment Canada \(2015\)](#); [Holleborne \(2015\)](#).

Oil will begin to sink when its density exceeds that of water, which can occur when oil is mixed with heavier material such as sediment ([Lee et al., 2012](#); [Michael, 2010](#)). Oil sediment mixing can occur in two ways: 1) stranding onshore with the uptake of sandy sediment and 2) mixing with sediment in the water column by wave action, away from shore ([Michael, 2010](#)). [Michael \(2010\)](#) also notes that evaporation alone has been seen to be sufficient to cause oil to sink. Oil density must exceed 1.0 g/mL to sink in sea water ([Environment Canada, 2013](#)). While much work has been done regarding floating oil and its impact on the shorelines of the islands and mainland, little or no study has been undertaken to assess and mitigate the potential adverse impact to benthic habitats by non-floating or sinkable oil and sunken oil. “Sunken oil” is non-floating (persistent) spilled oil on the bottom of a water body ([WDOE, 2019, CH. 6, p. 79](#)).

Marine Transport of Dilbit – Shipping

“As one of North America’s major gateways to the Pacific Rim trade, Puget Sound is one of the busiest waterways in the world with vessel traffic going to several busy ports in Washington

State and to major facilities in Vancouver, British Columbia. More vessel tonnage moves through the Strait of Juan de Fuca than through the combined ports of Los Angeles and Long Beach, California.” (WDOE, 1997, p. 11). Transportation of bitumen is not new and was originally undertaken by the Nabatean traders of Petra during the Hellenic period (~AD106), prior to the Roman takeover, when bitumen along with aromatics of frankincense and myrrh were carried from the Dead Sea through the Sinai Desert to Egypt (Elborough, 2019, p.53). Our investigation and mapping primarily focuses on the potential consequences of accidental spills today associated with the shipping of dilbit, although spills of other sinkable oils such as heavy fuel oil (HFO) that is used to propel most freighters should be of consideration as well (Fred Felleman, Personal Commun., Nov. 2021). McWhinnie et al. (2021) undertook a comprehensive evaluation of marine traffic patterns of mostly commercial shipping in the Salish Sea using satellite Automatic Identification System (AIS) data and Geographic Information Systems (GIS) Esri™ mapping, an evaluation focused on the impacts to the Southern Residence Killer Whales (*Orcinus orca*) critical habitat. The International Chamber of Shipping reported that commercial shipping accounts for nearly 91,000 vessels plying the oceans (UNCTAD, 2017), which represents 90% of the global trade and is expected to increase substantially in the future along with numbers and sizes of ships and increased propulsion power (Cominelli et al., 2018; McWhinnie et al., 2021). Locally, the Salish Sea is one of the busiest water ways in North America and accounts for more than 50% of commercial marine traffic nationally (Simrad et al., 2014) with large economic centers that concentrate shipping (McWhinnie et al., 2021). In addition to the two largest ports on the west coast of the US, other significant ports are located at Port Angeles, Bellingham, Everett, and Olympia in Washington State with oil terminals sited at Anacortes, WA, Ferndale, WA, Victoria, B.C., Vancouver, B.C., and Roberts Bank, B.C. (WDOE, 2015, 2019; Fig 1). The Salish Sea is one of the ten most high-volume ports hub that move oil in the United States with Alberta crude oil, being one of the largest hydrocarbon sources in the world supplying products to Burnaby, British Columbia where the Olympic Pipeline has been operating at capacity and oil is shipped by tankers and rail to the former US Par Pacific refinery in Anacortes (Felleman, 2016).

WDOE (1997, P. 21) reported that “*heavy fuel and crude oils, which are the most environmentally damaging types, are the largest amount of oil spilled in the state.*” The central

Salish Sea (the San Juan Archipelago) is particularly susceptible to shipping accidents including oil spills. The shipping lanes that weave through the islands are narrow, rocky, and subjected to strong tidal currents. Commercial marine traffic has been increasing ([McWhinnie et al., 2021](#)). The Washington State Department of Ecology reports that with over 20 billion gallons of oil moving through Washington State by vessel, rail, pipeline, and road each year, much through the Salish Sea, the region faces new and evolving risks from an increase in movement of oils that have the potential to submerge or sink in water ([WDOE, 2019](#)). In 2017 ~4.1 billion gallons per year (gpy) of crude oil (~80.6 million gpy of dilbit) was delivered to various Washington State facilities by vessels – although it is declining somewhat today – with an average of 25 tank barges traveling from Canada to Tacoma in past years ([WDOE, 2019, Ch. 7, and references therein](#)). Future transportation of dilbit was predicted to increase 2.5-fold from its rate of transport from 2013 to 2030 ([Canadian Association of Petroleum Producers, 2015; NASEM, 2016](#)), however, it has recently been predicted to increase 7-fold with potential transport of dilbit from a Canadian port at the termination of the Trans Mountain Pipeline once its construction is completed ([Johannessen et al., 2019; Seattle Times, June 22, 2019](#)). This pipeline is expected to supply crude oil (dilbit) up to 650,000 barrels a day (bpd) or 26,460,000 gallons per day (gpd) from the Westridge Marine Terminal in Burnaby, B.C., located in Burrard Inlet near Vancouver where ~60 laden tank ships per year (~5 tankers/month) departed in 2019; it is expected to increase to 34 laden ships per month with future supply from the pipeline ([Johannessen et al., 2019; WDOC, 2019](#)). In addition to the added number of ships traveling through the central Salish, increase in ship sizes also adds to a greater potential for an oil spill.

Dilbit as a “diluted conventional heavy crude oil” is prepared for transport through unheated pipelines, while “undiluted conventional heavy crude oil” are transported through heated pipelines ([NASEM, 2016](#)). For this mapping effort we are concerned with the trans-shipment points within the Salish Sea such as at the termination of the Kinder Morgan Trans Mountain pipeline from Alberta, Canada in Burnaby, British Columbia and Anacortes and Tacoma, Washington State where outbound shipping of the oil originates ([Figs. 1, 4](#)). Dilbit, or any heavy crude oil, including HFO, spills at these points, as well as from maritime transport, can impact wetlands, bays, and waterways, which have distinct characteristics that would influence the fate and ecological effects of the spilled oil ([NASEM, 2016](#)).



Figure 4. Map showing the pipeline distribution of for oil including dilbit. Two endpoints for Kinder Morgan expansion are at Burnaby, B.C., Canada and Anacortes, WA, USA with dilbit scheduled to be transported by ships through the tidal straits of the Central Salish Sea. Modified after *NASEM (2016)*.

Green et al. (2016) reported that during the past half century considerable attention has been given to the potential ecological, economic, and societal impacts of conventional (non-persistent) oil spills (e.g., *Chang et al., 2014; Moore and Dwer, 1974; Teal and Howarth, 1984*; see also *Green et al., 2016, their Figs. 4 and 5*). However, dilbit, as are GPVRF0, LAPIO, HFO, decant, crude, asphalt, and asphalt products, is chemically distinct from conventional oil, and so the ample information on the effects of conventional oil entering the marine environment may not be applicable (*Green et al., 2016*). *Green et al, (2016)* further state that publicly available information on the behavioral fate and toxicity of bitumen to marine biota is almost absent and

that assumptions that risk management can be based on best practices for addressing conventional oil spills are not supported by scientific evidence. [Environment Canada \(2013\)](#) reported that “Effective spill response depends on good scientific understanding of petroleum product behaviors in the environment (e.g., movement and changes in physical properties and chemical composition of oil)”. Although the [Environment Canada \(2013\)](#) study’s results were intended to immediately help inform spill responders and computer modelers to better understand and predict the fate of non-conventional petroleum products in the marine environment, it did not indicate what critical habitats may be impacted from a dilbit or other persistent oil spill.

Spilled Oil

The Salish Sea is internationally regarded as an ecological and cultural significant body of water and the need for protection is high. Recent national and international history demonstrates a low probability of a major oil spill for the region, but the high consequences from such a spill requires increased diligence in preventing spills and protecting sensitive areas ([WDOE, 2019](#)).

Once oil is spilled into the marine environment alteration and modifications begin to occur immediately, and the longer the oil is present in the environment the more alterations take place. Density, pour point, flash point, and viscosity all increase with increasing evaporation ([Environment Canada, 2013](#)). For dilbit spills, a diverse, viscous material with a strong tendency to adhere to surfaces begins to form as a residue ([NASEM, 2016](#)). [NASEM \(2016, p. 3\)](#) report *“For this reason, spills of diluted bitumen pose particular challenges when they reach water bodies. In some cases, the residues can submerge or sink to the bottom of the water body.”* Through weathering¹ the loss of volatiles during a spill often leads to a residue very much like that of the original bitumen. The increase in density that occurs in the oil increases the likelihood that the residual oil will sink beneath the water surface and potentially sink to the bottom ([Environment Canada, 2013](#); [King, 2014, 2015](#)). Tracking and recovery of submerged and sunken oil is logistically challenging, time consuming, and expensive ([Dollopf et al., 2014](#)).

¹ “Weathering includes spreading, evaporation, biodegradation, emulsification, oxidation, and dissolution into water” ([WDOE, 2019, Ch. 6, p. 80](#)).

At normal temperatures dilbit is a tar-like substance (WDOE, 2019). Although weathering increases density, other factors play a role. Density of sea water at water temperatures above freezing is 1.03g/cm^3 while crude oils commonly range from 0.7 to 0.99g/m^3 and uptake of particles in the water column such as fine sand, silt, and clay can trigger submergence of the oil (NASEM, 2016). This oil-particle aggregate (OPA) can lead to submergence and possible sedimentation. High energy dissipation rates are required for OPA formation in waters with low suspended particle concentrations (Gong et al., 2014; Hospital et al., 2016). Phytoplankton blooms can also episodically increase particle concentrations (Johannessen et al., 2019). Where salinity stratification exists such as freshwater overlying salt water, which occurs in the central Salish Sea, submerged oils may accumulate at density interfaces beneath the surface (Short, 2013).

“All crude oils, even light oils such as Bakken crude, have the potential for some portion of the oil to weather and sink.” (WDOE, 2019, Ch. 6, p. 83). Therefore, it is important to prepare for the potential of oil to sink in fresh water, marine waters, shallow and deep waters, as well as in high current and high suspended sediment waters (WDOE, 2019, Ch. 6, p. 87).

Adhesion (“stickiness”) of some crude oils is higher than others. For example, dilbit is more strongly adhesive than light or medium crude oils or their evaporated residues due to greater abundances of resins and asphaltenes (NASEM, 2013, their Fig. 2-3). NASEM (2013) reported that the likelihood of submerged and sinking dilbit in a marine environment, often as OPAs, merits particular attention as it presents distinct routes of exposure to the biota.

The central Salish Sea is a low-energy wave regime limited foremost by fetch as coastal geometry and obstructions prevent wave propagation. However, strong tidal currents occur and can sweep in sediment supplied by rivers, creeks, and bays that debouch into the Salish Sea and can contribute to OPAs. The Fraser River is a major contributor to the sediment supply. As reported by Mullan (2017), the Fraser freshet accounts for $\sim 73\%$ of the $\sim 158 \times 10^9 \text{ m}^3$ mean annual freshwater discharge into the Strait of Georgia (Masson, 2002; Johannessen et al., 2003), which peaks around June at a volume of $\sim 7,000$ to $10,000 \text{ m}^3/\text{s}$ (Southerland et al., 2011; Johannessen et al., 2003). The particle load of the Fraser River is $19 \times 10^9 \text{ kg/yr}$. (Thomas and

[Bendell-Young, 1999](#)) with predominantly suspended silt and clay at the river mouth ([Milliman, 1980](#); [Stecko and Bendell-Young, 2000](#)).

Other significant rivers that contribute sediment to the Salish Sea include the Skagit and Snohomish rivers of Washington State that together have a maximum discharge of $\sim 7,000 \text{ m}^3/\text{s}$ and a mean discharge of $\sim 1,000 \text{ m}^3/\text{s}$ ([Southerland et al., 2011](#)). These rivers have extensive drainage basins from which sediment is eroded and contributed to the modern Salish Sea sediment supply. For example, the Fraser River drainage basin is $\sim 233,100 \text{ km}^2$ ([Mullan, 2017](#)). Approximately a third of the Fraser River suspended sediments are deposited on the Fraser River delta with the remainder two-thirds dispersed by turbid surface plumes ([Johannessen et al., 2003, 2005](#)).

Tidal Current Transport of Dilbit and Sedimentation

Tidal currents are the dominant mechanism within the Salish Sea for moving submerged and sinking oil. Tides in the Salish Sea are mixed because the dominant resonant period of the system is between semidiurnal and diurnal frequencies ([Crean et al., 1988a, b](#)). Within the central Salish Sea's tidal straits, the tidal ranges increase from 2.0 m in southern Haro Strait to 2.3 m at southern Rosario Strait and 2.6 m north of the San Juan Islands ([Mullan, 2017](#)). Locally fast currents that result from tidal exchange through flow-constricted straits of the Gulf-San Juan archipelagos obtain speeds between 1 to 3 m/s ([Dewey et al., 2014](#); [LeBlond et al., 1991](#)). However, 80% of tidal current kinetic energy from the tidal processes can be found within the Juan de Fuca Strait and the Strait of Georgia, while 100% of kinetic energy occurs in the narrow channels of the San Juan Archipelago ([Crean et al., 1988a, b](#); [Foreman et al., 1995](#); [Stronach et al., 1993](#)). Therefore, the strong tidal currents and exchanges can rapidly move submerged and sinking oil away from a spill and these currents need to be considered in predicting potential marine benthic habitat impacts by the projection of oil spill trajectories based on tidal currents.

Numerous submarine ridges and headlands within the central Salish Sea interrupt tidal flow and generate internal waves and eddies that act as drag to the flow providing energy for mixing, which destroys stratification in the water column ([Mullan, 2017](#); [Sutherland et al., 2011](#)). This is substantiated by [Farmer et al. \(2002\)](#), [Johannessen et al. \(2006\)](#), and [Pawlowics \(2001\)](#) who

report on the existence of turbulence and super-critical flow in the central Salish Sea and other settings. In addition, [Mullan \(2017\)](#) states that a proportion of energy dissipated by propagating tidal currents within the Salish Sea through erosion and sediment transport form modern seabed geomorphology, such as scour depressions and banner banks --- banner banks are elongate (generally oval or tear-dropped shaped) coastal sand and gravel deposits resulting from perturbation of a regional current by a coastal headland or seafloor obstruction leading to deposition in the lee of the obstruction ([Dyer and Huntley, 1999](#)). Small-scale bedload parting zones formed by symmetrical flood and ebb tidal currents can form a sequence of facies moving away from a headland or seafloor obstruction along either side of a coast from a central scoured bedrock or pebble-cobble pavement to mobile sand and silt ([Bastos et al., 2002](#); [Duffy, 2006](#); [Duffy and Hughes Clarke, 2005](#); [Harris et al., 1995](#); [Fig. 5](#)). Thus, any sinking oil that reaches the seabed would be incorporated into this complex sediment transport and depositional process.

Regarding bedform sediment transport, the intra-archipelago network of waterway geometry presents a complex configuration of sediment transport conduits and barriers ([Mullan, 2017](#)). Dilbit, and other persistent oil density, especially if adhesive (sticky) can increase by OPA from the high perennial load of suspended particles near the seabed in the energetic Haro Strait-Boundary Pass corridor ([Fig. 1](#)), sustained by local erosion of Pleistocene deposits and seasonally down-mixed sediment from the Fraser River ([Johannessen et al., 2006](#)). Sediment, including incorporated dilbit can travel far in a relatively short time as modeled by [Mullan \(2017\)](#) where it was found that medium-size sand released along the eastern Strait of Juan de Fuca south of Haro Strait traveled ~56 km to enter the Strait of Georgia in less than 16 days ([Fig. 1](#)). (This same type of modeling can be used to track dilbit along the seafloor.) The tidal straits (elongate passageways connecting marine basins) such as the Strait of Juan de Fuca (mapped as a basin by [Mullan, 2017](#)), Haro Strait, Rosario Strait, and the Strait of Georgia and others such as the more globally known Golden Gate into San Francisco estuary and Dover Strait into the Mediterranean according to [Dalrymple \(2010\)](#) and [Longhitano \(2013\)](#) may be the most understudied tide dominated environments for sedimentation and facies studies. Thus, the fate of sinking oil in these areas would also be little known.

