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ORIGINAL RESEARCH ARTICLE

Hazards evaluation of a valuable vulnerable sand-wave field forage fish habitat in the marginal Central Salish Sea using a submersible

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Abstract The Salish Sea is a marginal inland sea of the NE Pacific (NW North America) that includes the Georgia Strait-Gulf Islands Archipelago of British Columbia, Canada and the San Juan Archipelago, Strait of Juan de Fuca, and the Lower Puget Sound of Washington State, USA. This marginal seafloor has been extensively mapped and according to criteria presented and discussed at GeoHab conferences critical marine benthic habitat types are identified. One such habitat that is the focus of this paper is the deep-water sub-tidal habitat of Pacific sand lance (PSL). The PSL (*Ammodytes personatus*) is a critical forage fish for a variety of mammals, birds and fish including minke whales and salmon as it preys upon zooplankton and acts as an energy transfer species from the lower to higher trophic levels. Pacific sand lance seeks refuge and overwinters in sand-wave fields consisting of dynamic bedforms. The species prefers loosely packed, well-aerated, well-sorted, medium- to coarse-grain (˜1 phi [φ], 500 μm) sand that it can burrow into easily. Such geomorphic features as active dynamic bedforms provide preferable habitats for PSL and depends on specific and unique oceanographic processes that can maintain the habitat's morphology and grain sizes. Understanding these processes is essential in forecasting alteration or destruction of such features, including changes that may be brought about by sea level rise. Using the five-person submersible *Cyclops 1*, we recently

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examined a well-studied sand-wave field in the San Juan Archipelago of Washington State, USA, which has been reported to harbor up to 12 million PSL. Observations, video recordings, and photography from this vehicle allowed us to assess modern seafloor processes of the central Salish Sea that can be used along with fish and sediment sample data to determine physical preferences this fish needs to sustain its population. Changes in the seafloor current regime, sediment source, and anthropogenic disturbances can critically alter these dynamic bedforms. This research provides insight into the structure of these bedforms, their composition, their persistence, their resilience to disturbance, and the susceptibility as an impact and becoming impacted.

1. Introduction

The dynamic nature of sediment-wave fields presents a potential hazard to seabed infrastructure, with the degree of impact being a function of current strength and sediment supply. In other words, dynamic geomorphic features that may impact anthropogenic structures on the seafloor may, as a valuable biological resource, in turn be adversely impacted if disturbed or altered in any way. Here we investigate the impact that may occur from the disturbance of a sand-wave field that harbor PSL and in turn may impact infrastructure.

With the increase of infrastructure development in the marginal sea environment worldwide the stability of the seafloor upon which structures are emplaced is critical to the safe maintenance and life of the infrastructure. Dynamic bedforms present a hazard to seafloor development and can displace and cover pipelines, cables, and other infrastructures through natural oceanographic processes such as strong currents, storm waves, earthquakes, and tsunamis. In addition, these bedforms are sought after for their aggregate resources because of their natural sorting of clasts and can be completely destroyed by mining activity such as occurred in San Francisco Bay, California USA (Chin et al., 1998, 2004; Greene et al., 2007, 2013). However, it has been found that many of these bedforms act as preferential sub-tidal habitats for forage fish such as the Pacific sand lance (PSL), *Ammodytes personatus* within the Salish Sea (Greene et al., 2011, 2017, 2020; Haynes et al., 2007; Robinson et al., 2013; Selleck et al., 2016; Sisson and Baker, 2017). In the context of this study a marine hazard is considered anything that impacts a resource, either natural or anthropogenic.

The PSL is an important forage fish along the coastal North Pacific Ocean extending from northern California to northern Hokkaido, Japan, and is one of six species in the genus *Ammodytes* (Orr et al. 2015; Robards et al., 1999a,b). *Ammodytes* spp. are dependent upon seafloor sediment habitats to burrow into and is most often associated with oxygenated fine- to coarse-grain sand or gravel sediment (Auster and Stewart, 1986; Baker et al., 2021; Bizzarro, 2016; Meyer et al., 1979) in the nearshore inter-tidal and shallow ($<$100 m) habitats (Auster and Stewart, 1986; Ostrand et al., 2005; Pinto, 1984; Quinn, 1999; Robards et al., 1999a,b; Wright et al., 2000), although they have been observed to be present in deeper water in a Washington Department of Fish and Wildlife (WDFW) remotely operated vehicle (ROV) survey at depths up to 262 m. In the inter-tidal zones sand lance were found to be buried up to 5.0 cm deep, oriented horizontally in an oxygenated sediment layer with densities of 5 fish/m^2, and remained buried within inter-tidal sediments exposed during low tidal sequences (Quinn, 1999). Sediment sizes conducive for sand lance to penetrate and burrow into range in sizes from 0.36 to 1.0 mm (1.5—0 phi [φ]) in diameter (Baker et al., in prep b; Bizzarro et al., 2016; Greene et al., 2011; Quinn, 1999). Inter-tidal beaches have been documented as PSL recruitment habitat where they deposit their eggs (Moulton and Penttila, 2000; Pentilla, 2007; Selleck, 2016). Unconsolidated sandy sediment provide habitat for over-wintering (Healy, 1984), to rest and conserve energy (Quinn, 1999), to avoid predation (Reay, 1970), and as spawning substrate where adhesive eggs attach to substrate while incubating. When the fish emerge from the substrate, they form large schools and feed on zooplankton in the water column during the day (Auster and Stewart, 1986; Dick and Warner, 1982; Geiger, 1987; Robards et al., 1999a,b). They emerge from the sand at dawn and are vulnerable to predators as they enter the water column (Hobson, 1986; Walters Foraging Arena Theory). PSL have also been found to burrow into microplastic associated sediments (Peters, 2018), which can be considered as another anthropogenic influence of PSL marine benthic habitats.

