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B.J. Burd, P.A.G. Barnes, C.A. Wright, R.E. Thomson. A review of subtidal benthic habitats and invertebrate biota of the Strait of Georgia, British Columbia. *Marine Environmental Research*, 2008, 66, <10.1016/j.marenvres.2008.09.004>. <hal-00563056>

HAL Id: hal-00563056

<https://hal.science/hal-00563056v1>

Submitted on 4 Feb 2011

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PII: S0141-1136(08)00212-2

DOI: [10.1016/j.marenvres.2008.09.004](https://doi.org/10.1016/j.marenvres.2008.09.004)

Reference: MERE 3288

To appear in: *Marine Environmental Research*

Received Date: 14 November 2007

Revised Date: 28 August 2008

Accepted Date: 20 September 2008



Please cite this article as: Burd, B.J., Barnes, P.A.G., Wright, C.A., Thomson, R.E., A review of subtidal benthic habitats and invertebrate biota of the Strait of Georgia, British Columbia, *Marine Environmental Research* (2008), doi: [10.1016/j.marenvres.2008.09.004](https://doi.org/10.1016/j.marenvres.2008.09.004)

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Abstract

The initial phase of a collaborative Ambient Monitoring Program (AMP) for the Strait of Georgia (SoG) (Marine Environmental Research Vol. x, pp.) has focused on the benthos, sedimentary regimes, organic and contaminant cycling in subtidal regions of the strait. As part of that project, we review the primarily subtidal benthic invertebrate faunal communities found in the SoG, with particular reference to habitats and sediment conditions. This topic has not been addressed in the primary literature for over 20 years. Benthic biota are the baseline sentinels of the influence of natural and anthropogenic inputs to sediments. They are also a fundamental component of the food chain at the seafloor, and their community ecology must be clearly understood in order to predict how anthropogenic activities and climate change will affect our coastal oceans. The purpose of this review is to provide context on habitats and biota in the SoG, and to highlight topics and geographic areas where our knowledge of the benthos is limited or lacking.

Keywords: benthos; Strait of Georgia; subtidal communities; intertidal communities; British Columbia; anthropogenic influences

1. Introduction

The introduction (Section 1) includes the background to this review (Section 1.1), plus overviews of the oceanography (Section 1.2) and sedimentary regimes (Section 1.3) of the SoG. Section 2 reviews information available on the SoG's benthic habitats and invertebrate

communities, with specific sections on intertidal (Section 2.1) and subtidal (Section 2.2) communities and habitats. Section 2.2 is further divided into subsections based on subtidal depth range and substrate type. Anthropogenic influences on benthic environments and invertebrates of the SoG are summarized in Section 3; case studies of each type of anthropogenic influence are also presented. Section 4 provides a brief summary of the review paper.

1.1 Background

Sources, and availability, of information for this review depended largely on the depth range of interest. For example, one source of information on intertidal habitats and biotic conditions for the SoG includes broad-scale mapping, or monitoring, studies with the purpose of managing broader geographic regions for multi-user inputs and conservation. Mapping data are limited to intertidal zone and the shallow subtidal (<30 m) habitats that have broad aerial, or ground survey coverage. Unfortunately, at depths >30 m, such mapping and survey data do not exist for the SoG. Rather, information for these depths comes primarily from ship-board sampling as part of studies designed to address specific questions for limited geographic areas. These studies tend, therefore, to be focused on a defined area, a specific anthropogenic influence and/or on data collection in support of fisheries and/or environmental management. Similar sources of information are also available for intertidal and shallow subtidal (0-30 m) habitats for the SoG. While most marine habitats are discussed, at least briefly, in this review, the paper was conceived within the context of a project which was biased towards subtidal, sedimentary habitats, and hence it is these latter habitats that are the focus of this review.

In temperate coastal areas world-wide, most benthic biological research and monitoring programs focus on macrobenthic invertebrates (those captured with $\geq 500 \mu\text{m}$ mesh screens). For this reason, macrobenthic invertebrate communities are the main subject of this review. In addition to size, the life histories, responses to natural and anthropogenic conditions and changes, and trophic strategies of macrobenthic invertebrates are far better understood and documented than those of smaller invertebrates and protozoans. For example, many commercially important macroinvertebrate species live within the sediments (e.g., clams) or on the surface of the sediments or hard substrata (e.g., crabs). In addition, benthic macroinvertebrates have often been the subject of anthropogenic impact studies; as a result of being largely sedentary, these organisms are exposed to ambient conditions and may serve as the first-line sentinels reflecting localized impacts (c.f. Warwick and Clark, 1993; Pohle et al., 2001). It should be noted that many benthic macroinvertebrates have a pelagic larval development stage and, as a result, are part of an extensive and intricate food chain which is not limited to the benthos but which can extend throughout the water column.

Benthic invertebrates process the particulate, organic materials (detritus, small organisms) that are deposited on the seafloor or that are suspended within reach of the organisms, using a wide range of feeding strategies such as deposit feeding, suspension feeding, filter feeding, or scavenging. Benthic invertebrates may also be predators, herbivores (grazing on living plant material) or they may rely, at least partially, on chemoautotrophy via symbioses with bacteria for their nutrition (Barnes, 1987). Schwinghamer (1983) estimated that, in soft sediments in temperate coastal regions, macroinvertebrates constitute approximately 95% of the total invertebrate biomass. Similarly, Rowe et al. (1991) found that in coastal areas in global

temperate regions, benthic macroinvertebrates tend to dominate the benthic biomass (excluding fish) in mid-depth subtidal areas (i.e. below the euphotic zone) followed by the other two major benthic consumer groups, the meiofauna (interstitial invertebrates sized 42 μm to 1 mm) and the single-celled organisms (primarily bacteria). While single-celled organisms are beyond the scope of this review, meiofaunal community studies, where applicable, have been incorporated. With the exception of foraminifera (for which taxonomy based on shell morphology has been extensively used in modern and ancient sediments for interpolation of biological and environmental conditions), however, the availability of information on meiofaunal taxonomy, life histories, and environmental tolerances is limited.

In contrast to diversity and biomass patterns, Schwinghamer (1981) estimates that, because of their small size, approximately 95% of the total abundance of benthic invertebrates consists of nematodes and harpacticoid copepods. Included in this total abundance estimate are the larvae of larger invertebrates and a series of less common phyla, typically captured only by 63 μm mesh screens, which prey on benthic bacteria, flagellates, ciliates, foraminifera, and diatoms or blue-green algae in shallower muds (Schwinghamer, 1981; Gerlach et al., 1985). The importance of meiofauna as the base heterotrophs in the food chain varies depending on habitat type and depth (Coull and Bell, 1979). Certainly, components of the meiofauna can be very important in intertidal, and shallow subtidal (i.e. photic zone) benthos where there is considerable primary production occurring in the sediments (Schwinghamer, 1981, 1983; Rowe et al., 1991).

Copepods, in particular, can be a vital food resource for juvenile fish in near-shore nursery areas (for review see Tito de Moraes and Bodiou, 1984). Harpacticoid copepods in sediment core samples from *Zostera marina* beds in the Nanaimo River Estuary and the Cowichan Estuary were diverse (over 50 species from the Nanaimo River Estuary) and abundant (Levings et al.,

1983). In contrast to their global findings for mid-depth subtidal coastal areas, Rowe et al. (1991) suggest that meiofauna may be a more important component of deep subtidal biomass than are macroinvertebrates. In the SoG, a moderately deep coastal area, it is reasonable to assume, therefore, that benthic macroinvertebrates are the primary consumers at the base of the (benthic) food chain and are more important than meiofauna in this regard.

The SoG is part of the broader coastal region of southwest BC and northwest Washington State. Therefore, biological reference materials for the Pacific northwest (e.g. Carefoot 1977; Kozloff 1987) have general applicability to the SoG. The most recently published review of the benthos of the SoG is Levings et al. (1983). This review included reference to broad-scale, historical biological surveys from the 1960s and 1970s that were based primarily in intertidal and shallow subtidal areas; at the time of the review, there was very little available research on mid-subtidal to deep subtidal benthic invertebrate fauna. These surveys included a few studies of soft substrate infaunal invertebrates (Ellis, 1967a, b, 1968a, b, c) and descriptions of an extensive trawl survey of larger epifauna (Bernard 1978). A general description of fjord cliff fauna, based on submersible surveys from three contiguous fjords, was also included in the review of Levings et al. (1983). Although not included in the subject matter of this review, intertidal research on algal and marine vascular plant communities in the SoG was reviewed by Levings et al. (1983) and, more recently, by Watson (1998). In addition to the general lack of research on subtidal invertebrate fauna, Levings et al. (1983) point out that there were no data at all from the deep basin of the SoG and also that little was known about the type, source or composition of sediments, or sedimentation rates, in the SoG. In the past twenty-five years, a great deal of effort has been expended to map biophysical conditions in the substrates of the intertidal and shallow subtidal zones in the SoG; this information is reviewed in Sections 2.1 and 2.2. However, this

review concentrates, primarily, on the less accessible and less well understood, subtidal regions of the SoG.

From 1986 to 1992, a series of primarily deeper (>30 m) subtidal benthic surveys were conducted by the Canadian Department of Fisheries and Oceans and Environment Canada in the SoG and surrounding areas (Burd and Brinkhurst, 1990; Cross and Brinkhurst, 1991; Burd and Brinkhurst, 1992). Only one study, carried out in Boundary Bay, conducted both intertidal and shallow subtidal benthic surveys (Burd et al., 1987). These surveys were briefly referred to in Brinkhurst et al. (1994) and Watson (1998). The original data, and a meta-analysis for these coastal surveys, are provided in Burd (1992). Wilson et al. (1994) edited a trans-boundary (Canada-USA) symposium report reviewing the marine environment and biota of the SoG, Puget Sound and Juan de Fuca Strait. Several research papers from this report are included in this review. A broadly based trans-boundary trawl survey of macroinvertebrates and bottom fish species, which included the southern SoG (Canadian and US), was conducted in 2001 by the Washington State Department of Fish and Wildlife (Palsson et al., 2003). Although 117 taxa of large invertebrates were enumerated from trawls, the focus of the survey was on fish stocks, historical trends, and exploitation rates. However, the distributions of commercial invertebrates (notably Dungeness crab and pandalid shrimp) were highlighted.

Aside from a small number of government studies focused on historical environmental issues (e.g. the Britannia Mine in Howe Sound (G3 Consulting, 2003; Hagan et al., 2004; Levings et al., 2004; Zis et al., 2004), the remaining benthic subtidal habitat and invertebrate sampling has been carried out, primarily, as part of monitoring programs (data collection either for establishing a

baseline or as part of an ongoing program) related to specific anthropogenic inputs into the SoG or its fjords.

Much of the benthic infaunal data available from the SoG since 1986 has been collated into a taxonomically coded and consistent meta-database which includes data from background (or reference) areas, data from areas of known anthropogenic input, and accompanying sediment physical and geochemical data (Burd et al., in press). Burd et al. (in press) also provide a detailed discussion of the biotic responses of benthic invertebrate communities in the SoG to sedimentation rate and organic flux.

1.2. Oceanography

The oceanography of the SoG, and a number of surrounding fjords and inlets, is described by Thomson (1981), LeBlonde (1983), Crean et al. (1988), and Stacey et al. (1991), with updates by Thomson (1994, 1998), Li et al. (1999), and Masson and Cummings (2004). Early numerical tidal current models for the SoG were reported by Thomson (1981) and Crean et al. (1988); more recent tidal current models are described in Foreman et al. (1995, 2004). Models of current variability due to wind, river discharge (estuarine circulation), winter cooling and other non tidal factors, as well as bio-physical aspects of the water column variability, are currently being developed by scientists at the University of British Columbia, (through the STRATOGEM project (<http://www.stratogem.ubc.ca/>), the University of Victoria (VENUS project; <http://www.venus.uvic.ca/index.html>) and the Canadian Department of Fisheries and Oceans Institute of Ocean Sciences (IOS) (Masson and Cummings, 2004).

The SoG is 222 km long and approximately 28 km wide with a mean depth of roughly 155 m (Thomson, 1981; Davenne and Masson, 2001). Additional characteristic features of the SoG, taken from England et al. (1996), Thomson (1998), and Thomson and Foreman (1998) are summarized in Table 1. Fig. 1 shows the depth topography, sills and surrounding inlets of the Strait.

The two primary components of circulation in the SoG, and the dominant factors determining the rate of basin flushing and exchange, are the diurnal and semidiurnal tidal currents and the seasonally variable estuarine circulation driven by fresh water fluxes into the strait. The strength of estuarine circulation in the SoG is affected seasonally by the volume of runoff discharge from the major rivers (mainly the Fraser River) which enter mostly in late spring to early summer, with a secondary surge in late fall. Estuarine circulation is strongly affected by the intensity of vertical tidal mixing which becomes maximal in the narrow channels leading into the strait. Winds, surface heating and cooling, intrusions from adjoining Juan de Fuca Strait and Discovery Passage, and variations in offshore oceanic conditions also affect the circulation in the strait. Other factors influencing the circulation are the shape of the coastline and slope of the bottom topography, bottom and internal friction, inertial forces and external factors related to up-strait propagation of oceanic “events” originating over the outer continental margin. These factors are discussed in Thomson (1998) and outlined in detail in Griffin and LeBlonde (1990), Thomson (1994), and Thomson et al. (2007). Detailed discussion on the estuarine circulation in the SoG can be found in Marinone and Pond (1996), Li et al. (1999), Pawlowicz (2001) and Masson (2002).

There are a number of distinct oceanographic regimes in the SoG (Thomson, 1998). These include the three main basin oceanographic regimes (delineated in Fig. 1) that are described by Thomson (1981, 1998) as follows:

- 1) the Southern SoG, which has vigorous flow exchange and mixing between the southern channels (Haro Strait and Rosario Strait) and the main body of the Strait;
- 2) the Central SoG, which extends northward to the southern end of Texada Island, and receives the main volume of fresh water from the Fraser River runoff; and
- 3) the Northern SoG, which occupies the northern portion of the Strait (from the southern end of Texada Island northwards) but excludes the margin along the eastern side of Vancouver Island where the water properties appear to be strongly affected by the southward density jet entering through Seymour Narrows on the flood tide.

Connecting oceanographic regimes include Juan de Fuca Strait, which extends from the Pacific continental shelf to the entrance to the southern end of Haro and Rosario straits (two tidally active channels with very similar temperature and salinity structure (Thomson, 1998). The northern end of the SoG is connected to the Pacific Ocean through Discovery Passage and Johnstone Strait (Harrison and Yin, 1998). These oceanic connections at the northern and southern ends of the SoG have strong tidal flow and intense turbulent mixing, which is further enhanced through the narrow adjoining channels (Thomson, 1981). At the southern end of the SoG, for example, a complex topography of islands and sills creates strong vertical and lateral tidal mixing (Masson and Cummings, 2000; Pawlowicz, 2002; Thomson et al., 2007), which is also evident in the vertically mixed particulate distributions in this region (Johannessen et al., 2005b). There is nominal surface outflow at both ends of the SoG, with approximately 85-95%

of the flow volume through Haro and Rosario straits and the remaining flow through Johnstone Strait. Thomson (1981) examined the cross-sectional areas of all channels leading into the SoG and found that the southern channels account for 93% of the cross-sectional area and the northern channels only 7%. The major inlets adjoining the SoG are Burrard Inlet, Howe Sound, Jervis Inlet (including Sechelt Inlet), Bute Inlet and Saanich Inlet (Harrison and Yin, 1998). Knight Inlet and Toba Inlet connect through a northern island-strewn archipelago, so can be considered a separate oceanographic regime. Surface outflow of riverine water strongly affects the water property structure in this region (Thomson, 1998).

The southern SoG is defined as the area extending south from the main arm of the Fraser River to the eastern end of Juan de Fuca Strait (Thomson, 1981; Harrison and Yin, 1998; Thomson, 1998). This oceanographic regime is dominated by the Fraser River plume when it moves southward (e.g. during northwest winds and an ebb tide) and is significantly influenced by tidal mixing over the shallow sills of Rosario and Haro straits during spring tides. Tidal mixing injects nutrient-rich water into the southern Strait which lessens the occurrence of nitrogen limitation episodes in the summer. It is, therefore, considered a highly productive area even though it has not been well studied (Harrison and Yin, 1998). Haro Strait, which separates the southern Gulf Islands and Vancouver Island from the San Juan Islands, is the most important of these channels. The flow exchange through this channel is strongly three-dimensional, with variation over multiple time scales (Pawlowicz, 2002). The exchange undergoes marked variability at fortnightly, monthly and seasonal time scales due to corresponding variations in the intensity of the tidal mixing in the channels (i.e., the hydraulic control mechanism outlined by Griffin and LeBlonde, 1990). During the neap tide portion of the fortnightly cycle, when the

tidal currents in Haro Strait are minimal, surface brackish waters from the SoG are able to “slide” seaward over the more dense oceanic waters entering at intermediate to near-bottom depths from Juan de Fuca Strait. In summer (July to October), the deep estuarine inflow in Juan de Fuca Strait carries warm, salty (high density), low-oxygen, high nutrient water inward from the coastal ocean. This water is then able to penetrate to the bottom of the SoG in a series of monthly pulses, renewing the deep water nutrient levels in the region; in winter (November to March), this subsurface inflow occurs only to intermediate depths (Masson and Cummings, 2004). Deep water oxygen levels are increased during deep water intrusions of cold highly oxygenated water in spring. During the spring tidal portion of the fortnightly cycle, when tidal currents are maximal, turbulent vertical mixing in Haro Strait and other passages prevents the simple exchange of brackish SoG water with deeper oceanic water. In this case, there is a reflux of water from the passages back into the SoG at intermediate depths. Additional details on the exchange processes through Haro Strait are found in Griffin and LeBlonde (1990), Thomson (1994), Pawlowicz (2002), Masson and Cummings (2004), and Thomson et al. (2007).

The central SoG is defined herein as the area from the south end of Texada Island to a line drawn from Point Roberts to the Saanich Peninsula (Waldichuk, 1957; Thomson, 1981, 1998). This oceanographic regime is complex due to the seasonal influences of the Fraser River plume, which is characterized by low salinity, very high light-extinction coefficients, high SiO_4^{-4} , low chlorophyll and low primary productivity. During freshet, the sediment-laden surface plume is 2-10 m thick (Thomson, 1981), thus reducing the depth of the euphotic zone and primary production within the surface waters, while greatly enhancing primary (Stockner et al., 1979) and secondary (Mackas and Louttit, 1988) production at the plume margins. Surprisingly,

chlorophyll levels and the abundance of zooplankton and fish are frequently high under the plume (Harrison and Yin, 1998). Bacterioplankton production is greatly enhanced within the brackish plume water (Albright, 1983). The area of the Fraser River plume undergoes marked seasonal variability, with the maximum variations in extent, as well as chemical and biological parameters, occurring in June, at which time the plume can dominate the central SoG. At any given time, the distribution of the plume is influenced by the stage of the tidal currents (flood versus ebb tide) and by surface wind speed and direction (Harrison and Yin, 1998). After wind and tidal mixing, the third largest mechanism for transporting deep nutrient inputs into the surface layer of the SoG is the entrainment of nitrate-rich salt-wedge water directly into the base of the Fraser River outflow (Harrison and Yin, 1998). Seasonal cycles in nutrients, chlorophyll and primary productivity are relatively predictable in the central SoG (Harrison et al., 1983) but the day-to-day variation is high, with values ranging over one order of magnitude in some months (e.g. June). Nitrogen limitation frequently occurs in July and August, depending on the magnitude of the wind events. As a consequence, it is difficult to draw a reliable map of annual primary productivity for the SoG (Harrison and Yin, 1998). Modelling surface layer productivity is also a major component of the STRATOGEM project (<http://web.uvic.ca/~dower/dowerlab/research.html>).

As with the southern passages, flow through the northern passages of Discovery Passage and Johnstone Strait is strongly tidal with a pronounced estuarine circulation component driven by runoff from the Fraser River. Hydraulic processes again modify the fortnightly, monthly and seasonal exchange of waters through this region. Although the flow dynamics in the northern passages are similar to those in the southern passages, the flow tends to have a weaker cross-

channel component and experiences less variability in water properties due to the greater narrowness of the channels (Thomson, 1981, 1994). Considerable oceanographic information is available for this region as a result of current and water property surveys conducted in the region in the 1970s. For data on currents and estuarine-type circulation see Thomson (1976, 1977), Huggett et al. (1980), Thomson and Huggett, (1980), and Thomson et al. (1980a, b). Haigh and Taylor (1991) studied microplankton communities in the northern SoG and determined that, because of the long wind fetch and weak halocline (relatively little influence of the Fraser River compared to the southern regions), wind mixing is likely to prolong or prevent pronounced bloom formation. By late summer, the west side of the SoG is diatom-dominated and more productive due to a nutrient-rich tidal jet flowing out of Discovery Passage during a flood tide. The east side is more stratified due to surface heating and a somewhat lower salinity due to the Fraser River plume (mainly in June and July) (Haigh and Taylor, 1991).

The fjords adjoining the SoG represent a separate oceanographic domain due to the relative isolation of their water masses from the rest of the strait (Thomson, 1998). The mainland fjords include Howe Sound, Jervis Inlet, Bute Inlet, Toba Inlet, Knight Inlet, and Saanich Inlet (the latter being the only fjord on the eastern side of Vancouver Island). Toba and Knight inlets are not always considered to be part of the SoG (Harrison and Yin, 1998). All fjords are separated from the main basin by sills shallower than the fjord basin. Only Burrard Inlet, discussed later in this section, lacks a sill and is not a fjord. Behind the sills, the fjords have glacially-carved basins which are often far deeper than the SoG itself; the deepest fjord basin (700 m) is found in Jervis Inlet. Tidal and estuarine currents over the sills provide for an exchange of material with the SoG, including the possibility of intermittent deep-water exchange events dependent on

conditions inside and outside of the silled basins. The sill regions are characterized by enhanced tidal currents due to restricted openings and shallow depths; this is particularly true in Knight Inlet (Farrow et al., 1983; Tunnicliffe and Wilson, 1988) and at the famous Skookumchuk Narrows opening into Jervis Inlet (Thomson, 1981). However, inlets with especially shallow sills at the mouth tend to have low bottom currents in the deep basins located behind the sill, which can lead to stagnation resulting in low dissolved oxygen levels in bottom waters and sediments (Thomson, 1981). Basic features of basin topography and oceanography for the SoG fjords are described by D. Stucchi (IOS, Sidney, BC) (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/default_e.htm).

Saanich Inlet, the best studied of the SoG inlets in terms of sediments (note that this is not true with respect to physical oceanography, where Knight Inlet is better understood), is smaller than most of the mainland fjords and has a relatively minor freshwater input but a substantial freshwater source just outside the sill (Cowichan River). The Inlet has a shallow sill at 70 m depth and a maximum basin depth of 225 m. Saanich Inlet is unique in that it is the only marine fjord in the SoG system with bottom water (>120-140 m) that is anoxic for most of the year. These conditions are due to high primary production, in addition to restricted bottom water exchange that occurs over extremely limited duration (Gargett et al., 2003). During fall upwelling conditions, Saanich Inlet bottom waters are oxygenated for a short time interval only, with anoxic conditions returning rapidly and extensively throughout the deep waters and sediments (Anderson and Devol, 1973). Fall upwelling in the SoG usually pushes the bottom anoxic layer up to mid-water depths prior to complete flushing. Deep water renewal in Saanich Inlet is described in detail by Anderson and Devol (1973).

Howe Sound, a fjord located just north of Vancouver, has the second largest freshwater discharge into the SoG. The Squamish River, along with the Cheakamus River and some input from the Fraser River plume, creates low surface salinities in the head of the fjord, along with a strongly stratified water column with moderate oxygen in the top 30 m. These conditions, in combination with the heavy glacial silt load carried by the Squamish River from May to September, result in a high, near-surface, suspended silt load and brackish surface layer that greatly restrict light penetration (McDaniel, 1973; Hoos and Vold, 1975). Similar conditions are present in other glacially-fed fjords, such as Bute Inlet and Knight Inlet, although fresh water input is lower in these latter two fjords (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references_e.htm). Deep water (>180 m) in Howe Sound tends to be seasonally hypoxic, with flushing of bottom water occurring at the time of seasonal upwelling (Levings, 1980a, b).

Knight Inlet has a maximum depth of 540 m and two basins; the sill to the inner basin is located at 48 m depth and the sill to the outer basin, at the mouth of the inlet, at 60 m depth. Bottom water oxygen levels are higher than most of the mainland fjords (~3 ml/L), indicating frequent renewals and exchange of a large fraction of the deep water (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/knight_inlet_e.htm). Bute Inlet has a maximum depth of 650 m, with a relatively deep sill at 370 m depth and good bottom water oxygenation and renewal. Bute Inlet has two rivers at the head, with mainly glacial sedimentation (D. Stucchi, http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references_e.htm).

As noted earlier, the deepest mainland fjord is Jervis Inlet, with a maximum depth of 670 m. The sill to the outer basin in Jervis Inlet is relatively deep (240 m) and bottom water exchange is sufficient to maintain reasonable oxygen levels in the deep basin all year. This inlet also has the lowest freshwater input of all the mainland fjords (D. Stucchi, http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references_e.htm). The oceanographic energetics of Jervis Inlet are described by Freeland and Farmer (1980). Haigh et al. (1992) and Taylor et al. (1994) described the seasonal cycle of temperature, salinity, nutrients, chlorophyll, and phytoplankton species for Sechelt Inlet, an arm of Jervis Inlet. Sechelt Inlet is composed of the well mixed Skookumchuck Narrows, and the more stratified waters of the main inlet and Salmon Inlet.

Burrard Inlet, composed of Vancouver Harbour, Indian Arm and Port Moody Arm, receives moderate runoff from the Indian River, with the outer section of the inlet influenced by the Capilano and Seymour Rivers (Harrison and Yin, 1998). Burrard Inlet is located within the Greater Vancouver Regional District and is the most heavily industrialized inlet in British Columbia. The inlet has a maximum depth of 90 m and the main basin, as well as the shallow, isolated arms, are well oxygenated throughout the year and flush rapidly (Levings and Samis, 2001; Stacey and Pond, 2003). During a large part of the phytoplankton growing season (May to July), high-silt water from the Fraser River decreases light penetration in the surface layer and hence, primary productivity is reduced (Harrison and Yin, 1998). Although it does not have a sill at the mouth, Burrard Inlet does have several constrictions within the Inlet which create high currents (Thomson, 1981). Partially as a result of the lack of sill, fine silt sediments in the outer inlet flow out into the main basin of the SoG. Indian Arm, located at the far northeastern end of Burrard Inlet, is more fjord-like in structure with a 220 m deep basin and a shallow sill (15 m to 25 m).

1.3. Sedimentary Regime

1.3.1 Shoreline Description

For the SoG, both the total shoreline length inclusive of fjords (3721 km), and the area of benthic habitat (substrate) types were estimated by Levings et al. (1983). The authors note that, for their estimates, data from hydrographic charts on bottom type was sufficiently detailed only for intertidal and subtidal habitats down to 20 m. The authors use “shoreline” to represent intertidal and subtidal habitats down to 20 m and note that rocky and sandy shores make up 88% of the total shoreline length. However, when area is calculated, sand and mud substrates account for 66.8% (832 km²) of the total 1245 km² of intertidal and shallow subtidal habitats. In contrast, rocky shores contribute only 320 km² or 25.7% to the total area. Using Natural Resources Maps, Levings et al. (1983) computed subtidal areas at depths >20 m. While only 11% of the subtidal area of the SoG is in the 20-50 m depth range, approximately 71% of the subtidal area is within the 50-300 m depth range, encompassing most of the main basin of the Strait, with the majority of the substrate soft sediments (see Figs. 2, 3). Only 18% of the subtidal area is >300 m deep and the majority of these areas are in the mainland fjords (Levings et al., 1983).

Zacharias et al. (1998a) used the BC Physical Shorezone Mapping System (Howes et al., 1993) as the basis of an analysis that provides an estimate of the total shoreline length of the SoG, including fjords (4107 km). The SoG’s intertidal length is estimated to be composed of 26% rocky cliffs, 16% rock with gravel beach, 11% sand/gravel flats, 9.5% rock with sand/gravel beach and an additional 10 representative types each composing $\leq 7\%$ of the shoreline; flats are those areas with slopes $< 5^\circ$, while beaches have slopes from 5° - 20° or higher (Zacharias et al.

1998b). The same authors estimate that the intertidal area of the SoG consists of 34% estuary wetland, 17% sand/gravel flat, 9% sand/gravel beach and an additional 11 types, each composing $\leq 6\%$ of the intertidal area.

A review of marine ecosystem, or habitat, classification systems available for the SoG benthos, from the intertidal to the deep subtidal areas, is provided by Watson (1998). One of these, the British Columbia Marine Ecosystem Classification (BCMEC) system, was first developed in 1995 (Zacharias et al., 1998b, <http://ilmbwww.gov.bc.ca/cis/coastal/bcmec/index.html>). BCMEC uses a tiered hierarchical system to define ecological boundaries for planning and administrative purposes (Howes et al., 1996). There are 12 ecosections in British Columbia, based on differences in ocean circulation, mixing, salinity, temperature, primary and total productivity, continental slope and shelf influence and freshwater influence (Harper et al., 1993a, b; Howes et al., 1996; Zacharias et al., 1998a). The SoG represents one ecosection, which is divided into smaller ecounits (ecological regions) based on a combination of five physical characters: wave exposure, depth, subsurface relief, current regime, and substrate type (Table 3–Wainwright et al., 1995; Howes et al., 1996; Zacharias et al., 1998a). Salinity and temperature data were later incorporated at the ecounit level into the SoG ecosection (Zacharias and Howes, 1998), as were stratification and slope (<http://ilmbwww.gov.bc.ca/cis/coastal/bcmec/index.html>). Depth, current and relief data used to develop BCMEC came from Canadian Hydrographic Service charts (depth, current, relief) (Lamb and Edgell, 1986; Wainwright et al., 1995), models (exposure) (Harper, 1995), and Geological Survey of Canada mapping of benthic sediments (substrate) (see Zacharias and Howes, 1998 for more detail) with intermittent ground-truthing (Howes et al., 1994; <http://ilmbwww.gov.bc.ca/risc/>). Fig. 2 illustrates the coarse resolution

classification of the SoG, based on the system described above and using much of the collected data from the Provincial Physical Shore Zone Mapping System (Howes et al., 1994).

The subtidal components of the ecounits (Fig. 2) are based on extrapolation from data on the intertidal to shallow subtidal zones (≤ 20 m). This method produces a simplistic rendering of substrate types; the soft substrate areas are typically much more of a mosaic, frequently with mixtures of mud and sand, than are depicted, for example, in Fig. 2. This simple scheme is not designed, therefore, to capture the complexity of substrate types, but rather to provide a general perspective. Much more accurate and detailed information on subtidal slope, topography and substrate diversity is available from multibeam data (Fig. 3), as well as from collated sediment core and grab samples from a variety of sources (see Fig. 4). For example, the multibeam data show the deep subtidal reefs which have been found, using video transects, to be relic (or living) sponge and coral reefs (Conway et al., 2007; Cook, in press). Similarly, multibeam data have shown the complex delta structure and sedimentation around the mouth of the Fraser River and the southern portion of the Strait (Hill et al. in press). Although, the multibeam data is not useful at shallower depths (< 30 m) (see Fig. 3), in combination with the physical and biological shore zone data (Howes et al., 1994; Frith et al., 1994), it provides a fairly comprehensive and reliable overview of the full range of benthic habitat depths in the SoG (Fig. 4) (see Burd et al, in press; Cook et al., in press; Hill et al., in press; Macdonald et al., in press).

Figure 4 shows a plot of sediment percent fines (silt+clay $< 63 \mu\text{m}$ particle size) to illustrate sediment types in the SoG. A more detailed map of the near-shore sediment types around the Fraser River delta north to Burrard Inlet is shown in Hart et al. (1998). Note that the greater

detail in Fig. 4 can aid in identifying localized “anomalies”. For example, coarse sand is evident around the Iona outfall (source unclear), at sand heads just south of the mouth of Burrard Inlet, and at the mouth of the south arm of the Fraser River.

1.3.2. Sedimentary Processes

The sedimentary regime for the SoG is extremely complex, particularly around the Fraser River delta and associated areas receiving maximum deposition from the river (see Hart et al., 1998). Sedimentary features of this area are described in detail by Hill et al. (in press). Sedimentation rates, organic and inorganic fluxes for the Strait are described in more detail in Burd et al. (in press). For the sake of simplicity, this section on sedimentary processes divides the SoG into two equal regions north and south of the deepest part of the main basin (~400 m) which is located just south of Texada Island. North of this dividing line (which includes the northern basin regime; Section 1.2), the basin rapidly becomes narrower and much shallower (<200 m) creating a barrier to bottom-transported particulate material from the Fraser River (Johannessen et al., 2005b). Sediment characteristics north of Texada Island suggest that Fraser River material does not contribute to particulate deposition, and that natural sedimentation and organic flux, mainly from marine detritus, are much lower than in the southern half of the basin (Burd et al., in press).

In contrast to the northern half of the basin, the southern half of the basin (which includes the central and southern oceanographic regimes; Section 1.2) receives markedly higher sedimentation (organic and inorganic) (see Macdonald and Crecelius, 1994 for literature review) which is from the Fraser River (Burd et al., in press). This higher sedimentation is related to heavier material deposited primarily at the mouth of the river (up to 10 cm/yr–Hart et al., 1998)

and transported along the bottom northward along the bank straddling the Fraser River mouths, as well as down the slopes to deeper areas (McClaren and Ren, 1995; Hodgins and Hodgins, 2000). As one progresses northward from the river mouth, sediments become progressively finer (see Fig. 4), and show characteristics of declining proportions of Fraser River deposits (Burd et al., in press).

However, the high sedimentation rates to the south of the Fraser River are also related to particulate deposition from the Fraser River plume during freshet. The dispersion patterns of the Fraser River plume, which can extend 2-10 m down from the sea surface during freshet (Thomson, 1981), are aerially visible during the summer months and have been tracked in detail with satellite imagery (Fig. 5). South of the Fraser River, sedimentation may also be related to upwelled fine sands (glacial material) from the southern Gulf Islands (Johannessen et al., 2006). This creates a patchy mosaic of mixed sand and silt substrates in the southernmost portion of the southern half of the Strait (Fig. 4). The sediments of the deep southern portion of the basin that are most subject to plume deposition are somewhat sandy, but finer in texture than those along the slope and bank on the east side of the SOG which receive the coarser, bottom-transported materials from the Fraser River. Therefore, it can safely be said that the southern and northern halves of the SoG constitute very different sedimentary regimes (see also Johannessen et al., 2003).