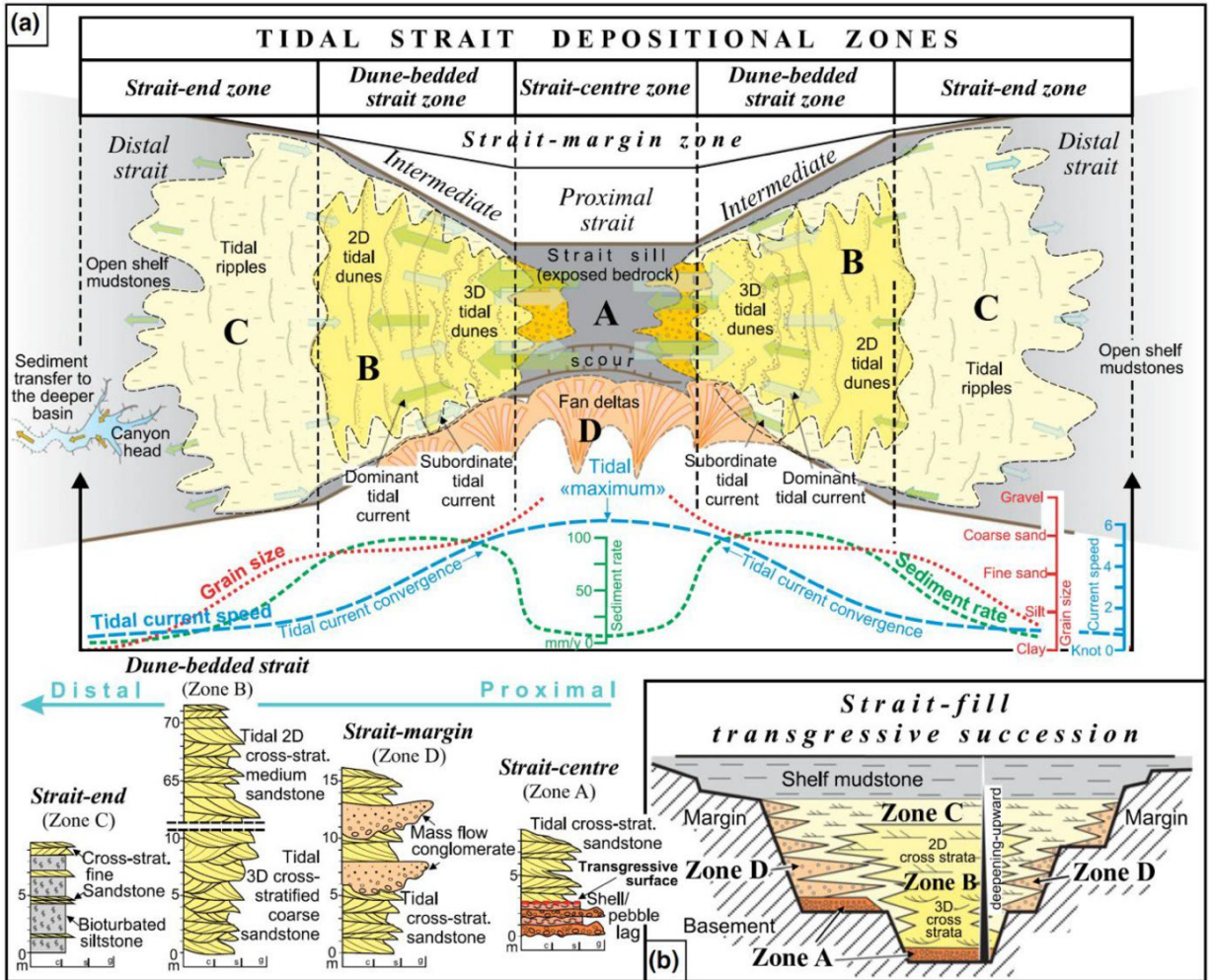


Figure 5. Sediment depositional model for tectonically controlled narrow tidal straits that applies to the central Salish Sea. This illustrates how basically sediment is distributed outward from the center of a tidal strait with finer sediment being gradationally deposited as current strength diminishes outward from a tidal strait. From Longhitano (2013), after Mullan (2017, his Fig. 1.02).

The results of model simulations by Mullan (2017) show fluid-dominated sediment transport through Haro and Rosario straits towards and into the Strait of Georgia (Fig. 1) for every grain size (gravel to silt) used suggesting that the Strait of Georgia is a sediment sink or depotcenter. In shallow water, tidal wave asymmetry (as flood tidal currents are of shorter duration than ebb) tends to result in flood dominance and net movement of sediment at faster rates than ebb (Dalrymple, 2010; Mullan, 2017). Flow expansion within a wide basin such as the Strait of Georgia results in reduced peak current speeds and tidal ellipses that assume a more rotary

motion (Mullan, 2017). However, Mullan (2017) also found that clockwise rotation of tidal current occurs around Waldron Island (Fig. 6a).

Like rivers, the straits and channels of the central Salish Sea transport sediment and associated crude oils by wash load (very fine particles relatively distributed throughout the water column), suspended load, and bedload (Mullan, 2017; Shen and Julien, 1993). Once on the bottom dilbit can be transported along with bedload sediment and incorporated into this bedload and deposited in sandy substrate such as banner banks. The mobility of crude oil in porous media such as sand

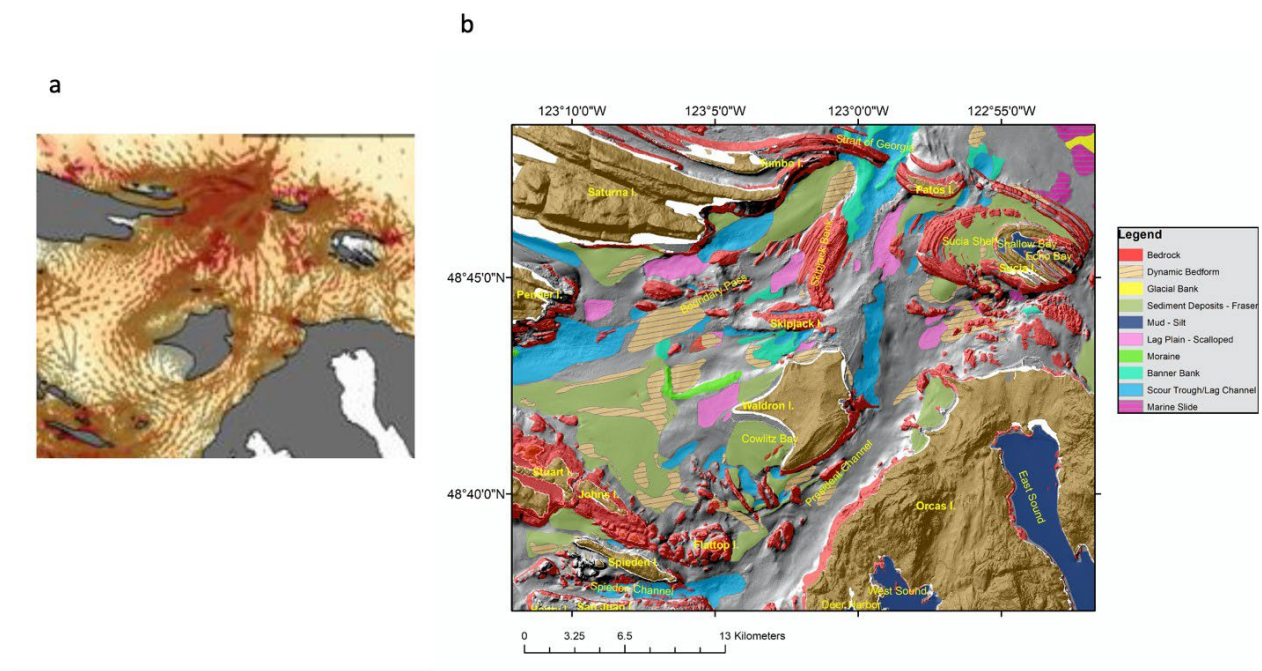


Figure 6. Maps showing rotary tidal circulation around Waldron Island. a) bottom current vectors after Mullan (2017, his Fig. 2.02b) of modeled maximum speeds from 3D bottom layer results, and b) diverse morphology resulting from strong rotary bottom currents.

is inversely proportional to its viscosity and, thus high viscosity oils such as weathered dilbit tend to penetrate very little into porous sediment (NASEM, 2016). In addition, the high adhesion of weathered dilbit further reduces mobility, and allows substrate to stick to or armor tar balls. Therefore, high viscosity, high adhesive dilbit has the propensity to coat porous sandy surfaces or stick to hard substrate such as bedrock – although WDOE (2019) report that seagrass beds, eelgrass meadows, and kelp forests, habitats that support migrating spawning fish species and

forage fish (e.g., Pacific sand lance, herring), are more sensitive than rocky substrate to dilbit adherence. This propensity is advantageous for the cleanup of beaches and rock outcrops along coasts and in the inter-tidal zones but presents an unaddressed problem in the sub-tidal areas.

In addition to direct adhesion and coating of substrate, direct chemically based mechanisms (toxicity) of crude oils including dilbit can result in acute and sublethal effects to the ecology in the bedload transport path of the spilled oil through physically coating biological surfaces, thus impeding an organism's movement, and can alter behavior and/or hamper respiration by coating gills and permeable skin surfaces of fish, along with hampering feeding, and thermoregulation (NASEM, 2016). However, for the past 45 years there are very few laboratory experiments specifically focused on investigating the toxicity of dilbit, as well as its use and transport in North America (NASEM, 2016).

Major Historical Oils Spills

No major crude oil spill has been reported in the Salish Sea within this decade. However, in 1980 the grounded *ARCO Anchorage* tanker spilled 239,000 gals of crude oil at Port Angeles, in the Strait of Juan de Fuca, the state's largest oil spill at that time (Seattle Times, Tomas Guillen, Feb. 25, 1991). In 1991, U.S. Oil refinery spilled 600,000 gals of crude oil but most was prevented from entering State waters, and in 1991, Texaco refinery spilled 130,000 gals of crude in Anacortes with 40,000 gals going into Fidalgo Bay (WDOE, 1997). This spill into Fidalgo Bay had long-term impacts due to low bottom current energy and soft unconsolidated sediment substrate (Fred Felleman, Personal Commun., Nov. 2021). There was a small spill of 224 m³ (59,175 gals.) of dilbit in 2007 within Burrard Inlet, off Vancouver, B.C. where only intertidal sediments were oiled (Johannessen et al., 2019; see Fig. 1). Two oil spills have been reported by ClearSeas (see clearseas.org) to have taken place offshore northern BC and offshore central Washington. However, in 1994 Barge 101 in tow by tugboat *Mercury* grounded on Clements Reef while southbound to Anacortes and spilled 27,000 gallons of diesel oil (Office of Marine Safety, 1995 as reported in WDOE, 2019, Ch. 2, p. 24). In 1988 a ship collision by *Nestucca* spilled 874,430 liters of oil, the largest oil spill on Canada's Pacific coast. In 2016 the ship grounding of the *Nathan E. Stewart* spilled 110,000 liters of diesel fuel offshore central western Washington, the most recent spill of note for the region (Environment Canada, 2013). Also, in

2016 the *MV Marathassa* spilled 2,700 litres (~713 gals.) of bunker fuel in English Bay at Vancouver, B.C. (See <https://globalnews.ca/news/4235090/english-bay-oil-spill-vancouver-compensation/>)

There have been several reports of oil spills in the US from pipelines and rail accidents with some of the spilled oils reaching aquatic environments such as rivers and wetlands. One such spill into the Kalamazoo River of Michigan showed that oil-spill aggregates readily form from native river sediments and dilbit, possibly caused by sediment agitation techniques being used for clean-up and observed to be stable after two years (Lee et al., 2012; Environment Canada, 2013). Whether a spill is from a pipeline, rail car, or ship/barge vessels, the resulting impacts to the marine environment are likely the same, although mitigating actions will be unique to each spill event. Every spill presents a unique combination of conditions to be assessed for mitigating actions. In other words, the transport, fate, and effects of spilled oil depend not only on the characteristic of the oil but on the environment and conditions at the time and place of the spill (NASEM, 2016). Natural and economic resources can be at risk of damages from a non-floating oil spill, thus substrate types (e.g., mud, sand, rock) and underwater obstructions that present a safety risk (e.g., electrical power cables and pipelines) need to be identified during a spill (WDOE, 2019).]

Planning for an Oil Spill

In urban marginal seas such as the Salish Sea the vulnerability of communities and environments can be assessed in advance and these factors can become a key component of spill response planning. The types of environments, communities, and facilities that could potentially be impacted along with their sensitivities and vulnerabilities, can thus be identified in advance, which are essential elements of spill response planning (NASEM, 2016, Ch. 4).

For non-floating crude (persistent) oil the objective of spill response would be to track the suspended material and predict where it may sink to the bottom (NASEM, 2016, Ch. 4). As pointed out in the NASEM (2016) report, a major environmental concern is the weathering of spilled dilbit into a heavy, sticky residue that cannot be recovered and has the potential threat of fouling habitats and wildlife. The NASEM (2016) report concluded that detection of dilbit when

submerged remains a problem and better research needs to be undertaken to understand the diversity of the water body environment where a potential spill could occur. In detail, the [NASEM \(2016, p. 3\)](#) report states:

“In cases where traditional removal or containment techniques are not immediately successful, the possibility of submerged and sunken oil increase. This situation is highly problematic for spill response because (1) there are few effective techniques for detection, containment, and recovery of oil that is submerged in the water column, and (2) available techniques for responding to oil that has sunk to the bottom have variable effectiveness.” Certainly, the complexity of the seafloor of the Salish Sea and its modern sedimentary processes would need to be understood if a rational sunken oil spill response is initiated.

Mechanisms to assess potential oil spill impacts are in place and one such mechanism is called “Area Contingency Planning” (ACP), which addresses local conditions. Within the boundary of an ACP, subareas with unique circumstances that warrant tailored response, such as in the central Salish Sea, can be defined. ACPs are designed to ensure that all responders have access to essential area-specific information and can identify in advance spill scenarios that can damage areas that are environmentally sensitive or of special economic or cultural importance ([NASEM, 2016, Ch. 5](#); [USEPA, 2018](#)). Further, the Washington State Department of Ecology in addressing recent legislation (Wash, Rev. Code § 90.56.569, 2008) is updating Geographic Response Plans (GRPs) that will describe important sensitive resources within a GRP area and will include narrative descriptions at risk for non-floating oil (including sunken oil) and an analysis of potential response tactics based on the area’s sensitivity and complexity ([WDOE, 2019, Ch. 6](#); see <https://ecology.wa.gov/Regulations-Permits/Plans-policies/Contingency-planning-for-oil-industry/Geographic-response-plans-for-oil-spills>). These 2008 adopted changes in Washington State Law provide the Department of Ecology with direction and funding to identify water column and seabed resources at risk from non-floating oils ([WDOE, 2019, P. 87](#)).

Objective

United States Coast Guard data indicate that tanker spills account for the overwhelming proportion of oil spills in US waters since 1973 and the costs for cleanup and damages were estimated by DOE (1993) to be over \$1 billion (in 1993 dollars). The [WDOE \(1997, p. 21\)](#)

reported that “heavy fuel and crude oils, which are the most environmentally damaging types, are the largest amount of oil spilled in the state.” Thus our major objective of this study is to construct the Oil Spill Assessment Maps that exhibit interpreted marine benthic habitats and substrate types, highlighting areas where potential dispersal (transport), accumulation, embedment, trapped sinkable and sunken oils could occur. The map is based on the recently in house (Tombolo Mapping Lab) compiled five sheet dilbit “Oil Spill and Benthic Habitats” maps of the San Juan Archipelago.

Oil dispersal corridors (seafloor oil transport routes), tidal flow velocities, potential oil spill risks, marine and coastal habitats, and other data have been compiled, condensed, re-interpreted, and plotted from our DilBit Oil Spill and Benthic Habitat map series with expert interpretations based on the most significant and highest density clustering of critical habitats. This map is supplemented with new information obtained during the construction of the San Juan Archipelago Geologic Map, an exercise still in progress.

Research priorities recommended in the [NASEM \(2016\)](#) report directly apply to this investigation. [NASEM \(2016, P. 122\)](#) state that: “*These research priorities are targeted broadly to the research community, but a specific mention is needed regarding the role of local and regional scientists in spill response [McNutt, M.A., 2015]. Improved access and collaboration with these scientists would help advance the scientific understanding of how oil behaves in the environment, particularly for emerging issues such as spill of diluted bitumen. Scientists from outside of the formal response framework are typically not included in formal oil spill response activities and, as a result, are often barred from site access by response officials and their requests for source materials are denied. This situation hinders fundamental research on spill events---research that should ultimately benefit spill planning---and may also provide immediate benefit to response officials.*” Our objective for providing the Oil Spill Assessment Maps is to assist in addressing this research priority.

In addition, our study addresses [Green et al. \(2016, their Table 1\)](#) high to very high research priorities of “Bitumen in the Environment”. At the time of the publication of the [Environment Canada \(2013\)](#) report little information on spill behavior, fate, impacts, and remediation options

were available, even though dilbit was being piped to coastal ports for trans-shipment. The Oil Spill Assessment Maps addresses this priority.

METHODOLOGY

Multiple data sets were used for the construction of the Oil Spill Assessment Maps, consisting of the multibeam echosounder (MBES), tidal current data, shipping lane locations, mapped coastal and subtidal habitats, in situ bottom samples and video/still photography, and shipping frequencies based on AIS data.

Tools used to construct the Oil Spill Assessment Map include the following Esri software products:

- ArcGIS Online
- ArcMap Version 10.6
- ArcGIS Pro 10.8.0

Data acquired and used to identify and construct the components and layers for the Oil Spill Assessment Maps ([Plates 1 and 2](#)) in a GIS project include geologic polygons from a presently developing geologic map (construction in progress) and from the published Potential Marine Benthic Habitats of the San Juan Archipelago of the Geological Survey of Canada Marine Map Series ([Greene and Barrie, 2011](#)) to locate important benthic habitats and to categorize the probable behavior of oil at the seafloor ([Table 1](#)).

Geologic units, geomorphological features, sedimentary deposits, and substrate types interpreted from the MBES data set were used to classify potential dilbit behavior and impact on a few selected benthic habitats ([Table 2](#)). In addition, previously mapped habitat types from the [Greene and Barrie \(2011\)](#) published maps were used to flesh out areas where the behavior and fate of dilbit may impact a habitat ([Table 3](#)). The benthic habitat maps used in this project have created habitat interpretations, represented in GIS as polygon features with specific habitat codes and habitat types defined. We have used these definitions to supplement the geologic interpretations defined in [Table 2](#).

Map Components and Layers	Description and Data Sources
Bathymetric Imagery and data	<p>Hillshade Images and Depth Contours at 25 m intervals were created primarily from multibeam echosounder (MBES) surveys obtained by the Tomolo Mapping Lab/SeaDoc Society-Moss Landing Marine Labs (MLML) in cooperation with the Geological Survey of Canada (GSC).</p> <p>These were supplemented with data from a set of National Oceanographic and Atmospheric Agency/ National Ocean Survey (NOAA/NOS) surveys. <i>Source: "Bathymetric Data Viewer."</i> https://www.ncei.noaa.gov/maps/bathymetry/</p> <p>In some mostly nearshore areas, these images have been supplemented from other available bathymetry. These include private and public sources. <i>Source: D. Finlayson (2019). UW Ocean - Digital Data Archives for Puget Sound. Available:</i> https://www.ocean.washington.edu/data/pugetsound/</p> <p>The hillshade image mosaics use the highest resolution images available from overlapping surveys.</p>
Terrestrial imagery	<p>A mosaic of terrestrial hillshade imagery was developed primarily from the processing of bare earth light detection and ranging (LiDAR) data obtained from Puget Sound LiDAR Consortium and from Washington Department of Natural Resources.</p> <p>These data were supplemented with data from Esri Basemaps and United States Geological Service (USGS) digital elevation models (DEMs).</p> <p><i>Sources: Washington Lidar Portal. https://lidarportal.dnr.wa.gov/</i> <i>Puget Sound Lidar Consortium(2019). Lidar data set for the San Juan Archipelago http://pugetsoundlidar.ess.washington.edu</i></p>
Interpretations of Seafloor Geomorphology and Potential Benthic Habitats	<p>Interpretations of seafloor geomorphology and potential benthic habitats were made from two sources: benthic habitat maps (Greene and Barrie, 2011) and a geologic map currently under construction. The methodology used in developing the maps made use of the MBES dataset (bathymetry and backscatter), seafloor sediment samples, and analysis of the geological and oceanographic processes.</p> <p>Table 2 and Table 3 show how the feature attributes in these maps translate to habitat and oil spill assessment categories in the resulting Oil Spill Assessment Map.</p>

<p>Rockfish (<i>Sebastes</i> spp.) survey data</p>	<p>These data represent locations of observed rockfish from surveys conducted by Washington Department of Fish and Wildlife (WDF&W) using Remotely Operated Vehicles (ROV) and drop camera surveys from 1994-2016 along with NOAA’s line catch survey data. These included a variety of fish considered species of concern - including rockfish species (<i>Sebastes</i> spp.) -- yelloweye rockfish (<i>S. ruberrimus</i>), bocaccio rockfish (<i>S. paucispinis</i>), canary rockfish (<i>S. pinniger</i>), copper rockfish (<i>S. caurinus</i>), greenstriped rockfish (<i>S. elongatus</i>), quillback rockfish (<i>S. maliger</i>), and vermilion rockfish (<i>S. miniatus</i>).</p> <p>Source: Spreadsheets provided by WDFW and NOAA as part of rockfish habitat analysis project</p>
<p>Pacific sand lance (<i>Ammodytes personatus</i>) observations</p>	<p>These are locations (features) where subtidal Pacific sand lance (<i>Ammodytes personatus</i>) have been observed from studies at Friday Harbor Labs using underwater video and Van Veen sampling methods.</p> <p>Source: Data provided as spreadsheets from Matt Baker of Friday Harbor Labs</p>
<p>Eelgrass (<i>Zostera marina</i>)</p>	<p>Identified deep-water edge (“outline”) of surveyed eelgrass beds.</p> <p>Source: Slocumb et al. (2004).</p> <p>Surveys from Friends of San Juans “Research & Maps Friends of the San Juans.” https://sanjuans.org/nearshorestudies-htm/</p>
<p>Bull kelp (<i>Nerocystis luetkeana</i>)</p>	<p>Identified locations of surveyed bull kelp. These data represent observed locations for canopy bull kelp. Indicates rocky substrate.</p> <p>Source: Surveys from Friends of San Juans “Research & Maps Friends of the San Juans.” https://sanjuans.org/nearshorestudies-htm/</p>
<p>Diluted Bitumen (dilbit) Vessel Routes</p>	<p>Diluted bitumen oil transit routes are identified from Washington State Department of Ecology “Report of Vessel Traffic and Vessel Traffic Safety: Strait of Juan de Fuca and Puget Sound Area.” (Figure 34). https://apps.ecology.wa.gov/publications/SummaryPages/1908002.html (accessed Aug. 17, 2021).</p> <p>Felleman (2016). Report on transport of dilbit from Westridge to processing facility in Tacoma.</p> <p>These routes were mapped to coincide with frequent vessel traffic routes for tanker vessels using data from Automatic Identification Systems (AIS) provided by NOAA (using data from the year 2017).</p>

	<p>“MarineCadastre.gov Vessel Traffic Data.” https://marinecadastre.gov/ais/ (accessed Mar. 27, 2018).</p>
Tidal Currents – current strength and direction	<p>Indications of relative strength and direction of tidal currents were obtained from two major sources.</p> <p>NOAA’s model predictions for 57 locations for the year 2018 were downloaded and processed. We selected the maximum predicted ebb and flood for the year. The average ebb and flood directions at maximum flow were extracted. Accessed and downloaded from “NOAA Current Predictions,” 2018. [Online]. Available: https://tidesandcurrents.noaa.gov/noaacurrents/Stations?g=698</p> <p>We obtained measured currents from 54 Acoustic Doppler Current Profiler (ADCP) stations collected from a survey conducted from the years 2015 through 2017. The ADCP measurements were taken at various depths, and in the maps we used the measurements for the maximum depths provided, and used the maximum current measured through a four week period. Source: NOAA, National Oceanographic and Atmospheric Agency Current Station ADCP Data, 2019, https://tidesandcurrents.noaa.gov/cdata/StationList?type=Current+Data&filter=historic&pid=38</p>
Oil Spill Behavior Class	<p>The map defines polygon areas categorized by the expected behavior of spilled dilbit as it reaches the seafloor.</p> <ul style="list-style-type: none"> ● Embedment sites ● Accumulation locations ● Dispersal Corridors ● Traps and Gyres <p>These categories have been created by translating attributes from the Geologic Map (under development) and the Benthic Habitat Maps (Green and Barrie, 2011). Table 2 and Table 3 show that translation.</p>

Table 1. GIS components and layers established to characterize, and map spilled dilbit behavior and fate on the subtidal seafloor of the central Salish Sea and the data sources used in the study.

Table 2 Translation of Geologic Map Features to Oil Behavior Classes and Potential Habitats		
Geologic Feature	Oil Spill Behavior Class	Potential Habitat
Bedrock	Embedment Sites	Rockfish
Rubble-Debris Apron	Embedment Sites	Rockfish
Esker - Moraine	Embedment Sites	
Moraine	Embedment Sites	
Glacial Banks	Accumulation Locations	Pacific Sand Lance
Dynamic Bedform	Accumulation Locations	Pacific Sand Lance
Sediment Deposits - Fraser	Accumulation Locations	
Banner Bank	Accumulation Locations	
Mud - Silt	Trap	
Lag Slope	Dispersal Corridors	
Lag Plain- Scalloped	Dispersal Corridors	
Scour Trough/Lag Channel	Dispersal Corridors	

Table 2. *Geologic units, geomorphologic features, and substrate types related to the four types of oil spill behavior class and potential habitats that might be impacted by a dilbit oil spill.*

Table 3 Translation of Benthic Habitat Map Features to Oil Behavior Classes and Potential Habitats			
Habitat Code	Description – Habitat Type	Oil Spill Behavior Class	Significant Habitat
lhe_f/s	Fractured bedrock	Embedment Sites	Rockfish
lh(b)/p	Pinnacle or boulder	Embedment Sites	Rockfish
lhed_d/s	Sedimentary bedrock	Embedment Sites	Rockfish
lhe_g/s	Granitic bedrock	Embedment Sites	Rockfish
lhl	Rock fall	Embedment Sites	Rockfish
ls(s)w_u	Sediment bedforms (sand)	Accumulation Locations	Pacific Sand Lance
ls(s/g)w_s/u	Current-scoured sediment bedforms (sand/gravel)	Accumulation Locations	Pacific Sand Lance
ls(s/g)w_u	Sediment bedforms (sand/gravel)	Accumulation Locations	Pacific Sand Lance

Table 3. *Selected habitat types from the Greene and Barrie (2011) Potential Marine Benthic Habitat Map of the central Salish Sea that compares the habitat code and description along with the potential interpreted behavior of a spilled dilbit oil spill.*

Multibeam Echosounder Data and Terrestrial Imagery

We used Multibeam Bathymetric Echosounder System (MBES) bathymetry (Fig. 7) and backscatter (Fig. 8) data to construct the Oil Spill Assessment Maps (Plates 1 and 2). The MBES data were acquired in cooperation with the Geological Survey of Canada, Canadian Hydrographic Service, and the Center for Habitat Studies, Moss Landing Marine Laboratories. From 2001 through 2008 the Canadian Coast Guard Ships *Otter Bay*, *Revisor*, *Young* and *Vector*, under the direction of the Canadian Hydrographic Service (CHS), acquired extensive high-resolution bathymetric datasets of the waterways surrounding the Southern Gulf Islands and the San Juan archipelagos (see Table 1). The MBES Simrad EM 1002 (95kHz frequency) and EM 3000-3002 (300 kHz frequency) systems were used for deep (>80 m) and shallow (<80 m) waters with resolutions of 5 and 2 m. In most of the areas, the tracks were positioned to insonify 100% of the seafloor with a 100% overlap, providing 200% coverage. Positioning was accomplished using a broadcast Differential Global Positioning System (DGPS) and MBES data were corrected for sound speed variations in the stratified water column using frequent sound speed casts. Data from recently constructed habitat and DilBit maps (Tombolo Mapping Lab in house report; see Table 3) were used in the interpretations of the substrate and habitat types identified in our Oil Spill Assessment Map. The base images in these maps use a mosaic of hillshades and 25 m depth contours derived from multiple sources (Fig. 7). The most precise images are from the San Juan Islands MBES Tombolo Mapping Lab's/Geological Survey of Canada (GSC) data sets, and from a set of National Oceanographic and Atmospheric Agency/National Ocean Survey (NOAA/NOS) surveys. In some mostly nearshore areas, these images have been supplemented from other available bathymetry (Finlayson, 2019; Table 1). The mosaics use the highest resolution images available from overlapping surveys. The MBES data along with side-scan sonar mosaics and 3.5 kHz sub-bottom seismic-reflection profiles were used to produce habitat types after Greene et al. (2007) and published in a marine benthic habitat map series (Greene and Barrie, 2011). Most of the terrestrial images were derived from bare earth LiDAR data obtained from the Puget Sound LiDAR Consortium (2019; Table 1), supplemented from other digital elevation model data of the United States Geological Survey (USGS; Table 1).

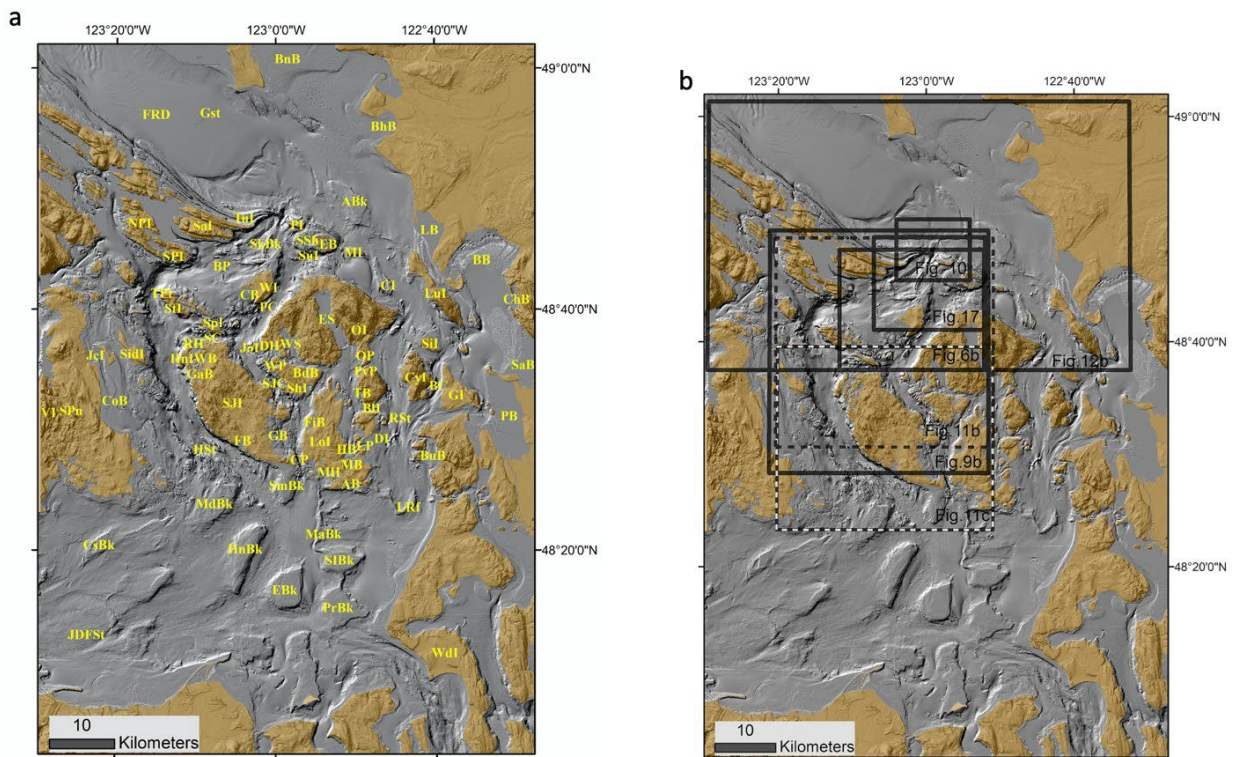


Figure 7. Multibeam bathymetric echosounder system (MBES) bathymetry imagery used for the interpretation of the seabed geomorphology and benthic habitat characterization within the central Salish Sea with geographic features noted. a) **Islands:** BIBarnes; BII=Blakley; CyI=Cypress; CyI=Cypress; DI=Decatur; Fd=Flattop; GI=Guemes; HnI=Henery; JI=James; JhI=Johns; JoI=Jones; LoI=Lopez; LuI=Lummi; MI=Matia; NPI=North Pender; OI=Orcas; PI=Patos; SJI=San Juan; SaI=Saturna; ; ShI=Shaw; SiI=Sinclair; SJI=Skipjack; SPI=Pender; SpI=Spieden; Sbl=Strawberry; Sti=Stewart; SuI=Sucia; TuI=Tumbo; VI=Vancouver; WI=Waldron, WdI=Whidbey Island; **Tidal Straits:** HSt=Haro; GSt.=Georgia. (marine basin); RSt=Rosario; SJDfT=Strait of Juan de Fuca (marine basin); **Channels and Passes;** BC=Bellingham Channel; PC=President Channel; SJC=San Juan Channel; BP= Boundary Pass; CP=Cattle Pass; LP=Lopez Pass; OP=Obstruction Pass; PvP=Peavine Pass; SC=Spieden Channel; WP=Wasp Passage; **Bays and Sounds;** AB=Aleck Bay; BB=Bellingham Bay; BdB=Blind Bay; BhB=Birch Bay; BiB=Barlow Bay; BnB=Boundary Bay; BuB=Burrows Bay; CB=Cowlitz Bay; ChB=Chukanut Bay; CoB=Cordova Bay; DH=Deer Harbor; EB=Echo Bay; ES=East Sound; FB=False Bay; FiB=Fisherman Bay; GaB=Garrison Bay; GB=Griffin Bay; HB=Hunter Bay; LB=Lummi Bay; MB=Mud Bay; MH=Mackaye Harbor; PB=Padilla Bay; SaB=Samish Bay; SB=Shallow Bay; TB=Thatcher Bay; WB=Wescott Bay; WS=West Sound; **Banks, Reefs, and Points;** ABk=Alden Bank; BSh=Blakely Island Shoal; CsBk=Constance Bank; EBk=East Bank; FRD=Fraser River Delta; HnBk=Hein Bank; LRf=Larson Reef; MaBk=McArthur Bank; MdBk=Middle Bank; PrBk=Partridge Bank; RRk=Race Rocks; SIBk=Smith Island Bank; SkBk=Skipjack Bank; SmBk=Salmon Bank; SPn=Saanch Peninsula; SSh=Sucia shelf; PtC=Point Caution; SBk=Salmon Bank; TPt=Turn Point. b) figure locations.