Boundary areas of high primary production occur in areas of turbulent mixing in the vicinity of the north and south island chains which constrict the entrances to the SoG (Parsons et al., 1981). However, the constrictions at both the north and south end of the SoG result in very little

exchange of particulates and, therefore, of contaminants which are bound to particulates, between the Strait and surrounding waters (Macdonald and Crecelius, 1994, Johannessen et al., 2003). In contrast, however, water-soluble contaminants can spread broadly outside the confines of the Strait (Macdonald and Crecelius, 1994).

Sedimentation in the fjords of the SoG is largely isolated from the effects of the Fraser River. Within the fjords, sedimenting material may arise from freshwater sources, delta slope failures, marine detritus and/or terrigenous erosion of the steep surrounding rock cliffs. The mainland fjords are bounded by the coast mountain range, so that much of the runoff in stream sources is of glacial origin (www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets). Material sedimenting within fjords is typically fine and is trapped within the fjords' basins by the shallow sills at the mouth (Thomson, 1981).

Turbidity in BCs mainland fjords increases as the degree of freshwater and glacial runoff increases. Turbidity currents originating with delta slope failures at the heads of inlets are likely responsible for the bottom water turbidity in some inlets (Pickard and Giovando, 1960; Bornhold et al., 1994). In Knight Inlet, extremely high turbidity and seasonal vertical flux of glacial silt from the two rivers that discharge into the head of the Inlet result in suspended matter concentrations >100 mg/L and a delta slope sedimentation rate of $4 \text{ kg/m}^2/\text{d}$ in summer. As commonly occurs in the mainland fjords, vertical flux and turbidity in Knight Inlet decrease progressively down the Inlet (Farrow et al., 1983). In contrast, Jervis Inlet has very low freshwater input and, thus, has remarkably clear water throughout the Inlet and at all depths

(www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets/Jervis_Inlet_e.htm; observations from the submersible PICES IV, Burd, unpublished data).

Sedimentation rates for the main basin of Howe Sound have been estimated at 0.4 cm/yr (Hickin, 1989) and for the area just outside the Sound's sill at 0.4 to 0.78 cm/yr (Johannessen et al., 2003). Howe Sound has a relatively high freshwater input (Section 1.2) which results in high levels of glacial, suspended particulates near the estuaries. Sediment types and probable transport patterns in Burrard Inlet are complex but have been described by McLaren et al. (1993) and McLaren (1994). Constrictions within the Inlet and high currents create zones of coarse sand grading to hard substrate beds (Thomson, 1981), and tend to maintain particulates in suspension throughout the Inlet. Dredging is required to maintain the channel at First Narrows (near the Lions Gate outfall), suggesting net deposition. Similarly, high net sedimentation rates (1 cm/yr) in Port Moody Arm necessitate continued dredging of the deep-sea berths (Levings and Samis, 2001).

In Saanich Inlet, the majority of the shoreline consists of steep, rocky cliff walls with embayments consisting of typical mud/sand flats with some eelgrass beds. The BC Provincial synthesis report for the Saanich Inlet Study initiated in 1994 concisely summarizes the benthic habitats and sediment types for different sections of Saanich Inlet (BC Ministry of Environment Lands and Parks, 1996). The information is limited primarily to habitats at depths ≤ 50 m adjacent to the shore; due to the hypoxic/anoxic nature of the deeper basin areas >50 m, biotic production is limited considerably.

2. Benthic Habitats and Invertebrate Communities

Although this review is concerned primarily with subtidal habitats in the SoG, Section 2.1 provides a brief overview of pertinent studies on the intertidal invertebrate communities and habitats of the SoG; descriptions of the intertidal invertebrate biota are not included *per se* but can be found in the references cited. For example, Watson (1998) provides a list, and a short review, of studies on intertidal benthic community structure studies that were carried out in the SoG prior to 1997. Major sources of data on the intertidal zone in the SoG, specifically mapping programs and surveys associated with commercially important species, are reviewed in Sections 2.1.2 and 2.1.3, respectively. The bio-physical structure of the intertidal zone can strongly influence the habitat type and biota of the subtidal region and, therefore, aids in providing context for understanding subtidal habitats (Section 2.2).

2.1. Intertidal Zone

2.1.1. Intertidal Habitats

In contrast to subtidal habitats, which tend to be more physically predictable, intertidal habitats are influenced by greater variability in physical factors (e.g. waves, tidal currents, erosion, slope, light, air exposure, temperature, salinity, sediment stability). Factors that also affect subtidal habitats, such as tidal currents, can also affect intertidal areas; for example biodiversity tends to be enhanced in intertidal areas with fast currents (Levings and Thom, 1994). The influence of these factors, as well as biological factors, can lead to spatial heterogeneity of intertidal assemblages in what appear to be similar habitats (Dayton, 1971; Denny et al., 1985; Maurer and

Aprill, 2007). Section 1.3 describes the estimated proportions of the intertidal zone of the SoG that are made up of the different habitat types described below.

Levings and Jamieson (2001) assessed the fish habitat significance of the marine riparian habitat in the SoG. The marine riparian area is defined, by the authors, as the ecotone where aquatic habitat at higher tides merges into terrestrial habitat (i.e. the supralittoral). Levings et al. (1983) reviewed intertidal benthic communities in the SoG in relation to habitat type, specifically sand beaches, rocky shores, mud flats and vegetated areas. The authors provide a list of invertebrate studies conducted in each habitat type prior to 1982. Several studies on sand beaches, with many focusing on Boundary Bay, report on a range of invertebrates from macrofauna to meiofauna (Kellerhals and Murray, 1969; Harrison, 1981; Smith, 1981; Swinbanks and Murray, 1981). The most extensive mudflats in the SoG, and those most heavily researched in terms of invertebrates, are in the Fraser River estuary (see Levings et al., 1983) but research has also been carried out on the mud flat invertebrate communities of the Squamish Estuary (Levings, 1980b) and Vancouver Harbour (Levings and McDaniel, 1974). In the SoG, there is considerable variation in the slope and geology of the rocky shores, with corresponding biological changes (Bousfield, 1957; Levings et al., 1983). Faunal composition in this intertidal habitat type is thought to be influenced predominantly by these geological factors, in addition to water characteristics, wave energy and biological interactions (Levings et al., 1983). In their review of research on invertebrate communities in vegetated intertidal areas, Levings et al. (1983) demonstrate the importance of algae and eelgrass in structuring these communities.

The importance of substrate type and vertical zonation on intertidal community composition is emphasized in most studies in the SoG (c.f. Stephenson and Stephenson, 1961a, b; 1972). For example, Burd et al. (1987) concluded that beach assemblages in Boundary Bay, BC are strongly controlled by sediment grain size. Early synoptic helicopter surveys of rocky shorelines in the strait are described in Ellis (1966), and the concept of vertical zonation and succession developed by Stephenson and Stephenson (1972) in the Strait has also been applied to locations outside the SoG in BC (Ellis, 2002, 2003). Rock and gravel habitats are crucial for shellfish species, especially the recreational and commercially harvested bivalves (Levings and Thom, 1994). Larval settlement of Dungeness crabs (*Cancer productus*), as well as that of Manila clams (*Venerupis philippinarum*), tends to be higher in areas of shell hash, gravel or eelgrass (Thompson and Cooke, 1991; Dumbauld et al., 1993; Levings and Thom, 1994).

Other sources of information on intertidal restoration, conservation and mapping projects in the SoG include the BC Community Mapping Network (<http://www.shim.bc.ca/>) and the BC Coastal Eelgrass Stewardship Project (http://www.stewardshipcentre.bc.ca/eelgrass/eelgrassfinalreport12_04.pdf). While invertebrate communities in eelgrass beds in the SoG have not been studied extensively, there is some evidence that these communities are biotically more diverse and structurally different than those in nearby bare sediments (Levings and Coustalin, 1975; Sibert, 1979; Burd et al. 1987; Seacology et al., 2001). The roots and rhizomes of eelgrass and the tubes of infaunal invertebrates reduce the mobility of a variety of burrowing species, including polychaetes, bivalves, crustaceans, and some echinoderms (Brenchley, 1982). Not only is burrowing time increased but hard bodied taxa, in particular, are restricted by the biogenic structures (Brenchley, 1982). In addition, eelgrass beds are known to

provide protection from predators (Heck et al., 1989) and to encourage the settlement of fine, suspended particulate material, a potential factor in the noted differences in invertebrate community composition (Fonseca and Fisher, 1986).

Considerable baseline environmental information on the intertidal zone of Saanich Inlet was generated as a result of two proposed foreshore developments: a ferrochromium production facility in the 1980s (see Rescan Environmental Services, 1988) and, a large-scale residential development at the site of the defunct cement plant at Bamberton (Williams, G.L. & Associates Ltd., 1991; Madrone Consulting Ltd., 1993). Neither of the proposed developments came to fruition, however. An extensive, and more recent, database is available from the sanitary surveys of clam beaches in Saanich Inlet (see Walker, 1995) and from eelgrass restoration projects in Todd Inlet (BC Coastal Eelgrass Stewardship project; http://www.stewardshipcentre.bc.ca/eelgrass/eelgrassfinalreport12_04.pdf). Similarly, the Saanich Inlet Seagrass Survey studied 67 locations (40.9 hectares total area) surveying intertidal and shallow subtidal areas; eelgrass was limited to three areas with soft bottom substrates (<http://www.env.gov.bc.ca/wat/wq/saanich/siscr.html>). There is also a wealth of uncollated information on the foreshore biota of Saanich Inlet from the local shore-keepers surveys (see Section 2.1.2), as well as unpublished data collected by W. Austin (Khoyatan Marine Laboratory, Sidney, BC).

At Boatswain Bank, just north of the Saanich Inlet sill, recent intertidal transect surveys were done as part of the baseline assessment for a proposed landfall site for the GSX pipeline (Seacology et al., 2001). This is an area of extensive intertidal eelgrass beds, as well as green algae (e.g. *Ulva/Enteromorpha*). Such habitats are considered to be important nursery and

feeding grounds for juvenile fish and were meant to be avoided by the pipeline drilling rig.

Although the pipeline project did not go forward, the report contains detailed data listing algae and invertebrates that are commonly associated with sheltered, near shore habitats in southern BC fjords. The authors describe this ecotype as a typical south-coast, shallow, sloping beach with mixed cobble/sand/ gravel substrate (Seacology et al., 2001).

The intertidal wetlands of the Fraser River estuary cover an estimated 17,000 hectares (<http://www.env.gov.bc.ca/cdc/>) and are also one of the most biologically productive systems in Canada (Levings et al., 1983; Kennett and McPhee, 1988; Harrison et al., 1999). Estimated productivity (based on biomass) for the 14,000 hectares of Sturgeon and Roberts Bank, including the main mud flats on the outer shores of Lulu Island totals 1440.6 kcal/m², broken down into vascular plants (eelgrass) (1320 kcal/m²), microbenthic algae (diatoms) (65 kcal/m²), benthic organisms (invertebrates) (40 kcal/m²), phytoplankton (in water) (15 kcal/m²) and zooplankton plus epifaunal invertebrates (0.6 kcal/m²) (Levings, unpublished data). Macroalgae such as *Ulva/Enteromorpha* are not included in these estimates (Levings, unpublished data) but are occasionally present (Harrison et al., 1999). Plants clearly make up the greatest bulk of living material on the mud flats, by far, and likely provide critical habitat and/or food resources for the benthic invertebrate fauna. The diverse invertebrate fauna are described in Otte and Levings (1975). Primary benthic production and nutrient dynamics of the delta, as well as the foreshore area of Boundary Bay at the Canada/US Border (i.e. outside the influence from the Fraser River), were recently reviewed by Harrison et al. (1999).

All the other major estuaries in the SoG are subject to various conservation and restoration programs, for which information is available from a variety of sources. For example, research on

the benthos of the Squamish River estuary was reviewed by Hoos and Vold (1975) and Levings et al. (1983), with an inventory of research efforts in the estuary basin provided by Hickin (1992). Research in the Nanaimo River estuary includes a study on the intertidal hyperbenthic populations (Sibert, 1981) and the relationship between meiofaunal abundance and intertidal log storage (Sibert et al., 1979). The Nanaimo and nearby Gulf Island marine shorezone areas were also the focus of rocky shoreline zonation studies by Stephenson and Stephenson (1961a, b; 1972). Reports on the SoG estuaries can also be found on websites, such as that of BC Hydro (http://www.bchydro.com/bcrp/reports/lower_mainland.html).

2.1.2. Shore Zone Mapping Programs

The Provincial Biological Shore Zone Mapping (and database) System (Frith et al., 1994) for British Columbia was designed to integrate with the Physical Shore Zone mapping (Howes et al., 1994; see Section 1.3) and is based on taxonomic groupings. The boundaries for units and components in the physical system, based on geomorphological parameters, are used to define boundaries for species assemblages (bands) in the biological system. A hierarchical coding system for biota is included and is based on taxonomic groupings. Components are sub-divided into across- shore areas of common species assemblages termed bands. Bands are defined by the dominant cover species and the colour and texture of that band visible from aerial videography, photography, or from ground surveys (Frith et al., 1994). Maps on a fine scale resolution can be attained at <http://ilmbwww.gov.bc.ca/>. Publications describing the development of this system, modeled characterization of intertidal communities and regional diversity are cited in Zacharias et al. (1998a, b, 1999), and Zacharias and Roff (2001).

The Canadian Department of Fisheries and Oceans began the Shorekeepers' program for monitoring the intertidal zones of the British Columbia coast in 1996 in response to need for a new data acquisition program. The program, aimed at involving coastal communities and fostering stewardship of the coastal zone, was designed for the monitoring of intertidal habitat by non-professionals. Full details including survey design, field sampling, data acquisition, etc., can be found in Jamieson et al. (1999). Data from surveys conducted between 1996 and 2005 are accessible online (<http://www.shim.bc.ca/atlasses/sk/main.htm>). Although the design and limitations of survey methods for this program tend to produce a bias towards larger macrofauna, the resulting data set is cumulative and relatively large, which allows comparison of the biomass-dominant fauna to the physical characteristics used in the BC Shore Zone Mapping System. The Shorekeepers' program (Fig. 6) provides a refinement to the habitat classification of the BC system, including not only substrate type but also dominant algal coverage.

2.1.3 Surveys and Studies Associated with Commercially Important Invertebrates

The BC Shore Zone Mapping Program is also used to assess suitable habitat for invertebrate taxa with commercial or recreational fishery value. For example, based on species-specific substrate and habitat preferences, the relative suitability/rating for the success of Pacific oyster viability at beach locations in SoG can be mapped (Fig. 7). Manila clam suitability shows a very similar distribution (Fig. 7). The areas of "good" and "medium" viability correspond to sand and gravel platforms and sometimes the presence of eelgrass (Fig. 7) (<http://ilmbwww.gov.bc.ca/>).

The BC Clam Atlas was developed as a means of mapping commercial intertidal clam beaches (Manila, Littleneck and Butter) on the BC coast. The maps, area calculations and historical

landings for the SoG area were published by Harbo et al. (1997), and the maps are presently online (http://www-heb.pac.dfo-mpo.gc.ca/maps/maps-data_e.htm). Information on stocks of these and other clams can also be accessed using the Canadian Department of Fisheries and Oceans Stock Status Reports and the Fisheries Management Plans for each species. Geoducks prefer to burrow in sand, silt and gravel from the intertidal to a depth of 110 m (Canadian Department of Fisheries and Oceans, 2000). Landings in the SoG are minor (less than 1/3 of the BC total) and most are collected subtidally by divers. Of the three typical intertidal species, Manila clams are the species harvested primarily from the SoG (Canadian Department of Fisheries and Oceans, 1999a, b; 2007). The Fisheries Management Plan for Intertidal Clams suggests that, presently, stocks are healthy but that the commercial trend is toward reduced landings as a result of reduction in overall effort, lower prices, and increasing alienation of beach space for shellfish aquaculture tenures.

2.2. Subtidal Zone

Levings et al. (1983) reviewed the available sources of subtidal benthic biotic data for the SoG up to that time. Examples of several large, unanalyzed data sources noted in that review include Ellis (1967a, b, 1968a, b, c), who provided quantitative data (including abundance of “apparent” species) resulting from comprehensive surveys of the subtidal fauna and sediments from a wide variety of geographic locations with the SoG. These studies employed similar methodologies (grab samples) to those used in more recent, similar studies (see Levings et al., 1983; Burd, 1992; Burd, 2006). Bernard (1978) reported the results of an extensive subtidal bottom survey of invertebrate fauna from the SoG. The author described, but did not enumerate, the dominant organisms captured primarily by trawling and divided the sampled

areas according to depth range and substrate type. Although some grab sampling was carried out at key locations, the fauna included in Bernard (1978) are primarily epibenthic.

This section is based primarily on background conditions where anthropogenic impacts are expected to be absent or limited. Descriptions of subtidal biotic assemblages based on recent studies are separated by depth range and substrate type in a manner similar to Bernard (1978) but with two notable differences. First, four substrate types (mud/silt, sand, gravel and rock/cobbles) are used in Bernard (1978) while here we employ the following five substrate types: mud, silt/sand, sand, coarse sand/gravel/cobbles and rock (consolidated). Given that trawling was the main sampling method used in Bernard (1978), it is assumed that the rock substrate in rock/cobbles is not consolidated; therefore, the gravel and rock/cobbles substrates of Bernard (1978) are considered equivalent to our coarse sand/gravel/cobbles substrate. Inherent in these, and similar habitat classification systems, is that mixed habitats will have overlapping biotic community types. Second, whereas Bernard (1978) described biota from 20-50 m, and 50-100 m (primarily for logistical reasons related to towed sampling patterns), biota and available information for the SoG are reviewed herein for 3 depth ranges (see below: 0-30 m, 30-100 m, >100 m) based on evident biotic shifts noted at these approximate depths from the literature reviewed herein (see Burd, 2003a). An example of such a depth factor can be seen in Palsson et al. (2003), who state that in the fully surveyed Washington State side of the BC/Washington transboundary bottom trawl survey of 2001, 60% of the invertebrate biomass was found in the 5-20 fathom (approximately 10-37m) depth range. Although this depth range was not surveyed on the BC side of the SoG, invertebrate biomass declined dramatically with depth in the deeper sampling strata.

The depth ranges are defined as follows:

- A.** 0-30 m corresponds, approximately, to the euphotic zone (depths within which light penetrates), although the depth of this zone varies considerably along the BC coast in relation to exposure and water clarity. 0 m depth is considered to be mean low tide, so that habitats within this depth range are subtidal;
- B.** 30-100 m encompasses the zone which, generally, has adequate water oxygenation due to influence of wind and tidal currents and which includes subtidal organisms and no primary producers. In any one location, the consistency of benthic communities in this depth range will depend on depth-related shifts in habitat type, physical features and hydrographic processes. Many of the major taxa, however, have habitat depth ranges which span 30-100 m;
- C.** >100 m encompasses habitats which experience a progressive decline in organic input and bottom currents, leading to considerable change in the benthic communities. In near-shore areas, these depths often occur at the bottom of basins (e.g. fjords) or the foot of coastal slope areas (SoG).

Because the complete particle size distribution (including an assessment of flocculent material) provides the most thorough information about depositional history, it is recognized that the following five substrate types are simplistic (Burd 2003a). In addition, many habitats, particularly near shore, are a heterogeneous mix of different substrate types over relatively small areas. The 5 substrate types, and general features of these substrates regardless of depth, are summarized below.

1. **Mud bottoms (>95% silt/clay)** typically occur in low energy areas and are sticky and tightly packed; mean sediment grain size is <0.06 mm.
2. **Silt/Sand** substrates are a mixture of these two sediment types. The mean sediment grain size for this substrate type ranges from 0.04 to 0.5 mm.
3. **Sand (>90% sand)** substrates are typical of areas with moderate to high bottom currents and/or wave action and exposure, which prevent deposition of finer, marine deposits. Sediment grain size ranges from 0.5 mm to 2 mm.
4. **Coarse sand, gravel or fine cobble** sediments have a grain size from 2 mm to 26 cm. These substrates are less mobile than the previous substrate type, due to the size and weight of the particles, and are mobile only in high energy habitats.
5. **Rocky** substrates are composed of large cobble, boulders or bedrock and include reefs and outcroppings, rocky shorelines and fjord walls.

The above 5 substrate types are discussed in more detail below, citing research from both the SoG and similar environments elsewhere. These more detailed descriptions are relevant to understanding the diversity of subtidal habitats in the SoG. These depth- and substrate-specific habitats are described, including biotic structure, for the SoG using information gathered from a variety of data sources including unpublished remote sampling, submersible and ROV work, collections of data in unpublished data reports. Hence, these generic descriptions of the SoG subtidal habitats are synthesized and, in some cases, extrapolated from a variety of sources and do not lend themselves to specific citations. However, specific type examples from the SoG are provided for each depth- and substrate-specific habitat, including benthic invertebrate community data, when available.

2.2.1 Mud (silt/clay) Habitats

The finest substrate habitats in the SoG are found typically in low energy areas. Although bottom turbidity is unlikely due to storm, wave or current exposure in these low energy environments, it can be caused by physical disturbance such as bioturbation and anthropogenic mechanisms. The fine, often flocculent bottom material may take some time to settle once it is suspended via bioturbation (c.f. Orvain et al., 2003). This is likely the case at fish farms, for example, where organic ooze under the nets is sometimes resuspended by falling debris (e.g. sloughed material) from the overlying nets (Stucchi et al., 2005). However, a distinction should be made between turbidity resulting from static resuspension, due to physical disturbance in mud substrates, and turbidity due to mobile suspended solids resulting from up-stream slope failures in estuaries (c.f. Prior et al., 1987). In the first case, and for most mud sediments, typical bottom disturbances result in low net sediment transport. However, for up-slope failures or slumps, there likely will be considerable transport and bottom turbidity can persist for some time (Prior et al., 1987; Bornhold et al., 1994).

Sediment organic content can be highly variable in silt/clay sediments, depending not only on organic deposition but also on inorganic deposition (see Burd et al., in press). For example, high glacial silt deposition in more northerly mainland fjords tends to be low in organic content (c.f. Farrow et al., 1983). The ratio of organic to inorganic deposition can be related to water depth since, with increasing depth, inorganic (land-based) deposition tends to decrease while the deposited material becomes increasingly dominated by marine detritus (c.f. Rhoads and Young,

1970). In the southern SoG (i.e. south of Texada Island), deposition to mud substrates is dominated by particulates from the Fraser River (Thomson, 1981; Harrison et al., 1983; LeBlonde, 1983; Johannessen et al., 2003). This deposition produces organic carbon levels in surface sediments averaging around 1% near shore in the most southerly portion of the main basin and around 2% in the deeper basin sediments, closer to Texada Island (Burd et al., in press). This observed trend is due to declining riverine deposits and increasing marine deposition (Johannessen et al., 2005b). In the northern SoG, the basin sediments show unusually high %TOC (3-6%) but the overall flux of organic material, and total sediment, to the benthos is low (Johannessen et al., 2003; Burd et al., in press). Stable isotope data and biological samples also suggest that organic material in sediments in the northern SoG is not particularly labile (Burd et al., in press; Macdonald et al., in press).

Not surprisingly, mud substrates are usually suboxic or anoxic, although %TOC varies (~1-7%) depending on the levels of inorganic input, and hydrogen sulphides or other metabolic byproducts may build up depending on redox levels and labile organic input. In shallow mud (silt/clay) substrates, sulfate reduction tends to be linked to a significant proportion (>50%) of carbon oxidation, whereas in deeper mud sediments (continental shelf) the breakdown of organic material is relatively evenly distributed between aerobic and anaerobic (sulfate reduction) processes (Kristensen and Kostka, 2005). The density of infaunal burrows, however, can have a profound dampening effect on anaerobic metabolism as a result of the increased oxygen supply to subsurface sediment layers. The predominant type of burrowing is related to trophic mode (Nickel and Atkinson, 1995), as well as sediment texture and geochemistry. Fine sediments tend

to be dominated by surface deposit feeders or above-surface filter feeders (Kristensen and Kostka, 2005), rather than sub-surface deposit feeders.

Extensive surface bioturbation without the binding influence of intact burrows can destabilize fine surface sediments by producing a surface (“fluff”) layer which is readily re-suspended (c.f. Rhoads and Young, 1970; Orvain et al., 2003). Rhoads and Young (1970) even suggest that surface fluff layers tend to prevent suspension feeding due to the clogging of feeding apparatus and the inhibition of larval settlement. The authors use this suggestion to explain the distinct dichotomy in dominant feeding types: deposit-feeders in soft, fine sediments versus suspension feeders in sandier, or firmer, mud sediments. Following this line of reasoning, an assessment of the feeding guilds in sediments could provide some insight into the sediment texture and porosity, as well as near-bottom turbidity.

The fine-grained particles of mud substrates tend to contain considerable organic particulate material in various forms, thereby providing a good substrate for bacterial and/or algal production (Kristensen, 1988). Key general biotic features of mud bottoms include extensive bacterial or algal mats or shallower near-surface invertebrate burrows that provide sediment surface cohesion in shallow depths, or from invertebrate burrows. Microbial activity, which breaks down organic material in marine sediments (Kristensen and Kostka, 2005), can be stimulated by the presence of surface mucous layers from meiofauna (see Probert, 1984). The stimulation of both microbial and meiofaunal activity creates a rich organic food layer for macrofaunal deposit feeders (Hoskins et al., 2003, Hannides et al., 2005; for review see Kristensen and Kostka, 2005). In addition, mucous layers from intertidal mudflat diatoms,

bacteria and mucous-lined burrows can also help to bind the sediment surface (c.f. Decho, 2000; de Brouwer et al., 2005). Mucous burrows are often impermeable to dissolved organic material and redox chemicals in order to protect the animal from harsh chemical environments (c.f. Hannides et al., 2005; Kristensen and Kostka, 2005). However, depending on their structure, these burrows do provide a pathway for exchange of overlying water with deeper sediments, thus preventing the buildup of potentially inhibitory metabolic byproducts (see Zorn et al., 2006). However, the importance of both bacterial and diatomaceous mucous layers in sediments declines in importance with increasing depth from the intertidal zone to the bottom of the euphotic zone (Ziervogel and Forster, 2006).

Where oxic sediments are present in these habitats, macrofauna are primarily deposit feeding shallow burrowers, such as polychaetes and bivalves, and predators such as various flatfish and crabs from surrounding rocky areas. Megafauna typically include a variety of echinoderms such as mud stars and burrowing holothurians.

2.2.1.1 Shallow (0-30 m) mud

Mud substrates in the shallow subtidal tend to be protected from wave exposure and typically have low tidal currents. Bottom turbidity in these habitats is likely due to physical disruption from erosional events, delta slope failures or other unusual events. These habitats typically occur in low flow estuaries and at the base of low current rocky outcrops. Shallow mud habitats can be found in quiescent bays surrounded by rocky headlands, and in wave and current protected estuaries with either low freshwater flow or where there is heavy glacial silt in runoff (i.e. estuaries of mainland fjords; see Farrow et al., 1983).

897
 898 These are typically highly productive areas because they are within the euphotic zone, which
 899 allows primary production as well as bacterial production on and within the sediments. They are
 900 also common in coastal areas with physical developments that block or break up wave erosion
 901 (e.g. marinas, breakwaters, etc.). Surface shell debris can be common, attesting to the
 902 importance of bivalves in this food chain. Organic carbon flux to the sediments may be high
 903 and, hence, sediment %TOC may also be high depending on the level of inorganic input. (Boyd
 904 et al., 1998). If the input is primarily salt-marsh plant debris, however, the organic material may
 905 have low lability. Primary production in these habitats is primarily from benthic micro-algae and
 906 blue-green algae (refs). These sediments typically have a high level of bacteria, which can
 907 include sulphur-fixing species (refs).

908
 909 Usually, these areas have oxygenated bottom water, with sufficient oxygen for shallow
 910 burrowers that are mostly deposit feeders (bivalves and polychaetes), epifauna (scavenging
 911 amphipods and bottom shrimp), surface grazers (gastropods) and predators (mud stars, brittle
 912 stars, heart urchins, echinurans, drills, fish) (Burd, 1992). In some habitats, mud-dwelling sea
 913 cucumbers such as *Molpadia* or *Chirodota* may be found if there is sufficient oxygen in surface
 914 sediments (Burd, 1992). Meiofauna, particularly nematodes, are important in these shallow
 915 subtidal mud habitats (see section 1.1).

916
 917 Examples can be seen in areas such as Patricia Bay, Saanich Inlet, and around numerous
 918 estuarine bays in the Strait. Unfortunately, there are few published examples of shallow subtidal
 919 mud studies in the SoG. Burd (1992) and Boyd et al. (1998) described mud assemblages from

shallow areas of the innermost part of Burrard Inlet (Port Moody Arm). These substrates had low invertebrate abundance and biomass compared with deeper, coarser substrate areas further out in the inlet, and were dominated by polychaetes, followed by bivalves and crustaceans. Faunal composition was distinct between Port Moody Arm and areas further out in the inlet (Burd, 1992) and in some areas with reducing sediments, dominated by the tolerant opportunistic polychaete *Capitella capitata* complex (Boyd et al., 1998). Considerable sediment chemical contamination and organic enrichment are evident in the Port Moody Arm area (see Burd, 1992; Boyd et al., 1998).

2.2.1.2 Mid-depth (30-100 m) mud

Mud substrates at 30-100 m depth are a common marginal habitat around the SoG, particularly on the eastern side, including Burrard Inlet, north along the coast, and in isolated bays with low bottom currents (Fig. 1). These fine-grained substrates are not found in areas exposed to sandy deposition from the southern Gulf Islands, the Fraser River discharge and other relatively large freshwater estuaries such as the Cowichan River (north of Saanich Inlet), and the Squamish River (Howe Sound). This type of habitat is commonly found inside the sill, or near the mouth of fjords, in areas with either limited, or absent, bottom currents and very low freshwater runoff. These habitats may also occur surrounded by, or at the base of, rocky outcrops or cliffs. Bernard (1978) lists the dominant invertebrate epibenthic megafauna (11 species) found in mud/silt habitats from 20-100 m depth at multiple locations within the SoG.

Because of the depth range, these habitats tend to have limited tidal influence and no wave influence. In addition, as the mud substrates are below the euphotic zone, the development of

surface biofilms may be less extensive than in shallow subtidal mud habitats (c.f. Ziervogel and Forster, 2006). If the redox boundary occurs at the sediment surface, however, sulfide-fixing bacteria such as *Beggiatoa* spp. may produce mucous mats. For example, *Beggiatoa* spp. mats can be found between 65-100m depth in areas of Saanich Inlet (Burd, unpublished data; see >100 m anoxic basins, below).

An example of this type of habitat is bottom areas shallower than sill depth in Saanich Inlet, such as Patricia Bay (<http://www.env.gov.bc.ca/wat/wq/saanich/siscr.html>). Although there have been no studies focused on the benthic soft-bottom fauna in the mid-depth range of Saanich Inlet sediments, another example of this habitat type in the SoG, for which data are available, is outer Burrard Inlet. Sedimentation rates are low in this region (Johannessen et al., in press), although the complex hydrographic mixing results in high suspended particulates in the water column (as noted during reconnaissance ROV surveys – CORI, 2002) and sediment TOC levels between 1.5 and 2% (McPherson et al., 2006b). Although there are a variety of anthropogenic discharges and physical disturbances in the inlet (see Section 3), long-term monitoring for the outer inlet suggests that benthic infauna are not impoverished and are not dominated by opportunistic polychaetes (c.f. PICES, 2001; McPherson et al., 2006b). Fauna within the inlet are dominated by small burrowing bivalves, which constitute ~55-85% of the total abundance over a range of sediment enrichment conditions and which contribute the largest percentage of biomass of any major taxonomic group (McPherson et al., 2006b). Polychaetes constitute 10-40% of the total abundance and species numbers are within the ranges expected for this depth range in the SoG (Burd et al, in press). Ophiuroids are patchily abundant and both crustaceans and holothurians are rare in this inlet.

Data are also available for shoreline areas just outside the north side of Burrard Inlet which fit this habitat type (McPherson et al., 2004a). Biotic samples taken from a similar depth to the outermost Burrard Inlet show similar species richness to the Burrard Inlet samples but somewhat lower abundance levels (McPherson et al., 2004 a, c). Fauna increase in abundance from outside the inlet to the innermost part of the outer basin (west of 1st Narrows) (Fig. 1), with bivalves showing the clearest abundance gradient (McPherson et al. 2004 a,c). Like Burrard Inlet, the area just outside the north side of the inlet experiences relatively low sedimentation rates compared to the rest of the southern SoG, as well as moderate %TOC in the sediments (~1.5%) Burd et al., in press; (Johannessen et al., in press).

Biotic and synoptic sediment geochemical and contaminant sampling data have been collected for parts of inner Burrard Inlet (past 1st Narrows), including the two inner arms (see Fig. 1) (Burd and Brinkhurst, 1990; Cross and Brinkhurst, 1991; Boyd et al. 1998; PICES, 2001; Je et al., 2003). In addition, samples from the outer inlet were collected by Ellis (1971). These studies suggest that faunal abundance and species richness decline along a gradient from 1st Narrows inward towards Port Moody Arm (Fig.1), where the heaviest organic enrichment and contamination is found. In Port Moody Arm, which has fine mud sediments with poor flushing, faunal abundance tended to be temporally variable relative to the rest of Burrard Inlet (Burd 1992; Boyd et al., 1998) but faunal biomass was consistently lower.