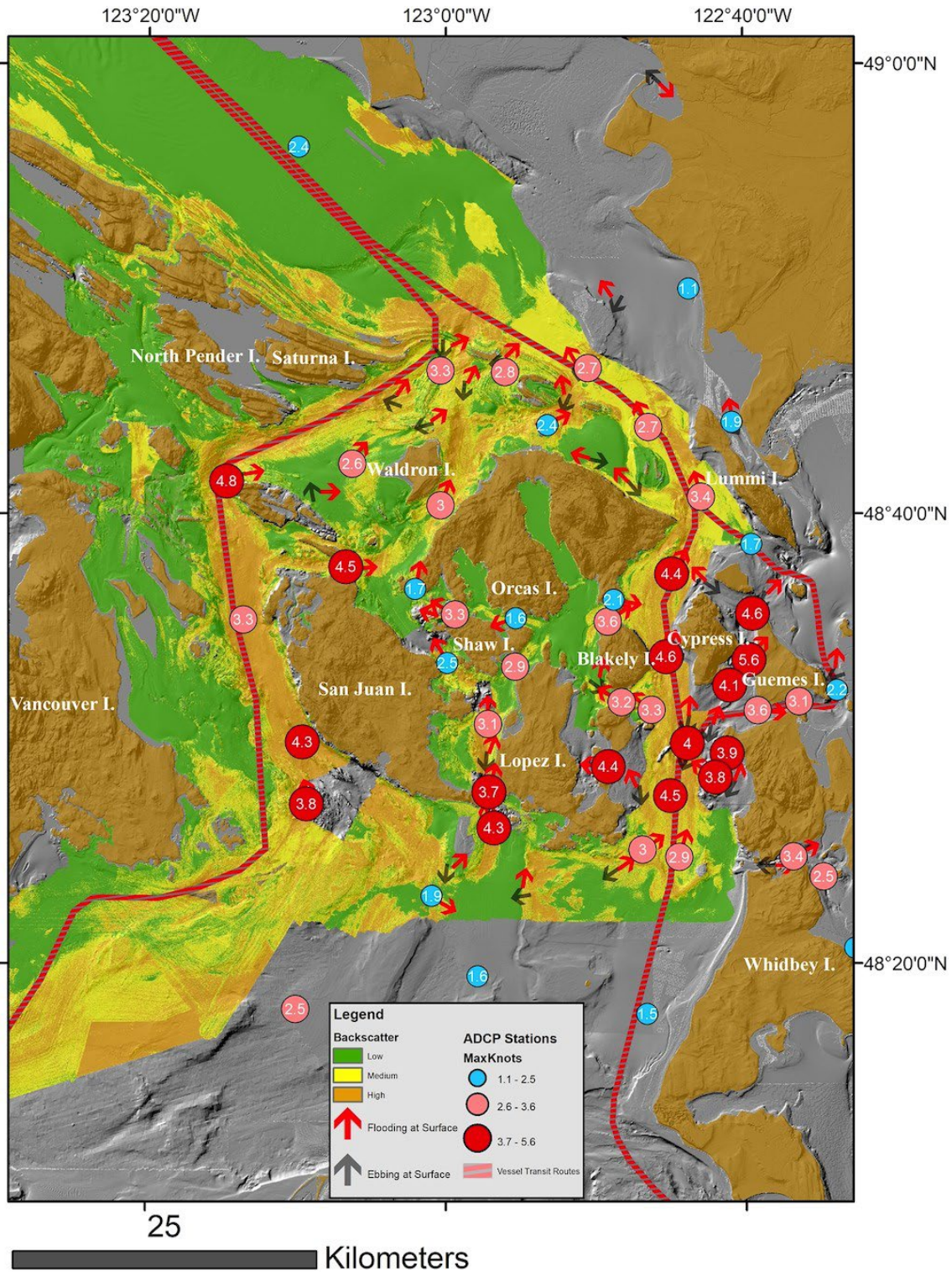


Figure 8. Multibeam bathymetric echosounder system (MBES) backscatter imagery used for the interpretation of the substrate types within the central Salish Sea. The major shipping lanes from (WDOE, 2019) and tidal speeds in knots (NOAA, 2018) are also included on this image.

Tidal data

Indications of relative strength and direction of tidal currents were obtained from NOAA's model predictions for 57 locations in and around the region (NOAA, 2018; Table 1). We used the predictions for the year 2018 and selected the maximum predicted ebb and flood for the year. The average ebb and flood directions at maximum flow are also shown (Plate 1). The predicted (modeled) current strength from this source is shown as "P=nn.n". In addition, measured currents from 54 Acoustic Doppler Current Profiler (ADCP) stations collected from a survey conducted from the years 2015 through 2017 are included. The ADCP measurements were taken at various depths, we used the measurements for the maximum depths provided, and used the maximum current measured through a four-week period in our mapping. The actual measured current strength is shown as "A=nn.n".

Images of backscatter acoustic intensity has been presented on the maps as a loose approximation of current strength, the assumption being that lower backscatter intensities suggest softer sediments that may have recently accumulated, and by inference suggesting lower current strengths (Fig. 8). The backscatter mosaic is constructed from MBES data obtained from two primary data sets: a working set from the Tomolo Mapping Lab's inventories and a separate set provided by the GSC.

Shipping lanes

Several shipping lanes have been identified. The primary tanker traffic path is shown from the Westridge Terminal in Burnaby, Vancouver, B.C., Canada through Haro Strait on the west side of San Juan Island and through the Strait of Juan de Fuca (Fig. 8). We also identify a secondary path that has been used by tug-and-tow vessels for transporting dilbit from Burnaby to a refinery in Tacoma, Washington, through Rosario Strait east of the San Juan Archipelago (Felleman, 2016; WDOE, 2019) also identifies Anacortes, Washington as a transport facility (Plates 1 and 2). Shipping lanes were mapped to correspond to high volume tanker traffic based on year 2017 identified Automated Identification Systems (AIS) data.

In Situ Ground Truth Data (Bottom Samples & Seafloor Photos)

Data from a comprehensive sediment sampling effort of the central Salish Sea prior to 2011, using Van Veen and Ponar grab samplers is used in groundtruthing the map (Greene et al., 2011)

as is sampling data obtained by Matt Baker of Friday Harbor Labs and Gary Greene of Tombolo Mapping Lab (Baker et al., 2021; Greene et al., 2017, 2021). Sediment analyses were undertaken with a RoTap[®] sieving machine using screens that sieved sediment ranging from silt to coarse gravel at 1φ sieve intervals (see Table 1 of Blott and Pye, 2001). We used these experimental results to assist in refining the substrate characteristics in this study.

In situ observations and photos were collected for groundtruthing using drop cameras and the five-person submersible *Cyclops I* was used for collecting video and stereo-camera images of the seafloor within the San Juan Channel sand-wave field, a banner bank. Observations made during these dives facilitated the understanding of banner banks as forage fish habitats.

Interpretation

Identification and mapping of the modern seafloor geomorphology of the central Salish Sea was accomplished using common marine geology nomenclature. Much of the Quaternary map units represent the modern seafloor processes active in the region today and remnant glaciated rock and deposits. Much of this mapping nomenclature is taken from the habitat maps edited by Greene and Barrie (2011) and correlated with the geomorphic units of maps described by Mullan (2017; see Table 4).

RESULTS

The central Salish Sea Oil Spill Assessment Maps are provided in an electronic form as a PDF map (Plates 1 and 2). Future versions may will include an Esri Storymap and an interactive Esri Web Map. Due to the geologic history and modern seafloor processes of the region the seafloor of the central Salish Sea exhibits a complex and dynamic morphology that is locally influenced by strong tidal currents. The maps are presented as a visualization that can be used to take the guess work out of estimating where sunken oil will go and accumulate (Plate 1). While the components of the map may be time sensitive in that it represents the seafloor conditions at the time the data used to construct the maps were collected, it nevertheless accurately represents the critical habitat and substrate types on the seafloor (Plate 2) as they are primarily based on present-day processes that formed or modified the habitats.

Map Terminology	Mullan (2017) Terminology	Symbol
Scour	Flow construction scour trough (ST)	ST/LC
	Lag channel (LC)	
Flat scour	Lag plain -scalped (LP)	LP/SB
	Scalloped bedform texture (SB)	
Scour deposits	Flood banner bank (F-BB)	BB
	Ebb banner bank (E-BB)	
Bedform	Locally constrained dunes (CD)	CD/GSW
	Giant fine-grained sediment waves (GSW)	
Rubble apron	Debris apron (AP)	AP
Slides	Landslides (LS)	LS
Habitat - Rock	Exposed bedrock (B)	B
Deposits - Fraser	Asymmetrical delta (AD)	AD/FD
	Asymmetrical flow constriction sequence (AFCS)	
	Symmetrical flow constriction sequence (SFCS)	
Current swept slope	Lag plain	LP

Table 4. Correlation of map units used in the construction of the Oil Spill Assessment Map and the map units reported by *Mullan (2017)*.

While it is impossible to predict where or when an oil spill may occur, once a spill takes place, oil spill response teams must track the trajectory of the oil. Parameters that will need to be considered for estimating the dispersal of the oil include real time assessment of tidal currents, the type of oil spilled, weather conditions (especially wind) solar radiation, suspended sediment (e.g., if a Fraser River freshet is occurring), estimated descent (sinking) rate, and other natural seasonal conditions such as water temperature and tidal cycle. Once the trajectory of the spilled oil is known, the map can be used to predict what critical subtidal habitat lies in its path, and how

the oil might disperse, become embedded, trapped, or accumulate as it reaches the seafloor as sunken oil.

Four major geomorphic categories indicative of the predictive fate of persistent oil are identified from the interpreted ArcGIS database and consist, in order of increasing severity of: 1) dispersal corridors (scours [flow constriction scour troughs, lag channels]², flat scours [lag plains, scalloped bedforms]²); 2) accumulation locations (sediment deposits [locally constrained dunes, giant fine-grained dunes]², scour deposits [banner banks]², depressions, kettles, slides, deltas); 3) embedding sites (rock outcrops, rubble aprons [debris aprons]² moraines); and 4) traps (bays, sounds, channel margins) and gyres (e.g., Waldron Island rotation, off-channel intra-island stagnations). Glacial banks may also accumulate sunken oil but their capability for attracting dilbit is not fully understood. A general description of the four major geomorphic features is given below:

Dispersal Corridors

Areas of relatively strong bottom currents in contrast to areas of weak currents (e.g., accumulation locations) have been mapped ([Fig. 9a](#)) and classified as dispersal corridors for persistent oil and tar balls ([Plate 1](#)). These are areas where bathymetric morphology, coarse-grain substrate (gravel, pebbles, cobbles), and bedrock exposures (see [Fig. 8](#), [Plate 2](#)) indicate strong bottom current flow (flow constriction scour troughs, lag channels, lag plains, scalloped bedforms, banner banks). These are areas where oil is expected to be rapidly transported along the seafloor and should not accumulate ([Plate 1](#)). We estimate that approximately 230 km² of area exist as dispersal corridors within our mapped area.

We used the interpreted geomorphology and backscatter data supplemented with available in situ groundtruth data and the modeled sediment bedload transport vectors reported by [Mullan \(2017\)](#) to map the areas of strong bottom currents that have potential to transport sunken dilbit along the waterways of the central Salish Sea ([Plate 1](#)). The major dispersal arteries for the central Salish are Haro and Rosario straits, the main and secondary shipping lanes for the region (see [Fig. 8](#)).

² Terminology from [Mullan \(2017\)](#).

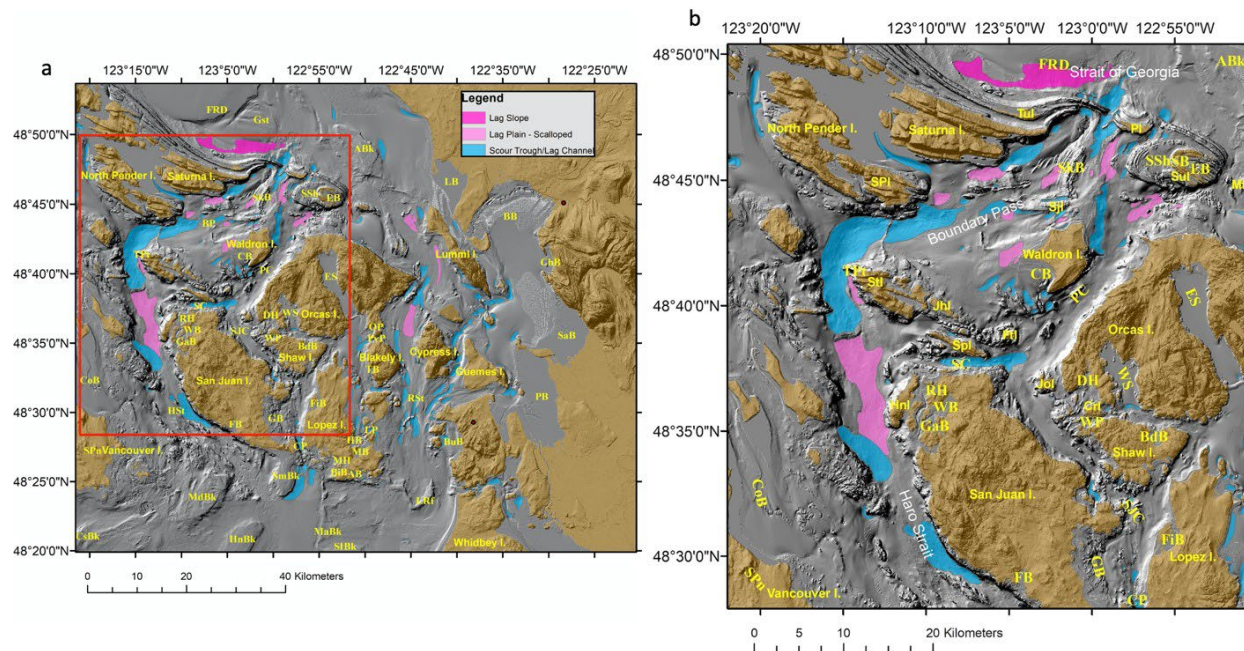


Figure 9. Interpreted MBES bathymetric image showing areas where sinking dilbit most likely would be carried along with bedload sediment through tidal straits and not expected to accumulate. a) area of investigation, b) expanded view of the strongest bottom tidal flow area in the northern part of the study area. Note: blue color = deep scours (ST/LC), pink = flat scour (LP/SB), buff = bedforms (CD/GSW), and light blue = current swept slope (LP), see [Table 1](#) for crosswalk from our interpretations to that of [Mullan \(2017\)](#) using code in parentheses above. See [Fig. 7a](#) for other code explanations.

The ADCP tidal current speeds recorded by [NOAA \(2018; Table 1\)](#) show them to be as fast at ~ 4.76 knots (2.45 m/s) in northern Haro Strait near Turn Point at the northern tip of Steward Island, with the next fastest speed recorded at ~ 4.64 knots (2.39 m/s) in Rosario Strait between Blakely and Cypress islands ([Plate 1](#)). Within the inter-island channels the fastest ADCP speed recorded was ~ 4.5 knots (2.31 m/s), found in Spieden Channel between northern San Juan Island and Spieden Island, followed by a speed of ~ 4.36 knots (2.24 m/s) in Lopez Pass between Lopez and Decatur islands, and speeds between ~ 3.74 knots (1.92 m/s) and 4.30 knots (2.21 m/s) in Cattle Pass between San Juan and Lopez islands ([Plate 1](#)). Generally, the fastest tidal speeds are found in the narrow passes between islands, and all would be expected to rapidly transport sunken dilbit to the more quiescent locations along the margins of the inter-island channels.

The seafloor geomorphology in Boundary Pass suggest that strong bottom currents maintain a seafloor devoid of accumulating sediment and that highly focused flow between Tumbo Island

ridge and Patos Island, where deep flow constriction scours (scour troughs, lag channels) and both flood and ebb banner banks exist, exhibit strong current morphologies (Fig. 10). The flood tide influence on the seafloor morphology in this area appears the most severe as flood banner banks extend well to the north ending where a retrogressive slump or scallop bedform is imaged. Sediment along with any sunken dilbit would be rapidly swept through this corridor (Fig. 10a) as indicated by the bottom current vectors modeled by Mullan (2017, his Fig. 3.07; see Fig. 10b). Turn Point area in the northern Haro Strait area is another place where counter currents occur and create complex bottom vectors that can keep sinking dilbit mobilized (Fig. 9b). The bathymetric image exhibits the intensity of scours including deep scour troughs and scalloped bedform textures (lag plain).

Embedment Sites

Sites where persistent oil and adhesive tar balls could stick or be embedded upon or into substrates generally consisting of rock outcrops (especially bedded and deformed sedimentary rock), boulders, moraines, and possibly glacial banks (Fig. 11a; Plate 1). These areas represent subtidal geologic extensions of islands and are swept with strong tidal currents. Unless the oil is well-armored, the cragginess of the outcrop and high current velocity trajectories of the oil facilitates embedment on rock surfaces. Within our mapped area approximately 258 km² of embedment sites exist.

Potential dilbit embedment sites located along the margins of Haro Strait are mapped in a thin, near vertical fiord rock wall of western San Juan Island from False Bay up to the Roche Harbor area, in a broader area of irregular rock exposures along the eastern margin of the strait, and in scattered locations at the entrance to Haro Strait from the Strait of Juan de Fuca (Figs. 7, 11a; Plate 1). Fewer embedment sites are mapped in Rosario Strait with the boulder moraine known as Lawson Reef being a potential area (Fig. 7), scattered rock exposures offshore of eastern James, Blakely and SE Orcas islands, the rock outcrops of Barns, Clark, and NW Lummi islands, and the faulted end moraine between northern Lummi Island and Alden Bank (Figs. 7, 11a; Plate 1).

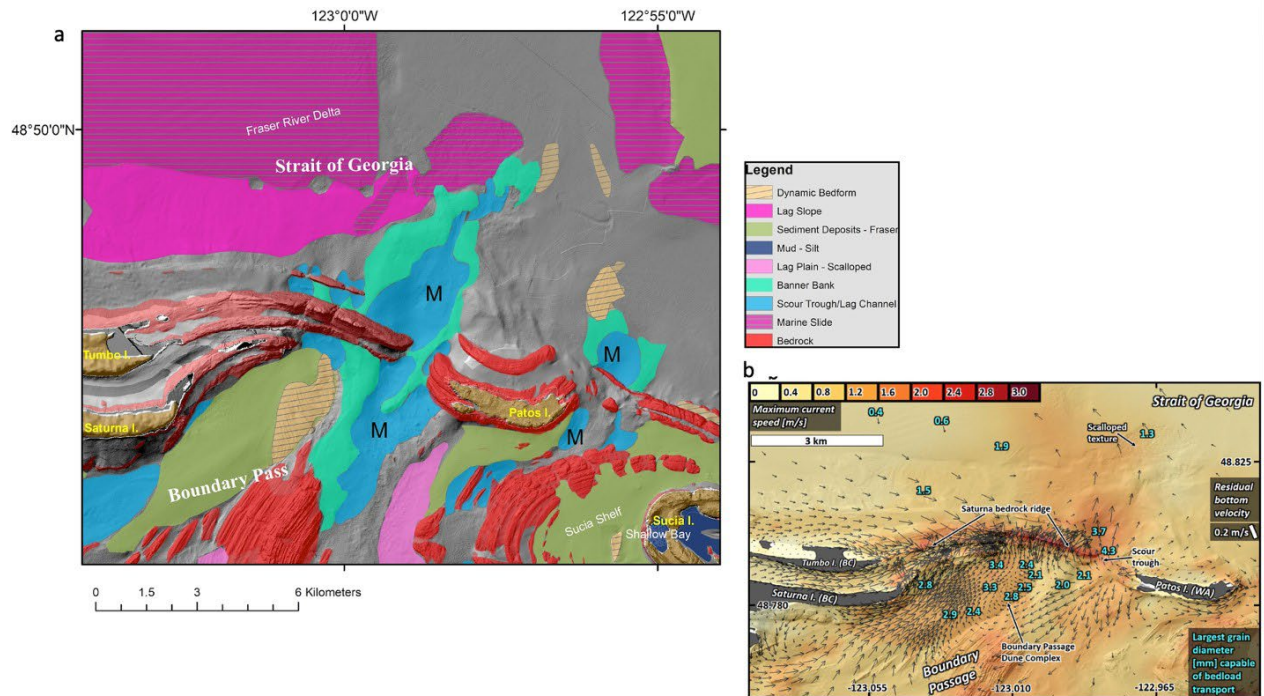


Figure 10. Interpreted MBES bathymetric image of the Boundary Pass area showing geomorphology and current vectors: a) modern seabed morphology formed by bottom tidal currents (see Table 1 for symbol explanations), b) bottom current vectors after Mullan (2017, his Fig. 3.07) from the modelled near-seabed maximum flow speed, residual tidal velocity vectors and maximum grain size diameters (mm) capable of bedload, and dilbit transport. The area is a significant mixing zone (M) where dilbit can be combined with sediment and sinks.

Extensive scattered embedment sites consisting of bedded and deformed Tertiary sedimentary rock exhibiting differentially eroded strata forming crevices, cracks, and overhangs are mapped along the northern extent of the Haro Strait-Boundary Pass area between Turn Point and the entrance into the Strait of Georgia (Figs. 7, 11b). These bedrock exposures are densely concentrated in the area between northern Orcas and Sucia islands, around Matia, Sucia, and Patos islands, around and north of Skipjack Island including Skipjack Bank, and the eastern extension of Tumbo ridge. Other extensive scattered embedment sites are in the Cattle Pass-southern Lopez Island local, consisting of faulted and irregularly eroded volcanic, metamorphic, and meta-sedimentary rocks located within the bays and islands, and bounding the very narrow Cattle Pass (Plate 2).

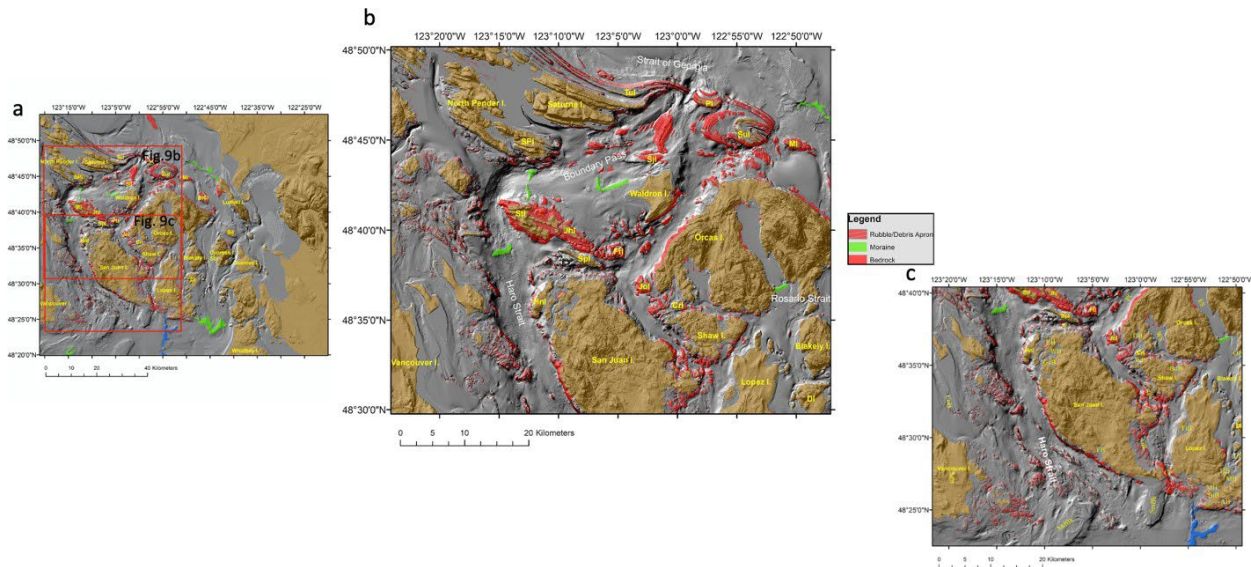


Figure 11. Interpreted dilbit embedment sites from MBES bathymetry located within the central Salish Sea (San Juan and Gulf Islands archipelagos) consisting of bedrock exposures, boulders and dynamic bedforms (banner banks), areas where sticky dilbit could be embedded. a) interpreted MBES bathymetric map in survey area showing all rock outcrops and boulder apron; b) areas that are most extensive in the northern survey area between Turn Point and Boundary Pass of northern Haro Strait. c) embedment sites based on rock outcrops in the southern part of the survey area where heavy concentration of rocks exists in central San Juan Channel, Cattle Pass, central and southern Haro Pass areas. BI=Barnes Island; JIc=James Island, Canada; SidI=Sidney Island. See Fig. 7a for other feature codes.

Within the inter-island waterways several concentrated and complex embedment sites are mapped and include Griffin Bay of SE San Juan Island, central San Juan Channel between San Juan and Shaw islands, northern San Juan Channel along western Orcas Island and Deer Harbor area, northern San Juan Island, Stewart Islands, and the area between Spieden and Waldron Islands (Fig. 11b, c). The steep rock walls along Wasp Passage and President Channel (Fig. 7) are also included in areas where potential dilbit embedment may occur if spilled sunken oil were to be transported through these passageways. Cattle Pass and southern Lopez islands area contains scattered rock exposures upon which sticky dilbit could embed (Fig. 11c; Plate 1).

Accumulation Locations

Oil that sinks may form into sticky blobs or balls (tar balls) that have the potential to armor themselves or stick to sediment where they may accumulate and/or be buried. This of course

depends upon suspended sediment concentrations and substrate types along with the strength of seafloor currents. We map areas of substrate types, such as fine-grain sediment (mud, silt, sand) that can armor tar balls, and modern sediment accumulation (sediment deposits, banner banks, locally constrained dunes, giant fine grain sediment waves, deltas, kettles, bedforms) locations where tar balls may concentrate and be buried (Fig. 12a; Plate 1). These locations show where seafloor currents are relatively weak compared to elsewhere in the Archipelago where the tidal currents are strong. These mapped areas should provide information that would be helpful in mitigation activities as estimated trajectories of the oil should show where the oil would go and concentrate.

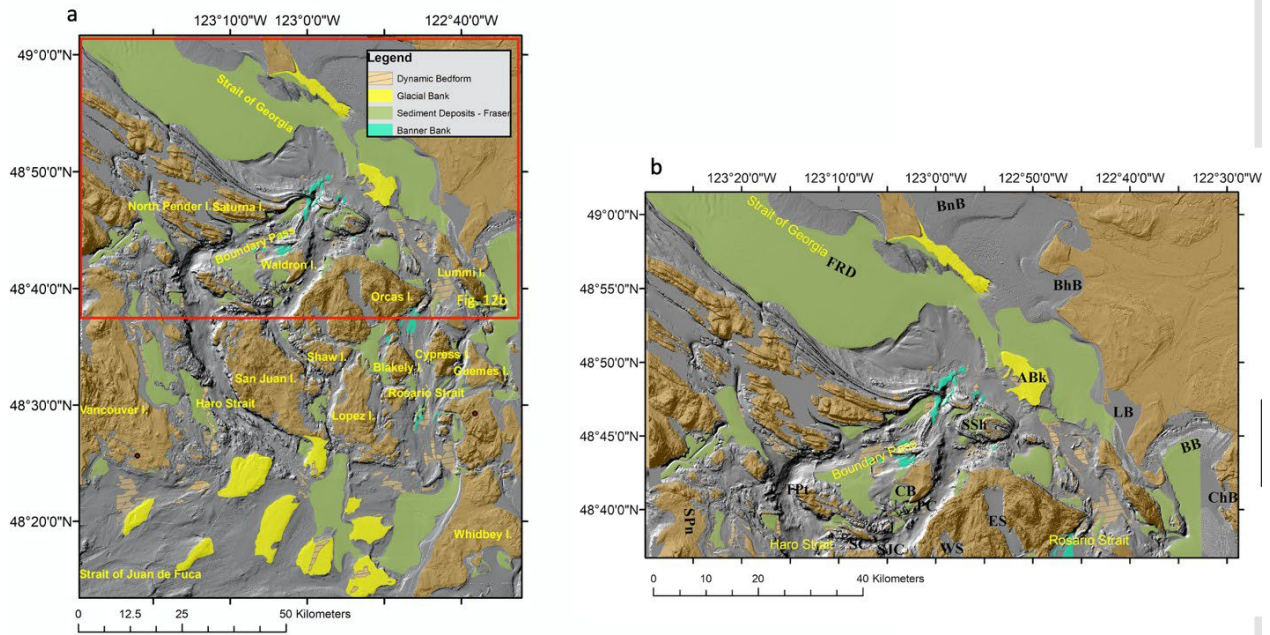


Figure 12. Areas of sediment accumulation, most likely from Fraser River sediment distribution. a) survey area where dilbit could be swept into and buried. b) large area of sediment deposits including submarine slides in the northern part of survey area on the Fraser River Delta, a sediment sink, or depotcenter, which results primarily from flood tides as modelled by Mullan (2017). See Fig. 7a for code exploration.

Approximately 1,025 km² of sedimentary deposits that could accumulate sunken dilbit oil are identified in our mapped area. The largest areas of sediment accumulation are the Fraser River Delta and other areas within southern Georgia Strait, a major depotcenter or sediment sink

(Mullan, 2017; Figs. 7, 12a; Plate 1), Boundary Bay, Birch Bay, and adjoining areas east of Alden Bank (523 km²) are areas where a potential concentration and burial of sunken dilbit may occur (Fig. 12b). Other areas of significant concentration of modern sedimentary deposits where sunken dilbit may accumulate are west Haro Strait along the eastern shelf offshore of the Saanich Peninsula of Vancouver Island, specifically Cordova Bay and east of Rosario Strait, Lummi Island, and Guemes Island in Bellingham and Samish bays (Figs. 7, 12a; Plate 1).

Within the inter-island waterways many smaller areas of sediment accumulation have been mapped with the largest and most significant areas being in the vicinity of Blakely Shoal, extending south into Lopez Sound and the small bays to the south (Fig. 12a), Cowlitz Bay of Waldron Island and the depositional plain between Waldron and Stewart islands, eroded bedrock platform west of Sucia Island (Figs. 6b, 12b), and a depositional bulge between Orcas and Matia islands (Figs. 7, 12b). Several banner banks and shallow water sediment accumulation sites are mapped in southern San Juan Channel and Griffin Bay of SW San Juan Island. Other sediment accumulation features are located around the periphery of the San Juan Islands and represent glacial deposits, remnants of ice strandings and in place melting from the last major glacial advance.

Traps and Gyres

Traps are features such as bays and sounds where materials are collected from incoming tides and storms that are generally retained within the feature, thus trapping these materials. Gyres are rotating currents that can also trap material and keep it relatively in place for short lengths of time. Both could accumulate sediment and other materials such as sunken dilbit. We estimate that approximately 123 km² of areas within our mapped area that have the potential to trap sunken oil.

The bays adjoining the shipping corridors of the central Salish Sea that are most likely to receive and trap sediment and dilbit consist of False Bay on SW San Juan Island and the interlocking bays (e.g., Westcott Bay, Garrison Bay) in the Roche Harbor areas of northern San Juan Island, and the relatively protected Mackaye Harbor/Barlow Bay area, and Aleck Bay of southern Lopez

Island (Figs. 1, 7, 13; Plate 1). For the Rosario Strait corridor Padilla, Samish, Bellingham, and Lummi bays are all susceptible to the retention of sediment washed in including dilbit.