The spectrum of studies utilizing the same locations in Burrard Inlet but using different mesh sizes (0.3, 0.5 mm and 1 mm) for screening biotic samples, provides a unique opportunity to

examine the difference in interpretation which is potentially possible for community structure based on methodology. Ignoring potential differences in quality control of sampling, increasing screen mesh size led to a decreasing proportion of juvenile (non-adult) forms at one outer harbour station (~ 50% to 10%) but no notable shift in species number. However, the proportion of abundance made up of bivalves shifted from ~35% to 55%, with a commensurate decrease in proportion of polychaetes. In addition, although usually ignored in benthic macro-infaunal studies, the proportion of nematodes collected decreases with increasing mesh size. Hence, the 1mm screen appears to eliminate most of the juvenile fauna, as well as a modest proportion of the smaller adult polychaetes and most of the “meiofauna” (primarily nematodes and harpacticoid copepods). The most dramatic change in metazoan size spectra, biota types and life history strategies appears to be found at about the 0.5 mm screen size, and the evolutionary drivers for the meiofaunal/macrofaunal dichotomy are discussed by Warwick et al. (2006). The various studies agree that polychaete dominance increased from the outer inlet towards the more eutrophic Port Moody Arm (Boyd et al., 1998; Burd and Brinkhurst, 1990; Je et al., 2003), with some examples of opportunistic enrichment of *Capitella capitata* complex (Burd and Brinkhurst, 1990; Je et al., 2003).

2.2.1.3 Deep (>100 m) mud

Deep water mud habitats are not subject to tidal or wave influences, usually have very low bottom currents and limited flushing of bottom water. The origin of organic material in these environments is primarily marine detritus or terrestrial erosion from cliffs in fjords. Bottom turbidity can occur as a result of turbidity flows from delta slope failures in fjords (Prior et al., 1987; Bornhold et al., 1994). In general, substrates get finer with increasing depth in coastal

areas (Striplin, 1996; Llansó et al., 1998) because the input of coarser land-based erosional, riverine and current-transported material tends to decline with increasing depth. Organic carbon flux to these deep sediments is typically, although not always (Burd et al., in press), lower than in similar sediments in shallower areas, unless there is a specific source of organic input nearby (e.g. fish farms).

Areas with oxygenated, mud sediments are extensive throughout both the deep basin of the SoG and many of the fjords, and probably make up most of the subtidal bottom area of the SoG (Levings et al., 1983). Bottom water oxygen levels vary, depending on basin topography, but low bottom currents and shallow, isolating sills in fjords can result in significantly reduced bottom oxygen levels. Hence, there is limited oxygen replenishment to the sediments. These habitats are typical of the main basins of fjords and the deep basin of SoG. These sediments are dominated by near-surface, or epifaunal, deposit feeders and predators. Bivalves and ophiuroids are less abundant in these deep habitats than in shallower areas, while polychaetes, holothurians and echinoids increase in dominance (see Burd et al., in press). Bernard (1978) provides a list of the dominant (largely epibenthic) megafauna collected in trawl samples at locations throughout the SoG at depth ranges of 100-200 m, 200-300 m, and 300-400 m. Bernard's (1978) species list is the most diverse in all depth ranges for this substrate type, and includes bivalves, polychaetes, echinoderms and crustaceans.

Because organic carbon flux is low, faunal abundance and species richness is generally lower than in the mid-depth marginal SoG mud habitats discussed earlier. Llansó et al. (1998) describe biotic conditions in deep clay habitats >80 m in Puget Sound. They suggest that, on average,

species richness and abundance was lowest in deep (>80 m) clay sediments of any soft substrate types in the sound or on the Washington shelf. Llansó et al. (1998), Burd and Brinkhurst (1992) and Burd (2003b) agree that several of the large, important bioturbators (the echinoderms *Molpadia intermedia* and *Brisaster latifrons*) seem to be primarily found in deep-water sediments, which in the fjords and main basin of the SoG are typically mud (silt/clay).

Some data on the benthic infaunal biota, collected using visual and remote sampling methods, are available for the fjords (Burd and Brinkhurst, 1992; Ellis, 1971; Levings, 1980a, b). Burd and Brinkhurst (1992) report infaunal abundances in silt sediments at depths of >100 m in of three of the SoG fjords: Bute, Toba and Jervis. Faunal abundance was low at all sampling stations in that study and was dominated by polychaetes; occasional high abundances of sipunculids were recorded but few echinoderms and virtually no crustaceans or bivalves were observed (Burd and Brinkhurst, 1992). Burd (1992) did a multivariate comparative assessment of biotic assemblages from a series of deep fjord samples along BC's mainland coast compared with other assemblages found throughout BC. One notable feature of BC's deep fjords is the relative uniformity of benthic assemblages in the deep mud benthos, compared to other coastal areas, in the absence of overwhelming physical drivers such as anoxia or hypoxia, heavy glacial deposition or freshwater runoff (c.f. Burd 1992).

Ellis (1971) described fauna from some grab samples taken in the deepest basin of Jervis Inlet on the mainland BC coast. They note that about 80% of biomass from that area was contributed by the echinoderm *Brisaster latifrons* and a surface tube-mat forming polychaete; approximately 10% of the total biomass was contributed by bivalves.

1058

1059 A deep mud-bottom habitat in Knight Inlet (located immediately north of the SoG), described in

1060 Farrow et al. (1983), is a good example of a fjord with high loads of river-borne glacial silt.

1061 These loads of glacial silt add to the inorganic loading near the head of the inlet, while also

1062 introducing sufficient energy and flocculent material into the system to produce high turbidity

1063 and bottom resuspension or turbidity flows. This turbulent type of habitat is unsuitable for many

1064 soft-bottom species which may suffer from smothering (e.g. Holte and Gulliksen, 1998;

1065 Wlodarska-Kowalczyk et al., 2005). In Knight Inlet, BC, Farrow et al. (1983) found a down-inlet

1066 gradient of increasing diversity of large suspension-feeding organisms, and a change in epifauna

1067 from mobile shrimp and crabs at the turbid, high inorganic input head of the inlet, to burrowing

1068 shrimp in the middle inlet, to ophiuroids in the least turbid and least inorganic input areas of the

1069 lower inlet. Similar trends have been observed elsewhere; for example Wlodarska-Kowalczyk et

1070 al. (2005) describe the spatial gradient in sediment biota away from heavy glacial silt

1071 sedimentation towards the head of a European fjord as showing similar trends in faunal

1072 abundance and species richness as those found in organic enrichment gradients. Changes in

1073 species diversity and types of sponges related to water turbulence and sedimentation in an Irish

1074 sea lough were also noted by Bell and Barnes (2000a, b).

1075

1076 During the SoG Ambient Monitoring Program (Wright et al., in press), deep-water mud habitats

1077 were sampled at two stations. One station was within the deepest part of the SoG basin (388 m),

1078 just south of Texada Island (Fig. 1), and had moderate organic flux to sediments while the

1079 second station was north of the mid-basin sill near Texada Island (187 m) and was within the low

1080 organic flux regime in the northern SoG (see Burd et al., in press). In addition, the organic

carbon at the shallower, more northern station was relatively refractory compared with the deeper, southerly station, and had a high clay component, with virtually no terrigenous or shell debris. The difference in these substrate conditions produced a striking difference in biota, which was much more abundant and diverse at the deeper, southerly station. However, similarities between the two stations include polychaete dominance, the lack of bivalves and crustaceans, and the presence of large burrowing holothurians. In fact, this latter group was responsible for the relatively high faunal biomass at the deeper, southerly station (Burd et al., in press).

Saanich Inlet, below sill depth (70 m) (Fig. 1), is an example of a deep anoxic basin. It experiences progressive hypoxia and anoxia from winter through summer. In the fall, upwelling within the SoG spills dense, oxygenated water over the sill and, sinking to the bottom, this water pushes the anoxic layer up to mid-water depths before the anoxic waters disperse (http://www.pac.dfo-mpo.gc.ca/sci/OSAP/projects/bcinlets/saanich_inlet_e.htm). Saanich Inlet has high organic carbon content in deep sediments (Bornhold, 1978) but a moderate C/N ratio (~6.8), suggesting that, historically, the origin of organic input has been largely marine. The high carbon content in Saanich Inlet deep sediments has been supported by more recent studies (Boatman and Murray, 1982; Tunnicliffe, 2000), however Tunnicliffe (2000) indicates that increasing terrestrial input over the past century has resulted in shifts in organic carbon content, and therefore, the C/N ratio. Organic carbon may build up in sediments because overlying water hypoxia and anoxia greatly slow the decomposition and consumption of this material by bacteria and invertebrates, respectively (Emerson and Hedges, 2003). Although the cliff fauna of Saanich Inlet have been studied, (Tunnicliffe, 1981; Burd and Brinkhurst, 1984), information on the infaunal benthos of the deep mud basin is lacking. However, because of the occasionally

vertically mobile anoxic water layer in this inlet, along with observed mass mortalities of cliff fauna (Tunncliffe, 1981; Burd and Brinkhurst, 1984), it has been assumed that soft-bottom areas influenced by long-term anoxia will be largely azoic.

At the sediment interface, where dissolved oxygen is minimal and sediments are anoxic, white mucous mats of *Beggiatoa* spp. and similar sulphur-fixing bacteria may form (Burd and Brinkhurst, 1984). In this oxycline, the sediments are devoid of any sign of bioturbation or evidence of infaunal or epifaunal life (Gucluer and Gross, 1964; Burd, unpublished data; PICES IV observations 1980-1983), with the following exceptions. A benthopelagic amphipod species (*Orchomene obtusus*) can tolerate anoxic conditions for extended periods of detrital scavenging, after which they migrate back up to oxygenated water periodically (De Robertis et al., 2001). The galatheid crab, *Munida quadrispina*, has been observed to frequent silty bottom areas where the mucous mats are present and near-bottom water oxygen levels are very low (Burd and Brinkhurst, 1984) and has been observed, *in situ* and in the laboratory, to feed opportunistically on sediment detritus and the aforementioned amphipods. The crabs have exceptional metabolic regulation under low oxygen conditions in the laboratory (Burd, 1985), along with significantly hypertrophied gill tissue in the deep areas of Saanich Inlet (Burd, 1988), compared with surrounding areas outside the inlet. In the deep, severely hypoxic to anoxic sediment areas, these are the only visually evident fauna although facultative anaerobic meiofauna (typically nematodes) may be present in sediments.

Like Saanich Inlet, Howe Sound on the mainland coast of BC has a shallow sill at the entrance and experiences hypoxic conditions in the deep basin for part of the year. Historical bottom

trawl surveys in Howe Sound related to bottom hypoxia are described in Levings (1980a, b) and Levings et al. (1983). Survey data show that the relatively immobile invertebrates and a few slow-moving fish experienced mass mortalities during severe hypoxic periods; bottom fish catches declined, presumably due to migration to shallower, more oxic waters. The mobile epifauna appeared to return fairly rapidly following hypoxic periods, including the galatheid crabs also found in Saanich Inlet, and various shrimp species (Levings 1980a, b).

2.2.2 Silt/Sand Habitats

The presence of sand implies transport of inorganic material, from nearby glacial deposits or moderate to high input from freshwater sources nearby. Although variable spatially and temporally, these sediments are net depositional. In coastal areas with a source of relatively coarse, inorganic material from large riverine inputs, the sediments tend to be mixed. This type of habitat is common in marginal coastal areas in the southern SoG, particularly along the eastern margin of the southern Strait where the Fraser River discharges. For a description of sedimentary dynamics along the Fraser River delta, see Hill et al. (in press). Most notable about these sediments is the input of coarse material that increases mobility beyond that found in mud substrates. The delta sediments along the bank and slope where the Fraser River discharges into the SoG provide a good example of this mobility, as the sediments appear to be continuously transported to the north and downslope (McLaren and Ren, 1995; Hodgins and Hodgins, 2000). The importance of sediment mobility in determining the distribution and stability of coastal benthic infauna has been documented in Australia (Post et al., 2006), New Zealand (Hewitt et al., 1997; for a general review see Newell et al., 1998), and in laboratory experiments (Roegner et

al., 1995; Dunn et al., 1999; Hunt and Mullineaux, 2002). Research in the northeast Pacific has focused on transport of sediment particle sized organisms such as foraminifera (Snyder et al., 1990).

In the sediments influenced by Fraser River deposits, the relatively high deposition of inorganic riverine material seems to limit the TOC levels to values $<1.5\%$ (McPherson et al., 2006a; Burd et al., in press). However, these TOC values are not indicative of the productivity of these sediments, which is more closely related to the input of organic material (see Burd et al., in press). Because of the inorganic input to these sediments, however, and their tendency to be less sticky and cohesive than mud, they are usually better oxygenated than marine muds. Surface mixing layer depths related to bioturbation in substrates affected by Fraser River discharge are estimated at between 7-10 cm deep (Johannessen et al., in press). These substrates tend to be located in moderate or variable current regimes and, because the sediments are easily re-mobilized, bottom turbidity may occur. These substrates are typically oxic but, if organic carbon loading is high, can be suboxic.

A wide range of habitat types, based on fine-scale structural features, can be found in these substrates, along with a mixture of biotic features of both mud and sand communities. Analyses of biotic data with an extensive geographic distribution within the SoG (Burd et al., in press), indicates that this silt/sand habitat along the Fraser River delta appears to have a high abundance of invertebrate fauna compared with the rest of the SoG. Biota are diverse in terms of species richness, type (polychaetes, bivalves, echinoderms, crustaceans and more) and size spectrum of organisms, as well as feeding types (mixed deposit and/or suspension feeders, scavengers and

predators) (McPherson et al., 2006a). Using functional group categories for benthic fauna, Pearson and Rosenberg (1978) suggest that off-shore silt/sand habitats in temperate coastal areas tend to have the greatest diversity of functional groups in soft sediments.

2.2.2.1 Shallow (0-30 m) silt/sand

Shallow silt/sand habitats in the SoG are usually semi-protected in regard to wave exposure and tidal currents. Sediment is either fluvial in origin or from an along-shore source. Oxygen levels in bottom water are reasonable and natural sediments tend to have some oxygenation. In the SoG, eelgrass occurs in oxic sediments in areas with “clean” water and at depths usually <10 m. Both red and green macroalgae are associated with eelgrass beds, as a result of the low sediment mobility (eelgrass roots/rhizomes stabilize the sediments). In the shallow silt/sand habitats in the SoG, mobile macrofauna (e.g. sea stars and crabs) are abundant and, usually outside of the eelgrass beds, deep-burrowing large bivalves as well as burrowing anemones, agglutinated tube-building worms and tubicolous amphipods occur.

Bazan Bay on Vancouver Island, serves as an example of some of the more interesting features that may occur in these shallow silt/sand habitats. A mixed eelgrass, red and green filamentous algal community is evident to the 10 m depth (J. Harper, CORI, Sidney, BC, pers. comm.), along with patches of eelgrass that vary in density (see Bornhold and Harper, 2002). Eelgrass beds are typically considered to be important habitat and nursery areas for various species of fish and mobile, or epiphytic, macro-invertebrates (Goldstein et al., 1996; Heck et al., 2003; <http://www.ecy.wa.gov/programs/sea/pugetsound/species/eelgrass.html>)

In deeper waters, but still within this habitat type, foliose red algae and other macroalgae are seasonally abundant, suggesting attachment in the relatively stable silt/sand substrates. Benthic invertebrate data from close proximity to an abandoned outfall pipe in Bazan Bay was collected (Glaholt et al., 2002) as part of the reconnaissance information related to the proposed SoG Crossing pipeline project. The study was designed to show the expected changes in biota related to the introduction of an artificial reef (a pipeline), into a shallow, silty sand habitat in the SoG. The faunal assemblage in these substrates is dominated, to an indeterminate water depth, by a dense sediment-surface mat of tube-dwelling amphipods, sponges and hydroids, with lesser dominance by polychaetes, followed by bivalves (Glaholt et al., 2002). The presence of these mats suggests a lack of bottom disturbance from excessive sedimentation, organic input or physical disruption. The presence of sponges and hydroids in the mats suggests a strong suspension feeding component within the community. The amphipod tubes produce a micro-heterogeneity of structure which benefits other species, such as the hydrozoans and a multitude of other amphipods and crustaceans. Faunal distributions were highly variable spatially, with isolated patches of anoxic sediments and higher silt content where drift algae had piled up on the quiescent down-current side of the Bazan Bay pipeline (Glaholt et al., 2002). Other infaunal organisms which may be common in shallow silt/fine sand habitats include relatively deep burrowing, large bivalves, burrowing anemones, and larger mobile predators and scavengers (e.g. mud stars, crabs, shrimp and nudibranchs).

Another example of a shallow mixed silt/sand habitat study is Boatswain Bank along the eastern coast of Vancouver Island just north of Saanich Inlet. A shallow subtidal study was done along an onshore/offshore transect at the proposed landfall for the SoG pipeline. The relevant habitat,

macroalgae and surface megafauna are described based on diver surveys in Seacology et al. (2001). Megafauna included sea-pens, tubeworms, gastropods, hermit crabs, sand stars, and various fish. Beach seining in the same study showed a number of rock, kelp and helmet crabs. Concurrently, a study of the infauna (Burd and Glaholt, 2000) showed a diversity of polychaete, bivalve, crustacean and echinoderm fauna with numerous bryozoan and cnidarian colonies attached to fauna and macroalgae. The diversity of this assemblage appeared to be comparable to the deeper, siltier samples in Satellite Channel (Burd et al. 2000a), except for a much lower abundance of shallow burrowing bivalves in the Boatswain Bank area. The area was also surveyed by video to map the habitat, extent of eel-grass beds and other macro-algae (Archipelago Marine Research Ltd., 2000).

2.2.2.2 Mid-depth (30-100 m) silt/sand

Mid-depth silt/sand habitats in the SoG tend to have a broad range of organic carbon fluxes and bottom water oxygen levels. An example of the mid-depth silt/ sand habitat is found on the western side of the SoG, straddling the Fraser River discharges. Extensive biological and geochemical monitoring of these sediments has been conducted as part of the Iona outfall monitoring program for GVRD (Burd, 2000; Burd, 2003b; Bailey et al., 2003, McPherson et al., 2003, 2004b, 2005a, 2006a, 2007a), providing extensive data on both background and impacted areas (see Section 3). This area spans the Fraser River delta and hence receives the maximum influence from plume particles and bottom transported material, particularly from the south arm of the Fraser River (Hill et al., in press). Bioturbation in the area is considerable, with a surface mixed layer of up to 5-10 cm (Johannessen et al., in press). The area has a rich and diverse macrofaunal community dominated by a broad size range of bivalves, although 40- 60% of the

total faunal abundance is contributed by one small, burrowing species, *Axinopsida serricata*. A second bivalve, *Macoma carlottensis*, comprises ~10% of the abundance. All bivalves comprise ~50% of the organismal biomass in these sediments (McPherson et al. 2006a). The remaining biomass is mostly comprised of echinoderms, primarily the brittlestar *Amphiodia urtica/periercta* complex, and a few large holothurians (*Molpadia intermedia*). Although there is a diversity of polychaete taxa present, these organisms are clearly of minor importance in the productivity of these sediments. Infaunal crustaceans are rare, comprising less than 1% of faunal abundance and far less than 1% of biomass (McPherson et al., 2007a).

The bivalve dominance evident in the 30-100m silt/sand sediments spanning the Fraser River delta, discussed above, appears to be unusual within the SoG (Burd et al., in press). Burd et al. (op. cit.) suggest that the bivalve dominance is related to the high sedimentation rates along the delta (see Johannessen et al., in press), which are less easily tolerated by infaunal polychaetes (Reid and Baumann, 1985; Burd, 2002). Brittle stars may also have an advantage in this habitat type in regard to the speed and extent of their burrowing capability. Close to the south arm discharge of the Fraser River, the sedimentation rates are too high to be measured in the standard box cores used in other locations (Johannessen et al., in press). In this location, the dominant bivalve (*Axinopsida serricata*) and the ophiuroids periodically decline, with a concurrent increase in abundance of small polychaetes typically considered to be primary colonizers (McPherson et al., 2006a). Presumably, there is therefore a limit in the ability of the infaunal bivalves and brittle stars to cope with heavy sedimentation conditions (or events).

Although mid-depth (30-100 m) sampling stations in outer Burrard Inlet are described as having mud substrate (see earlier), several stations in this area have silt/sand substrates (i.e. stations close to the 1st Narrows bridge and near the mouth on the south side of the inlet (Fig. 1) Conversely, some areas along the bank and slope between the south arm of the Fraser River and the opening to Burrard Inlet can be classified as primarily mud. Species richness values and faunal types are similar throughout the Fraser River delta and Burrard Inlet (McPherson et al., 2006 a, b), illustrating the overlap in faunal types between mud and sandy silt habitats. However, regardless of substrate type, species abundance and biomass values have been consistently lower in outer Burrard Inlet than along the Fraser River delta (McPherson et al., 2006 a, b), and total sediment flux and organic flux are higher along the river delta than in Burrard Inlet (Burd et al., in press; Johannessen et al., in press). These patterns suggest that faunal productivity in the main basin of the SoG is more dependent on the Fraser River discharge than on substrate type or depth (Burd et al., in press).

2.2.2.3 Deep (>100 m) silt/sand

Silt/sand habitats are rare below 100 m depth in the SoG, since most of the sand (coarser, land-based material) deposits closer to shore. In most of the deeper parts of the main basin of the SoG, and at the bottom of fjords, substrates are mud (see earlier text). In the southernmost part of the main basin of the SoG, however, intense mixing throughout the water column in Haro Strait (Masson and Cummings, 2004) (see Fig. 1) may carry sandy material eroded from the southern gulf islands to the deep basin of the SoG (see also Johannessen et al., 2006), explaining why these sediments have some sand content. In addition, some of the coarse, sandy sedimenting material from the Fraser River is transported northward and downslope off the delta, ultimately

ending up in the deep basin of the eastern margin of the southern SoG and resulting in mixed sand and silt substrates at depths greater than 100 m (McPherson et al., 2004a).

The example used to provide a description of the biota in these habitats is the area at the foot of the slope (120 m) on the south-eastern margin of the SoG, along the Fraser River discharge area. The biotic community of this area overlaps with that for the mid-depth range to some extent, but there are marked differences in faunal dominance (McPherson et al., 2004a). For example, the mid-depth bivalves, such as *Axinopsida serricata*, which are dominant from 30-100 m in the Fraser River delta and outer Burrard Inlet, decline in abundance at depths >100 m in these same areas (McPherson et al., 2004a, b, c). Brittle stars are also rare below 100 m, whereas large holothuroids such as *Molpadia* increase in abundance and the crustacean fauna changes. Number of taxa and total abundance tend to decline somewhat with increasing depth but are still relatively high at 120 m. At a location close to the south arm of the Fraser River discharge (Fig. 1) the main features of the fauna tend to be similar at depths from 60-120 m, because this entire habitat is overwhelmed by continuous high deposition of river-derived material. At 500 m north of the Iona outfall (McPherson et al., 2004b) (Fig. 1), and another location just outside the mouth of Burrard Inlet (McPherson et al., 2004a), faunal abundance and diversity decline dramatically with depth. Near the outfall, the faunal decline may be related to slumping of elevated (outfall-related) deposits along the steep slope areas. However, in both the aforementioned more northerly locations, faunal declines may be related to a combination of decreased sediment organic flux with depth and natural declines in bivalve abundance below 100 m (Burd et al., in press).

Several stations sampled in the deep, southern basin of the SoG as part of a collaborative ambient monitoring program between the Canadian Department of Fisheries and Oceans,, Natural Resources Canada and the Greater Vancouver Regional District (Wright et al., in press) showed infaunal biomass as high, or higher, than that observed in the mid-depth zone along the Fraser River delta (see earlier text this section; Burd et al., in press). Faunal abundance and species richness were also considerably higher than those found in either of the deep, mud habitats in fjords or other deep areas of the BC coast (Burd, 1992; Burd, 2006; Burd et al., in press). At one southern SoG station, sediments had unusually high organic and inorganic flux, biomass and species richness (see Burd et al., in press) and were dominated (e.g. ~40% of total abundance) by crustaceans, particularly a cumacean (*Eudorellopsis integra*) and an ostracod (*Eudorella pacifica*); both these crustacean species were rare in the proximate mid-depth zones for this substrate type (McPherson et al., 2007a). Approximately 25% of the total faunal abundance at the same station consisted of bivalves, which is unusually high for the deep habitats, and 25% consisted of polychaetes. The remaining fauna consisted of gastropods, aplacophorans, and a few echinoderms. The second station was dominated by polychaetes with few bivalves but had a high biomass due largely to echiurans (Burd, et al., in press). A third station in the southern main basin of the Strait appeared to have a faunal composition that was intermediate between the other two stations, albeit with a lower overall biomass and abundance than the other two stations along with a lower organic flux to bottom sediments (Johannessen et al., in press). These differences illustrate the wide variety of faunal types which may occur at depth within the deep basin of the SoG, presumably related to differences in sedimentation conditions (Burd et al., in press).

2.2.3 Sand Habitats

Unlike the previous two substrate types, sand substrates are non-cohesive and, potentially, are highly mobile. Sand habitats are abundant in areas with high energy currents and a proximate source of either land-based or glacial deposit sands. These habitats may be depositional or erosional, depending on the currents and the source and persistence of the sedimenting material. In some cases where there is on-going input of sand from erosion or freshwater runoff, the area may be net depositional with variable bottom currents. In addition, seasonal deposition of finer substrates may occur based on water column productivity, but these deposits may be resuspended and transported away during winter storms.

Sand substrates are porous and well oxygenated, often to sediment depths >10 cm; they are subject to both diffusion and lateral seepage of oxygen and dissolved organic material. Low porewater oxygen would be expected only in very unusual circumstances, such as may be found in a stagnant basin with high inorganic input. Organic flux may vary greatly but the deposition of typically fine, organic material is limited such that sediment TOC content is generally low (<1%). Sand habitats are the most extensively bioturbated of all the habitat types, as the sediments tend to be loosely packed, and, thus, are relatively easy to move through. Sand habitats may be subject to considerable transport in high energy areas, so that biotic community types and stability are directly related to the frequency and type of high energy, remobilizing events.

Biotic factors in sand substrates include a high potential for bioturbation; tube-building polychaetes and amphipods are frequently found in these substrates. Sand substrates tend to

have a higher proportion of suspension feeders than deposit feeders, and epifaunal predators and scavengers are common. While some species that are found in the mixed silt/sand habitats may also be present in sand habitats, the strictly deposit-feeding species are typically absent or rare (Rhoads and Young, 1970).

2.2.3.1 Shallow (0-30 m) sand

In the SoG, sand substrates in depths <30 m range from being semi-protected to semi-exposed to wave and storm disrupted, and some bottom turbidity is possible. Sediment sources may be fluvial, along-shore or onshore/offshore. Predominantly sand substrates in low to moderate energy areas in the SoG typically include high numbers of deep burrowing bivalves, such as horse clams (Lauzier et al., 1998) butter clams, littleneck clams (Gillespie and Bourne, 1998). These species are common throughout BC and Alaska. Where clam populations are high, the surface sediments are commonly littered with shell debris resulting from predation. The surface of the sediments in shallow sand habitats may be dominated by sand dollars, sea pens or surface bivalves such as *Tellina* spp. (Burd, 1992). Mobile predators such as small to mid-size crabs, sea stars and drills, are common. Grazers such as small and large gastropods (such as *Gastropteron* sp.) may be present. Epibenthic amphipods can be highly concentrated, scavenging in areas of detrit. Polychaetes are common in sandy substrates, but tend to be dominated by mobile forms, which may be predators or suspension feeders. Palsson et al. (2003) note that Dungeness crab were most abundant in this depth range in the Washington State SoG (southernmost part) during the 2001 transboundary trawl survey, although they were not surveyed in this depth range in the SoG. However, there is an active crab fishery in the sandy sediments east of Vancouver Island within the southern Gulf Islands. Filamentous red and green macroalgae occur in undisturbed

sediments and foliose red algae may be found, drifting, in the deeper areas in this habitat. In more exposed areas (or where herbivorous predators such as sea urchins are abundant), encrusting coralline algae may predominate. Eelgrass beds occur in clean water, relatively low energy (i.e. sheltered) areas in these sand habitats. While the epiphytic fauna in eelgrass beds in this habitat may be similar to that found in the shallow silt/sand habitat, the infaunal communities will be composed primarily of suspension feeders rather than deposit feeders. In the deeper areas of this habitat, in specific and spatially limited patches, deep burrowing geoduck populations may be present.

An example of the shallow sandy habitat is found in Boundary Bay, which is a typical sand beach in the southern SoG (Fig. 1). Burd et al. (1987) identified 200 taxa as part of a study on the distribution and abundance of macrofauna in Boundary Bay. Most of the shallow, sand substrate stations were dominated numerically by nematodes plus several species of bivalves, amphipods and echinoderms. Polychaetes were less prominent than the aforementioned taxa. The authors note that their study illustrates the spatial heterogeneity of shallow subtidal benthic communities. Cluster analysis of the abundance data showed considerable dissimilarity between and within sand stations, particularly when compared with similar analyses for deep water benthic communities in BC (Brinkhurst, 1987). Using visual counts of specific large macrofauna along transects in Boundary Bay, Swinbanks and Murray (1981) concluded that in predominately sand substrates, tidal exposure was an important factor delineating communities. Burd et al. (1987) suggest that the spatially and seasonally patchy distribution of eelgrass in Boundary Bay (Swinbanks and Murray, 1981) is a potential factor related to the distribution patterns of species.

Another example of a relatively unimpacted shallow sandy habitat was studied on the western margin of the Strait, just north of Saanich Inlet (Boatswain Bank). This location was discussed earlier (under shallow silt/sand habitats; section 2.2.2.1), and included both habitat types along an on-shore/offshore gradient, with sandy substrates in the shallower subtidal region.. Epifaunal biota and macroalgae (Seacology et al., 2001) and infauna (Burd and Glaholt, 2000) were surveyed along several transects perpendicular to shore at the proposed SoG crossing pipeline landfall site. Eelgrass beds and other macroalgae were mapped more extensively in the area by video survey (Archipelago Marine Research Ltd., 2000). The sandy stations were all found at less than 10 m depth, below a typical cobble intertidal beach, and were dominated by infaunal bivalves and crustaceans, along with polychaetes and a few echinoderms within patchy eelgrass beds. The authors noted that juvenile fauna were numerous, which would be consistent with the concept that eel-grass beds are important nursery grounds for many types of fauna (Archipelago Marine Research Ltd., 2000).

2.2.3.1 Mid-depth (30-100 m) sand

Mid-depth sand habitats in the SoG are subject to a variety of wave exposures, are often affected by currents or swells and may be influenced by large storm events. Bottom turbidity is usually low in these sand substrates, however, because these sediments are heavy and settle quickly. The biota found include burrowing bivalves that may be smaller, on average, than those found in the shallower sand habitats. Burrowing polychaetes and mat-forming tubicolous polychaetes occur in mid-depth sand habitats, as do ophiuroids, although these are found in lower abundance than in finer grained habitats (Burd et al., 2000a; McPherson et al., 2007a). Crustacean fauna are an important component in these habitats and depths, including Dungeness crabs (Palsson et al.,

2003). Sea pens and sea whips are found in higher current areas (Burd, unpublished data) and some attached forms of invertebrates (e.g. hydroids) occur on larger fauna and debris (V. Macdonald, pers. comm. Biologica Environmental Services Ltd, Victoria, BC).

The mid-depth sandy habitat type example from the SoG is the Ecological Reserve 67, located in Satellite Channel. Although an Ecological Reserve, this area was neither regulated nor subject to enforcement until several years ago. However, the only major impact on the area has been bottom trawling and, despite the known biotic changes that can occur in areas of concentrated bottom trawling (Engel and Kvitek, 1998; and see Conservation Biology issue 12: Vol. 6, 1998), a reconnaissance survey in 2000 for the proposed GSX pipeline suggested that the benthic biota are typically diverse and abundant compared with other areas of the SoG (Burd et al., 2000a; Burd et al., in press). Fauna in the reserve are dominated by bivalves and a mixture of mobile and non-mobile polychaetes (epibenthic and burrowing, free-living and tube-dwelling); the latter group may have comparable or lower abundances than the bivalves. The fauna also includes abundant crustaceans but relatively few gastropods. Echinoderms are rare which may be because large, mobile organisms with patchy distribution are not readily sampled using the methodology (grabs) of the studies cited here or, alternatively, the low abundance may reflect the adverse effects of bottom trawling. Older studies of the same area suggest that echinoderms were more common in the late 1960s (Ellis, 1970; 1971), before bottom trawling was frequent in this area. Ophiuroids also are relatively rare, which may be related either to the non-selective deposit-feeding habits of these animals and the lower organic content of sediments or, again, to the damage caused to these near-surface fauna by bottom trawling. Mats of tube-dwelling polychaetes *Galathowenia oculata* and *Owenia fusiformis* were abundant in the Satellite Channel

area in the late 1960s (Ellis, 1970, 1971), but were not abundant in 2000 (Burd et al., 2000a). Bottom trawling is likely to cause disruption of tube mat structures on the sediment surface. Largely because mid-depth sand habitats typically have moderate sediment oxygen levels and low turbidity, hydroids are found attached to shelled organisms on or just below the surface (Burd et al. 2000a), and may be an important component of the filter feeding biota of these habitats.

During the 2001 PICES Burrard Inlet workshop, fauna were sampled from a mid-depth sand habitat reference station outside the sill of Howe Sound (PICES, 2001; Je et al., 2003). Results using similar sampling methods showed species richness at this station was similar to that of samples from the ER67 Satellite Channel stations (Burd et al., 2000a; Je et al., 2003). Faunal abundance, however, was much higher in the Satellite Channel samples, as there were fewer bivalves present in the Howe Sound location. Polychaetes, rather than bivalves, were dominant at the Howe Sound location. A range of epifaunal types (8 taxa) are listed in Bernard (1978) to occur at depths of 20-100 m in sandy areas sampled in the SoG.

2.2.3.1 Deep (>100 m) sand

Deep sand habitats only occur, typically, in moderate to high current (erosional) areas. In low current areas, the deposition of fine marine detritus would cover the sands eventually. The epibenthic list of Bernard (1978) includes 4 taxa for the 100-200 m depth range but only one polychaete (*Pectinaria californiensis*) is listed for the 200-300 m depth range and one scaphopod (*Dentalium rectius*) for the 300-400 m depth range. Although no other data or studies are available from such habitat types in the SoG, these sand habitats may occur in deep water in

isolated areas near the southern Gulf Islands or in the northern half of the SoG (Fig. 3). Information on the biotic communities in these habitats outside the SoG, specifically in Hecate Strait and la Perouse Bank, is available in Burd and Brinkhurst (1987) and Brinkhurst (1987), respectively.