Within the inter-island waterways Fisherman Bay of Lopez Island, Friday Harbor west of Brown Island on San Juan Island, and Park Bay on Shaw Island, all adjacent to the San Juan Channel have the potential of trapping sediment and dilbit (Figs. 7, 13). Also, Hunter and Mud bays of southern Lopez Sound of Lopez Island, Thatcher Bay on Blakely Island, and Blind Bay on Shaw Island, Echo and Shallow bays of Sucia Island are all candidate trapping features. However, the largest features capable of retaining materials are East Sound, West Sound, and Deer Harbor of Orcas Island (Figs. 7, 13).

Mullan (2017) first described a rotational bottom current around Waldron Island that would carry bedload, and dilbit, around in a circle of the island. We describe this phenomenon as a gyre with Waldron Island as the nucleus of rotation. The seafloor morphology surrounding the island attests to this rotation with scours, banner banks, lag plains, lag channels, and sediment deposits (accumulation site) located around the island (Fig. 6b). This complex modern geomorphology indicates dispersal corridors are located around the northern, southern, and eastern margins of the islands with accumulation of sediment within the two western horns of the island that forms Cowlitz Bay (Figs. 7, 6b, 12b). Other smaller gyres or eddies exist within the inter-island waterways but have not been mapped.

Glacial Banks

Glacial banks, remnants of the last glacial advance and local stagnation of ice are present in northern and southern central Salish (Fig. 14; Plate 2). These banks consist of unconsolidated sediment including glacial till, boulders, and sands dropped by the melting ice, which have been modified and sculptured by strong bottom currents. We have not fully assessed what the impact to these features would be by the presence of sinking oil, however depending on the stickiness of the oil, some embedment may occur and the bedforms on the top of the banks could potentially be coated by sticky oil. We estimate that approximately 285 km² area within our mapped area is occupied by glacial banks that may have the capability to accumulate sunken dilbit oil.

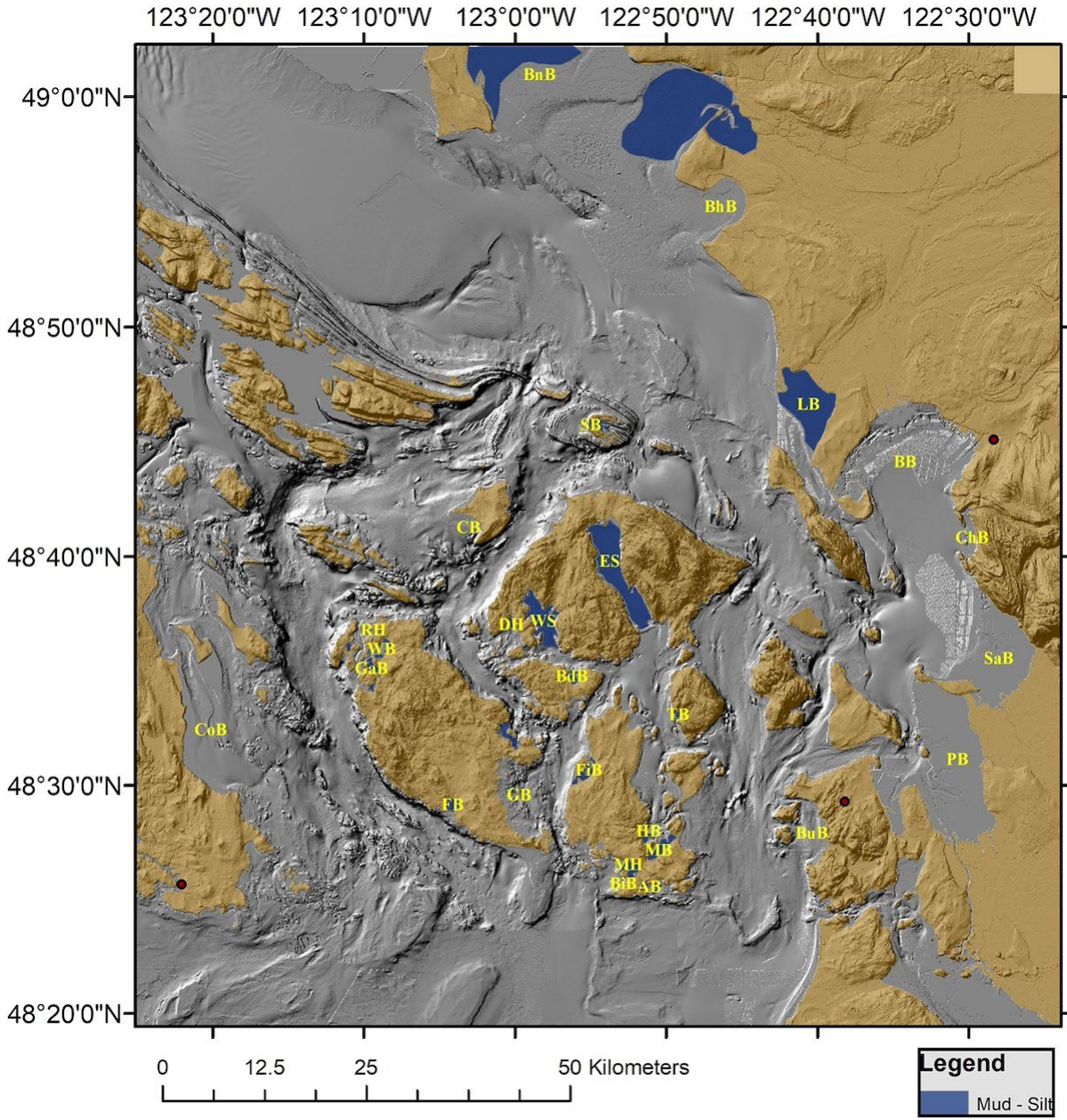


Figure 13. *Interpreted sediment and dilbit traps from MBES bathymetry within the central Salish Sea (San Juan Archipelago). These are bays and sounds that retain fine grain sediment such as sand, silt, and mud. See Fig. 7a for code explanation.*

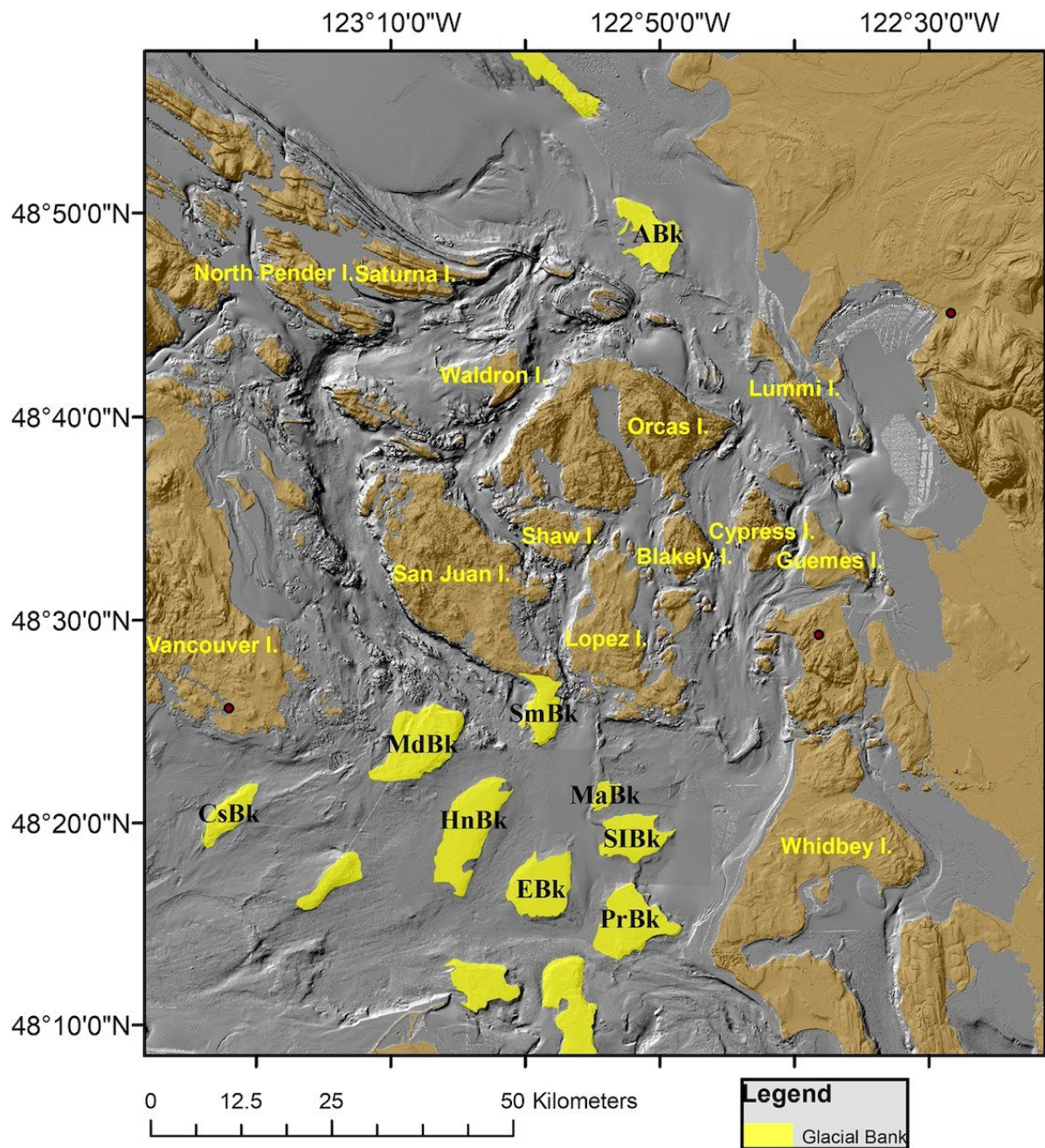


Figure 14. *Interpreted glacial banks from MBES bathymetry within the central Salish Sea, outside of the San Juan Archipelago that possibly could be covered with sticky sinking dilbit, potentially impacting forage fish (Pacific sand lance) habitats. See Figure 7a for code explanation.*

DISCUSSION

In 1970s WDOE (1997) completed shoreline sensitivity studies focused on the San Juan Islands in anticipation of an influx of Alaskan oil, but no sub-tidal sensitivities were considered. Often the physical characteristics of the subtidal seafloor and its associated benthic habitats are unknown along shipping lanes where the potential for oil spills exist. This lack of knowledge burdens mitigation processes that take place after an oil spill occurs. Intense marine shipping occurs around the San Juan Archipelago, central Salish Sea, and up to now no subtidal imagery or maps have been produced that can be used to plot (track) and visualize the impact sites of spilled persistent oils. We have interpreted a high-resolution MBES data set for the purpose of identifying areas where persistent, non-floating, and sunken oil may be rapidly dispersed (transported), embedded, accumulate and/or buried, or trapped in critical sub-tidal benthic habitats. The adverse impacts of such spills not only depend on the distribution of critical habitats in the vicinity and along the trajectory of such spills, but the type and quantity of oil spilled, time and season of the spill, tidal conditions at the time and after the spill, water temperature, local weather conditions, and equipment and response time needed for mitigation are also critical to the protection of the marine environment from oil spills.

Substrate and seafloor habitats interpreted from the MBES dataset in ArcGIS are clustered into four major data layers for the ease of assessment (Plate 1): 1) dispersal corridors, 2) embedment sites, 3) accumulation locations, and 4) traps and gyres. Once the location of an oil spill is known its coordinates can be plotted on an Oil Spill Assessment Map and using real time data such as tidal current direction and force, sinking oil descent rate, and estimated seafloor current directions a potential oil trajectory can be drawn. Using the resultant trajectory, the dispersal corridor for the oil can be estimated along with the most probable embedment, accumulation, or trap sites. In addition, mixing points where floating heavy crude or dilbit can be mixed with water column particles (e.g., sediment, phytoplankton) to form OPAs are mapped and can be used to assess the fate of oil heading towards such areas (see Figs. 9, 10). Evaluation of the habitat types in the path of the oil trajectory can then be made along with a focus on those most critical habitats that need protection, thereby reducing guess work and constructively deploying mitigation tools.

To facilitate early assessment before real-time on-site data is available, we have plotted the available tidal current directions and force for ebb and flood tidal cycles that can be used to initiate the potential oil vectors (Plate 1). Modification of these vectors would occur once on-site data is available. In addition, coastal intertidal habitats were compiled from published data and shown on the map to assist in evaluation of any non-persistent oil impact (Plate 2). The major shipping lanes from which an oil spill may occur are also shown on the maps.

Over 60 different marine benthic habitat types have been mapped for the central Salish Sea based on MBES data (Greene and Barrie, 2011), the foundation data set for this study (Fig. 15). These habitat types have been reduced to eight and clumped into three major substrate types (hard, soft, and mixed) based on induration (Fig. 16). Out of the 1, 875.46 km² of habitat mapped area, approximately 154.09 km² (8.22%) of hard substrate consisting of bedrock, boulders and pinnacles, anthropogenic features, and other hard substrate were mapped and are considered potential persistent non-floating oil embedment sites. Approximately 1,693.70 km² (90.31%) of soft substrate consisting of glacial features, sediment waves (dynamic bedforms, including banner banks), mounds and depressions, anthropogenic features, and other soft substrate types, cover the mapped area and are considered potential sites for the accumulation of dilbit and other sunken crude oils. Mixed substrate types consisting of soft sediment (pebbles, cobbles, gravels, sand) overlying hard substrate and prone to remobilization cover approximately 27.67 km² (1.48%) of the mapped area and are considered as potential persistent sunken oil dispersal areas (Fig. 16).

Those habitats we consider critical are rocky outcrops and boulder substrates (Plate 2). These are potential primary rockfish (*Sebastes* spp.) habitats whose cracks and crevices can be clogged with sticky tar-like oil such as dilbit (Greene and Barrie, 2011). A good example of these types of habitats are shown in Figure 17 where bedded and deformed sedimentary rock crop out on the seafloor around Sucia Island. In addition, these types of habitats often host a diverse and dense verity of attached and sessile organisms critical to the ecological wellbeing of the region. Other important habitats include sand wave fields (banner banks) and glacial bank tops that are sub-tidal habitats for the forage fish Pacific sand lance (*Ammodytes personatus*), an important forage fish for salmon, minke whales, birds, and ground fish (Greene et al., 2011a, 2011b, 2017, 2021;

Marine Benthic Habitats for the Southern Gulf Islands and San Juan Archipelago, Canada and USA

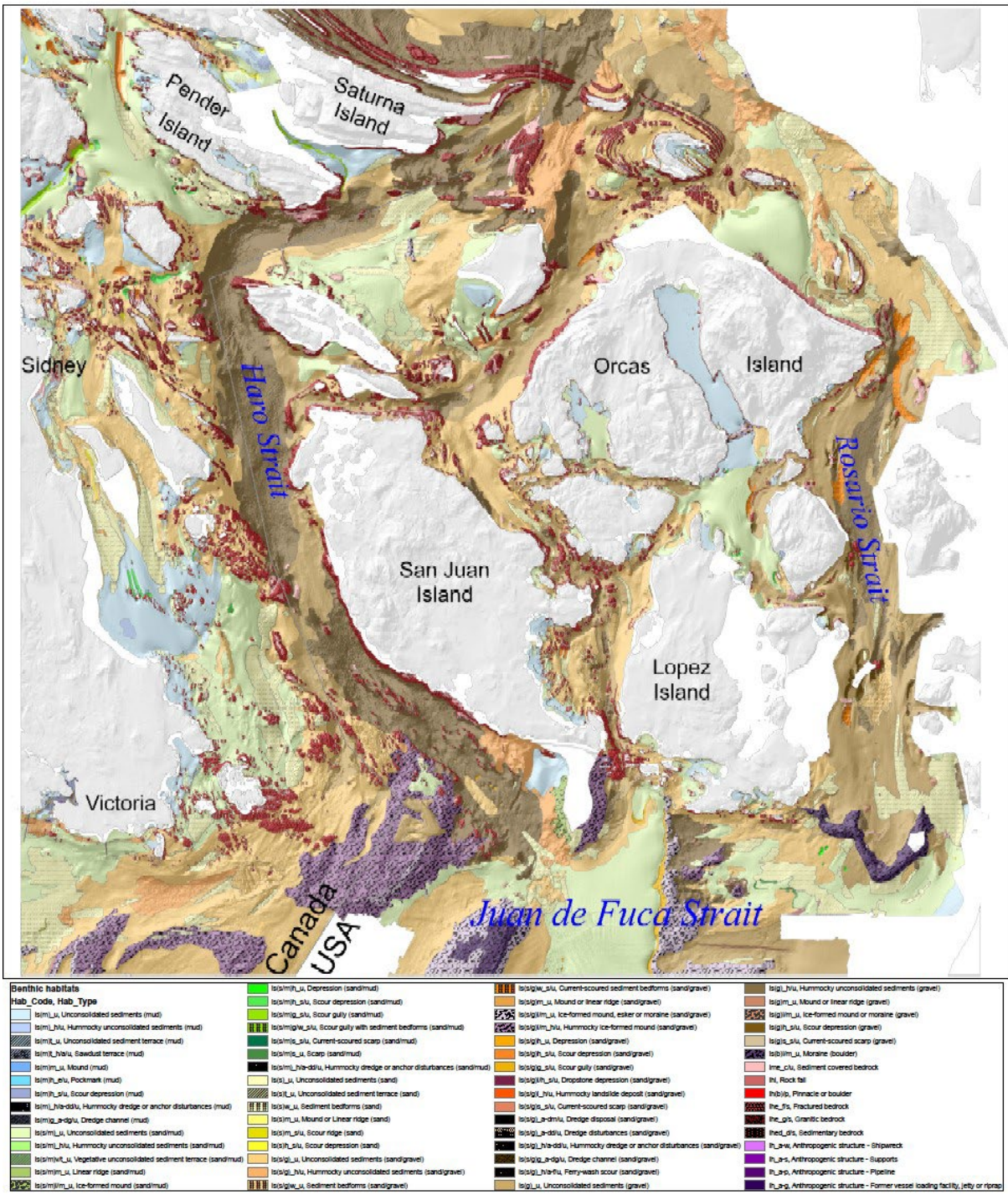


Figure 15. Map of potential marine benthic habitats within the central Salish Sea. Generally red colors represent hard bedrock outcrops, dark brown color represent coarse grain unconsolidated (e.g., cobble, pebbles, gravel) soft sediment types, light brown, green, and blue represent fine grain (e.g., sand, silt, mud) soft substrate while purple and pink colors represent mixed soft over hard substrates. Modified from *Greene and Barrie (2011)*.

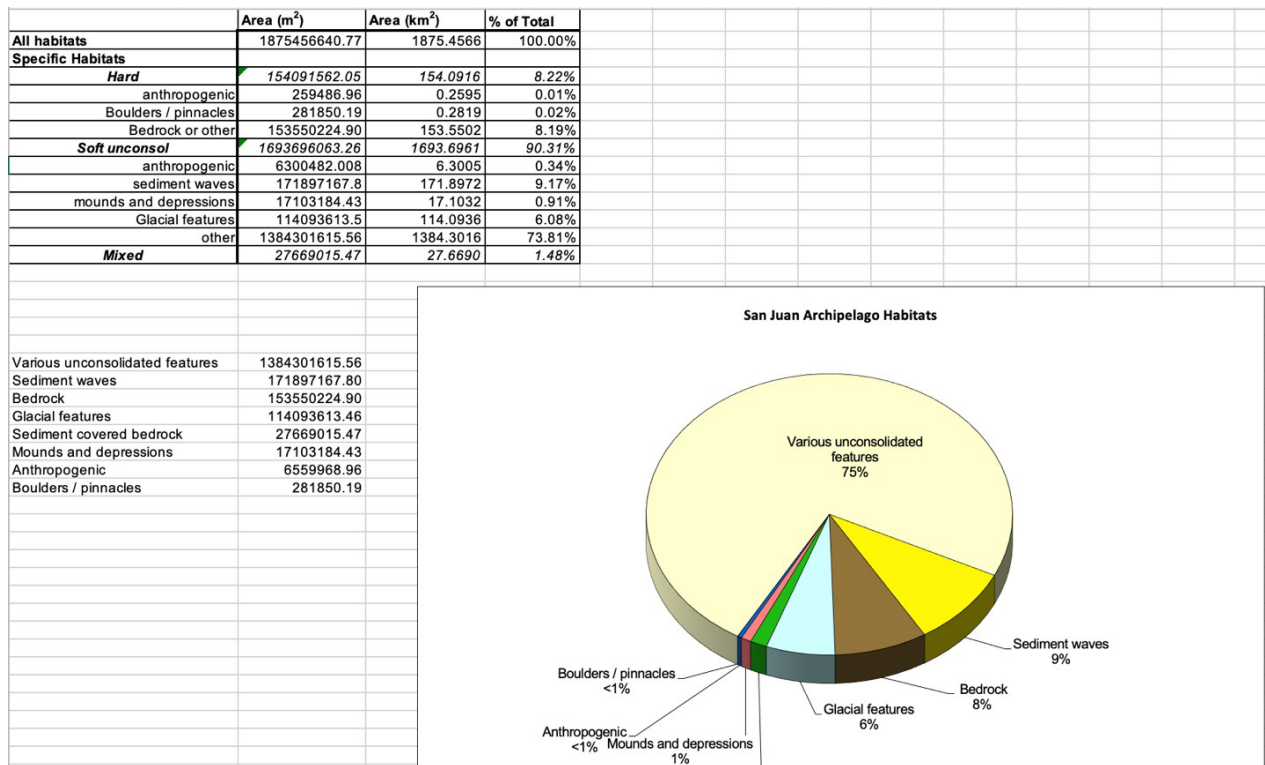


Figure 16. Areas within the central Salish Sea that are covered with hard, soft, and mixed substrate types and the percentage of potential marine benthic habitats that exist within the area surveyed and represented in Figure 15.

Baker et al, 2021). Incorporation of persistent oil could fill the interstices of the sediment thereby reducing the ability for PSL to burrow into a well-aerated substrate, as well as affect the fish respiration while in their burrows (Fig. 18). On the map, these types of habitats, and others are well-represented (Plate 2)

From published data we include kelp and eelgrass as habitats that exist in the nearshore sub-tidal and intertidal areas that would also need to be protected if spilled oil was headed toward them (Plate 2). Both persistent and non-persistent oils have a potential of adversely impacting these habitats.

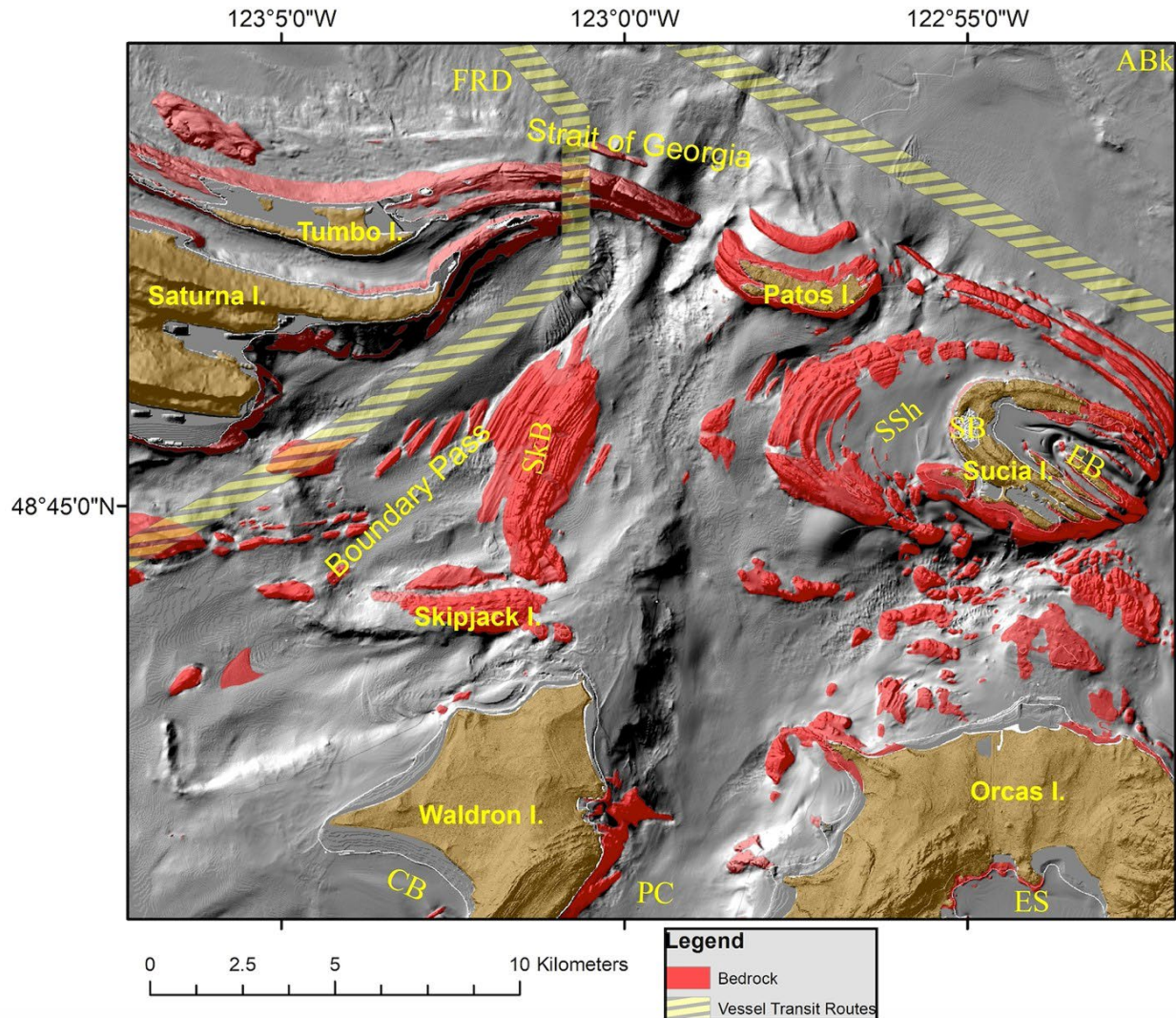


Figure 17. Interpretation of critical rockfish (*Sebastes* spp.) habitats interpreted from MBES bathymetry in the Sucia Island area. This area represents the highest density within the central Salish Sea and would need to be considered a critical area for protection from spilled sunken oil such as dilbit. See [Figure 7a](#) for code explanations. Modified after [Greene and Barrie \(2011\)](#).

Dispersal Corridors for Spilled Dilbit Oil

While not knowing when and where a possible oil spill will occur within the central Salish Sea (San Juan Archipelago), we assume it will take place somewhere along the major shipping lanes of the region, within the Strait of Juan de Fuca, Haro Strait, Boundary Pass, or Rosario Strait areas, what we consider as major sinking oil dispersal corridors ([Figs. 8, 9a; Plate 1](#)). These waterways are tidal straits that connect the marine basin of the Strait of Georgia with the Pacific Ocean, and thus are the major pathways for tidal flow that concentrate the strongest bottom

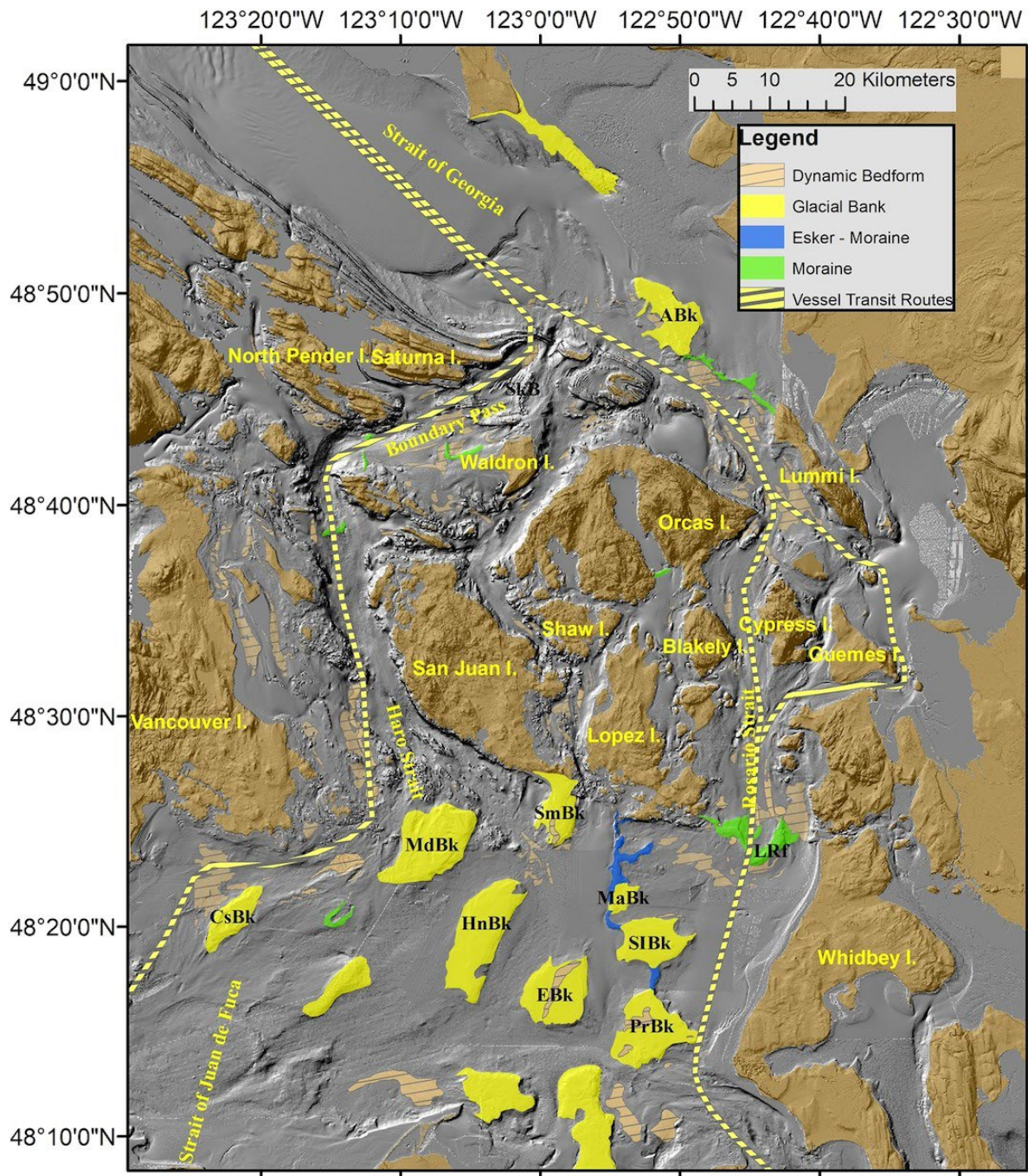


Figure 18. Interpretation of the forage fish (PSL) marine benthic habitat based on MBES bathymetry. These habitats consist of dynamic bedforms (banner banks), glacial banks, eskers, and moraines. See [Figure 7a](#) for code explanation.

currents (see [Mullan, 2017](#)). Spilled oil within these straits would rapidly be dispersed and any sinkable (persistent) or sunken oil to reach the bottom would be rapidly transported in the direction of the tidal flow (i.e., flood or ebb flow direction). In addition, in local areas where the tidal energy is the highest ([Cornett, 2006; Mullan, 2017, his Fig. 1.06](#)), spilled oil would be mixed with the water and any sediment within the water column resulting in the formation of OPAs. This increases the density of the oil, thus causing it to sink below the water surface, a likely event during a Fraser River freshet or perhaps during a major phytoplankton bloom. In addition to the major oil dispersal corridors, President Channel, and parts of the San Juan Channel within the inter-island areas of the San Juan Archipelago are also considered persistent oil dispersal corridors. Observation of the Mean-Depth Average Current Power Density map of [Cornett \(2006; Fig. 19\)](#) shows that the highest (>16.0 kW/m) tidal energy potential lies in Cattle Pass and eastern Spieden Channel, while moderately high (~ 2.0 - 4.0 kW/m) potential tidal energy occurs at Race Rocks off southern Vancouver Island in the Strait of Juan de Fuca, at Turn Point in Haro Strait, at Boundary Pass, and at Strawberry Island constriction in Rosario Strait, Point Caution area of San Juan Channel, Peavine and Obstruction passes, and central President Channel between Orcas and Waldron islands ([Figs. 7, 19](#)). We consider these points to be particularly prominent in mixing spilled oil with water and any suspended sediment present. [Johannessen et al. \(2019\)](#) noted that turbulence or strong, coherent mixing might draw dilbit down beneath the surface of the water.

Dilbit Embedment

Oil embedment sites generally consist of bedrock, boulders, and other hard surfaces upon which sticky oil (dilbit) can be embedded. Sticky sinking dilbit brought into contact with hard surfaces by either fast and hard current force or from gentle contact with hard surfaces has the likelihood of adhering to the surface. This contact can be from oil in suspension within the water column or as part of sediment bedload transport. Therefore, it is desirable to know to what depth dilbit is at during a tidal cycle to determine surfaces that the oil may encounter. If sticky dilbit is being transported along the seabed, then any rocky, boulder, or gravel/sandy substrate that it encounters could be coated by the oil. Transport of sticky oil over silty or sandy substrate could armor the tar, thus preventing it from sticking to hard surfaces down current.