2.2.4 Cobble, Gravel and Coarse Sand Habitats

Cobble, gravel and coarse sand habitats are usually found in moderate to high energy locations. This substrate can also occur, however, where there are coarse glacial deposits in lower energy locations with no source of finer glacial or freshwater-derived inorganic particulates (finer sands). These substrates can be both mobile and immobile. For example, constant deposition of substrate material from a major land-based source would probably lead to unstable deposits subtidally, particularly on slopes. In stable habitats, however, these substrate materials tend to be heavy and can only be moved by high energy waves or storm events, particularly in shallow subtidal areas. Similarly, the coarse materials are a difficult substrate for the burrowing activities of bivalves and other fauna and, as a result, bioturbation may be limited. Because the substrate materials in these habitats are so coarse, sediments tend to be well-flushed and oxygenated. The benthic fauna are dominated by suspension feeders and mobile predators, particularly in high current areas. Cobble substrates in particular are likely to have fauna similar to rocky substrates (Section 2.2.5).

Bernard (1978) includes a few dominant epifauna from these habitats at various depths, but the epifauna list is short relative to that for soft substrates due perhaps to the difficulties in sampling

this habitat type. These habitats can be viewed as “intermediate”, as they are neither soft enough for effective grab samples to be taken nor flat and smooth enough for visual transect surveys. Much of the fauna is interstitial (ie. living between sediment particles) and there is no efficient way to sample them. Similarly, while trawls may collect some epibenthic forms, both the nets and the captured biota are prone to damage by cobble and gravel substrates. Bottom sampling is further hampered by the fact that these habitats are usually very high current areas. Hence, there is very little information about these habitats in the SoG, and none of the information available is quantitative.

2.2.4.1 Shallow (0-30 m) cobble, gravel and coarse sand

In shallow depths in the SoG, these coarse substrates are found most often on high energy or exposed to semi-protected areas, extending from the intertidal to the shallow subtidal. An example of such a habitat is given in Seacology et al. (2001) and Burd and Glaholt (2000), but it is noted in both studies that the cobble or gravel does not extend very far below the intertidal, and tends to occur in patches along with coarse sand. These habitats are usually non-depositional but may be influenced by seasonal onshore/offshore movement of material due to storm events and strong currents. In addition, periodic storms may lead to patches of storm or tidal debris (organic and inorganic) which are usually transitory. If these shallow habitats are not too high energy, seasonal macroalgae such as the brown algae *Laminaria*, *Costaria* and *Desmarestia* may be dense along with patches of bull kelp (Seacology et al., 2001) along with epifaunal grazers. A variety of mobile epifauna are found in these habitats, including amphipods, sea stars, nudibranchs, gastropods, echinoids and large mobile polychaetes, shrimp and crabs, and is also noted to be a nursery habitat for juvenile Pacific cod. Sessile invertebrates attached to the larger

substrate particles include bryozoans, hydrozoans, small sponges and anemones. If the sand content is high, deep burrowing bivalves may occur. However, in larger particle mixes (gravel, small cobble), near-surface bivalves may be common, and shell debris extensive. Coarse, unconsolidated habitats, if stable, can have extensive macroalgal growth seasonally, with all the associated grazing, epiphytic and epifaunal biota associated with it. Typically, this may include extensive bryozoan (in shallow, near-subtidal) and hydrozoan growth, shrimp, crabs, amphipods and other crustaceans, nudibranchs, gastropods, sea-stars and sea-urchins, with anemones, small sponges and tunicates attached to larger, stable debris. One common bivalve which can be seen “walking” through coarse sands is *Tellina* sp., which can be found intertidally to subtidally in Hecate Strait and throughout southern Alaska, BC and Washington State. Other, larger echinoderms may be present in coarser debris, such as the sea-cucumber *Parastichopus* sp.

2.2.4.2 Mid-depth (30-100 m) cobble, gravel and coarse sand

Cobble, gravel, and coarse sand habitats below 30 m water depth are rare in the SoG, with the exception of very high energy environments such as tidal channels, on fjord sills, and high current areas. Because of the size of the substrate particles, these habitats are relatively physically stable, although they may be mobile in rare, large storm events. Suspended particles may be extensive, given the high energy nature of these habitats. Generally, the faunal community in these habitats includes mobile epifauna (e.g. sea stars, nudibranchs, gastropods, amphipods), as well as ‘surface film’ grazers and attached forms (e.g. hydroids, small sponges, anemones) on the larger sediment particles (see Farrow et al., 1983).

An example of mid-depth coarse habitats is the sill of Knight Inlet, which is located immediately north of the SoG. The Knight Inlet sill is also a tidal channel, with coarse sand, gravel and large boulders which can be moved by the strong tidal currents (see Farrow et al., 1983). Tunnicliffe and Syvitski (1983) describe how large gorgonian corals attached to boulders provide “windage” which contributes to the transport of boulders in this area. The authors found that these rare habitats may contain typical rock cliff epifauna occurring in patches but, unlike cliff fauna, the forms are usually encrusting which may be related to the potential physical damage caused by the moving boulders and high currents. The distribution of the large planktivorous corals was patchy but the organisms were most concentrated on the sill crest, where the zooplankton were visually dense (Tunnicliffe and Syvitski, 1983). The level of heterogeneity within this type of habitat will determine the abundance of small mobile fauna that like to hide, such as shrimp and small crabs.

Although the extensive outfall monitoring program in outer Burrard Inlet focused on soft substrate, video assessment of the nearfield substrate revealed the presence of cobble, gravel and coarse sand substrate (CORI, 2002). Flocculant levels were high in the water column, reducing visibility. However, large concentrations of the anemone *Metridium senile* suggested opportunistic utilization of the suspended organic material (CORI, 2002). Visual surveys by the Victoria Capital Regional District describe the 40-60 m depth range off southern Victoria near Clover Point (just outside the SoG, in Juan de Fuca Strait) as cobble-gravel, with extensive horse mussel and scallop growth (Capital Regional District, 2000). Bernard (1978) listed 2 bivalve species, (*Glycymeris subobsoleta* and *Mysella tumida*) sampled by trawl from gravel substrates and 6 different species found in rock/cobble substrates.

2.2.4.3 Deep (>100 m) cobble, gravel and coarse sand

These coarse grained habitats seem to be rare in the deeper parts of the SoG (Fig. 3). It is likely that these habitats are limited to the few deep, strong tidal channels in the SoG at the north and south end (Section 1.2) and to areas where debris resulting from cliff erosion has settled at the foot of steep slopes. These areas have been observed, occasionally, using a submersible (Burd, unpublished data) and, although most fish farms in BC are located outside the SoG, information on these habitats under fish farms in the fjords of the SoG may also be archived in ROV video footage maintained by the provincial Ministry of Environment.

There is very limited information about these coarse habitats and associated biota in depths >100 m within the SoG. However, it is expected that the faunal communities would be of similar composition to those described earlier for the mid-depth coarse habitat. The only caveat is that at these depths, it is likely that organic flux to the bottom is reduced, so that there may not be as much labile organic suspended material available for bottom organisms. Bernard (1978) describes invertebrate epifauna from trawls conducted at 100-200 m depths in gravel habitat type and lists the same two species found in the 20-100 gravel substrates, the bivalve *Glycymeris subosoleta* and the crustacean *Munida quadrispina*. The author lists no species for sampling conducted in gravel substrates >200 m. Invertebrate species were more abundant in the rock/cobbles substrate than in the gravel substrate, but only the cloud sponge *Aphrocallistes vastus*, was reported from the rock/cobbles substrate type at >200 m depths. As noted earlier,

archived information on videos from deep ROV work related to fish farms may be one of the best sources of epifaunal data available.

2.2.5 Rock (consolidated) Habitat

In exposed coastal areas, these substrates are subject to very high wind and wave exposure and/or tidal currents, preventing any deposition. However, in isolated basins such as fjords, the steep sides prevent accumulation from sedimentation regardless of current conditions. Some island archipelagos, with no freshwater or nearby glacial deposits, can retain rocky substrates in lower energy habitats. Although high levels of suspended organic particles occur, depending of the current regime and organic input, organic flux to the sediments is virtually nil.

Rocky habitats are abundant in the SoG and Levings et al. (1983) note that rocky and sandy shores combined make up 88% of the total length of the shoreline (shoreline consists of the intertidal and subtidal habitats ≤ 20 m), while the area of rocky substrate accounts for ~25% of the total area (see Section 1.3.1). Many of the SoG's mainland fjords have extensive, near-vertical rocky cliffs, limiting the fauna to those that can attach to vertical rock and that can tolerate sediment deposition. These rock wall communities are dominated by sessile filter feeding invertebrates or mobile scavengers and predators. Tidal currents in these habitats are usually low due to the near-vertical walls which don't "channel" or intensify tidal surges.

2.2.5.1 Shallow (0-30 m) rock (consolidated)

1607

1608 The diversity and coverage of rocky shoreline communities is dependant on exposure to waves,
 1609 freshwater, salinity, light and currents and is, therefore, seasonally variable. The presence of
 1610 crevices or heterogeneous structure for hiding and attachment also affects both the plants and
 1611 invertebrates found in these shallow rock habitats. The bottom water in these habitats is usually
 1612 highly oxygenated. If there is a rich supply of suspended particulate material, these areas can be
 1613 ~100% covered by sessile invertebrates and plant growth. Seasonal macroalgal cover of
 1614 filamentous and bladed red, green and brown algae is extensive in the upper photic zone, with
 1615 foliose reds commoner in slightly deeper areas (i.e. >10 m).

1616

1617 The fauna found in these habitats, both sessile and mobile forms, tends to be relatively consistent
 1618 throughout the BC coast. The diverse fauna in these habitats includes bivalves, calcareous tube
 1619 worms, ascidians, bryozoans, hydrozoans, small sponges, as well as echinoderms and
 1620 crustaceans. Because these rocky habitats have been so well described by scuba surveys at these
 1621 shallow depths, the flora and fauna are not described in detail herein (e.g.
 1622 http://ilmbwww.gov.bc.ca/lup/coastal/north_island/cortes/docs/2-description.pdf; Levings et al.,
 1623 1983 and references therein). An example of a shallow rock habitat just outside the SoG is Race
 1624 Rocks, near Sooke, BC. Race Rocks, a tidally-exposed rocky outcrop in a “clean” environment
 1625 which has been well studied using SCUBA. The area has a remarkably rich and diverse flora and
 1626 fauna (see Wright and Pringle, 2001 for references) and is a federal marine protected area. The
 1627 invertebrate fauna tolerates strong currents and high wave exposure and includes abundant
 1628 barnacles, goose-neck barnacles, and mussels, as well as a variety of anemone species, surface-
 1629 grazing gastropods, mobile predators such as sea-stars, nudibranchs, crabs and gastropods.

1630
 1631 Shallow rock habitats may be structurally heterogeneous as a result of algal growth and also
 1632 from faunal communities such as mussel beds. Up to 300 species have been identified inhabiting
 1633 the interstices of established mussel beds (Seed and Suchanek, 1972; Suchanek, 1979) and
 1634 species richness has been shown to increase with increasing age and thickness of the mussel bed
 1635 (Asmus, 1987; Jamieson et al., 1999; Ragnarsson and Raffaelli, 1999; Smith et al., 2006).

1636
 1637 In the deeper, high current areas of shallow rock habitats, bull kelp can form dense forests which
 1638 modify currents and light penetration and provide important refugia for fish, as well as food for
 1639 sea urchins and other grazers. Sea urchins are known to be a key species which controls and
 1640 modifies algal community associations in near-shore rocky habitats on the west coast of North
 1641 America (Paine and Vadas, 1969; Duggins, 1981). Abalone may play a similar role but tend to
 1642 be less widely distributed in BC coastal waters than are sea urchins due to excessive fishing
 1643 pressure over the years (http://www.dfo-mpo.gc.ca/species-especes/species/species/northernAbalone_e.asp).

1645 1646 **2.2.5.2 Mid-depth (30-100 m) rock (consolidated)**

1647
 1648 Mid-depth rock habitats in the SoG typically have moderate to steep slopes; accumulation of
 1649 deposited material is unlikely to occur on steep slopes but pockets of deposition may occur on
 1650 lesser slopes. These habitats are exposed to limited, or no, wave exposure, while levels of tidal
 1651 currents vary. Bottom water renewal, and therefore bottom water oxygenation, in these habitats

in the SoG is variable and depends on the physical topography and, in fjords, also depends on the depth of the sill.

Because these habitats can only be studied using ROVs or submersibles, they are, therefore, less well studied than soft substrate habitats at comparable depths. The majority of this research in the SoG was conducted in the early 1980s, when the research submersible PICES IV was available through the Canadian Department of Fisheries and Oceans. Much of this research is published (e.g. Tunnicliffe, 1981; Levings et al., 1983; Tunnicliffe and Wilson, 1988) and additional, unpublished information is archived in video or still photographic form (Tunnicliffe, unpublished; Burd, unpublished). The following general descriptions of the faunal communities in the mid-depth rock habitats of the SoG are based on both sources of data.

The spatial cover by invertebrates in the mid-depth rock habitats does not vary as much seasonally as it does in shallow subtidal areas. However, there may still be some encrusting coralline algae present at the shallow end of this depth range, depending on light penetration (e.g. Farrow et al., 1983; Spalding et al., 2003). Rather, the spatial cover by invertebrates declines with increasing depth and decreasing oxygen levels in the water. Examples of the mid-depth rock habitat are the rock cliff walls of fjords in the SoG. These mid-depth habitats contain a number of species, such as eel-pouts, that are more common in the deep sea. Similarly, sea fans (gorgonians, soft corals) are common on the walls of some of the SoG inlets (Tunnicliffe, 1981; Tunnicliffe and Wilson, 1988) but are also found when sampling in the deep water off the continental shelf. Huge glass sponges, normally associated with polar or deep seas, are also common in mid-depth rock habitat in the SoG fjords (Tunnicliffe, 1981; Burd, PICES IV–

unpublished data). Tunnicliffe (1981) describes tube worms, sponges, brachiopods, cup corals, extensive gorgonian sea fans, anemones and colonial tunicates as some of the dominant sessile organisms on the vertical rock walls. Some of the larger sponge and erect coral growths are expected to be very old, as these habitats are typically less susceptible to physical damage than are level bottom habitats.

Tunnicliffe and Wilson (1988) describe the distributions of 3 species of brachiopods from Knight, Jervis and Saanich inlets; brachiopods are a ubiquitous group reaching extremely high densities (average density of $190/\text{m}^2$, maximum density of $945/\text{m}^2$) at depths >30 m on the cliff walls of the fjords. Depth ranges were noted for each species of brachiopod. All brachiopod species seem to be relatively tolerant of low oxygen and a species in Saanich Inlet was found to be highly tolerant of periodic low oxygen levels down to 0.1 ml/L. Another brachiopod species from Saanich Inlet was found in abundance in high energy and/or high suspended sediment conditions. Thus, brachiopods are an important structural component of mid-depth cliff faunas and may be good indicators of sedimentary conditions. In contrast to brachiopods, bivalves are almost absent on the vertical cliff walls, suggesting that they do not settle on vertical surfaces. In addition, as a group they do not seem to be particularly tolerant of low oxygen (see also Burd, 2006).

Several mobile crustaceans are common on, or near, the rocky cliff walls of the fjords at mid-depth. These areas encompass the prevailing prawn fishery habitats, as the larger pandalid species tend to be abundant in the rocky crevices and on larger, upright epibenthos. Predatory crabs are less common in this depth range than in the shallow rocky cliff areas, (Burd, unpublished), however, a small anomuran crab (*Munida quadrispina*), with feeding and habitat

requirements similar to prawns co-exists with the prawns on the cliffs (Burd and Brinkhurst 1984). Examination of prawn catches and habits of prawn fishermen in a series of coastal fjords in the SoG in 1983/84 (Burd, unpublished) made it clear that when *M. quadrispina* were dominant, this necessitated a change in the location for setting traps.

Saanich Inlet and Howe Sound, as noted earlier, can experience severe annual stagnation and this can lead to mass mortalities of sedentary cliff fauna (Tunncliffe, 1981) as well as mobile forms such as prawns and *Munida quadrispina* (Burd and Brinkhurst, 1984; Jamieson, 1988). Tunncliffe (1981) described a high biodiversity in the mid-water cliff assemblage of Saanich Inlet, however, despite annual low oxygen, *M. quadrispina* is usually far more abundant in extreme habitats, such as the very low oxygen areas (~0.1ml/L) in Saanich Inlet (Burd and Brinkhurst, 1984) than in areas with higher oxygen levels. The higher abundance (and lack of normal territorial and hiding behaviour) of the crabs has been speculated to be related to a lack of predators in these extreme habitats (Burd and Brinkhurst 1984), whereas the tolerance of very low oxygen areas is due to unusual respiratory and gill adaptations (Burd, 1985, 1988). In addition, the pelagic amphipod *Orchomene obtusens* is found in extremely high numbers on, or near, the rocky cliffs in hypoxic to anoxic conditions in Saanich Inlet (De Robertis et al., 2001), where it is extremely efficient at consuming any detrital animal tissue used as bait in traps (Burd, unpublished data).

Farrow et al. (1983) describe the fauna of the cliff walls in Knight Inlet along vertical cliff transects which include the mid-depth zone. The along-inlet differences in faunal structure were compared with a suspended particulate gradient which typifies the faunal changes that are likely

to occur in areas of high, moderate, and low bottom turbidity from glacial runoff. In the high turbidity areas, the authors describe the dominant suspension feeders as sabellid worms and brachiopods (see also Tunnicliffe and Wilson, 1988) which take small particles ($<8 \mu\text{m}$). Crinoids and gorgonian corals are more prevalent in the moderate turbidity areas and take larger particles, while barnacles and glass sponges predominant where turbidity is low. In general, the turbidity, oxygen and organic carbon content of suspended particulates within these habitats play a significant role in determining which species will dominate. For example, brachiopods are tolerant of relatively low oxygen conditions and can also tolerate relatively high turbidity. Passive feeders, such as sponges, require some current movement for adequate feeding, but may be tolerant of low oxygen (e.g. Tunnicliffe, 1981), and are usually found in deeper regions in more quiescent waters (Tunnicliffe, 1981; Farrow et al., 1983) with limited sediment deposition (Farrow et al., 1983 and see below).

A bottom hexactinellid sponge reef has been recently discovered at an unprecedented shallow depth of about 60 m near the sill of Howe Sound (see Cook et al., in press). Most of these reefs in the Strait are deeper than 120 m, making this location unusual. This reef has not been visually surveyed yet. A description of other, deeper reefs in the Strait is given in the next section.

2.2.5.3 Deep (>100 m) rock (consolidated)

While deep subtidal rock habitats in the main basin of the Strait of the Georgia are mostly confined to elevated rocky outcrops on the bottom of the basin (evident in detailed multibeam and side-scan sonar transects e.g. Conway et al., 2007), these habitats are often dominant in

many of the steep-sided fjords. Many of the SoG fjords are much deeper (up to 800 m) than the adjoining continental shelf (<400 m deep), with extensive rock cliffs. The same limitations for studying the mid-depth rock habitats, discussed earlier, apply to these much deeper habitats.

In deep rock habitats that are “flushed”, bottom currents are generally low to moderate. Bottom water oxygen is likely to be moderate. Spatial cover of sessile invertebrates on these “flushed” rock substrates is moderate to low, declining with increasing depth and decreasing oxygen levels and is also related to current levels. The faunal composition does not necessarily change significantly from that described for mid-depth rock habitats except that, as suspended organic material and oxygen levels decline with increasing depth, spatial coverage may decrease and some organisms or trophic forms may decline while other, more tolerant forms increase. For example, as noted earlier, prawns decline with increasing depth and anemones such as *Metridium senile* are not found below 80-100 m (Tunncliffe, 1981; Burd, unpublished data). The faunal community may include calcareous tube worms, brachiopods, ascideans, hydrozoans, small sponges, boot and cloud sponges, gorgonian and small corals, large plumose anemones and tunicates.

It should be noted that deep rock habitats in the SoG are also found on the walls of isolated fjords in stagnant basins. The water column in the deep rock habitats in the fjords may flush seasonally or only occasionally. Generally, the rock may be too steep for sediment accumulation but small pockets of organic material may accumulate in crevices and become suboxic or anoxic with filamentous bacterial mats. In these low current areas, the rock is usually minimally colonized with numerous areas of bare rock. As mentioned for mid-depth rocky areas, the fauna

in these deep stagnant areas may include small anemones, encrusting sponges and brachiopods, as well as specialized mobile predators (e.g. amphipods, *M. quadrispina*) (Burd and Brinkhurst, 1984).

An interesting example of the deep, rocky habitat is the relatively recently discovered deep rocky outcrops or reefs in the SoG that are covered in hexactinellid sponges (predominantly *Heterochone calyx* and *Aphrocallistes vastus*) or in a few cases, scleractinian coral reefs (*Lophelia pertusa*) (Conway et al., 2007). There are nine confirmed glass sponge reef complexes in what Thomson (1998) describes as the central Georgia Basin (Fig. 1). Each of these sites has been surveyed using multibeam acoustics and ground truthed using remote video techniques by the Geological Survey of Canada. There are a further 3 sponge reefs which have been located by multibeam and seismic surveys but which have not yet been visually examined using video (Conway et al., 2007). Of the nine reefs which have been visually surveyed, only three are in good health, with consistent areas of live reef-building sponges (Cook et al., in press). The three healthy reefs are located on rock pinnacles well above the surrounding seafloor, where bottom trawling is not feasible. The other six appear to have suffered extensive mechanical damage resulting in large areas of fragmented sponge skeleton, with 3 reefs showing some evidence of re-growth. (Cook et al., in press).). Conway et al. (2007) concluded that there has been considerable damage to the reefs in the SoG from trawling and possibly from ocean dumping and increased siltation in the southern areas. There is a marked difference in terms of abundance and diversity of rockfish on the healthy and damaged reefs, illustrating that these are likely important refugia for deep reef fish. An ecological description of these reefs is in Cook et al. (in press), including the current state of their health and faunal associations.

It is well documented that hexactinellid sponge communities, such as those found in deep rock habitats in the SoG, modify the environment around them. Bathyal environments in particular are enriched by enhanced supplies of organic matter associated with sponges and their spicule mats (Bett and Rice, 1992). In the Antarctic, Barthel, (1992) documented species-rich associations of sponges in areas of sponge spicule mats. These reefs trap fine sediments and provide habitat for annelid worms, bryozoans, bivalves, gastropods, rockfish, crabs, shrimp, prawns, sea stars, sea urchins and ophiuroids. In other areas of the world, hexactinellid sponges provide habitats for new and rare species, including numerous species of shrimps in the Bahamas (Berggren, 1993), Hawaii (Baba, 1983), New Zealand and South Africa (Bruce and Baba, 1973), and in the East China Sea (Hayashi and Ogawa, 1987). Their locally limited distribution and potential biological importance as refugia in the SoG warrant protection (Conway, 1999; Conway et al., 2001; Krautter et al., 2001).

Underwater cables provide hard substrate in deep water, albeit of anthropogenic origin. Levings and McDaniel (1974) describe encrusting macro-invertebrates collected off a deep-water telephone cable across the main basin of the SoG. This habitat appears to be a “refugia” containing fauna that are found on the steep rocky cliffs of the surrounding basin shoreline. The authors note that most of the deeper, hard-substrate species such as sponges, brachiopods and gorgonian corals were not present on the cables on the eastern side of the SoG (Point Grey), probably due to heavy sedimentation from the Fraser River. Even in these high sedimentation areas, however, several anemones, such as the ubiquitous and relatively tolerant *Metridium senile*, were found on the cables.

3. Anthropogenic Influences

Section 2 reviewed invertebrate communities likely to occur in a variety of undisturbed habitats (different depths and substrates) within the SoG. In this section, changes to habitats and invertebrate fauna found in areas of anthropogenic influence are examined and placed within the context of background biotic conditions in the SoG. Following a brief summary of anthropogenic sources and recognized influences of the type of major sources in the SoG, additional detail is provided on each source including case studies where appropriate. It should be noted that while input from some anthropogenic sources may affect intertidal or shallow subtidal areas, most of the major discharges into the SoG are deeper than the shallow subtidal (i.e. >30 m) and, consequently, habitats monitored for anthropogenic change also tend to be >30 m depth (mid- to deep subtidal).

The primary sources of anthropogenic influence in the SoG are municipal waste water outfalls (marine and along the Fraser River), ocean dumping sites (dredged material primarily from Burrard Inlet and terminal areas along the eastern margin of the southern Strait), pulp and paper mills, as well as runoff and discharges from agriculture and other industries along the Fraser River and Burrard Inlet. Localized sources of anthropogenic influence to marine habitats within the SoG include a small number of fish farms in several mainland fjords, log-booms, marinas, loading docks for industry, and stream runoff. While a large number of beach and near-shore shellfish aquaculture sites are located in the SoG, research into the potential impacts of these farms on benthic habitats and invertebrate community structure started only recently (e.g. Carswell et al., 2006) and, hence, the potential impact of these farms is largely unknown.

1836 Although the biotic effects of these localized small inputs can be varied and difficult to
1837 encapsulate, available studies on these inputs are summarized briefly in this review (and see
1838 Levings et al., 1983).

1839 Although the majority of the anthropogenic influences in the SoG include an organic enrichment
1840 component, virtually all of these influences also include some level of sediment contaminants
1841 which can make it difficult to determine causality. A huge literature on sediment and pore-water
1842 toxicity, much of it laboratory-based, illustrates the on-going struggle with these issues in the
1843 scientific community (Wang and Chapman, 1999; Burgess, 2000; Long et al., 2001). Burrard
1844 Inlet, the major harbour for Vancouver, provides an example of a body of water in the SoG that
1845 is subject to numerous sources of anthropogenic input. The proceedings of an international,
1846 cooperative research workshop in Burrard Inlet (Stehr and Horiguchi, 2001) include a summary
1847 of the discharges and contaminant sources in the inlet (Levings and Samis, 2001). This inlet
1848 receives the discharge from a major primary-treatment municipal wastewater outfall, about 32
1849 combined sewer overflows (CSOs) (GVRD, 2004), and 36 permitted industrial or municipal
1850 discharges (Levings et al., 2004). Several of the more isolated sections (or arms) of Burrard Inlet
1851 are considered to be severely chemically polluted by hydrocarbons (Yunker et al., 1999) and
1852 organically enriched (Burd and Brinkhurst, 1990). The multitude of discharges, along with
1853 complex hydrographic conditions, has made the design of monitoring programs for specific
1854 discharges in the Inlet challenging (c.f. McPherson et al., 2007b). Similarly, Howe Sound has
1855 been subject, historically, to notable industrial inputs including a chlor-alkali plant (mercury
1856 discharge) and a copper mine with contaminated tailings and acid drainage issues which are still
1857 evident many years after cessation of operations (Hagan et al., 2004). Contaminant inputs and

1858 transport from these sources were reviewed by Macdonald and Crecelius (1994), West et al.
1859 (1994) and see Johannessen et al. (in press).

1860 Despite the confounding influences described above, however, certain patterns of benthic faunal
1861 response seem to be common to all organic enrichment inputs in British Columbia regardless of
1862 contaminant input (Cross, 1990; Burd, 1997; Brooks, 2001; Burd 2003a,b,c; Cross et al. 2005;
1863 Golder Associates Ltd., 2005; Burd, 2006; McPherson et al., 2007a, b; EEM monitoring data
1864 www.ec.gc.ca/eem/english/PulpPaper/default.cfm;).

1865 Biotic responses in marine sediments to conditions resulting from extreme organic loading have
1866 been described by Pearson and Rosenberg (1978). Based on this model, when sulphides are high
1867 and/or sediments are anoxic to depth, most fauna disappear. When these sediment conditions
1868 occur, white fibrous mats of sulphur-fixing bacteria (e.g. *Beggiatoa* spp.) may become extensive
1869 on the seafloor. In addition to high sulphides, however, the bacteria need oxygen from the
1870 overlying water for metabolism and, therefore, these mats occur only at the oxidation-reduction
1871 (redox) boundary (Møller et al., 1985), making them a good indicator of underlying anoxic
1872 sediments or, in rocky areas, of an anoxic near-bottom boundary layer. In fact, the presence and
1873 extent of *Beggiatoa* mats is used as a monitoring indicator of benthic condition for fish farms in
1874 BC (MWLAP, 2002). The few organisms that can survive, or sometimes even thrive, in these
1875 conditions include certain mobile epibenthic forms such as demersal amphipods and squat
1876 lobsters (Burd and Brinkhurst, 1984), as well as burrowing organisms that can maintain access to
1877 the oxygenated overlying water, some of which may have a high tolerance to sulphide (Brooks,
1878 2001). Despite these organisms, however, infaunal production is typically low in extreme
1879 environments due to loss of most of the macrofauna and energetic constraints on microfauna

utilizing energy resources without available oxygen (Emerson and Hedges, 2003). In rocky habitats, most fauna will disappear, with the possible exception of some tolerant cup corals (Tunnickliffe, 1981). Examples of benthic environments in the SoG where anthropogenic inputs causing these conditions may arise or have been recorded include municipal wastewater outfall receiving environments (Capital Regional District 2003; 2004; 2005 and www.crd.bc.ca/wastewater/marine/reports.htm; McPherson et al., 2007a, b); log boom areas (Conlan and Ellis, 1979; Sibert et al., 1979; Sibert and Harpham, 1979; McGreer et al., 1984), the close vicinity of some fish farms (Brooks, 2001; Burd, 2006; Wright et al., 2007a-e), and areas subject to pulp and paper mill effluent (www.ec.gc.ca/eem/english/PulpPaper/default.cfm). These extreme conditions can also occur naturally in stagnant fjord basins (e.g. Saanich Inlet, Section 1.2).

3.1 Marine Outfalls

Benthic sediment and biological monitoring for the marine receiving environments of the Metro Vancouver (formerly the Greater Vancouver Regional District GVRD) outfalls that discharge into the SoG (Iona and Lions Gate) also encompasses the marine discharge zones of the other three outfalls along the Fraser River (Annacis, Lulu Island and Langley - GVRD 2004). These monitoring programs have essentially provided the bulk of present-day information about benthic infauna and habitats along the southeastern margin of the SoG (see McPherson et al. 2007a, b). The Iona outfall monitoring grid is along the 80 m depth contour (Figure 1) straddling the mouths of the Fraser River. The Lion's Gate monitoring grid encompasses all of the outer Burrard Inlet to 1st Narrows (Figure 1).

1903 Harrison et al. (1999), reviewing the heavy metal and organic contamination along the foreshore
 1904 of the Fraser River, found that most of the contamination in this area came from heavy
 1905 deposition of Fraser River sediments which had run the gauntlet of contamination sources.
 1906 However, at the north end of the delta, there was a fairly large historical (1962-1988) wastewater
 1907 discharge in the near shore. Harrison et al. (1999) showed that in the area of historical
 1908 wastewater discharge (which also receives about 15% of the industrial and municipal wastes
 1909 from the Fraser River), there is evidence of long term recovery in terms of organic loading, as
 1910 well as primary and secondary production of the benthos. Two moderately abundant invertebrate
 1911 indicators, the amphipod *Corophium salmonis* and the bivalve *Macoma balthica*, were selected
 1912 for measurements of biomass/production and growth, and were used to demonstrate the recovery
 1913 from basically azoic conditions (i.e. no life) to background conditions typical for the area. The
 1914 historical wastewater discharge noted above was replaced in 1988 with the Iona deep-sea outfall,
 1915 with diffusers which discharge along the slope fronting the Fraser River discharges.
 1916
 1917 The deposition model of Hodgins and Hodgins (2000) for the Iona outfall effluent solids
 1918 suggests that maximum deposition of outfall particulates occurs between 60-90 m depth along a
 1919 primarily north and secondarily south gradient away from the outfall. This model provided the
 1920 basis for a revised monitoring program for the outfall from 2000 onward (2WE Consulting,
 1921 1999). The maximum deposition zone corresponds to clear patterns in sediment chemistry and
 1922 geochemistry, including moderate organic enrichment (Burd, 2003b). The long-term monitoring
 1923 data for Iona (see McPherson et al., 2007a) clearly show subtle changes in biotic conditions
 1924 within a 3 km zone north of the outfall, which corresponds to the maximum deposition zone for
 1925 outfall particulates (Hodgins and Hodgins, 2000). Within this same area, clearly related to the

outfall, there is low to moderate biotic impoverishment (GVRD, 2004) and a modest enhancement of polychaete species known to be opportunistic in areas of organic enrichment. These changes can be explained by increased organic loading alone, with no evidence of biotic effects related to contaminants (Burd, 2003b). Certain contaminant inputs from the outfall are discussed in more detail in Johannessen et al. (in press) and Macdonald et al. (in press). Surrounding the impoverished zone is a region with less deposition of particulates that has no notable biotic impoverishment and shows enrichment of some taxa. Echinoderms and crustaceans, the taxa which are most impoverished in the maximum deposition zone, tend to have enhanced abundance in this enrichment zone (Burd, 2003b; McPherson et al., 2007a).

To the south of the outfall, where no outfall particulates deposition can be detected, a range of background biotic conditions provides context for the changes found within the two “effect” zones. Interestingly, however, biotic impoverishment within this background area can be similar to, or greater than, that found in the maximum deposition zone. This impoverishment does not co-occur with organic enrichment, or any contaminant loading, but seems, rather, to be characteristic of on-going and patchy physical disturbance of the sediment surface (Burd, 2003b, McPherson et al., 2004b).

McPherson et al. (2007a) includes a time-scale comparison of biotic and geochemical conditions which clearly show that both have remained relatively stable throughout the Iona outfall monitoring region since 2000, including consistently low total organic carbon levels in sediments throughout the monitoring grid, along with modest geochemical buildup of sulphides in the maximum deposition zone. The reason for the uniformly low organic carbon levels is mostly the

1949 high loading of inorganic material from the south arm of the Fraser River, which tends to
 1950 continually bury the organic input, keeping the entire system in a relatively steady state.
 1951 However, rapid oxidation of carbon at this location (Wright et al., in press) from benthic
 1952 organisms may also contribute to the stable sediment conditions. In the maximum deposition
 1953 zone, infaunal biomass does not show any clear or consistent depression, but the community is
 1954 conspicuously devoid of echinoderms and infaunal amphipods (Burd, 2003b; McPherson et al.,
 1955 2007a).

1956

1957 In support of the monitoring program for the receiving environment of the Lions Gate
 1958 Wastewater Treatment Plant Outfall located at 1st Narrows (Fig. 1), the Greater Vancouver
 1959 Regional District has conducted annual biological monitoring in outer Burrard Inlet since 2002.
 1960 Prior to that, historical data from the Inlet had been collected by Environment Canada (c.f. Boyd
 1961 et al., 1998, and references therein) and the Department of Fisheries and Oceans (Burd and
 1962 Brinkhurst, 1990; Cross and Brinkhurst, 1991; Burd, 1992; Je et al., 2003). Although the earlier
 1963 work is not directly comparable to the GVRD monitoring due to differences in sampling
 1964 protocols, a comparative assessment of the historical biotic conditions and geochemical sediment
 1965 conditions of the outer Inlet was conducted by Burd (2004).

1966

1967 Both the deposition model of Hodgins et al. (2000) for the Lions Gate effluent solids and
 1968 analysis of cores taken in 2004 (Burd, 2004) suggest that some material from the outfall is
 1969 carried along the north shore of outer Burrard Inlet before settling offshore near the mouth of the
 1970 inlet (Fig. 1). The model predicts that the remaining material will go into the inlet, past 1st

1971 Narrows (Inner Burrard Inlet), under specific tidal conditions, although sediment sampling has
 1972 not confirmed this.

1973

1974 Unlike the receiving environment of the Iona Deep-Sea Outfall, where sediment chemistry and
 1975 biota clearly show identifiable changes which can be directly related to the deposition of
 1976 particulates from the outfall, no biotic changes which can be related to the discharge from the
 1977 Lions Gate Outfall have been detected (McPherson et al., 2007b). This is partially because the
 1978 outer Burrard Inlet is very well mixed and flushed (Thomson, 1981), and partially because there
 1979 are numerous sources of anthropogenic discharge into the water body which can cause
 1980 conflicting signals in sediment chemistry. Beyond First Narrows, the inner Inlet is particularly
 1981 prone to the conflicting signals due to the greater intensity and frequency of various urban and
 1982 industrial discharges than are found in the outer Inlet (GVRD, 2004). Sediment organic
 1983 enrichment accompanied by sporadic elevated levels of typical sewage indicators or tracers (i.e.
 1984 acid volatile sulphide, total organic carbon, sediment fecal coliforms, silver, 4-nonylphenol,
 1985 coprostanol) do occur along the north shore of the outer inlet (McPherson et al., 2007b), with
 1986 these effects decreasing with increasing distance offshore. Biotic changes in these areas have
 1987 been noted, but are minor (McPherson et al., 2007b).

1988

1989 One location in the Burrard Inlet monitoring program, beyond First Narrows (in the inner inlet),
 1990 has consistently shown more extreme organic enrichment and biotic impoverishment than any
 1991 location in the outer inlet. Despite this, sewage indicators (e.g., silver, 4-nonylphenol and
 1992 coprostanol) are not elevated, suggesting that sediment conditions are unlikely caused by the
 1993 Lions Gate Outfall. Instead, combined sewer overflows are a potential source of the organic

1994 enrichment which could be related to the biotic changes in the inner harbour (GVRD, 2004),
 1995 although multiple discharges in the area make it difficult to determine the source or sources.
 1996
 1997 A detailed analysis of sediment and outfall effluent metals data for 2002 and 2003 by Paine
 1998 (2003 q.v. GVRD, 2004) suggested that elevated levels of some metals in outer Burrard Inlet are
 1999 not likely related to the Lions Gate outfall, and are present at levels and in a form which should
 2000 be biologically unavailable. Other metals are present below levels expected to cause any
 2001 biological toxicity, based on Canadian Environmental Quality Guidelines (CCME, 1999).
 2002
 2003 Although technically not in the SoG, Victoria's Macaulay Point and Clover Point outfalls have
 2004 been extensively studied and the long-term data on the benthos provide important context for
 2005 similar habitats in the SoG. Also, despite the fact that the depth and current regime trap the
 2006 plumes, suggesting that material from these outfalls is not likely to enter the SoG, there are times
 2007 when the plumes have been known to surface so that any dissolved organics or contaminants in
 2008 the upper water layer could enter through Haro Strait and eventually find their way to sediments
 2009 in the SoG (Thomson, 1981) (also see Section 1.2). For that reason, information about the
 2010 benthos near these two outfall areas is covered briefly below.
 2011
 2012 Victoria's Macaulay Point is an area of sandy substrate and high current that receives only
 2013 screened (i.e. primary treatment) wastewater that is discharged at an approximate mean depth of
 2014 60-65 m. The Clover Point outfall in Victoria discharges at a similar depth but into a rocky,
 2015 cobble environment that is dominated by a horse mussel (*Tressus tapyx*) community (Capital
 2016 Regional District, 2000). Environmental monitoring of the benthic receiving environment at

both of these major Victoria outfalls has been conducted since the early 1970s (Balch et al., 1973; 1975), with a revision of methods and quality control initiated in 2000 (http://www.crd.bc.ca/es/environmental_programs/wastewater_marine/macaulay/reports.htm). Numerous reports have been prepared by consultants on the results of this monitoring, along with annual monitoring reports (Capital Regional District, 2003, 2004, 2005; Paine, Ledge and Associates, 2004), along with a recent review of the Liquid Waste Management Plan and seafloor triggers by Stubblefield et al. (2006). Burd (2003c) reviewed the 1994 to 2001 data on benthic infauna and sediment geochemistry from the Macaulay Point outfall area and reported that the monitoring data show some faunal effects, but severe biotic degradation is not occurring in the vicinity of this outfall. Although, based on the available data, it is impossible to determine what toxic contamination effects may be important to the fauna of the receiving environment, the patterns of faunal change relative to the outfall strongly suggest that sediment geochemical changes and particle size are the predominant factors affecting faunal composition (Burd, 2003c). The sampling stations are situated radially around the outfall along a spatial gradient to 800m distant, with diminishing biotic and geochemical impacts to this distance in the E and SE (Burd, 2003c).

The biotic monitoring at the Clover Point outfall consists entirely of growth and condition factors for the dominant species, horse mussels. The hard substrates in this environment do not lend themselves to sediment sampling. Historically, the mussels within 800 m of the outfall tend to show a declining gradient of enhanced growth compared with reference locations (www.crd.bc.ca/wastewater/marine/reports.htm).

3.2 Ocean Disposal Sites

There are 11 designated ocean disposal sites regulated by Environment Canada in the SoG. Locations and annual dumping volumes for these sites are available at the Environment Canada website (http://www.pyr.ec.gc.ca/disposal_at_sea/sitemap_e.htm). The site also contains links to monitoring reports for all the sites over time. A brief overview of ocean dumping in BC is given in Ellis (1982), but there is almost no biological monitoring data from dumpsites in the SoG, except for the Point Grey dumpsite. Side-scan mosaicing has been proposed as an efficient method of monitoring new debris accumulation and dispersal at ocean disposal sites (Mosher et al., 1997).

The Point Grey disposal site, outside Burrard Inlet on the southeast side of the Strait, is the largest multi-user site in BC. This site has been in continuous use since the 1930s, and has been regulated by Environment Canada since 1975. Wilson and McKinnon (2003) reviewed the history, sediment and benthos monitoring data gathered for the Point Grey site from 1975 through 2001. The site is between 230 and 250 m deep, with 80% of the sedimenting material from dumping and most of the remainder from the Fraser River discharge. In the late 1970s there was clear evidence of material from Burrard Inlet dumped outside of, *en route* to, the disposal site and evidence of this trail was still present in the early 1990s (see Mosher et al., 1997 and www.gsc.nrcan.gc.ca/marine/_gbgi/proj_ptgrey_e.php). In addition, detailed investigation of polycyclic aromatic hydrocarbon (PAH) signatures based on area-wide data suggested that recently dumped contaminants from Burrard Inlet were evident at the north end of the Iona outfall monitoring transect (80 m depth) in 2000 (Yunker, 2000; Yunker et al., 2000), well outside the ocean disposal boundaries.

Benthic infaunal surveys were conducted periodically at the Point Grey disposal site (most recently in 1994) but sampling effort and taxonomic work varied considerably (Wilson and McKinnon, 2003). The accumulated material is presently significantly coarser than the surrounding area, probably due to winnowing and transport on the way to the bottom. Despite the limitations to interpretation imposed by taxonomic effort and quality control, and modification of substrates within the dumpsite, Wilson and McKinnon (2003) concluded that the Environment Canada monitoring data on benthic invertebrate biota did not show notable differences from biota found outside the dumpsite; for a guideline, the authors used the range in values expected within reference conditions for the Benthic Response Index (BRI) from the Southern California Coastal Water Research Project (SCCWRP). Unfortunately the BRI is based on local species-specific data, whereas the Point Grey biotic data were for different species identified only to the family level or higher, thus making extrapolation to the BRI problematic. Probably more convincing is the fact that on-going visual surveys (see below) show that the disposal site has historically been dominated by a range of polychaete taxa and had numerous burrowing and near-surface, echinoderms and amphipods, both of which groups are known to be sensitive to contamination and organic enrichment, as well as unusually high sedimentation (Burd, 2003b).

At the Point Grey disposal site, ROVs equipped with video and still cameras are used periodically to record images of the disposal site and the surrounding ocean floor (Wilson and McKinnon, 2003). Predetermined track lines plotted across the disposal site are followed by the ROV and continuous images of the ocean bottom are recorded. These visual images aid in the qualitative evaluation of the disposal site environment. ROV surveys show that the dumping of debris (e.g. logs, wire and construction materials) has created a more heterogeneous habitat than

would normally be present at this depth, resulting in an artificially increased biodiversity of hard and soft substrate fauna.

3. 3 Pulp and Paper Mills

Macdonald et al. (1991) concluded that the pulp and paper mills in the SoG and surrounding fjords were contributing significantly to organic carbon input into the sediments of the Strait. Since then, the draft Pulp and Paper Effluent Regulations (PPER) were promulgated by Environment Canada in 1992, put into effect in 1996 and revised in 2004 (Regulations Amending the Pulp and Paper Effluent Regulations, (RAPPER), in order to reduce and control emissions (<http://www.ec.gc.ca/nopp/pandp/en/p2004Letter.cfm>). There are 6 operating pulp and paper mills which discharge effluent into marine subtidal habitats in the SoG and which are regulated by Environment Canada under the PPER. The mills in the Strait are shown in Fig. 1 (Crofton, Harmac, Elk Falls, Powell River and two in Howe Sound). Monitoring takes place from 30 m to 135 m depth and all but one of the mills discharge primarily into soft substrates ranging from 98% sand to 98% silt/clay (<http://www.ec.gc.ca/EEM/English/PulpPaper/general.cfm>). The Elk Falls mill discharges onto hard substrates and the Environmental Effects Monitoring (EEM) program for that mill focuses on invertebrate communities found in intertidal *Fucus* beds (www.ec.gc.ca/eem/English/PulpPaper/data/showinfo.cfm?Mill_id=PP1122). The current Environmental Effects Monitoring (EEM) program for the pulp and paper mills has now completed 3 cycles: 1996, 2000 and 2004. Data collection for cycle 4 is complete and reports have been submitted to Environment Canada but are not yet publicly available. The EEM program and technical guidance for monitoring are available at <http://www.ec.gc.ca/EEM/>

2108 [English/PulpPaper/general.cfm](#), including the national database of benthic infauna and habitat
2109 conditions.

2110
2111 Results from Environment Canada's national synthesis reports available on the website show that
2112 although effluent quality from pulp and paper mills has vastly improved since initiation of the
2113 PPER (following the EEM cycle 1), effects on benthic invertebrates and fish are still observed.
2114 Some pulp and paper mill reports suggest that current effects on marine benthos are still related
2115 to historical deposition and that current inputs are much less of a problem. Aside from organic
2116 enrichment, the accumulation of wood fibre mats, organochlorines and dioxins/furans have been
2117 historical problems. Although the organic contaminants mentioned are now controlled (or
2118 banned) substances, their historical presence in these sediments suggests that they are still
2119 cycling through the food chain in the vicinity of pulp and paper mills.

2120
2121 The aforementioned synthesis reports further suggest that while eutrophication of the water
2122 column is the dominant factor affecting freshwater benthos exposed to pulp and paper mill
2123 effluent input, the typical response of biota in marine/estuarine benthic habitats is a decrease in
2124 abundance and richness of taxa that is more indicative of toxic, or smothering, effects
2125 (<http://www.ec.gc.ca/EEM/English/PulpPaper/general.cfm>). Near mill discharges, elevated C/N
2126 ratios (>15) are common while sediment sulphides are not particularly elevated in comparison,
2127 for example, with fish farm sediments (Burd, 2006). However, a re-examination of the EEM
2128 cycle 3 data from the SoG shows no trends in species richness or abundance related to distance
2129 from the discharge, sediment redox, sulphides, TOC or C/N ratio (Burd, unpublished data).

However, there is some indication that taxa number and abundance decline with increasing depth, as found overall in the SOG data (Burd et al. in press; see Section 2).

Although the pulp and paper mills in the SoG appear to have no gross impact on subtidal infaunal benthos, this should not be interpreted to mean that the mills are not affecting the benthos; for example, quality control has never been standardized for the taxonomy of the pulp and paper mills marine EEM (technical guidance document <http://www.ec.gc.ca/EEM/English/PulpPaper/general.cfm>).

Environment Canada's EEM program for pulp and paper mills includes one mill site in the SOG which is predominantly hard substrate and is thus not amenable to the regular infaunal sampling methods recommended in the technical guidance. Data from the Elk Falls mill includes mixed studies of *Fucus* recolonization baskets in some cycles and standard beach quadrat surveys in others. The recolonization studies show a limited (rapid colonizing) species list of amphipods, isopods, and nemerteans that is missing the typical hard substrate species such as the molluscs and polychaetes, and larger predators (http://www.ec.gc.ca/eem/English/PulpPaper/data/showinfo.cfm?Mill_id=PP1122). The quadrat studies provide a species list much more typical of *Fucus* habitats as described in the Shorekeepers lists (<http://www.shim.bc.ca/atlas/sk/main.htm>). At present, these studies have not shown any gradient responses in biota to distance from the discharge. Based on research in the SoG, Bard (1998) describes biotic sensitivities and a proposed biotic index related to intertidal rocky beach fauna in areas affected by pulp mill effluent in BC.

High organic loading from pulp mills and log boom areas is relatively refractory due to the slow rate of bacterial and invertebrate breakdown of organics. Therefore, the packing of dense debris typically causes severe sediment deoxygenation without dramatically elevated sulphides in sediments (<http://www.ec.gc.ca/eem/english/PulpPaper/default.cfm>; Samis et al., 1999). These areas may show a generalized depression of fauna (see Burd et al, in press), but be patchy, depending on deposition characteristics. The benthos may take a long time to recover in sediments with heavy wood-fibre mats due to the reduced and slow biotic activity, and sometimes low penetrability by burrowers.

3. 4 Log Booms

Areas of near-shore log booms are common along the SoG coastline. Log storage activities primarily impact low intertidal and shallow subtidal habitats within estuaries. Impacts include the physical shading of habitat by booms, leading to decreased primary productivity by algae and eelgrass (NEMP, 2002). At low tide, the physical grounding and abrasion by log booms result in compaction of sediments, scouring and physical disruption of habitats, particularly eelgrass beds (NEMP, 2002). Adjacent intertidal areas can be similarly impacted by escaped logs and propeller wash from tow boats can scour and increase the levels of suspended sediment in the water column (NEMP, 2002).

The working of logs against each other within the bundle results in deposition and accumulation of bark and wood debris on bottom sediments. These deposits are relatively refractory and the slow rate of bacterial and invertebrate breakdown can cause long-term stress to the benthic environment as a result of sediment deoxygenation, although sulphide levels are not dramatically

elevated (<http://www.ec.gc.ca/eem/english/PulpPaper/default.cfm>). General biotic effects may be similar to those described for pulp and paper receiving environments (Section 3.3), although the deposition of wood debris tends to be coarser and may be much heavier under log booms. McGreer et al. (1984) examined the recovery of an intertidal community in an area of the Nanaimo River estuary from which log booms had been removed. At 13 months after removal, common macro-invertebrate species were those typical of organic enrichment but the overall abundance was lower than that of the control area. The reduction in abundance was attributed to a shallow, but persistent, redox boundary at the log removal site. The effects of wood waste on near-shore sand beds (4-11 m) and associated fauna were studied by Conlan (1977) and Conlan and Ellis (1979), who found that deposition of >1 cm of wood debris caused notable faunal impoverishments, particularly in the suspension feeding fauna. Additional studies have suggested that wood debris may also inhibit the abundance of some infaunal bivalves (Burd et al., in press; Kathman et al., 1984; <http://www.mareco.org/report/intro.htm>). Kathman et al. (1984) examined the recolonization of settling trays in 15-20 m depth in outer Burrard Inlet, using different concentrations of wood waste from the Port Mellon pulp mill location in Howe Sound. After 11 weeks, they found that the 20% wood waste trays had a higher species diversity and lower dominance than found in the 0%, 50% and 100% wood waste trays, whereas abundance was equally high in the 20% and 100% trays. However, the 100% trays were dominated by nematodes, typical organic enrichment polychaetes and the wood-burrowing bivalve *Bankia setacea*. Other bivalves and polychaetes were abundant in the 0% and 20% trays, but rare in the 50% and 100% trays.

A larger-scale examination of benthic responses to log-boom operations for the north coast of British Columbia, as well as Esquimalt Harbour (Victoria) is underway as part of a Ph.D. project (http://www.erf.org/cgi-bin/conference_abstract.pl?conference=erf2003%id+755).

3.5. Mine Tailings and Acid Mine Drainage

Between 1902 and 1974, the Britannia copper/zinc mine discharged 40 million tonnes of tailings into Howe Sound. Tailings were concentrated on the slope within 3 km of Britannia Beach but also covered most of the floor of the Sound's inner basin. During mine operations, subtidal sediments in areas deeper than 30 m had levels of copper and zinc that were considerably elevated above background (Levings and McDaniel, 1973, 1976; McDaniel, 1973), as well as above the current Probable Effects Levels for marine sediments (CCME, 1999). They also found that burial by the Squamish River sediment load and inputs from local creeks had diluted, or covered, the deposited tailings and reduced the metal concentration in surface sediments. Below sill depth (73 m), waters in Howe Sound tend to be seasonally anoxic, limiting not only the mobility of metals from the sediments but also the biodiversity and abundance of benthic fauna, regardless of tailings (Levings et al., 1983). Several studies in the 1970s focused on the effects of deposition of metals and tailings from the active Britannia Mine operation on the macrobenthos (Levings and McDaniel, 1973; McDaniel, 1973; Levings and McDaniel, 1976), but based on more recent studies near Britannia (Ellis and Hoover, 1990) and on long-term recovery of sediments affected by tailings from mines located outside the SoG in British Columbia (Burd et al., 2000b; Burd, 2002), it is assumed that the deep benthos has recovered some 30 years after cessation of tailings deposition. However, it is also clear that considerable acid mine drainage is still leaching out into the near shore area around the historical Britannia

mine. Recent studies confirm impacts on near shore fish and fish habitat (for an overview, see Hagan et al., 2004). In addition, Grout and Levings (2001) examined the effects of acid mine drainage on intertidal mussels in the area and showed that caged and ambient mussels were adversely affected by elevated tissue copper levels to a distance of about 2 km N and S of the discharge creek. In December 2001, the acid mine drainage was diverted to an outfall at 30 m depth into Howe Sound. Zis et al. (2004) looked at the intertidal community recovery at Britannia Beach after diversion, and found that some, but not total recovery was evident in invertebrate species number and abundance, as well as transplanted mussels. The authors concluded that some continued seepage from the old mine was still inhibiting normal growth and survival in the intertidal area. G3 Consulting (2003) provided a report on the shallow subtidal (<30 m depth) biota, sediment metals and organics from the foreshore around the Britannia mine. Levings et al. (2004) describe the toxicity of the acid mine drainage to estuarine organisms from the discharge creek, noting that invertebrate food resources for juvenile salmonids in the intertidal near the drainage creek were adversely affected by the acid mine drainage.

3.6 Aquaculture

In BC, the majority of the finfish aquaculture industry in the inside waters is located north of the SoG; there are only a few salmonid farms at the south end of Johnson Strait (the north end of the SoG) and in some of the contiguous mainland fjords. Where organic deposition is excessive, and fauna have declined, reactive organic detritus may be present in a labile state as a flocculent layer on the sediment surface (Kristensen, 1988). Fish farms provide an example of an organic source with minor copper (antifoulants) and zinc (feed) contaminants (c.f. Brooks 2001). Studies of benthic faunal patterns and recovery at the few marine mine tailings deposition sites,

however, suggest that particulate levels of these metals typically found under fish farms do not seem to have a notable effect on infaunal benthos in the deeper subtidal, despite the fact that bivalves, in particular, can accumulate metals (Burd et al., 2000b; Burd, 2002). Rather, zinc and copper levels are typically used as deposition tracers around fish farms (Yeats, 2002).

The organic deposition in the vicinity of fish farms tends to be highly labile, as compared to wood fibre waste or other organic materials. Hence, the organic material tends to be broken down relatively quickly (e.g. in comparison to wood fibre debris) and recovery proceeds at a measurable pace. The effects of this highly labile deposition include sediment de-oxygenation and hydrogen sulphide accumulation which lead to the enrichment of some taxa such as the opportunistic polychaete *Capitella capitata* complex that are tolerant of these conditions and the impoverishment of sensitive taxa. At fish farms where organic enrichment loads are high and sediment geochemistry includes low oxygen levels and high sulfide accumulation (i.e. ~6000 μm), tolerant and opportunistic polychaete species tend to dominate on soft substrates and on hard substrates where sedimentation occurs, whereas most other fauna disappear under these extreme conditions (Brooks, 2001; Burd, 2006; Hargrave et al., 2008). However, some epifaunal crustaceans typically found in detritus mats nearshore may thrive in the debris mats under the net cages (Burd, 2006).

Under more moderate sulphide buildup conditions (1700-3000 μM), a variety of organism types may be present, but Burd (2006) show that some biotic impoverishments are highly likely, along with a potential proliferation of opportunistic polychaetes. In particular, echinoderms and infaunal crustaceans appear to be highly sensitive to organic enrichment conditions in sediments (Burd, 2006; McPherson et al., 2007a). On hard substrates, some cnidarians (such as *Metridium*

senile) may be opportunistic under moderate organic enrichment conditions, but echinoderms will still be absent, as will larger sponges (Emmett et al., 2005; 2006; 2007), due primarily to excessive deposition, and/or near-bottom low oxygen conditions. Where organic loading is elevated, but within the assimilative capacity of the sediments, a biotically-enriched community may be present (Burd, 2006; Brooks, 2001). Recent reviews of biotic effects related to fish farms in BC are given in Brooks (2001), Burd (2003a; 2006) and Hargrave et al. (2008). Some important information on general sediment sulphide tolerance of common BC species is available in Brooks (2001).

A large number of beach and near-shore shellfish aquaculture sites are located in Baynes Sound on the east coast of Vancouver Island. Carswell et al. (2006) describe an aerial survey method that has been used to show that >20% of the intertidal zone of the sound is occupied by shellfish tenures. A review of the available literature and monitoring data related to potential impacts from shellfish culture for the intertidal areas of Baynes Sound is given in Jamieson et al. (2001). To date, studies show that the benthic impact of deep-water suspended culture of Pacific oysters appears to vary depending on the specifics of the site, including hydrography, bathymetry and natural deposition rates and sediment characteristics (Barnes, 2006). Regardless, data revealed that the benthic invertebrate communities in close proximity to the shellfish farms showed no reduction in either faunal abundance or diversity (Barnes, 2006). In Baynes Sound, an area of the SoG heavily tenured by shellfish leases, Bendell-Young (2006) studied three geographically similar clam farm beach sites, along a farming intensity gradient (fallow, 3 years active, 5 years active). In contrast to the fallow site, the 3 and 5 year active sites had intertidal regions with heavier silt and organic matter, lower species richness and increased domination by bivalves. However, a geographically more diverse study, including a site on the west coast of Vancouver

Island, found that clam density on netted farm sites was significantly greater than on reference sites only in the low intertidal and that this significant increase in total clam density mirrored the increase in 1 species of bivalve, *Venerupis philippinarum*, in this stratum at farm sites (Whiteley and Bendell-Young, 2007). The study also demonstrated that bivalve species composition was not significantly different between farms and reference sites, suggesting that predator nets did not effectively change the structure of the infaunal communities at these sites. Farm sites were more similar to each other as a group than reference sites, however, and the authors suggest that this may lead to a loss of the regional distinctness that was evident among the reference sites (Whiteley and Bendell-Young, 2007).

3.7 Bottom Trawling

In near-shore coastal areas such as the SoG, bottom trawling is likely to result in physical disturbance. Bottom trawling can have devastating effects on bottom infaunal and epifaunal communities in other coastal areas (Watling and Norse, 1998). For example, otter trawling on soft bottoms has been found to significantly reduce the abundance of most invertebrate taxa (Engel and Kvitek, 1998; and other papers in Conservation Biology issue 12: Vol. 6). Effects on the benthos range from crushing, burying and dislocation of fauna, to habitat destruction and resuspension of fine particulates into a turbid boundary layer. Such practices can also damage nursery grounds or bottom fish stock. Various studies report a reduction in organism abundance and species richness $\geq 50\%$, and substantial reductions in biomass (for review, see Watling and Norse, 1998). The effects of bottom trawling do not resemble any of the contaminant impacts described in the literature (Burd 2003b; Cook et al., in press), and arguments have been made that certain refugia such as the sponge reefs in the Strait should be protected from bottom

trawling (Conway et al., 2007). Unfortunately, there is virtually no concurrent spatial or temporal information on the combined, or synergistic, biotic effects of contaminant discharges and bottom trawling in the SoG.

3.8 General Contaminants Loadings (non-point source)

There are numerous sources of contaminants entering the SoG, particularly originating from, or as a result of, the highly urbanized centers near the BC/Washington border. Aside from localized surveys of sediment contaminant loadings related to specific discharges (see references in above sections 3.1 to 3.7 related to monitoring programs for site-specific discharges), there have been a few broader-scale studies of certain contaminants of concern or tracers of discharge types, focusing on their distributions and budgets (c.f. Macdonald et al., 1991, 1992 – Pulp mills; Gordon, 1997 – silver; Shang et al., 1999 – nonylphenols; Yunker et al., 1999 – PAHs; Johannessen et al. 2005a – Mercury; Johannessen et al. in press – PCBs/PBDEs). In addition, the potential for development of bottom water and sediment hypoxia from organic loading have been discussed using organic carbon budgets (Johannessen et al., 2003), and evaluation of sediment organic/oxygen conditions based on redox chemicals in cores (Macdonald et al., in press).

Sediment guidelines and all the studies that have contributed to their development (CCME, 1999; BCWQO; http://www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html) provide some guidance related to possible responses of benthic invertebrate fauna to contaminants of concern. However, field validation of these hypothetical tolerances and responses is lacking for SoG fauna.

4. Conclusions

Although there is considerable descriptive information pertaining to invertebrate benthos (largely unpublished) of the SoG, quantitative evaluations are much less abundant and patchy spatially and temporally. Burd et al. (in press) provide a comparative assessment of infaunal biomass, species richness, and abundance measures which can be reasonably predicted by measurements of organic quality and flux to sediments in the SoG. Results are also dependent on the source and relative quantity of inorganic flux, with areas influenced by the Fraser River discharge providing apparently more productive substrate for macro-invertebrates than marine depositions. With a broader scale understanding of sediment organic and inorganic sources and fluxes in the SoG, it may be possible to begin to model and ground-truth subtidal benthic productivity of the SoG. This would also require a clearer understanding of how the smaller invertebrate groups (meiofauna) and microfauna respond to sediment organic and inorganic fluxes. The next logical step would be to interpret sediment productivity in the context of budgets/models of sediment contaminants, organic inputs and redox conditions for the SoG. In addition to understanding how benthic organisms may be affected by contaminant and organic loading on a regional scale, the potential for bio-accumulation and trophic transfer of contaminants of concern needs to be studied for the bottom-dwelling portion of the subtidal food chain. Predicting the effects of ongoing climate changes will also require an understanding of how the sessile components of the benthic ecosystem are likely to change in response to major sedimentation shifts or events.

5.0 Acknowledgements

2351 As in all reviews, acknowledgements must go primarily to all those researchers that have “gone
2352 before”. However, this review would not have been possible without the motivation and
2353 financial support of Metro Vancouver (formerly Greater Vancouver Regional District), through
2354 Dr. Albert van Roodselaar. This work was completed as part of a collaborative research program
2355 between Metro Vancouver, Canadian Department of Fisheries and Oceans and Natural
2356 Resources Canada.

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6.0 References

- 2WE Consulting, 1999. Iona Deep-sea Outfall 1998 Environmental Monitoring Program, Post-discharge Review, Report for Greater Vancouver Regional District by 2WE Associates Consulting Ltd., Victoria, B.C., 97 pp.
- Albright, L.J., 1983. Influence of river-ocean plumes upon bacterioplankton production of the Strait of Georgia, British Columbia. Marine Ecology Progress Series 12, 107-113.
- Anderson, J.J., Devol, A.H., 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Estuarine, Coastal and Shelf Science 1, 1-10.
- Archipelago Marine Research Ltd., 2000. Subtidal video (SIMS) survey of the Manley Creek landfall site at Boatswain Bank, British Columbia. Report to the Georgia Strait Pipeline Crossing Ltd.
- Asmus, H. 1987. Secondary production of an intertidal mussel bed community related to its storage and turnover compartments. Mar. Ecol. Prog. Ser. 39, 251-256.
- BC Ministry of Environment Lands and Parks, 1996. Saanich Inlet Study. Synthesis Report Summary, 35 pp.
- Baba, K., 1983. *Spongicoloides hawaiiensis*, a new species of shrimp (Decapoda: Stenopodidea) from the Hawaiian Islands. Journal of Crustacean Biology 3, 477-481.
- Bailey, H.C., McPherson, C.A., Hodgins, D.O., Fanning, L., Paine, M.D., Burd, B.J., Macdonald, V., Brooks, G.C., Chen, F., Brand, D., Raverty, S., 2003. Iona Deep-Sea Outfall, 2001 Environmental Monitoring Program. Final Report, Prepared for the Greater Vancouver Regional District by EVS Environmental Consultants Ltd., North Vancouver BC, 344 pp. + appendices.

- 2384 Balch, N., Brown, D., Pym, R., Marles, E., Ellis, D.V., Littlepage, J., 1975. Monitoring marine
2385 outfalls by using ultraviolet absorbance. *Journal of the Pollution Control Federation*, 47,
2386 195-202.
- 2387 Balch, N., Ellis, D.V., Littlepage, J., 1973. Macaulay Point outfall monitoring programme, May
2388 1970 – October 1972, Volume 1 and 2 final report to Capital Regional District, Victoria,
2389 BC by Department of Biology, University of Victoria.
- 2390 Bard, S.M., 1998. A biological index to predict pulp mill pollution levels. *Water Environment*
2391 *Research* 70, 108-122.
- 2392 Barnes, P.A.G., 1987. Aspects of the Ecology of the Gutless Protobranch Bivalve, *Solemya reidi*.
2393 University of Victoria, M.Sc. thesis, 435 pp.
- 2394 Barnes, P.A.G., 2006. Shellfish Culture and Particulate Matter Production and Cycling: A
2395 Literature Review, B.C. Aquaculture Research and Development Committee. Project
2396 AE02.03-02.01, 101 pp.
- 2397 Barthel, D., 1992. Do hexactinellids structure Antarctic sponge associations? *Ophelia* 36, 111-
2398 118.
- 2399 Bell, J.J., Barnes, D.K., 2000a. The distribution and prevalence of sponges in relation to
2400 environmental gradients within a temperate sea lough: vertical cliff surfaces. *Diversity*
2401 *and Distributions* 6, 283-303.
- 2402 Bell, J.J., Barnes, D.K., 2000b. The distribution and prevalence of sponges in relation to
2403 environmental gradients within a temperate sea lough: inclined cliff surfaces. *Diversity*
2404 *and Distributions* 6, 305-323.

- 2405 Bendell-Young, L.I., 2006. Contrasting the community structure and select geochemical
2406 characteristics of three intertidal regions to shellfish farming. *Environmental*
2407 *Conservation* 33, 21-27.
- 2408 Berggren, M., 1993. *Spongiocaris hexactinellicola*, a new species of stenopodidean shrimp
2409 (Decapoda: Stenopodidae) associated with hexactinellid sponges from Tartar Bank,
2410 Bahamas. *Journal of Crustacean Biology* 13, 784-792.
- 2411 Bernard, F.R., 1978. British Columbia Faunistic Survey: Subtidal and Deep-water Megafauna of
2412 the Strait of Georgia. Canadian Fisheries and Marine Services Manuscript Report 1488,
2413 41 pp.
- 2414 Bett, B.J., Rice, A.L., 1992. The influence of hexactinellid sponge (*Pheronema carpen-teri*)
2415 spicules on the patchy distribution of macrobenthos in the Porcupine Seabight (bathyal
2416 NE Atlantic). *Ophelia* 36, 217-226.
- 2417 Boatman, D.C., Murray, J.W., 1982. Modeling exchangeable NH_4^+ adsorption in marine
2418 sediments: Process and controls of adsorption. *Limnology and Oceanography* 27, 99-110.
- 2419 Bornhold, B.D., 1978. Carbon/nitrogen (C/N) ratios in surficial marine sediments of British
2420 Columbia, in: *Current Research, Part C*, Geological Survey of Canada, Scientific and
2421 Technical Notes, Paper 78-1C, 108-112.
- 2422 Bornhold, B.D., Harper, J.R., 2002. Pilot Nearshore Habitat Mapping Using Acoustic and Visual
2423 Techniques, Report Prepared for the North Pacific Research Board Anchorage, Alaska,
2424 (Project R0201), 128 pp.
- 2425 Bornhold, B.D., Ren, P., Prior, D.B., 1994. High-frequency turbidity currents in British
2426 Columbia fjords. *Geo-Marine Letters* 14, 238-243.