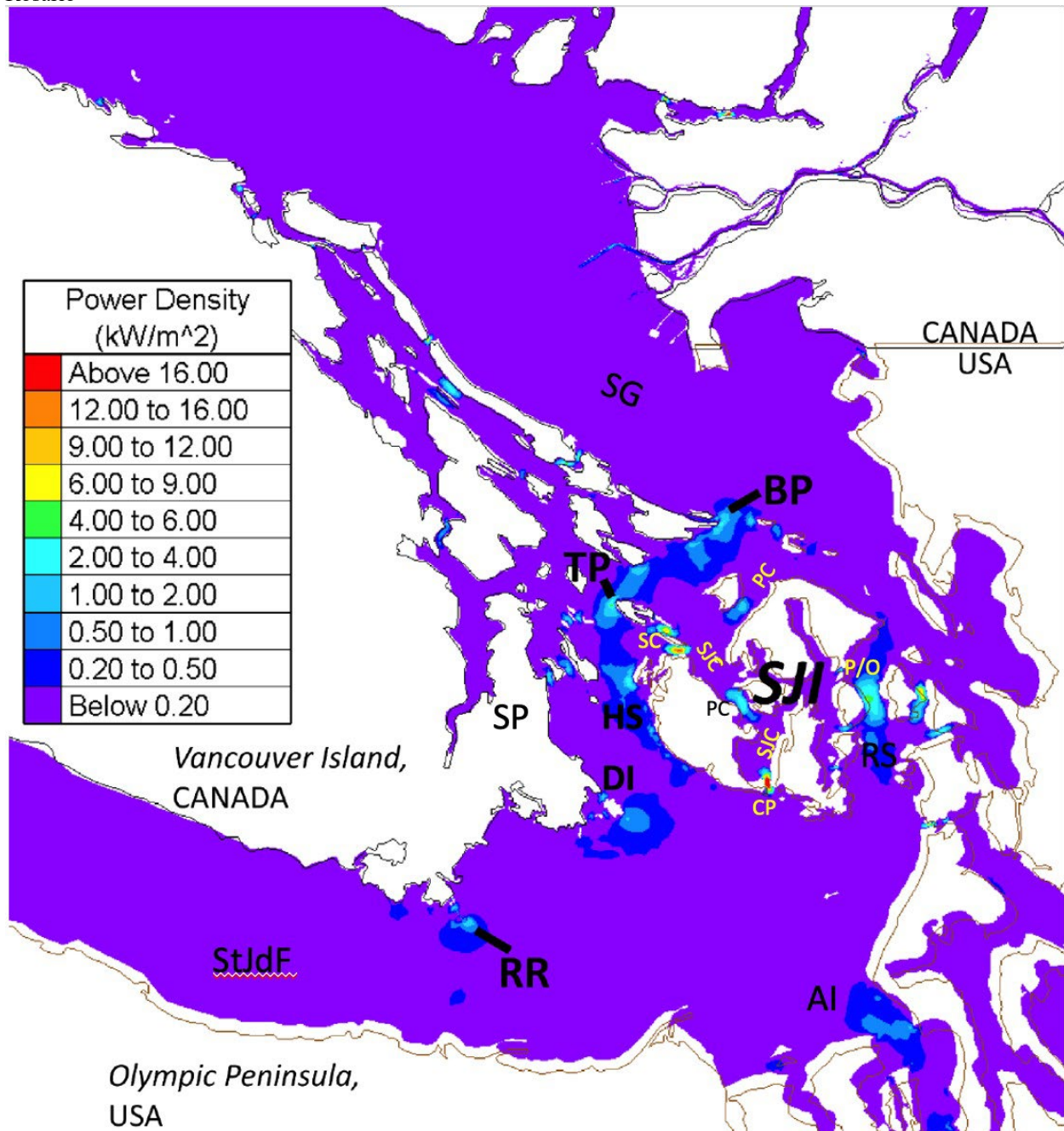


Figure 19. Dilbit mixing points. Mean depth-averaged tidal current power density (kWm^2) in central Salish Sea showing areas of greatest tidal energy that would mix dilbit if caught up in the turbulence. BP=Boundary Pass; AI=Admiralty Inlet; CP=Cattle Pass; DI=Discovery Island; PtC=Point Caution; PC=President Channel; P/O=Peavine and Obstruction passes; RR=Race Rocks; SC=Spieden Channel; SJC=San Juan Channel; StJdF=Strait of Juan de Fuca; SP=Saanich Peninsula; Modified after Mullan (2017, his Fig. 1.06; Source: Cornett, 2006).

In Haro Strait considerable scattered craggy surfaced bedrock crops out on the seafloor and along the steep walls of the fiord (Fig. 11c). These rocks are good rockfish (*Sebastes* spp.) habitat and

any embedment of sticky persistent oil such as dilbit would reduce the granularity of the rock surface and clog the crevices and cracks that make this habitat so valuable (Plate 2, Greene and Barrie, 2011). In addition, the nature and depth of the rock would make removal of the oil very difficult if not impossible. Therefore, the most promising result of an oil spill in Haro Strait is that it is rapidly swept into areas that would make recovery more possible. Extensive bedrock exposures are also mapped in the Haro Strait/Boundary Pass area where complexly deformed bedded sedimentary rocks that are differentially eroded form ideal habitat for rockfish (Fig. 11a, 17). This area, especially in and around Stewart, Patos, Tumbo, and Sucia islands are of particular concern because of the well-developed cracks, crevices, and overhangs that could be coated with sticky oil such as dilbit (Fig. 11b).

Embedment sites in Rosario Strait are less concentrated than in Haro Strait. In southern Rosario and eastern Strait of Juan de Fuca the areas most exposed to being coated by sinking sticky dilbit is the boulder moraine (Lawson Bank) and the rock outcrops in and around the bays, small islands, and bays of southern Lopez Island (Figs. 7, 11a, c). In northern Rosario Strait the rock exposures around Lummi, Clarke, Barnes, and Matia islands are all good rockfish habitat of well bedded, deformed sedimentary bedrock and could potentially be coated with sticky sinking dilbit (Fig. 11a). In addition, the recessional moraine that connects Lummi Island to Alden Bank and the rubble apron (debris apron) at the base of the NE face of Orcas Island are also good candidates for dilbit coating (Plate 1).

If sinking dilbit were to enter the inter-islands waterways several places would need mitigation attention. Specifically, the scattered rock outcrops in and along the central San Juan Channel and in Griffin Bay (Figs. 7, 11c; Plate 1). Spieden Channel, Wasp Passage and southern Orcas Island all have scattered rock exposures that could be coated by sticky dilbit (Fig. 11b). Most of the shallower areas are good dive sites for SCUBA divers and ideal habitats for rockfish and lingcod. Bull kelp (*Nereocystis, luetkeana*) use shallow bedrock outcrops and boulders as holdfasts and is limited in its distribution throughout the Salish Sea. Monitoring of bull kelp by the Washington Department of Natural Resources in 2017 and 2018 found that it was declining with substantial losses over recent years (Berrie et al., 2019). Oil coating of the holdfasts would add another stressor to those already influencing the degradation of the kelp. Any dilbit coating of the

substrate in these areas could potentially adversely impact the ecology (flora and fauna) of the region and cause economic hardship for the people of the islands whose occupation depends on recreational and commercial fishing, and tourism in these areas.

Accumulation of Sinking Dilbit

We surmise that any sinking oil (dilbit) that reaches the seafloor in the dispersal corridors will readily be transported away in the direction of the bottom tidal current flow and should not have a long residence time on the seabed there (should not accumulate). However, once the sunken oil is swept away and the bottom current is reduced, accumulation and/or embedment may take place. Current flow energy dissipates at the ends and margins of the tidal straits' thalwegs with finer sediment being carried further away from the coarser lag pavement and exposed bedrock in the thalwegs as described by Longhitano (2013; Mullan, 2017 his Fig. 1.02; Fig. 5). Generally, there are distinct progressive sedimentary facies changes that represent this reduction of current strength and consequent deposition of suspended sediment from gravel deposits to tidal dunes to rippled dunes, to mud that occurs in the central Salish Sea (see Longhitano, 2013; Mullan, 2017). While a clear example of this process is not readily seen in the central Salish Sea because of the complexity of the straits, channels, and islands, the depositional environments described by Longhitano (2013) as "dune-bedded strait zones" and "strait end zones" are recognizable from our interpretations and generally represent the "accumulation locations" for sinking dilbit. The primary mapped accumulation locations are positioned on the Saanich Peninsula shelf along the western margin of Haro Strait, in between Stewart and Waldron islands south of the Haro Strait/Boundary Pass segment, and along the eastern margin of Rosario Strait (Fig. 12a). Most of these areas can be considered as "dune-bedded strait zone" of Longhitano (2013) and if sunken dilbit is present it can accumulate and be buried at the mapped accumulation locations.

The southern Georgia Strait appears to be a major sediment depotcenter as accumulation of sediment is mapped in the Fraser River delta, Boundary Bay, and Birch Bay areas where Mullan (2017) reported that flood tide dominated bed load sediment deposition is taking place (Fig. 12b). In addition, modern accumulation of sediment is mapped at the confluences of Rosario Strait and the San Juan Channel at Cattle Pass with the eastern Strait of Juan de Fuca (Fig. 12a). These accumulation locations are considered a form of Longhitano's (2013) "strait end zone".

Trapped Dilbit

Many of the bays and sounds of the central Salish Sea have the potential to trap oil if it enters these areas (Fig. 13). Silt and mud with occasional sand is the predominant substrate type in the sounds and bays. Based on previous studies (e.g., Environment Canada, 2013; NASEM, 2016) dilbit OPAs can form from these substrate types, and thus be incorporated into the sediment of the sounds and bays (Plate 1). The fate of the oil once sequestered on the sound and bay floors is dependent upon the sedimentation rate for exposure before burial. Eel grass (*Zostera marina*), although declining locally, is often found in the inter-tidal and sub-tidal areas of the bays and sounds (Slocumb et al., 2004). The presence of dilbit has the potential of smothering the rezones and killing the plant, as well as impacting the epifauna, therefore remediation and clean up would be desirable for these areas (see Plate 2) if not possible to prevent dilbit from entering these traps to begin with.

While there are indications of rotating bottom current patterns or gyres within the San Juan Archipelago such as the one around Waldron Island (see Fig. 6) reported upon by Mullan (2017), the behavior and fate of dilbit trapped in such eddies are not known. We suspect that sinking persistent oil such as dilbit would eventually reach the seabed where it would be incorporated into accumulation locations, such as the one in Cowlitz Bay of Waldron Island or embedded on rock exposures in the area.

CONCLUSIONS

The Oil Spill Assessment Maps (Plates 1 and 2) for the San Juan Archipelago, central Salish Sea area, is designed and constructed to provide information that should be helpful in mitigating a persistent oil spill in the region. Rather than flying blind in evaluating the distribution of oil spills and their potential to accumulate on critical subtidal benthic habitats we constructed two maps that can be used to visualize the seafloor substrate and habitats that may be impacted by spilled dilbit. These are the first maps of this kind for the Salish Sea – and to our knowledge for any other region – and should be useful in mitigating any oil spill that occurs in the central Salish Sea region. The maps are based on expert interpretations of seafloor conditions using the most

up-to-date high-resolution MBES bathymetric and backscatter data, supplemental with seafloor samples and in situ photos and videos. Available tidal current information, shipping lanes, and selected nearshore/coastal habitat types are included on the maps. One map (Oil Spill Assessment Map of Central Salish Sea – Potential Behavior and Fate of Sunken Oil, [Plate 1](#)) is partitioned into four layers within ArcGIS to highlight the areas where spilled oil may be transported with little impact to the substrate (dispersal corridors), be embedded on substrate with high impact to habitat (embedded sites), accumulate or be buried with moderate to high impact to habitat (accumulation locations), or trapped in bays and sounds or caught up in a gyre (traps and gyres). The other map (Oil Spill Assessment Map of Central Salish Sea – Critical Habitat Types, [Plate 2](#)) highlights the habitats of the region that have a potential adverse impact from a persistent sunken oil spill.

The intent of the mapping is to provide subtidal seafloor conditions (substrate and habitat types) that can be evaluated during an oil spill and used in mitigation. The maps ([Plates 1 and 2](#)) are available to those agencies and interested individuals both as a hard copy and in ArcGIS through a request to the authors.

Based on the sub-tidal seafloor mapping and the evaluation of the marine oil tanker traffic routes, tidal cycles, bottom current sediment transport directions, and critical habitats, we conclude that there are several areas within the central Salish Sea that are most sensitive to adverse impacts from spilled dilbit. Since the shipping lanes are primarily located within the major tidal straits of the region and these appear to be the major dispersal corridors for sinking persistent oil ([Figs. 8, 9a; Plate 1](#)), where the oil would most probably be rapidly transported away from the nucleus of a spill, concern for a spill here should be focused primarily along the margins of the corridors and not within the thalwegs (deep channels, scour troughs, lag plains). However, the northern part of the San Juan Archipelago, from Turn Point on Stewart Island to Boundary Pass is different in that the complexity of bottom current circulation, the proximity of islands (Skipjack, Sucia, Patos, and Matia islands) and rocks (Skipjack Bank, Sucia Island shelf), and the presence of critical marine benthic habitats makes this area a prime candidate for severe impacts to the ecology if a sinkable dilbit spill were to occur (see [Fig. 17](#)). In our view this area along with the bays, islands, and exposed rocks of southern Lopez Island (see [Fig. 11c](#)) are the most critical

areas that could be severely impacted by a dilbit spill either in the Haro Strait-Boundary Pass or northern Rosario Strait areas.

Once spilled dilbit enters the inter-island waterways the tracking and predictive impact areas become more difficult. The most probable critical sub-tidal benthic habitat areas to be concerned with would be the Roche Harbor-Spieden Channel area and the San Juan Channel near Friday Harbor and in Griffin Bay (see [Fig. 11b](#); [Plate 1](#)). Efforts should be made to prevent dilbit from entering sounds and bays, where the oil would become trapped and adversely impact the ecology of these areas.

This report and associated maps, the Oil Spill Assessment Maps ([Plates 1 and 2](#)), directly addresses Washington State Department of Ecology's mandate to "identify water column and sea floor resources at risk from non-floating oils" ([WDOE, 2019, P. 87](#)). In addition, this work directly pertains to Ecology's charge to update GRPs, specifically the one for the central Salish Sea, including a narrative description of risks associated with non-floating oil and an analysis of potential response tactics based on area sensitivity and complexity ([WDOE, 2019, Ch. 6](#)). It should be noted that the Oil Spill Assessment Map could be integrated into Ecology's ongoing shipping modelling efforts in that it could provide early warning for potential grounding and consequence spilling of non-floating oil and used to visualize spilled oil trajectories and assessment of sensitive sub-tidal marine benthic habitats in its path.

Based on our study and mapping effort we provide below some recommendations that we think may help those charged with prediction of the behavior and fate of spilled oil within the Salish Sea and assigned the task of remediation:

RECOMMENDATIONS

1. Determine best way to distribute the Oil Spill Assessment Maps to those interested in the product and see it as useful in the mitigation of oil spills.
2. Encourage the construction of similar maps for the remaining areas of the Salish Sea.
3. Continue adding data to the Oil Spill Assessment Maps such as tidal current vectors and ecological parameters. Encourage full water column tidal current modeling for the region.

4. Encourage modeling of spills based on the map data.
5. Provide an interactive Web Map with selectable layers
6. Complete a Story Map presentation for public consumption.
7. Research technology that can track sinking dilbit such as water column MBES.
8. Publish maps and report in a peer-reviewed journal (e.g., Continental Shelf Research).
9. Consideration be given to stationing an oil spill response vessel in the Roche Harbor or Bellingham areas, close to the most critical marine benthic habitats and outfitted with electronic instrumentation that can track sinking oil.
10. Compile a list of scientists and other knowledgeable persons that can assist in oil spill mitigation and support an ACP as stated in [NASEM \(2016, Ch. 5\)](#) and [USEPA \(2015\)](#).
11. Continue monitoring oil types being shipped and the intensity of shipping in the Salish Sea.

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PLATES (Separate PDFs)

Plate 1. Oil Spill Assessment Map – Behavior and Fate of Dilbit in the Central Salish Sea

Plate 2. Oil Spill Assessment Map – Potential Critical Benthic Habitats in the Central Salish Sea