- 2427 Bousfield, E.L., 1957. Ecological investigations of shore invertebrates of the Pacific coast of
2428 Canada. National Museum of Canada Bulletin 147, 105-155.
- 2429 Boyd, J., Baumann, J., Hutton, K., Bertold, S., Moore, B., 1998. Sediment Quality in Burrard
2430 Inlet Using Various Chemical and Biological Benchmarks, Burrard Inlet Environmental
2431 Action Program, Burnaby, British Columbia, 87 pp. + appendices.
- 2432 Brenchley, G.A., 1982. Mechanisms of spatial competition in marine soft-bottom communities.
2433 Journal of Experimental Marine Biology and Ecology 60, 17-33.
- 2434 Brinkhurst, R.O., 1987. Distribution and Abundance of Macrobenthic Fauna from the
2435 Continental Shelf off Southwestern Vancouver Island, British Columbia. Canadian
2436 Technical Report on Hydrography and Ocean Sciences 89, 45 pp.
- 2437 Brinkhurst, R.O., Casillas, E., Word, J.Q., 1994. Marine benthos of British
2438 Columbia/Washington State boundary waters, in: Wilson, R.C.H., Beamish, R.J.,
2439 Aitkens, F., Bell, J., (Eds.), Review of the Marine Environment and Biota of Strait of
2440 Georgia, Puget Sound and Juan de Fuca Strait. Canadian Technical Report of Fisheries
2441 and Aquatic Sciences 1948, 187-202.
- 2442 Brooks, K.M., 2001. An evaluation of the relationship between salmon farm biomass, organic
2443 inputs to sediments, physiochemical changes associated with those inputs and the
2444 infaunal response-with emphasis on total sediment sulfides, total volatile solids, and
2445 oxidation reduction potential as surrogate endpoints for biological monitoring, Technical
2446 Advisory Group, Ministry of Environment, Lands, and Parks, Port Townsend,
2447 Washington, 172 pp. + appendices.

- 2448 Bruce, A.J., Baba, K., 1973. *Spongiocaris*, a new genus of stenopodidean shrimp from New
2449 Zealand and South Africa waters, with a description of two new species (Decapoda:
2450 Nutantia, Stenopodidea). *Crustaceana* (Leiden) 25, 153-170.
- 2451 Burd, B.J., 1985. Respiration of a low oxygen tolerant galatheid crab, *Munida quadrispina*
2452 (Benedict, 1902). *Canadian Journal of Zoology* 63, 2538-2542.
- 2453 Burd, B.J., 1988. Comparative gill characteristics of *Munida quadrispina* (Decapods,
2454 Galatheidae) from different habitat oxygen conditions. *Canadian Journal of Zoology* 66,
2455 2320-2323.
- 2456 Burd, B.J., 1992. Qualitative and quantitative studies of benthic marine infaunal communities in
2457 British Columbia coastal waters, University of Victoria, Ph.D thesis., 375 pp.
- 2458 Burd, B.J., 1997. Part D: Waste Discharges Discussion Paper. Salmon Aquaculture Review,
2459 Technical Advisory Team Discussion Papers, B.C. Environmental Assessment Office,
2460 Victoria, B.C., 3:D1-D118.
- 2461 Burd, B.J., 2000. Ecological Effects and Indicators Analysis for the IONA Receiving
2462 Environment, in: Greater Vancouver Regional District, (Ed.), Development of a
2463 Receiving Environment Monitoring Approach to Liquid Waste Management: Progress
2464 Workshop 2, Burnaby, B.C., 48 pp.
- 2465 Burd, B.J., 2002. Evaluation of mine tailings effects on a benthic marine infaunal community
2466 over 29 years. *Marine Environmental Research*, 53 481-519.
- 2467 Burd, B.J., 2003a. Review and Prioritization of Benthic Invertebrate Indicator Species, Species
2468 Assemblages, and Chemical Characteristics that Could be Used in Assessing Effects of
2469 Marine Finfish Farms on Fish Habitat, Report to the Department of Fisheries and Oceans,
2470 Pacific Region, 59 pp.

- 2471 Burd, B.J., 2003b. Ecological Significance of IONA 2000-2002 Monitoring Results for Benthic
2472 Infaunal Communities, in: Greater Vancouver Regional District, 2004. Greater
2473 Vancouver Regional District. Cautions, Warnings & Triggers: A Process for Protection of
2474 the Receiving Environment, Appendices: Technical Reports and Monitoring Programs.
- 2475 Burd, B.J., 2003c. Ecological Effects Related to the Outfall Particulates Discharge Determined
2476 from the Macaulay Point Monitoring Program 1994-2001, Report to Capital Regional
2477 District, Victoria, British Columbia.
- 2478 Burd, B.J., 2004. Comparative Assessment of Biological and Related Sediment Factors for Outer
2479 Burrard Inlet: Historical and Current Monitoring Data: Ambient Monitoring Data; Iona
2480 Monitoring Data, Prepared for the Greater Vancouver Regional District, 83 pp.
- 2481 Burd, B. J., 2006. Analysis of Historic Benthic Biological Data to Determine Validity of the
2482 Ecological Threshold Concept for Soft Substrate Impacts Related to Coastal BC Fish
2483 Farm Discharges. Report to BC Ministry of Environment, December 6, 2006, 62 pp.
- 2484 Burd, B.J., Brinkhurst, R.O., 1984. Distribution of the galatheid crab, *Munida quadrispina*
2485 (Benedict 1902) in relation to oxygen concentrations in British Columbia fjords. Journal
2486 of Experimental Marine Biology and Ecology 81, 1-20.
- 2487 Burd, B.J., Brinkhurst, R.O., 1987. Macrobenthic infauna from Hecate Strait, B.C. Canadian
2488 Technical Report of Hydrography and Ocean Sciences 88, 123pp.
- 2489 Burd, B.J., Brinkhurst, R.O., 1990. Vancouver Harbour and Burrard Inlet Benthic Infaunal
2490 Sampling Program, October 1987. Canadian Technical Report of Hydrography and
2491 Ocean Sciences 122, 49 pp.
- 2492 Burd, B.J., Brinkhurst, R.O., 1992. Benthic Infaunal Surveys of British Columbia Fjords, 1988 to
2493 1990. Canadian Data Report of Hydrography and Ocean Sciences 114, 37 pp.

- 2494 Burd, B.J., Glaholt, R., 2000. Survey of benthic infauna at the Manley Creek landfall site at
- 2495 Boatswain Bank, British Columbia. Ecostat Research Ltd. and Tera Environmental
- 2496 Consultatns (Alta) Ltd. Report to the GSX Pipeline Crossing Project.
- 2497 Burd, B.J., Glaholt, R., Macdonald, V., 2000a. Reconnaissance Level Baseline Survey of
- 2498 Benthic Infaunal communities at Ecological Reserve 67 and Adjacent Satellite Channel,
- 2499 June 4, 2000. Georgia Strait Crossing Pipeline Ltd., 14 pp. + appendices.
- 2500 Burd, B.J., Macdonald, R.W., Boyd, J., 2000b. Punctuated recovery of sediments and benthic
- 2501 infauna: a 19-year study of tailings deposition in a British Columbia fjord. Marine
- 2502 Environmental Research 49, 145-175.
- 2503 Burd, B.J., Macdonald, R.W., Johannessen, S.C., Hill, P.R., van Roodselaar, A., *In Press*. A.
- 2504 Responses of subtidal benthos of the Strait of Georgia to ambient sediment conditions
- 2505 and natural and anthropogenic depositions. Marine Environmental Research,
- 2506 Burd, B.J., Moore, D., Brinkhurst, R.O., 1987. Distribution and Abundance of Macrobenthic
- 2507 Fauna from Boundary and Mud Bays near the British Columbia/U.S. Border. Canadian
- 2508 Technical Report of Hydrography and Ocean Sciences 84, 1-34.
- 2509 Burgess, R.M., 2000. Characterising and identifying toxicants in marine water: a review of
- 2510 marine toxicity identification evaluations (TIEs). International Journal of Environment
- 2511 and Pollution 13, 2-33.
- 2512 Canadian Department of Fisheries and Oceans, 1999a. Manila Clam, DFO Science Stock Status
- 2513 Report, C6-03.
- 2514 Canadian Department of Fisheries and Oceans, 1999b. Native Littleneck Clam, DFO Science
- 2515 Stock Status Report, C6-02.

- 2516 Canadian Department of Fisheries and Oceans, 2000. Geoduck Clam, DFO Science Stock Status
2517 Report, C6-05.
- 2518 Canadian Department of Fisheries and Oceans, 2007. Pacific Region, Intergrated Fisheries
2519 Management Plans, Intertidal Clams, January 1, 2007 to December 31, 2009, Fisheries
2520 and Oceans Canada, Nanaimo, BC. 71 pp.
- 2521 Capital Regional District, 2000. Core Area Liquid Waste Management Plan, CRD, Victoria,
2522 British Columbia, 104 pp. + appendices.
- 2523 Capital Regional District, 2003. Macaulay and Clover Point Wastewater and Marine
2524 Environment Program 2002 Annual Report, Capital Regional District, Environmental
2525 Services Department, Victoria, B.C., 63 pp. + appendices.
- 2526 Capital Regional District, 2004. Macaulay and Clover Point Wastewater and Marine
2527 Environment Program 2003 Annual Report, Capital Regional District, Environmental
2528 Services Department, Victoria, B.C., 93 pp. + appendices.
- 2529 Capital Regional District, 2005. Macaulay and Clover Point Wastewater and Marine
2530 Environment Program 2004 Annual Report, Capital Regional District, Environmental
2531 Services Department, Victoria, B.C., 127 pp. + appendices.
- 2532 Carefoot, T., 1977. Pacific Seashores: A guide to intertidal ecology. University of Washington
2533 Press, Seattle, WA., 208 pp.
- 2534 Carswell, B., Cheesman, S., Anderson, J., 2006. The use of spatial analysis for environmental
2535 assessment of shellfish aquaculture in Baynes Sound, Vanocuver Island, British
2536 Columbia, Canada. Aquaculture 253, 408-414.

- 2537 CCME, (Canadian Council of Ministers for the Environment) 1999. Protocol for the Derivation
- 2538 of Canadian Sediment Quality Guidelines for the Protection of Aquatic Life, Canadian
- 2539 Council of Ministers of the Environment, Ottawa, Ontario. 35 pp. + summary tables.
- 2540 Conlan, K.E., 1977. The effects of wood deposition on from a coastal log handling operation on
- 2541 the benthos of a shallow sand bed in Saanich Inlet, British Columbia, University of
- 2542 Victoria, M.Sc. thesis, 203 pp.
- 2543 Conlan, K.E., Ellis, D.V., 1979. Effects of wood waste on sand-bed benthos. *Marine Pollution*
- 2544 *Bulletin*, 10 262-267.
- 2545 Conway, K.W., 1999. Hexactinellid Sponge Reefs on the British Columbia Shelf: Geological
- 2546 and Biological Structure with a Perspective on Their Role in the Shelf Ecosystem.
- 2547 Canadian Stock Assessment Secretariat Research Document 99/192, 21 pp.
- 2548 Conway, K.W., Barrie, J.V., Hill, P.R., Austin, W.C., Pickard, K., 2007. Mapping sensitive
- 2549 benthic habitats in the Strait of Georgia, coastal British Columbia: Deep-water Sponge
- 2550 and Coral Reefs, in: *Current Research*, Geological Survey of Canada, 2007-A2, 6 pp.
- 2551 Conway, K.W., Krautter, M., Barrie, J.V., Neuweiler, M., 2001. Hexactinellid sponge reefs on
- 2552 the Canadian continental shelf: A unique "living Fossil". *Geoscience Canada* 28, 71-78.
- 2553 Cook, S., Conway, K.W., Burd, B. *In press*. Status of the glass sponge reefs in the Georgia
- 2554 Basin, *Marine Environmental Research*.
- 2555 CORI (Coastal Ocean and Resources Inc), 2002. Lions Gate ROV far-field imaging survey.
- 2556 Report prepared for the Greater Vancouver Regional District, Burnaby, B.C., 30 pp. +
- 2557 appendices.

- 2558 Coull, B.C., Bell, S.S., 1979. Perspectives in marine meiofauna ecology, in: Livingston, R.J.,
2559 (Ed.), *Ecological Processes in Coastal Marine Systems*, New York: Plenum Press, pp.
2560 189-216.
- 2561 Crean, P.B., Murty, T.S. and Stronach, J.A., 1988. *Mathematical modelling of tides and estuarine*
2562 *circulation: the coastal seas of southern British Columbia and Washington State*.
2563 Heidelberg: Springer Verlag, 471 pp.
- 2564 Cross, S.F., 1990. Benthic impacts of salmon farming in British Columbia, report prepared for
2565 the Ministry of the Environment, Water Management Branch, Government of British
2566 Columbia, 78 pp.
- 2567 Cross, S.F., Brinkhurst, R.O., 1991. Spatial distribution of macrobenthos infauna in Burrard
2568 Inlet: November, 1989. Canadian Data Report of Hydrography and Ocean Sciences 92,
2569 40 pp.
- 2570
- 2571 Cross, S.F., Mehlenbacher, N., Lipovsky, S., Williams, A., 2005. Biological Monitoring of
2572 Salmon Aquaculture Benthic Impacts - Methods Review and Options Analysis, Report to
2573 the British Columbia Aquaculture Research and Development Committee, 123 pp. +
2574 appendices.
- 2575 Davenne, E., Masson, D. 2001. Water properties in the Straits of Georgia and Juan de Fuca,
2576 Fisheries and Oceans Canada, [www-sci.pac.dfo-](http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/straitofgeorgia/JdFG_e.pdf)
2577 [mpo.gc.ca/osap/projects/straitofgeorgia/JdFG_e.pdf](http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/straitofgeorgia/JdFG_e.pdf).
- 2578 Dayton, P.K., 1971. Competition, disturbance, and community organization: the provision and
2579 subsequent utilization of space in a rocky intertidal community. *Ecological Monographs*
2580 41, 351-389.

- 2581 de Brouwer, J.F.C., Wolfstein, K., Ruddy, G.K., Jones, T.E.R., Stal, L.J., 2005. Biogenic
2582 stabilization of intertidal sediments: The importance of extracellular polymeric
2583 substances produced by benthic diatoms. *Microbial Ecology* 49, 501-512.
- 2584 De Robertis, A., Eiane, K., Rau, G.H., 2001. Eat and run: anoxic feeding and subsequent aerobic
2585 recovery by *Orchomene obtusus* in Saanich Inlet, British Columbia, Canada. *Marine*
2586 *Ecology Progress Series* 219, 221-227.
- 2587 Decho, A.W., 2000. Microbial biofilms in intertidal systems: An overview. *Continental Shelf*
2588 *Research* 20, 1257-1273.
- 2589 Denny, M.W., Daniel, T.L. and Koehl, M.A.R., 1985. Mechanical limits to size in wave swept
2590 organisms. *Ecological Monographs* 55, 69-102.
- 2591 Duggins, D.O., 1981. Sea urchins and kelp: The effects of short term changes in urchin diet.
2592 *Limnology and Oceanography* 26, 391-394.
- 2593 Dumbauld, B.R., Armstrong, D.A., McDonald, T.L., 1993. Use of oyster shell to enhance
2594 intertidal habitat and mitigate loss of Dungeness crab (*Cancer magister*) caused by
2595 dredging. *Canadian Journal of Fisheries and Aquatic Sciences* 50, 381-390.
- 2596 Dunn, R., Mullineaux, L. S., Mills, S.W., 1999. Resuspension of postlarval soft-shell clams *Mya*
2597 *arenaria* through disturbance by the mud snail *Ilyanassa obsolete*. *Marine Ecology*
2598 *Progress Series* 180, 223-232.
- 2599 Ellis, D.V., 1966. Aerial photography from helicopter as a technique for intertidal surveys.
2600 *Limnology and Oceanography* 11, 299-301.
- 2601 Ellis, D.V., 1967a. Quantitative Benthic Investigations. I. Satellite Channel biomass summaries
2602 and major taxon rank orders, February 1965-May 1967. Fisheries Research Board of
2603 Canada Technical Report 25, 49 pp.

- 2604 Ellis, D.V., 1967b. Quantitative benthic investigations. II. Satellite Channel species data,
2605 February 1965-May 1967. Fisheries Research Board of Canada Technical Report 35, 170
2606 pp.
- 2607 Ellis, D.V., 1968a. Quantitative Benthic Investigations. III. Locality and environmental data for
2608 selected stations (mainly from Satellite Channel, Straits of Georgia and adjacent inlets),
2609 February 1965-December 1967. Fisheries Research Board of Canada Technical Report
2610 59, 61 pp. + figures and appendices.
- 2611 Ellis, D.V., 1968b. Quantitative benthic investigations. IV. Biomass summaries and major taxon
2612 rank orders for selected stations (mainly Straits of Georgia and adjacent inlets), May
2613 1965-December 1967. Fisheries Research Board of Canada Technical Report 60, 91 pp.
- 2614 Ellis, D.V., 1968c. Quantitative Benthic Investigations. V. Species data from selected stations
2615 (Straits of Georgia and adjacent inlets), May 1965-May 1966. Fisheries Research Board
2616 of Canada Technical Report 73, 307 pp.
- 2617 Ellis, D.V., 1970. Ecologically significant species in coastal marine sediments in southern British
2618 Columbia. Syensis 2, 171-182.
- 2619 Ellis, D.V., 1971. A review of marine infaunal community studies in the Strait of Georgia and
2620 adjacent inlets. Syensis, 4, 3-9.
- 2621 Ellis, D.V., 1982. Ocean disposal in British Columbia. Oceans 14, 1101-1106.
- 2622 Ellis, D.V., 2002. Underwater biodiversity surveys and biological colonization of the waste
2623 dump shoreline, (In) Poling, G.W., Ellis, D.V., Murray, J.W., Parsons, T.R. and Pelletier,
2624 C.A. Underwater Tailing Placement at Island Copper Mine. Society for Mining,
2625 Metallurgy and Exploration, USA, pp 137-146.

- 2626 Ellis, D.V., 2003. Rocky shore intertidal zonation as a means of monitoring and assessing
2627 shoreline biodiversity recovery. *Marine Pollution Bulletin*, 46, 305-307.
- 2628 Ellis, D.V., Hoover, P.M., 1990. Benthos on tailings beds from an abandoned coastal mine.
2629 *Marine Pollution Bulletin* 21, 477-480.
- 2630 Emerson, S., Hedges, J.I., 2003. Sediment diagenesis and benthic flux, in: Elderfield, H., (Ed.),
2631 *The Oceans and Marine Geochemistry*, Oxford: Elsevier-Pergamon, pp. 293-230.
- 2632 Emmett, B., Bornhold, B.C., Burd, B., 2005. Evaluation of Video and Non-video, Hard Substrate
2633 Seabed Monitoring Techniques, Prepared for the B.C. Aquaculture Research and
2634 Development Committee, B.C. Innovation Council, 78 pp.
- 2635 Emmett, B., Thuringer, P., Cook, S. 2006. The development of ROV video survey and data
2636 classification protocols for monitoring hard seabed substrates, Canadian Science
2637 Advisory Secretariat Working Paper I2006-04, Fisheries and Oceans Canada.
- 2638 Emmett, B., Thuringer, P., Cook, S., Burd, B., 2007. Evaluation of hard seabed monitoring
2639 techniques: Development of video survey and data classification protocols: Phase 2,
2640 report prepared for the Aqua E-Fund, Project AE 03.04-02.02 by Archipelago Marine
2641 Research, 70 pp. + appendices.
- 2642 Engel, J., Kvitek, R., 1998. Effects of otter trawling on a benthic community in Monterey Bay
2643 national marine sanctuary. *Conservation Biology* 12, 1204-1214.
- 2644 England, L.A., Thomson, R.E., Foreman, M.G.G., 1996. Estimates of seasonal flushing times for
2645 the Southern Strait of Georgia. Canadian Technical Report of Hydrography and Ocean
2646 Sciences 147, 24 pp.
- 2647 Farrow, G.E., Syvitski, J.P.M., Tunnicliffe, V.J., 1983. Suspended particulate loading on the
2648 macrobenthos in a high turbid fjord: Knight Inlet, British Columbia. *Canadian Journal of*
2649 *Fisheries and Aquatic Sciences* 40(Supplement 1), 273-288.

- 2650 Fonseca, M.S., Fisher, J.S., 1986. A comparison of canopy friction and sediment movements
2651 between four species of seagrass with reference to their ecology and restoration. *Marine*
2652 *Ecology Progress Series* 29, 15-22.
- 2653 Foreman, M.G.G., Sutherland, G., Cummings, P.F., 2004. M2 tidal dissipation around
2654 Vancouver Island: An inverse approach. *Continental Shelf Research* 24, 2167-2185.
- 2655 Foreman, M.G.G., Walters, R.A., Henry, R.F., Keller, C.P., Dolling, A.G., 1995. A tidal model
2656 for eastern Juan de Fuca Strait and the southern Strait of Georgia. *Journal of Geophysical*
2657 *Research* C1-100, 721-740.
- 2658 Freeland, H.J., Farmer, D.M., 1980. Circulation and energetics of a deep, strongly stratified inlet.
2659 *Canadian Journal of Fisheries and Aquatic Sciences* 37, 1398-1410.
- 2660 Frith, H.R., Searing, G., Wainwright, P., 1994. Methodology for a BC Shoreline biotic mapping
2661 system, Land Use Coordination Office, Government of British Columbia, Victoria, B.C.
- 2662 G3 Consulting, 2003. Britannia Beach subtidal sampling programs: Final report, prepared for
2663 Environment Canada, 62 pp.
- 2664 Gargett, A.E., Stucchi, D., Whitney, F., 2003. Physical processes associated with high primary
2665 production in Saanich Inlet, British Columbia. *Estuarine, Coastal and Shelf Science* 56,
2666 1141-1156.
- 2667 Gerlach, S.A., Hahn, A.E., Schrage, M., 1985. Size spectra of benthic biomass and metabolism.
2668 *Marine Ecology Progress Series* 26, 161-173.
- 2669 Gillespie, G.E., Bourne, N.F., 1998. Exploratory intertidal clam surveys in British Columbia-
2670 1997. *Canadian Manuscript Report of Fisheries and Aquatic Sciences* 2465, 43 pp.
- 2671 Glaholt, R., Burd, B., Haight, R., 2002. Preliminary report on the environmental effects of a
2672 marine pipeline on nearby soft bottom benthic infaunal communities, Bazan Bay, British

- 2673 Columbia, prepared for Georgia Strait Crossing Pipeline Limited by Tera Environmental
2674 Services, Ecostat Research Ltd., and Vacilador Productions Ltd., 21 pp. + appendices.
- 2675 Gordon, K., 1997. Sedimentary tracers of sewage inputs to the southern Strait of Georgia.
2676 University of British Columbia, M.Sc. thesis, 217 pp.
- 2677 Golder Associates Ltd., 2005. Potential environmental effects from the Macaulay and Clover
2678 Point Outfalls and review of the Wastewater and Marine Environment Program. Report
2679 prepared for the Capital Regional District, Victoria, BC, Canada. December 2005
- 2680 Goldstein, B.A., Perkins-Visser, E., Wolcott, T.G., Wolcott, D.L., 1996. Nursery role of
2681 seagrass beds: enhanced growth of juvenile blue crabs (*Callinectes sapidus* Rathbun). J.
2682 Exp. Mar. Biol. Ecol. 198: 155-173.
- 2683 Griffin, D.A., LeBlonde, P.H., 1990. Estuary/ocean exchange controlled by spring-neap tidal
2684 mixing. Estuarine Coastal and Shelf Science 30, 275-297.
- 2685 Grout, J.A., Levings, C.D., 2001. Effects of acid mine drainage from an abandoned copper mine,
2686 Britannica Mines, Howe Sound, British Columbia, Canada on transplanted blue mussels
2687 (*Mytilus edulis*). Marine Environmental Research 51, 265-288.
- 2688 Gucluer, S.M., Gross, M.G., 1964. Recent marine sediments in Saanich Inlet, a stagnant marine
2689 basin. Limnology and Oceanography 9, 359-375.
- 2690 GVRD, 2004. Greater Vancouver Regional District cautions, warnings, and triggers: A process
2691 for protection of the receiving environment, Prepared for the Ministry of Environment
2692 Land and Air Protection, Greater Vancouver Regional District, Burnaby, B.C., 170 pp. +
2693 appendices.

- 2694 Hagan, M., McCandless, R., More, B., Colodey, A., 2004. Nearshore contaminated sediment
2695 investigations at Britannia Beach, British Columbia, Environment Canada Pacific and
2696 Yukon Region, Regional Program Report, 03-06, 62.
- 2697 Haigh, R., Taylor, F.J.R., 1991. Mosaicism of microplankton communities in the northern Strait
2698 of Georgia, British Columbia. *Marine Biology* 110, 301-314.
- 2699 Haigh, R., Taylor, F.J.R., Sutherland, T.F., 1992. Phytoplankton ecology of Sechart Inlet, a fjord
2700 system on the British Columbia coast. I. General features of the nano- and microplankton.
2701 *Marine Ecology Progress Series* 89, 117-134.
- 2702 Hannides, A.K., Dunn, S.M., Aller, R.C., 2005. Diffusion of organic and inorganic solutes
2703 through macrofaunal mucus secretions and tube linings in sediments. *Journal of Marine*
2704 *Research* 63, 957-981.
- 2705 Harbo, R.M., Marcus, K., Boxwell, T., 1997. Intertidal clam resources (Manila, Littleneck and
2706 Butter Clam). Volume II: The southern inside waters of Vancouver Island and the British
2707 Columbia mainland, 16 pp. + maps.
- 2708 Hargrave, B.T. Holmer, M., Newcombe, C.P., 2008. Towards a classification of organic
2709 enrichment in marine sediments based on biogeochemical indicators. *Marine Pollution*
2710 *Bulletin*, 56, 810-824.
- 2711 Harper, J.R., 1995. Physical processes overview for the west coast of Vancouver Island, report to
2712 the Land Use Coordination Office, Victoria, Government of British Columbia.
- 2713 Harper, J.R., Christian, J., Cross, W.E., Frith, R., Searing, G., Thompson, D., 1993a. A
2714 classification of the marine regions of Canada, Environment Canada, Vancouver, B.C.
- 2715 Harper, J.R., Peters, S., Booth, J., Dickins, D.F., Morris, M. 1993b. Coastal information resource
2716 inventory, prepared for the Resources Inventory Committee, Province of British

- 2717 Columbia., Victoria, B.C., 81 pp. Available electronically at:
2718 http://www.ilmb.gov.bc.ca/risc/o_docs/coastal/cir/assets/coastal.pdf
- 2719 Harrison, P.J., 1981. The biological determinants of the structure of harpacticoid copepod
2720 communities on an estuarine intertidal flat (Fraser River Delta, B.C.), University of
2721 British Columbia, Ph.D. thesis, 455 pp.
- 2722 Harrison, P.J., Fulton, J.D., Taylor, F.J.R., Parsons, T.R., 1983. Review of the biological
2723 oceanography of the Strait of Georgia: pelagic environment. Canadian Journal of
2724 Fisheries and Aquatic Sciences 40, 1064-1094.
- 2725 Harrison, P.J., Yin, K., 1998. Ecosystem delineation in the Georgia Basin based on nutrients,
2726 chlorophyll, phytoplankton species and primary production, in: Levings, C.D., Aitkens,
2727 F., (Eds.), Approaches to Marine Ecosystem Delineation in the Strait of Georgia:
2728 Proceedings of a D.F.O. workshop, Sidney, B.C., 4-5 November, 1997, Canadian
2729 Technical Report of Fisheries and Aquatic Sciences 2247, 124-134.
- 2730 Harrison, P.J., Yin, K., Ross, L., Arvai, J., Gordon, K., Bendell-Young, L.I., Thomas, C., 1999.
2731 The delta foreshore ecosystem: past present status of geochemistry, benthic community
2732 production and shorebird utilization after sewage diversion, in: Gray, C., Tuominen, T.,
2733 (Eds.), Health of the Fraser River Aquatic Ecosystem, Environment Canada, Vancouver,
2734 B.C., pp. 189-210.
- 2735 Hart, B.S., Hamilton, T.S., Barrie, J.V., 1998. Sedimentation rates and patterns on a deep-water
2736 delta (Fraser Delta, Canada) integration of high-resolution seismic stratigraphy, core
2737 lithofacies, and ¹³⁷Cs fallout stratigraphy. Journal of Sedimentary Research 68, 556-568.

- 2738 Hayashi, K.I., Ogawa, Y., 1987. *Spongicola levigata* sp. nov., a new shrimp associated with a
2739 hexactinellid sponge from the East China Sea (Decapoda, Stenopodidae). Zoological
2740 Science (Tokyo) 4, 367-373.
- 2741 Heck, K.J., Able, K., Fahay, M., Roman, C., 1989. Fishes and decapod crustaceans of Cape Cod
2742 eelgrass meadows: Species composition, seasonal abundance patterns and comparison
2743 with unvegetated substrates. Estuaries 12, 59-65.
- 2744 Heck, K.L., Hays, G., Orth, R.J., 2003. Critical evaluation of the nursery role hypothesis for
2745 seagrass meadows. Mar. Ecol. Prog. Ser. 253: 123-136.
- 2746 Hewitt, J.E., Pridmore, D., Thrush, S.F. and Cummings, V.J., 1997. Assessing the Short-Term
2747 Stability of Spatial Patterns of Macrobenthos in a Dynamic Estuarine System. Limnology
2748 and Oceanography 42, 282-288.
- 2749 Hickin, E.J., 1989. Contemporary Squamish River sediment flux to Howe Sound. Canadian
2750 Journal of Earth Sciences, 26, 1953-1963.
- 2751 Hickin, E.J., 1992. An inventory of research conducted in Squamish Basin: Proceedings of the
2752 Howe Sound environmental workshop (September 30-October 3, 1991, Bowen Island,
2753 B.C.). Canadian Technical Report of Fisheries and Aquatic Sciences 1879, 43-47.
- 2754 Hill, P.R., Conway K., Lintern, G.D., Meulé, S., Picard, K., Barrie, J.V. *In press*. Sedimentary
2755 processes and sediment dispersal in the southern Strait of Georgia, BC, Canada. Marine
2756 Environmental Research.
- 2757 Hodgins, D.O., Hodgins, S.L.M., 2000. A Re-evaluation of Iona effluent solids deposition based
2758 on sediment grain size characteristics, in: Greater Vancouver Regional District, (Ed.),
2759 Development of a Receiving Environment Monitoring Approach to Liquid Waste
2760 Management. Progress Workshop 2 December 6, 2000, Support Material Part 2 of 3 Iona

- 2761 WWTP Receiving Environment, Draft Technical Report, GVRD, Burnaby, B.C., pp. 1.1
2762 -1.24.
- 2763 Hodgins, D.O., Chapman, P.M., Bailey, H.C., 2000. Lions Gate wastewater treatment plant
2764 monitoring program, proposed Cycle 1: Environmental monitoring program, Greater
2765 Vancouver Regional District, Vancouver, BC, Draft Report, 77 pp.
- 2766 Holte, B., Gulliksen, B., 1998. Common macrofaunal dominant species in the sediments of some
2767 north Norwegian and Svalbard glacial fjords. *Polar Biology* 19, 375-382.
- 2768 Hoos, L.M., Vold, C.L., 1975. The Squamish River Estuary: Status of environmental knowledge
2769 to 1974, Environment Canada Special Estuary Series Report 2, 361 pp.
- 2770 Hoskins, D.L., Stancyk, S.E., Decho, A.W., 2003. Utilization of algal and bacterial extracellular
2771 polymeric secretions (EPS) by the deposit-feeding brittlestar *Amphiopholis gracillima*
2772 (Echinodermata). *Marine Ecology Progress Series* 247, 93-101.
- 2773 Howes, D.E., Harper, J.R., Owens, E., 1994. British Columbia physical shore-zone, British
2774 Columbia Resource Inventory Committee, Victoria, B.C., 84 pp.
- 2775 Howes, D.E., Wainwright, P., Haggarty, J., Harper, J.R., Owens, E., Reimer, D., Summers, K.,
2776 Cooper, J., Berg, L., Baird, R., 1993. Coastal resource and oil spill atlas for the southern
2777 Strait of Georgia, B.C. Ministry of the Environment, Lands and Parks, Environmental
2778 Emergencies Coordination Office, Victoria, B.C., 317 pp.
- 2779 Howes, D.E., Zacharias, M.A., Harper, J.R., 1996. The Marine ecoregions of British Columbia,
2780 The Land Use Coordination Office, Government of British Columbia, Victoria, B.C.
- 2781 Huggett, W.S., Thomson, R.E., Woodward, M.J., Douglas, A.N., 1980. Data record of current
2782 observations, Vol. VII Johnstone Strait, 1976, 1977, 1978, Institute of Ocean Sciences,
2783 Sidney, B.C., 288 pp.

- 2784 Hunt, H.L., Mullineaux, L.S., 2002. The Roles of Predation and Postlarval Transport in
2785 Recruitment of the Soft Shell Clam (*Mya arenaria*). *Limnology and Oceanography* 47,
2786 151-164.
- 2787 Jamieson, G.S., 1988. Vertical distribution and mass mortality of prawns, *Pandalus platyceros*,
2788 in Saanich Inlet. *Fishery Bulletin* 86, 601-608.
- 2789 Jamieson, G.S., Chew, L., Gillespie, L., Robinson, g., Bendell-Young, L., Heath, W., Bravender,
2790 B., Tompkins, A., Nishimura, D., Doucett, P., 2001. Phase 0 review of the environmental
2791 impacts of intertidal shellfish aquaculture in Baynes Sound. Canadian Science Advisory
2792 Secretariat Research Document 2001/125. URL: [http://www.dfo-](http://www.dfo-mpo.gc.ca/csas/Csas/publications/ResDocs-DocRech/2001/2001_125_e.htm)
2793 [mpo.gc.ca/csas/Csas/publications/ResDocs-DocRech/2001/2001_125_e.htm](http://www.dfo-mpo.gc.ca/csas/Csas/publications/ResDocs-DocRech/2001/2001_125_e.htm)
- 2794 Jamieson, G.S., Levings, C.D., Mason, B.C. and Smiley, B.D., 1999. Shorekeepers' guide for
2795 monitoring Intertidal habitats in Canada's Pacific waters, Fisheries and Oceans Canada,
2796 Sidney, BC, Modules 1, 2, and 3.
- 2797 Je, J.-G., Belan, T., Levings, C., Koo, B.J., 2003. Changes in benthic communities along a
2798 presumed pollution gradient in Vancouver Harbour. *Marine Environmental Research* 57,
2799 121-135.
- 2800 Johannessen, S.C., Macdonald, R.W., Eek, K.M., 2005a. Historical trends in mercury
2801 sedimentation and mixing in the Strait of Georgia, Canada. *Environmental Science &*
2802 *Technology* 39, 4361-4368.
- 2803 Johannessen, S.C., Macdonald, R.W., Paton, D.W., 2003. A sediment and organic carbon budget
2804 for the greater Strait of Georgia. *Estuarine, Coastal and Shelf Science* 56, 845-860.

- 2805 Johannessen, S.C., Macdonald, R.W., Wright, C.A., Burd, B., Shaw, D.P., van Roodselaar, A., *In*
- 2806 *Press*. Joined by geochemistry, divided by history: PCBs and PBDEs in the Strait of
- 2807 Georgia sediments. *Marine Environmental Research*.
- 2808 Johannessen, S.C., Masson, D., Macdonald, R.W., 2006. Distribution and cycling of suspended
- 2809 particles inferred from transmissivity in the Strait of Georgia, Haro Strait and Juan de
- 2810 Fuca Strait. *Atmosphere-Oceans* 44, 17-27.
- 2811 Johannessen, S.C., O'Brien, M.C., Denman, K.L., Macdonald, R.W., 2005b. Seasonal and spatial
- 2812 variations in the source and transport of sinking particles in the Strait of Georgia, British
- 2813 Columbia, Canada. *Marine Geology* 216, 59-77.
- 2814 Kathman, R.D., Cross, S.F., Waldichuk, M., 1984. Effects of wood waste on the recruitment of
- 2815 marine benthic communities. *Canadian Technical Report of Fisheries and Aquatic*
- 2816 *Sciences* 1284, 50 pp.
- 2817 Kellerhals, P., Murray, J.W., 1969. Tidal flats at Boundary Bay, Fraser River Delta, British
- 2818 Columbia. *Bulletin of Canadian Petroleum Geology* 17, 67-91.
- 2819 Kennett, K., McPhee, M.W., 1988. The Fraser River Estuary: An overview of changing
- 2820 conditions, Fraser River Estuary Management Program, New Westminster, B.C., 31 pp.
- 2821 Kozloff, E. N., 1987. Marine invertebrates of the Pacific northwest. University of Washington
- 2822 Press, Seattle, WA., 511 pp.
- 2823 Krautter, M., Conway, K.W., Barrie, J.V., Neuweiler, M., 2001. Discovery of a living dinosaur:
- 2824 Globally unique modern hexactinellid sponge reefs off British Columbia, Canada. *Facies*
- 2825 44, 265-282.

- 2826 Kristensen, E., 1988. Benthic fauna and biogeochemical processes in marine sediments:
2827 microbial activities and fluxes, in: Blackburn, T.H., Sorensen, J., (Eds.), Nitrogen
2828 Cycling in Coastal Marine Environments, John Wiley & Sons, Chichester, pp. 275-299.
- 2829 Kristensen, E., Kostka, J.E., 2005. Macrofaunal burrows and irrigation in marine sediment:
2830 microbiological and biogeochemical interactions, in: Kristensen, E., Haese, R., Kostka,
2831 J.E., (Eds.), Interactions between Macro- and Microorganisms in Marine Sediments.
2832 American Geophysical Union, Washington, D.C., pp. 125-158.
- 2833 Lamb, A., Edgell, P., 1986. Coastal Fishes of the pacific northwest, Madiera Park, B.C., Harbour
2834 Publishing, 224 pp.
- 2835 Lauzier, R.B., Hand, C.M., Campbell, A., Heizer, S., 1998. A review of the biology and fisheries
2836 of the horse clams (*Tresus capax* and *Tresus nuttalli*). Canadian Stock Assessment
2837 Secretariat Research Document 1998/88, 33 pp.
- 2838 LeBlonde, P.H., 1983. The Strait of Georgia: functional anatomy of a coastal sea. Canadian
2839 Journal of Fisheries and Aquatic Sciences 40, 1033-1063.
- 2840 Levings, C.D., 1980a. Benthic biology of a dissolved oxygen deficiency event in Howe Sound,
2841 B.C., in: Freeland, H.J., Farmer, D.M., Levings, C.D., (Eds.), Fjord Oceanography, New
2842 York, Plenum Publishing, pp. 515-522.
- 2843 Levings, C.D., 1980b. Demersal and benthic communities in Howe Sound basin and their
2844 responses to dissolved oxygen deficiency. Canadian Technical Report of Fisheries and
2845 Aquatic Sciences,, 951, 27 pp.
- 2846 Levings, C.D., Barry, K.L., Grout, J.A., Piercey, G.E., Marsden, A.D., Coombs, A.P., Mossop,
2847 B., 2004. Effects of acid mine drainage on the estuarine food web, Britannica Beach,
2848 Howe Sound, British Columbia, Canada. Hydrobiologia 525, 185-202.

- 2849 Levings, C.D., Coustalin, J.B., 1975. Zonation of intertidal biomass and related benthic data
2850 from Sturgeon and Roberts Bank, Fraser River Estuary, British Columbia. Fisheries and
2851 Marine Technical Services 468, 138 pp.
- 2852 Levings, C.D., Foreman, R.E., Tunnicliffe, V.J., 1983. Review of the benthos of the Strait of
2853 Georgia and contiguous fjords. Canadian Journal of Fisheries and Aquatic Sciences 40,
2854 1120-1141.
- 2855 Levings, C.D., Jamieson, G.S., 2001. Marine and estuarine riparian habitats and their role in
2856 coastal ecosystems, Pacific Region. Canadian Science Advisory Secretariat Research
2857 Document 2001/109, 42 pp.
- 2858 Levings, C.D., McDaniel, N., 1973. Biological observations from the submersible PICES IV
2859 near Britannia Beach, Howe Sound, BC, Fisheries Research Board Technical Report,
2860 409, 23 pp.
- 2861 Levings, C.D., McDaniel, N.G., 1974. A unique collection of baseline biological data: Benthic
2862 invertebrates from an under-water cable across the Strait of Georgia. Fisheries Research
2863 Board of Canada, Technical Report 441, 19 pp.
- 2864 Levings, C.D., McDaniel, N.G., 1976. Industrial disruption of invertebrate communities on
2865 beaches in Howe Sound, B.C. Fisheries Marine Services Technical Report 663, 100 pp.
- 2866 Levings, C.D., Samis, S., 2001. Section II site description and oceanography, in: Stehr, C.M.,
2867 Horiguchi, T., (Eds.), Environmental Assessment of Vancouver Harbour Data Report for
2868 the PICES Practical Workshop, PICES Scientific Report No. 16, PICES Secretariat,
2869 Sidney, B.C., pp. 15-21.
- 2870 Levings, C.D., Thom, R.M., 1994. Habitat changes in Georgia Basin: Implications for resource
2871 management and restoration, in: Wilson, R.C.H., Beamish, R.J., Aikens, F., Bell, J.,

- 2872 (Eds.), Review of the Marine Environment and Biota of Strait of Georgia, Puget Sound
2873 and Juan de Fuca Strait: Proceedings of the BC/Washington Symposium of the Marine
2874 Environment, January 13 and 14, 1994. Canadian Technical Report of Fisheries and
2875 Aquatic Sciences 1948, 330-351.
- 2876 Li, M., Gargett, A., Denman, K., 1999. Seasonal and interannual variability of estuarine
2877 circulation in a box model of the Strait of Georgia and Juan de Fuca Strait. *Atmosphere-*
2878 *Ocean* 37, 1-19.
- 2879 Llansó, R.J., Aasen, S., Welch, K., 1998. Marine sediment monitoring program: II. Distribution
2880 and structure of benthic communities in Puget Sound 1989-1993, Washington State
2881 Department of Ecology: Environmental investigations and laboratory services program,
2882 Olympia, Washington, 114 pp. + appendices.
- 2883 Long, E.R., Hong, C.B., Severn, C.G., 2001. Relationships between acute sediment toxicity in
2884 laboratory tests and abundance and diversity of benthic infauna in marine sediments: a
2885 review. *Environmental Toxicology and Chemistry* 20, 46-60.
- 2886 Macdonald, R.W., Crecelius, E.A., 1994. Marine sediments in the Strait of Georgia, Juan de
2887 Fuca Strait and Puget Sound: What can they tell us about contamination? in: Wilson,
2888 R.C.H., Beamish, R.J., Aitkens, F., Bell, J., (Eds.), Review of the Marine Environment
2889 and Biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait. Canadian Technical
2890 Report of Fisheries and Aquatic Sciences 1948, 101-137.
- 2891 Macdonald, R.W., Cretney, W.J., Crewe, N., Paton, D., 1992. A history of octachlorodibenzo-p-
2892 dioxin, 2,3,7,8-tetrachlorodibenzofuran and 3,3', 4-4'-tetrachlorobiphenyl contamination
2893 in Howe Sound, British Columbia. *Environmental Science & Technology* 26, 1544-1550.

- 2894 Macdonald, R.W., Johannessen, S.C., Gobeil, C., Wright, C.A., Burd, B.J., van Roodselaar, A.,
2895 *In press*. Sediment redox tracers in the Strait of Georgia sediments - can they inform us
2896 of the loadings of organic carbon from municipal wastewater? Marine Environmental
2897 Research.
- 2898 Macdonald, R.W., Macdonald, D.M., O'Brien, M.C., Gobeil, C., 1991. Accumulation of heavy
2899 metals (Pb, Zn, Cu, Cd), carbon and nitrogen in sediments from the Strait of Georgia,
2900 B.C., Canada. Marine Chemistry 34, 109-135.
- 2901 Mackas, D.L., Louttit, G.C., 1988. Aggregation of the copepod *Neocalanus plumchrus* at the
2902 margin of the Fraser River plume in the Strait of Georgia. Bulletin of Marine Science 43,
2903 810-824.
- 2904 Madrone Consulting Ltd., 1993. Bamberton: Biological inventory and evaluation, 1992-1993,
2905 prepared for South Island Development Corporation, Victoria, B.C.
- 2906 Marinone, S.G., Pond, S., 1996. A three-dimensional model of deep water renewal and its
2907 influence on residual currents in the central Strait of Georgia, Canada. Estuarine, Coastal
2908 and Shelf Science 43, 183-204.
- 2909 Masson, D., 2002. Deep water renewal in the Strait of Georgia. Estuarine, Coastal and Shelf
2910 Science 54, 115-126.
- 2911 Masson, D., Cummings, P.F., 2000. Fortnightly modulation of estuarine circulation in Juan de
2912 Fuca Strait. Journal of Marine Research 58, 439-463.
- 2913 Masson, D., Cummings, P.F., 2004. Observations and modeling of seasonal variability in the
2914 Straits of Georgia and Juan de Fuca. Journal of Marine Research 62, 491-516.
- 2915 Maurer, D., Aprill, G., 2007. Intertidal benthic invertebrates and sediment stability at the mouth
2916 of Delaware Bay. International Review of Hydrobiology 64, 379-403.

- 2917 McDaniel, N.G., 1973. A Survey of Benthic Macroinvertebrate Fauna and Solid Pollutants in
2918 Howe Sound. Fisheries Research Board of Canada Technical Report 385, 64 pp.
- 2919 McGreer, E.R., Moore, D.M., Sibert, J.R., 1984. Study of the recovery of intertidal benthos after
2920 removal of log booms, Nanaimo River Estuary, British Columbia. Canadian Technical
2921 Report of Fisheries and Aquatic Sciences 1246, vii + 63 pp.
- 2922 McLaren, P., 1994. Sediment transport in Vancouver Harbour: Implications to the fate of
2923 contaminated sediments and/or dredged material disposal, A Report for the Burrard Inlet
2924 Environmental Action Program, Vancouver, B.C., 25 pp. + appendices.
- 2925 McLaren, P., Crenthey, W.J., Powys, R.I., 1993. Sediment pathways in a British Columbia fjord
2926 and their relationship with particle associated contaminants. Journal of Coastal Research
2927 9, 1026-1043.
- 2928 McLaren, P., Ren, P., 1995. Sediment transport and its environmental implications in the lower
2929 Fraser River and Fraser Delta, A Report for Environment Canada, DOE FRAP 1993.03,
2930 Vancouver, B.C., 38 pp.
- 2931 McPherson, C.A., Bailey, H.C., Chapman, M.K., Lee, M.K., Burd, B.J., Fanning, M.L., Paine,
2932 M.D., Hamilton, M.C., Chen, F., 2003. Iona Deep-sea Outfall, 2002 Environmental
2933 monitoring program: Sediment effects survey, prepared for the Greater Vancouver
2934 Regional District by EVS Consultants Ltd., Burnaby, B.C., 223 pp. + appendices.
- 2935 McPherson, C.A., Chapman, M.K., Fanning, M.L., Olson, J., Chen, F., 2004a. Georgia Strait
2936 ambient monitoring program - Data report, prepared for the Greater Vancouver Regional
2937 District by EVS Consultants Ltd, Burnaby, B.C., 28 pp. + appendices.
- 2938 McPherson, C.A., Chapman, M.K., Lee, M.K., Burd, B.J., Fanning, M.L., Hamilton, M.C.,
2939 Chen, F., 2004b. Iona Deep-sea Outfall, 2003 Environmental monitoring program:

- 2940 Sediment effects survey, prepared for the Greater Vancouver Regional District by EVS
2941 Consultants Ltd., Burnaby, BC, 262 pp. + appendices.
- 2942 McPherson, C.A., Chapman, M.K., Lee, M.K., Fanning, M.L., Olson, J., Chen, F., 2004c. Lions
2943 Gate Outfall, 2003 Environmental monitoring program: Sediment effects survey,
2944 prepared for the Greater Vancouver Regional District by EVS Consultants Ltd., Burnaby,
2945 B.C., 99 pp. + appendices.
- 2946 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,
2947 Hamilton, M.C., Chen, F., 2005a. Iona Deep-sea Outfall, 2004 Environmental monitoring
2948 program: Sediment effects survey, prepared for the Greater Vancouver Regional District
2949 by EVS Consultants Ltd., Burnaby, B.C., 222 pp. + appendices.
- 2950 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,
2951 Hamilton, M.C., Chen, F., 2006a. Iona Deep-sea Outfall, 2005 Environmental monitoring
2952 program: Sediment effects survey, prepared for the Greater Vancouver Regional District
2953 by EVS Consultants Ltd., Burnaby, B.C., 262 pp. + appendices.
- 2954 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,
2955 Hamilton, M.C., Chen, F., 2007a. Iona Deep-sea Outfall, 2006 Environmental monitoring
2956 program: Sediment effects survey, prepared for the Greater Vancouver Regional District
2957 by EVS Consultants Ltd., Burnaby, B.C., 240 pp. + appendices.
- 2958 McPherson, C.A., Chapman, P.M., McKinnon, S.J., Burd, B.J., Fanning, M.L., Olson, J.,
2959 Markovic-Mirovic, N, 2006b. Lions Gate Outfall, 2005 Sediment Effects Survey. Final
2960 Report prepared for the Greater Vancouver Regional District (GVRD), Burnaby, BC by
2961 Golder Associates Ltd. North Vancouver, BC. 222 pp. + appendices.

- 2962 McPherson, C.A., Chapman, P.M., McKinnon, S.J., Burd, B.J., Fanning, M.L., Olson, J., Ross-
2963 Easton, H., Brooks, G., 2007b. Lions Gate Outfall, 2006 Sediment Effects Survey. Prepared
2964 for the Greater Vancouver Regional District (GVRD), Burnaby, BC by Golder Associates
2965 Ltd. North Vancouver, BC. 238 pp. + appendices.
- 2966
2967 McPherson, C.A., Chapman, M.K., McKinnon, S.J., Fanning, M.L., Burd, B.J., Olson, J., Chen,
2968 F., Brooks, G., 2005b. Lions Gate Outfall, 2004 Sediment Effects Survey, Prepared for
2969 the Greater Vancouver Regional District by EVS Consultants Ltd, Burnaby, BC, 212
2970 pp.+ appendices.
- 2971 Møller, M.M., Nielsen, L.P., Jørgensen, B.B., 1985. Oxygen responses and mat formation by
2972 *Beggiatoa* spp. Applied and Environmental Microbiology 50, 373-382.
- 2973 Mosher, D.C., Currie, R.G., Sullivan, D., 1997. Monitoring of ocean disposal using side-scan
2974 mosaicing. Leading Edge 16, 1667-1669.
- 2975 MWLAP, 2002. Protocols for Marine environmental monitoring in support of finfish aquaculture
2976 waste control regulations, Ministry of Water Land and Parks, Environmental Protection
2977 Division, Victoria, B.C., 29 pp.
- 2978 NEMP, 2002. Final report of the log storage working group, prepared for the Nanaimo Estuary
2979 Management Plan Steering Committee, Ministry of Integrated Land and Management
2980 Bureau, Government of British Columbia, 27 pp.
- 2981 Newell, R. C., Seiderer, L. J., Hitchcock, D. R., 1998. The impact of dredging works in coastal
2982 waters: a review of the sensitivity to disturbance and subsequent recovery of biological
2983 resources on the sea bed. Oceanography and Marine Biology: An Annual Review 36,
2984 127-178.

- 2985 Nickel, L.A., Atkinson, R.J.A., 1995. Functional morphology of burrows and trophic modes of
2986 three thalassinidean shrimp species and a new approach to classification of thalassinidean
2987 burrow morphology. *Marine Ecology Progress Series* 128, 181-197.
- 2988 Orvain, F., Le Hir, P., Sauriau, P.-G., 2003. A model of fluff layer erosion and subsequent bed
2989 erosion in the presence of the bioturbator, *Hydrobia ulvae*. *Journal of Marine Research*
2990 61, 823-851.
- 2991 Otte, G., Levings, C.D., 1975. Distribution of macroinvertebrates communities on mudflat
2992 influenced by sewage. Fraser River Estuary, British Columbia. Fisheries Marine Series
2993 Technical Report 476, 78 pp.
- 2994 Paine, Ledge and Associates, 2004. Analyses of Macaulay Point sediment quality data: 1990-
2995 2003. Prepared for Capital Region District, Environmental Services, 137 pp. Paine,
2996 Ledge and Associates (PLA). North Vancouver, British Columbia.
- 2997 Paine, M.D., 2003. Environmental significance of sediment quality and tissue residue monitoring
2998 data for the GVRD Iona and Lions Gate outfall study areas. Draft Report, Prepared for
2999 the Greater Vancouver Regional District (GVRD) by Paine, Ledge and Associates (PLA),
3000 North Vancouver, 31 pp. + Tables + Figures.
- 3001 Paine, R.T., Vadas, R.L., 1969. The effects of grazing by sea urchins. *Strongylocentrotus* spp., on
3002 benthic algal populations. *Limnology and Oceanography* 14, 710-719.
- 3003 Palsson, W.A., Hoffmann, S., Clarke, P., Beam, J., 2003. Results from the 2001 transboundary
3004 trawl survey of the southern Strait of Georgia, San Juan Archipelago and adjacent waters,
3005 Report for the Washington Department of Fish and Wildlife, 117 pp.

- 3006 Parsons, T.R., Stronach, J., Borstad, G.A., Louttit, G., Perry, R.I., 1981. Biological fronts in the
3007 Strait of Georgia, British Columbia, and their relation to recent measurements of primary
3008 productivity. *Marine Ecology Progress Series* 6, 237-242.
- 3009 Pawlowicz, R., 2001. A tracer method for determining transport in two-layer systems, applied to
3010 the Strait of Georgia/Haro Strait/Juan de Fuca Strait estuarine system. *Estuarine, Coastal
3011 and Shelf Science* 52, 491-503.
- 3012 Pawlowicz, R., 2002. Observations and linear analysis of estuarine flow and sill-generated
3013 internal tides in Haro Strait. *Journal of Geophysical Research* 107, [np], DOI:
3014 10.1029/2000JC000504.
- 3015 Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment
3016 and pollution of the marine environment. *Oceanography and Marine Biology Annual
3017 Review* 16, 229-311.
- 3018 PICES (Ed.), 2001. Environmental assessment of Vancouver Harbour data report for the PICES
3019 practical workshop, North Pacific Marine Sciences Organization (PICES) Secretariat,
3020 PICES, Sidney, B.C., 203 pp.
- 3021 Pickard, G.L., Giovando, L.F., 1960. Some observations of turbidity in British Columbia inlets.
3022 *Limnology and Oceanography* 5, 162-170.
- 3023 Pohle, G., Frost, B., Findlay, R., 2001. Assessment of regional benthic impact of salmon
3024 mariculture within the Letang Inlet, Bay of Fundy. *ICES Journal of Marine Science* 58,
3025 417-426.
- 3026 Post, A.L., Wassenberg, T.J., Passlow, V., 2006. Physical surrogates for macrofaunal
3027 distributions and abundance in a tropical gulf. *Marine and Freshwater Research* 57, 469-
3028 483.

- 3029 Prior, D.B., Bornhold, B.D., Wiseman, W.J.J., Lowe, D.R., 1987. Turbidity current activity in a
3030 British Columbia fjord. *Science* 237, 1330-1333.
- 3031 Probert, P.K., 1984. Disturbance, sediment stability, and trophic structure of soft-bottom
3032 communities. *Journal of Marine Research* 42, 893-921.
- 3033 Ragnarsson, S.A., Raffaelli, D., 1999. Effects of the mussel *Mytilus edulis* L. on the
3034 invertebrate fauna of sediments. *J. Exp. Mar. Biol. Ecol.* 241, 31-43.
- 3035 Reid, B.J., Baumann, J., 1985. Preliminary laboratory study of the effects of burial by
3036 AMAX/Kitsault mine tailings on marine invertebrates. Canadian Manuscript Report of
3037 Fisheries and Aquatic Sciences 1781, 45 pp.
- 3038 Rescan Environmental Services Ltd., 1988. Preliminary environmental overview of proposed
3039 ferrochromium production facility Bamberton, B.C., prepared for the Ministry of
3040 Regional Development, Government of British Columbia.
- 3041 Rhoads, D.C., Young, D.K., 1970. Influence of deposit-feeding organisms on sediment stability
3042 and community trophic structure. *Journal of Marine Research* 28, 150-178.
- 3043 Roegner, C., Andre, C., Lindegarth, M., Eckman, J.E., Grant, J., 1995. Transport of recently
3044 settled soft-shell clams (*Mya arenaria* L.) in laboratory flume flow. *Journal of*
3045 *Experimental Marine Biology and Ecology* 187, 13-26.
- 3046 Rowe, G., Sibuet, M., Deming, J., Khripoundoff, A., Tietjen, J., Macko, S., Theroux, R., 1991.
3047 'Total' sediment biomass and preliminary estimates of organic carbon residence time in
3048 deep-sea benthos. *Marine Ecology Progress Series* 79, 99-114.
- 3049 Samis, S.C., Liu, S.D., Wernick, B.G., Nassichuk, M.D., 1999. Mitigation of fisheries impacts
3050 from the use and disposal of wood residue in British Columbia and the Yukon. Canadian
3051 Technical Report of Fisheries and Aquatic Sciences 2296, viii + 91 pp.

- 3052 Schwinghamer, P., 1981. Characteristic size distributions of integral benthic communities.
3053 Canadian Journal of Fisheries and Aquatic Sciences 38, 1255-1263.
- 3054 Schwinghamer, P., 1983. Generating ecological hypotheses from biomass spectra using causal
3055 analysis: A benthic example. Marine Ecology Progress Series 13, 151-166.
- 3056 Seacology, Pacific Marine Life Surveys Inc., Tera Environmental Consultants (Alta.) Ltd., 2001.
3057 Biological survey and assessment of benthic habitats for a proposed Manley Creek
3058 pipeline landfall at Boatswain Bank, British Columbia-July 2000, prepared for Georgia
3059 Strait Crossing Pipeline Ltd., 47 pp. + appendices.
- 3060 Seed, R., Suchanek, T.H., 1972. Population and community ecology of *Mytilus*, in: Gosling,
3061 E.M., (Ed.), The Mussel *Mytilus*: Ecology, Physiology, Genetics, Culture, Amsterdam,
3062 Elsevier Scientific, pp. 87-169.
- 3063 Shang, D.Y., Macdonald, R.W., Ikonomu, M.G., 1999. Persistence of nonylphenol and
3064 ethoxylate surfactants and their principle primary degradation products in sediments
3065 from near a municipal outfall in the Strait of Georgia, British Columbia, Canada.
3066 Environmental Science & Technology 33, 1366-1372.
- 3067 Sibert, J.R., 1979. Detritus and juvenile salmon production in the Nanaimo Estuary: 2.
3068 Meiofauna available as food to juvenile chum salmon (*Oncorhynchus keta*). Journal of
3069 the Fisheries Research Board of Canada 36, 497-503.
- 3070 Sibert, J.R., 1981. Intertidal hyperbenthic populations in the Nanaimo Estuary. Marine Biology
3071 64, 259-265.
- 3072 Sibert, J.R., Brown, T.J., Harpham, V.J., Kask, B.J., 1979. Meiofauna counts in relation to
3073 intertidal log storage on the Nanaimo River delta: Spring 1978. Fisheries and Marine
3074 Service Data Report 149, 105 pp.

- 3075 Sibert, J.R., Harpham, V.J., 1979. Effects of intertidal log storge on the meiofauna and
3076 interstitial environment of the Nanaimo River delta. Technical Report of the Fisheries
3077 Marine Service (Canada) 833, 31 pp.
- 3078 Smith, A.L., 1981. Comparison of macrofaunal invertebrates in sand dollar (*Dendraster*
3079 *excentricus*) beds and in adjacent areas free of sand dollars. Marine Biology 65, 191-198.
- 3080 Smith, J.R., Fong, P., Ambrose, R. F., 2006. Dramatic declines in mussel bed community
3081 diversity : Response to climate change? Ecology 87, 1153-1161.
- 3082 Snyder, S.W., Hale, W.R., Kontrovitz, M., 1990. Assessment of Postmortem Transportation of
3083 Modern Benthic Foraminifera of the Washington Continental Shelf. Micropaleontology,
3084 36, 259-282.
- 3085 Spaulding, H., Foster, M.S., Heine, J.N., 2003. Composition, distribution, and abundance of
3086 deep-water (>30 m) macroalgae in central California. Journal of Phycology 39, 273-284.
- 3087 Stacey, M.W., Pond, S., 2003. The dependence of the currents and the density on the spring-neap
3088 cycle and the diurnal-inequality in Burrard Inlet, British Columbia: simulations and
3089 observations. Journal of Physical Oceanography 33, 2366-2374.
- 3090 Stacey, M.W., Pond, S., LeBlonde, P.H., 1991. Flow dynamics in the Strait of Georgia, British
3091 Columbia. Atmosphere-Ocean 29, 1-13.
- 3092 Stehr, C.M., Horiguchi, T., (Eds.), 2001. Environmental assessment of Vancouver Harbour, data
3093 report for the PICES practical workshop 16, North Pacific Marine Sciences Organization
3094 (PICES) Secretariat, 205 pp.
- 3095 Stephenson, T.A., Stephenson, A., 1961a. Life between tidemarks in North America. IVA.
3096 Vancouver Island II. Journal of Ecology, 49, 1-29.

- 3097 Stephenson, T.A., Stephenson, A., 1961a. Life between tidemarks in North America. IVB.
3098 Vancouver Island II. Journal of Ecology, 49, 227-243.
- 3099 Stephenson, T.A., Stephenson, A., 1972. Life between tidemarks on rocky shores. Freeman,
3100 USA, 425 pp.
- 3101 Stockner, J.G., Cliff, D.D., Shortreed, K.R.S., 1979. Phytoplankton ecology of the Strait of
3102 Georgia, British Columbia. Journal of the Fisheries Research Board of Canada 36, 657-
3103 666.
- 3104 Striplin, P., 1996. Development of reference value ranges for benthic infauna assessment
3105 endpoints in Puget Sound, Washington, State Department of Ecology Sediment
3106 Management Unit, 44 pp. + appendices.
- 3107 Stubblefield, W.A., Servos, M., Gersberg, R.M., Riley, C., Simpson, D., Smith, D., Wells, P.,
3108 2006. Scientific and technical review. Capital Regional District core area Liquid Waste
3109 Management Plan, Submitted to the Capital Regional District, Victoria B.C. by the
3110 Scientific and Technical Review Panel, 131 pp.
- 3111 Stucchi, D.J., Sutherland, T., Levings, C., Higgs, D., 2005. Near-field depositional model for
3112 salmon aquaculture waste, in: Hargrave, B.T., (Ed.), Handbook of Environmental
3113 Chemistry: The Environmental Effects of Marine Finfish Aquaculture, Volume 5, Part M,
3114 Springer-Verlag, Berlin, pp. 157-179.
- 3115 Suchanek, T.H., 1979. The *Mytilus californianus* community: studies on the composition,
3116 structure, organization and dynamics of a mussel bed, University of Washington, Ph.D.
3117 thesis, 286 pp.
- 3118 Swinbanks, D.D., Murray, J.W., 1981. Biosedimentological zonation of Boundary Bay tidal
3119 flats, Fraser River Delta, British Columbia. Sedimentology 28, 201-237.

- 3120 Taylor, F.J.R., Haigh, R., Sutherland, T.H., 1994. Phytoplankton ecology of Sechelt Inlet, a fjord
3121 system on British Columbia coast. II. Potentially harmful species. *Marine Ecology*
3122 *Progress Series* 103, 151-164.
- 3123 Thompson, D., Cooke, W., 1991. Enhancement of hardshell clam habitat by beach gravelling, in:
3124 Puget Sound Water Quality Action Team (Eds.), *Puget Sound Research '91*. Seattle,
3125 Washington, Proceedings, pp 521-527.
- 3126 Thomson, R.E., 1976. Tidal currents and estuarine-type circulation in Johnstone Strait, British
3127 Columbia. *Journal of the Fisheries Research Board of Canada* 33, 2242-2264.
- 3128 Thomson, R.E., 1977. Currents in Johnstone Strait, British Columbia: supplementary data on the
3129 Vancouver Island side. *Journal of the Fisheries Research Board of Canada*, 34 697-703.
- 3130 Thomson, R.E., 1981. Oceanography of the British Columbia Coast. *Canadian Special*
3131 *Publication of Fisheries and Aquatic Sciences* 56, 235-258.
- 3132 Thomson, R.E., 1994. Physical oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca
3133 Strait system, in: Wilson, R.C.H., Beamish, R.J., Aitkens, F., Bell, J., (Eds.), *Review of*
3134 *the Marine Environment and Biota of Strait of Georgia, Puget Sound and Juan de Fuca*
3135 *Strait*. *Canadian Technical Report of Fisheries and Aquatic Sciences* 1948, 36-100.
- 3136 Thomson, R.E., 1998. Ecosystem classification of the Strait of Georgia: Physical oceanographic
3137 delineation, in: Levings, C.D., Pringle, J.D., Aitkens, F., (Eds.), *Approaches to Marine*
3138 *Ecosystem Delineation in the Strait of Georgia*. Proceedings from a DFO Workshop,
3139 Sidney, B.C. November, 1997. *Canadian Technical Report of Fisheries and Aquatic*
3140 *Sciences* 2247, 112-123.

- 3141 Thomson, R.E., Foreman, M.G.G., 1998. Basin areas and volumes of coastal southwest British
3142 Columbia and northwest Washington. Canadian Technical Report of Fisheries and
3143 Aquatic Sciences 196, 17 pp.
- 3144 Thomson, R.E., Huggett, W.S., 1980. M2 baroclinic tides in Johnstone Strait, British Columbia.
3145 Journal of Physical Oceanography 10, 1509-1539.
- 3146 Thomson, R.E., Huggett, W.S., Kuwahara, L.S.C., 1980a. Data record of current observations
3147 Vol. VIII Discovery Passage, Johnstone Strait and Queen Charlotte Strait, Part 1 - water
3148 property observations, 1976, 1977, 1978, 1979. Institute of Ocean Sciences, Sidney, B.C.,
3149 262 pp.
- 3150 Thomson, R.E., Huggett, W.S., Kuwahara, L.S.C., 1980b. Data record of current observations
3151 Vol. VIII, Discovery Passage, Johnstone Strait and Queen Charlotte Strait, Part 2-
3152 appendices A to E, Institute of Ocean Sciences, Sidney, B.C., 809 pp.
- 3153 Thomson, R.E., Mihaly, S.F., Kulikov, E.A., 2007. Estuarine versus transient flow regimes in
3154 Juan de Fuca Strait. Journal of Geophysical Research-Oceans 112, doi:
3155 10.1029/2006JC003925.
- 3156 Tito de Morais, L., Bodiou, J.Y., 1984. Predation on meiofauna by juvenile fish in a western
3157 Mediterranean flatfish nursery ground. Marine Biology 82, 209-215.
- 3158 Tunnicliffe, V., 1981. High species diversity and abundance of the epibenthic community in an
3159 oxygen-deficient basin. Nature 294, 354-356.
- 3160 Tunnicliffe, V., 2000. A fine-scale record of 130 years of organic carbon deposition in an anoxic
3161 fjord, Saanich Inlet, British Columbia. Limnology and Oceanography 45, 1380-1387.
- 3162 Tunnicliffe, V., Syvitski, J.P.M., 1983. Corals move boulders: An unusual mechanism of
3163 sediment transport. Limnology and Oceanography 28, 564-568.

- 3164 Tunnicliffe, V., Wilson, K., 1988. Brachipod populations: distribution in fjords of British
3165 Columbia (Canada) and tolerance of low oxygen concentrations. *Marine Ecology*
3166 *Progress Series* 47, 117-128.
- 3167 Wainwright, P., Harper, J.R., Searing, G.F., Howes, D., 1995. Ecological classification within
3168 British Columbia's marine regions: Methodology report, British Columbia Land Use
3169 Coordination Office, Victoria, BC, 17 pp.
- 3170 Waldichuk, M., 1957. Physical oceanography of the Strait of Georgia, British Columbia. *Journal*
3171 *of the Fisheries Research Board of Canada* 14, 321-486.
- 3172 Walker, D., 1995. Shellfish Contamination, in: Calder, A.M., Mann, G.S., (Eds.), *Saanich Inlet*
3173 *study: Synthesis workshop summary, April 25/26, prepared for the Water Quality*
3174 *Branch, British Columbia Ministry of Environment, Lands and Parks by EVS*
3175 *Environmental Consultants Ltd., and Sea Science, Vancouver, B.C., pp. 61-90.*
- 3176 Wang, F., Chapman, P.M., 1999. Biological implications of sulfide in sediment-a review
3177 focusing on sediment toxicology. *Environmental Toxicology and Chemistry* 18, 2526-
3178 2532.
- 3179 Warwick, R.M., Clarke, K.R., 1993. Comparing the severity of disturbance: A meta-analysis of
3180 marine macrobenthic community data. *Marine Ecology Progress Series* 92, 221-231.
- 3181 Warwick, R.M., Dshfield, S.L., Somerfield, P.J., 2006. The integral structure of a benthic
3182 infaunal assemblage. *Journal of Experimental Marine Biology and Ecology* 330, 12-18.
- 3183 Watling, L., Norse, E.A., 1998. Disturbance of the seabed by mobile fishing gear: A comparison
3184 to forest clearcutting. *Conservation Biology* 12, 1180-1197.
- 3185 Watson, J., 1998. A review of ecosystem classification: Delineating the Strait of Georgia, in:
3186 Levings, C.D., Pringle, J.D., Aikens, F. (Eds.), *Approaches to Marine Ecosystem*

- 3187 Delineation in the Strait of Georgia, Proceedings from a DFO Workshop, Sidney, B.C.
3188 November, 1997. Canadian Technical Report of Fisheries and Aquatic Sciences 2247, 3-
3189 71.
- 3190 West, P., Fyles, T.M., King, B., Peeler, D.C., 1994. The effects of human activity on the marine
3191 environment of the Georgia basin: Present waste loadings and future trends, in: Wilson,
3192 R.C.H., Beamish, R.J., Aitkens, F., Bell, J. (Eds.), Review of the Marine Environment
3193 and Biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait. Canadian Technical
3194 Report of Fisheries and Aquatic Sciences 1948, 9-35.
- 3195 Whiteley, J., Bendell-Young, L.I., 2007. Ecological implications of intertidal mariculture:
3196 observed differences in bivalve community structure between farm and reference sites.
3197 Journal of Applied Ecology 44, 495-505.
- 3198 Williams, G.L. & Associates Ltd., 1991. Coastal habitat inventory, in: The town of Bamberton
3199 Review Process. VII. II. Technical Background South Island, Prepared for the Ministry of
3200 Environment, Lands and Parks, Water Quality Branch, Government of British Columbia,
3201 pp. 113-120.
- 3202 Wilson, R.C.H., Beamish, R.J., Aikens, F., Bell, J., 1994. Review of the marine environment and
3203 biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. Proceedings of the
3204 BC/Washington Symposium on the Marine Environment, January 13 & 14, 1994.
3205 Canadian Technical Report of Fisheries and Aquatic Sciences 1948, 390 pp.
- 3206 Wilson, R.C.H., McKinnon, S.J., 2003. The Point Grey ocean disposal site, 1975-200: A 25-Year
3207 Review, Prepared for the Disposal At Sea Program, Environment Canada, Victoria, B.C.,
3208 118 pp.

- 3209 Wlodarska-Kowalczyk, M., Pearson, T.H., Kendall, M.A., 2005. Benthic response to chronic
3210 natural physical disturbance by glacial sedimentation in an Arctic fjord. *Marine Ecology*
3211 *Progress Series* 303, 31-41.
- 3212 Wright, C.A., Johannessen, S.C., Macdonald, R.W., Burd, B.J., Hill, P.R., van Roodselaar, A.,
3213 Bertold, S., In press. The Strait of Georgia ambient monitoring program, phase I 2002-
3214 2007: Sediment and benthos. *Canadian Data Report of Fisheries and Aquatic Sciences*,
3215 XX, xx.
- 3216 Wright, C.A., Pringle, J.D., 2001. Race Rocks pilot marine protected area: An ecological
3217 Overview. *Canadian Technical Report of Fisheries and Aquatic Sciences* 2353, 93 pp.
- 3218 Wright, C., Taekema, B., Burd, B., McGreer, E., 2007a. Salmon aquaculture environmental
3219 monitoring data report. Results of sampling program for year 2000, prepared for the
3220 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only
3221 URL: http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm.
- 3222 Wright, C., Taekema, B., Burd, B., McGreer, E., 2007b. Salmon aquaculture environmental
3223 monitoring data report. Results of sampling program for year 2001, prepared for the
3224 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only
3225 URL: http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm.
- 3226 Wright, C., Taekema, B., Burd, B., McGreer, E.R., 2007c. Salmon aquaculture environmental
3227 monitoring data report. Results of sampling program for year 2002, prepared for the
3228 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only
3229 URL: http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm.
- 3230 Wright, C., Taekema, B., Burd, B., McGreer, E.R., 2007d. Salmon aquaculture environmental
3231 monitoring data report. Results of sampling program for year 2003, prepared for the

- 3232 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only
- 3233 URL: http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm.
- 3234 Wright, C., Taekema, B., Burd, B., McGreer, E.R., 2007e. Salmon aquaculture environmental
- 3235 monitoring data report. Results of sampling program for year 2004, prepared for the
- 3236 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only
- 3237 URL: http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm
- 3238 Yeats, P.A., 2002. Trace metal tracers of fish farm wastes. 2002. In: Hargrave, B.T., (Ed.).
- 3239 Environmental Studies for Sustainable Aquaculture (ESSA): 2002 Workshop Report.
- 3240 Canadian Technical Report of Fisheries and Aquatic Sciences 2411, 82-85.
- 3241 Yunker, M.B., 2000. Sediment PAH signatures in the IONA receiving environment, in: Greater
- 3242 Vancouver Regional District, (Ed.), Development of a Receiving Environment
- 3243 Monitoring Approach to Liquid Waste Management: Progress Workshop 2, Chapter 3-
- 3244 23 pp.
- 3245 Yunker, M.B., Macdonald, R.W., Brewer, R., Sylvestre, S., Tuominen, T., Sekela, M., Mitchell,
- 3246 R.H., Paton, D.W., Fowler, B.R., Gray, C., Goyette, D., Sullivan, D., 2000. Assessment
- 3247 of natural and anthropogenic hydrocarbon inputs using PAHs as tracers. The Fraser
- 3248 River Basin and Strait of Georgia (1987-1997), Aquatic and Atmospheric Sciences
- 3249 Division, Environmental Conservation Branch, Pacific and Yukon Region, Environment
- 3250 Canada, Vancouver, B. C., 128 pp.
- 3251 Yunker, M.B., Macdonald, R.W., Goyette, D., Paton, D.W., Fowler, B.R., Sullivan, D., Boyd, J.,
- 3252 1999. Natural and anthropogenic inputs of hydrocarbons to the Strait of Georgia. Science
- 3253 of the Total Environment 225, 181-209.

- 3254 Zacharias, M.A., Howes, D.E., 1998. An analysis of marine protected areas in British Columbia,
3255 Canada, using a marine ecological classification. *Natural Areas Journal* 18, 4-13.
- 3256 Zacharias, M.A., Howes, D.E., Harper, J.R., Wainwright, P., 1998a. The British Columbia
3257 marine ecosystem classification: Rationale, development, and verification. *Coastal*
3258 *Management* 26, 105-124.
- 3259 Zacharias, M.A., Howes, D., Ogborne, C., 1998b. A biophysical habitat classification for
3260 intertidal environments in the Strait of Georgia, in: Levings, C.D., Pringle, J.D., Aikens,
3261 F., (Eds.), *Approaches to Marine Ecosystem Delineation in the Strait of Georgia*.
3262 *Proceedings from a DFO Workshop, Sidney, B.C. November, 1997. Canadian Technical*
3263 *Report of Fisheries and Aquatic Sciences* 2247, 105-111.
- 3264 Zacharias, M.A., Morris, M.C., Howes, D.E., 1999. Large scale characterization of intertidal
3265 communities using a predictive model. *Journal of Experimental Marine Biology and*
3266 *Ecology* 239, 223-242.
- 3267 Zacharias, M.A., Roff, J.C., 2001. Explanations of patterns of intertidal diversity at regional
3268 scales. *Journal of Biogeography* 28, 471-483.
- 3269 Ziervogel, K., Forster, S., 2006. Do benthic diatoms influence erosion thresholds on coastal
3270 subtidal sediments? *Journal of Sea Research* 51, 43-53.
- 3271 Zis, T., Ronningen, V., Scrosat, R., 2004. Minor improvement for intertidal seaweeds and
3272 invertebrates after acid mine drainage diversion at Britannica Beach, Pacific Canada.
3273 *Marine Pollution Bulletin*, 48, 1040-4047.
- 3274 Zorn, M.E., Lalonde, S.W., Gingras, M.K., Pemberton, S.G., Konhauser, K.O., 2006. Microscale
3275 oxygen distribution in variousl invertebrate burrow walls. *Geobiology* 4, 137-145.
- 3276

Figure Captions

Figure 1. The Strait of Georgia, including depth contours from multibeam imagery (see also Fig. 3), locations of important geographic units and discharge sources described herein, and theoretical boundaries of north, middle and southern oceanographic regimes within the main basin.

Figure 2. Physical parameters used to develop ecounits (Modified from the Ministry of Sustainable Resource Management (<http://ilmbwww.gov.bc.ca/risc/>). Substrate = mud, sand, hard (M,S,H); Exposure = high, moderate, low (H,M,L); Current = High >3knots, low <3 knots (H,L); Slope = Flat 0-5%, sloping 5-20%, Steep >20% (F,S,S); Depth = Shallow 0-20m; photic 20-50m, mid-depth 50-200m, deep 200-1000m; Temperature = warm 9-15°C, cold <9°C; Relief = low 0-1, medium 2, high 3-4. For example: ecounit = M/L/L/F/M/C/L: Substrate = mud; Exposure = low; Current = low; Slope = flat; Depth = mid-depth; Bottom Temperature = cold; Relief = low.

Figure 3. Multibeam imagery from the southern Strait of Georgia showing bottom relief and type, courtesy of Natural Resources Canada, Pacific Geoscience Center, Sidney, BC.

Figure 4. Plot of sediment percent fines (silt/clay <63 µm particle size) to illustrate sediment types in the Strait of Georgia (data from Burd, 2006; and courtesy of Natural Resources Canada, Pacific Geoscience Center, Sidney, BC).

3300 Figure 5. MERIS satellite taken 2007/07/10 (copyright, European Space Agency). True colour
3301 image, Courtesy of Jim Gover and Stephanie King, Institute of Ocean Sciences, Canadian
3302 Department of Fisheries and Oceans, Sidney, BC.

3303

3304 Figure 6. Shorekeepers' Program sites in the Strait of Georgia, BC.

3305 (<http://www.shim.bc.ca/atlas/sk/main.htm>).

3306

3307 Figure 7. Habitat (beach) suitability maps for Pacific oysters and Manila clams and a
3308 corresponding area map for kelp and eelgrass habitat as generated by the Internet. Framework
3309 Mapping tool provided by the Provincial Ministry of the Environment (<http://maps.gov.bc.ca/>).

3310

3311 Table 1. Gross features of the Strait of Georgia, B.C. (from England et al. 1996, Thomson 1998,
 3312 and Thomson and Foreman 1998).

Feature	Measure
Surface Area	6515 km ²
Area at 100m depth	4374 km ²
Volume	1050 km ³
Mean Depth	155m
Maximum Depth	420m (S Texada Island)
Annual Mean Runoff	5650±3500 m ³ /s
Drainage Area	286,890 km ²
Sill Depth – Haro Strait	90m
Sill Depth – Rosario Strait	50m
Summer Basin Flushing	50-75 days
Winter Basin Flushing	100-200 days

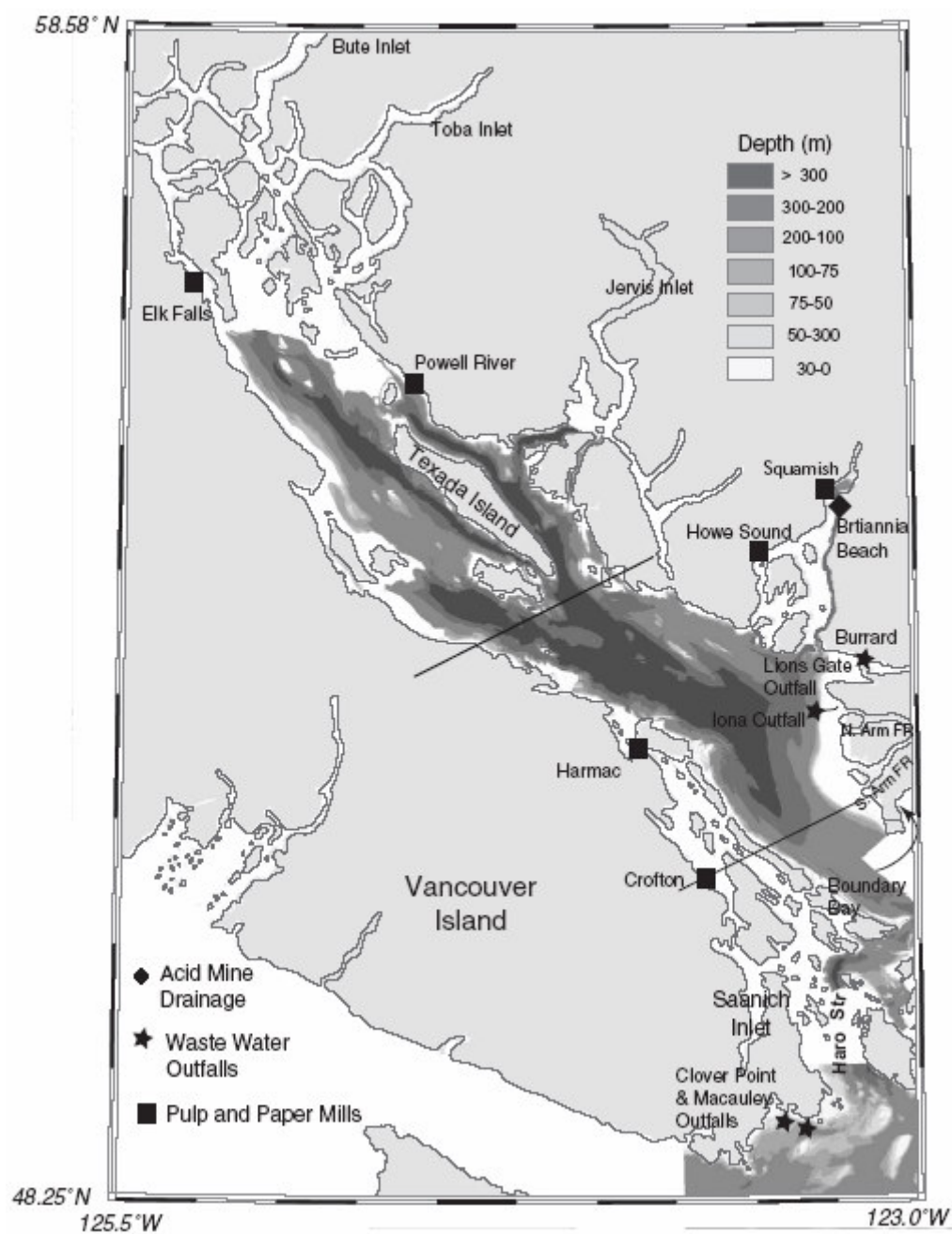
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3316 Figure 1

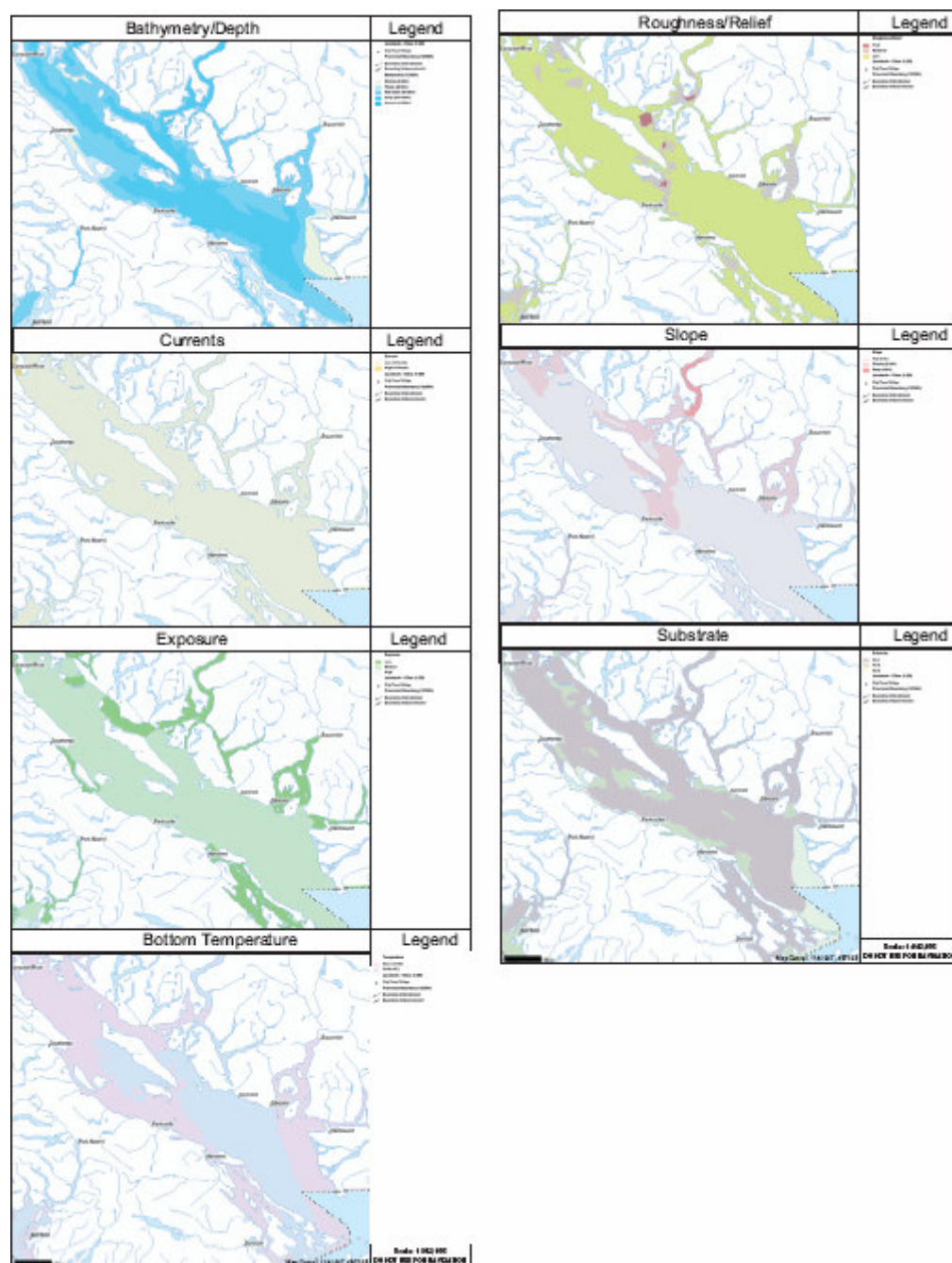
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3319 Figure 2

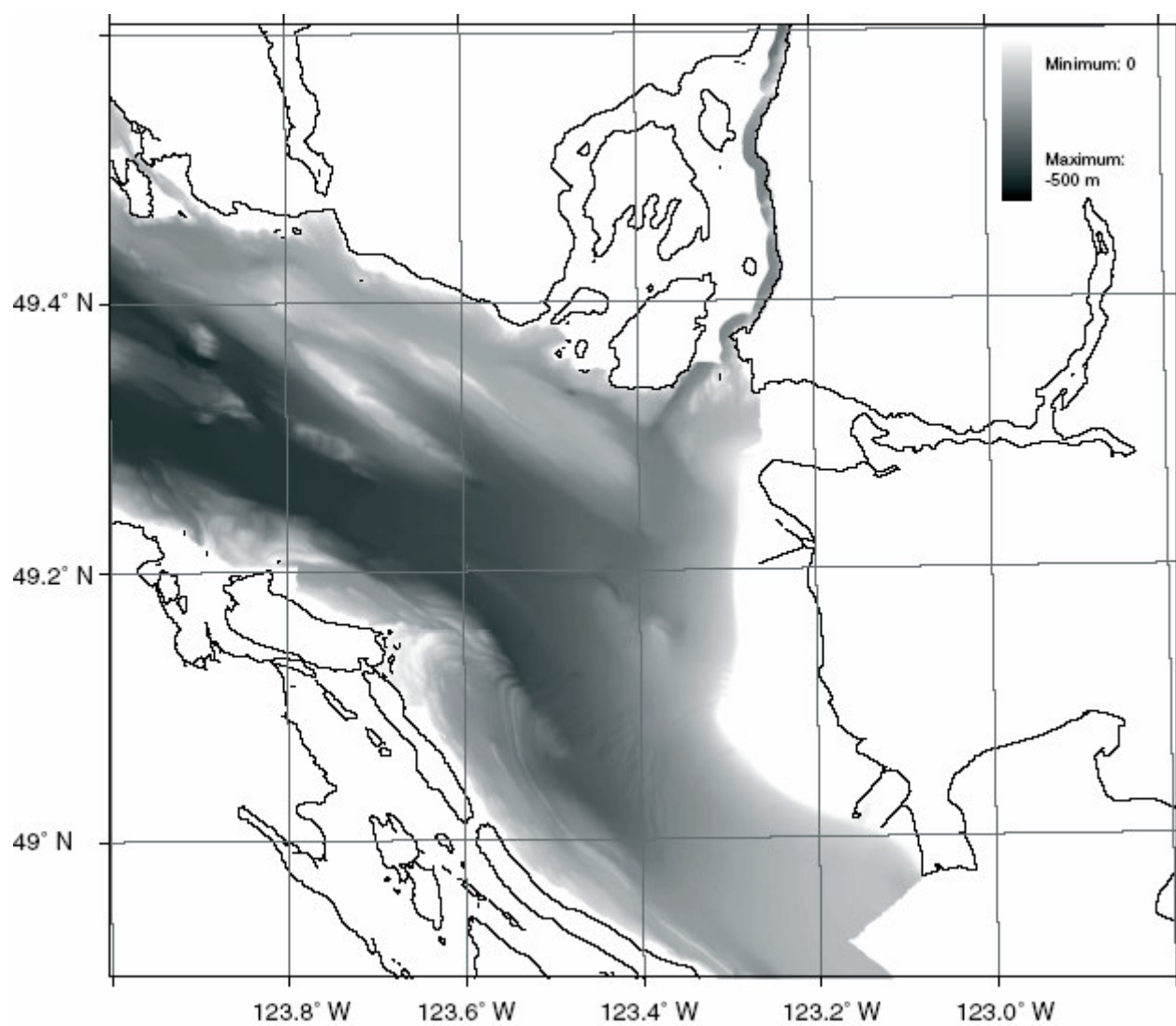
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3322 Figure 3

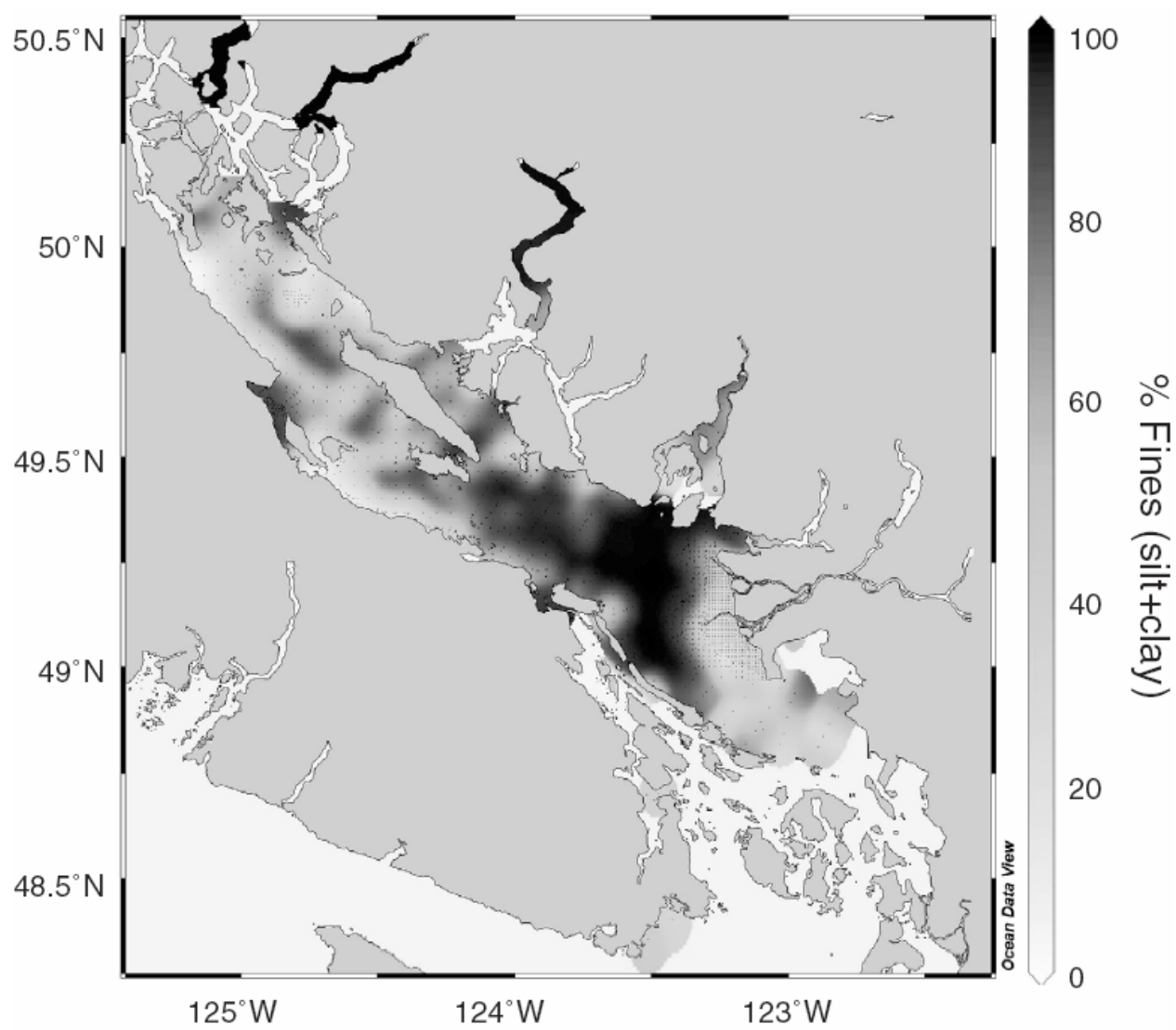
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3325 Figure 4

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3327

3328 Figure 5

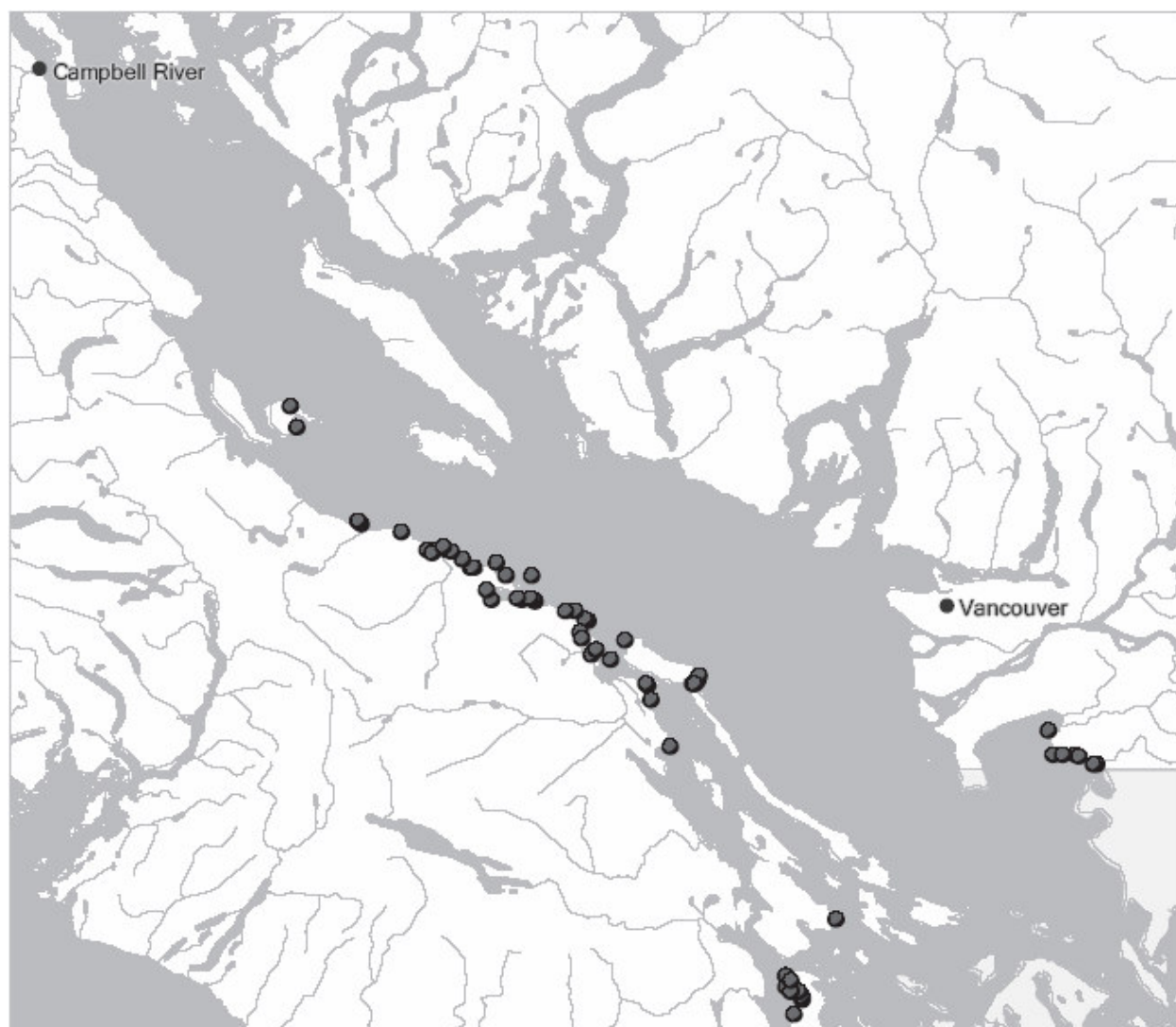
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3331 Figure 6

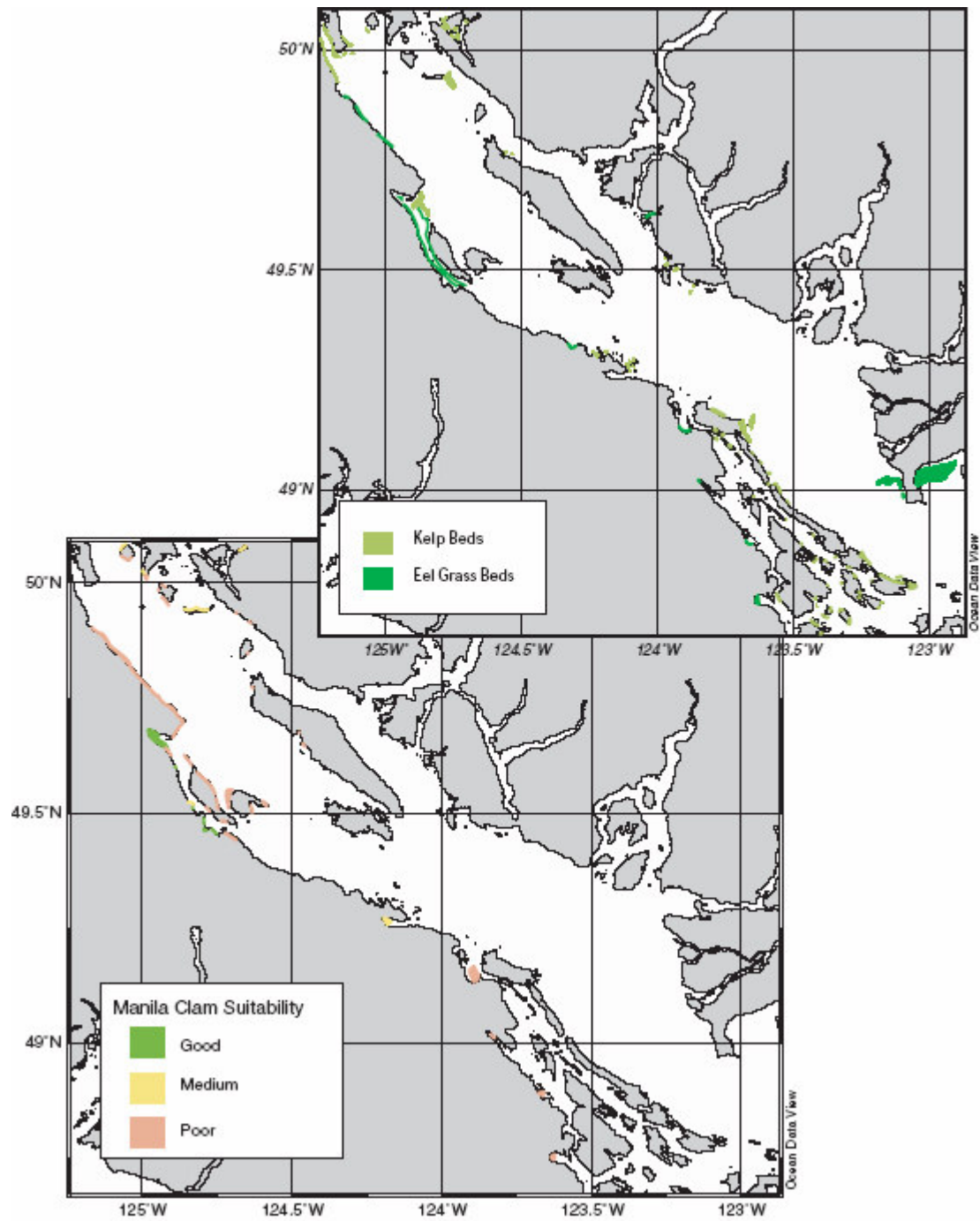
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3334 Figure 7

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