The basis of this study is the result of multiple studies, presentations, and discussions throughout the GeoHab community (see GeoHab.org), an informal marine scientific organization that focuses on mapping of the seafloor for habitat characterization. The latest conference in 2019 in St. Petersburg, Russia focused on marginal seas and their resources, living and non-living, and how the use of modern technologies such as multibeam echosounder (MBES) mapping, remotely and autonomous operated vehicles along with submersibles can be used to better understand the marine environment.

1.1. Objectives

Many dynamic bedforms exist within marginal seas such as the San Juan Archipelago of the central Salish Sea. Based on previous marine benthic habitat mapping of the Salish Sea, the major objectives of this study is to validate the mapping effort and to characterize the relationship of PSL to bedform processes occurring within a known sand-wave field that could be impacted by seafloor infrastructure development and disturbance from such activity as mining, trawling, and anchoring. To achieve these objectives, we made in situ observations of PSL and dynamic bedforms from the Ocean Gate submersible *Cyclops 1* supplemented with seafloor samples and photographs collected independently from the submersible dives. The submersible was primarily used as a static observational platform to observe both sedimentary and biologic activity on and within the sand-waves during different tidal cycles to characterize sedimentary transport processes and fish responses.

A primary goal of this study was to test several working hypotheses regarding PSL habitats, hypotheses developed from our previous studies, and critical to understanding the hazards associated with, and the potential impact upon, dynamic bedforms and associated ecology:

H_1 PSL prefer to burrow into well sorted, clean, aerated, medium to coarse (˜1φ) sand located near the crests of sand waves as inferred from our previous sampling work,
H_2 Sediment and PSL concentration differ on the edges and outside of the sand-wave field with similar concentrations of PSL regardless of morphology,
H_3 Sediment composition (sand size [$1-0\varphi$]) in crests and troughs of sand waves are similar.

1.2. PSL relationship to bedforms

Deposits of clean sand at the water depths where PSL reside in the sub-tidal and deep-water environments (typically <100 m) are common where relatively strong currents continuously sweep the seafloor. In order to maintain a deposit, a plentiful sand supply is necessary, or relic sediment is stable (no net transport), although finer sediment might transit through the area and coarser sediment might be present as a lag (Greene et al., 2011, 2017). Dynamic bedforms, such as ripples, waves and dunes are common in sand-wave fields of marginal seas, of which several have been mapped near the San Juan Islands as marine benthic habitats (Barrie et al., 2009; Greene et al. 2011). One such sand-wave field was documented and recently reported upon (Baker et al., 2019; Greene et al., 2011, 2017; Sisson and Baker, 2017) in San Juan Channel of the San Juan Islands of the central Salish Sea, located in Washington State of the U.S. Pacific Northwest, and found to be an extremely productive PSL habitat (Figure 1). The aerial extent (˜600,000 m^2 at water depths of 20—80 m) of this sand-wave field is delimited by a distinct boundary where the sand waves are in sharp contact with a relatively featureless surrounding seafloor. Similar abrupt transitions have been reported in other nearby sand-wave fields (Barrie et al., 2009; Greene et al., 2017).

The relationship of PSL to sediment in the San Juan channel sand-wave field (our proto-typical PSL deep-water habitat) has been extensively studied through multiple bathymetric imaging by Greene et al. (2011, 2017) at the Tombolo Mapping Lab of Moss Landing Maine Labs (San Jose State University) and the SeaDoc Society (University of California, Davis), sediment and fish sampling from surface vessels (Baker et al., 2019; Greene et al., 2011, 2017, 2020; Matta and Baker, 2020; Sisson and Baker, 2017), and with students at the Friday Harbor Labs (University of Washington). The number of fish caught in sediment samples collected within the sand-wave field between July 2010 and June 2011 are shown in Figure 2, which appears to be closely related to sediment grain size.

Prior to this study marine benthic habitat mapping of the central Salish Sea was accomplished (Greene and Barrie, 2011), a mapping effort accorded the oversight of GeoHab, the geological and biological mapping scientific organization, that identified many dynamic bedforms and sediment wave fields that are considered potential PSL habitats. Based on these maps we undertook cursory sub-tidal PSL habitat characterization and mapping, as well as initiated laboratory experiments to test the hypothesis that PSL prefer certain grain sizes, compaction (packing), and density levels (i.e., substrate habitat types) when burrowing and to assess the range of habitat types that they are able to burrow into (Bizzarro et al., 2016).

1.3. Geologic setting

The San Juan Channel sand-wave field is located within the San Juan Archipelago of the marginal central Salish Sea, Washington State, in the Pacific Northwest of North America (Figure 1). The field is elongated in a general N-S direction, approximately 1.75 km long and 0.4 km wide, covering an area of approximately 0.7 km^2 at water depths ranging from 20 to 75 m (Figure 2). The sand-wave field is delimited by distinct boundaries where the sand-waves are in sharp contact with a relatively featureless surrounding sea floor. The stability of sand-wave field is governed by variations in bottom current strength (measured at 5 m above seabed at 87 cm/sec., Greene et al., 2017), a function of atmospheric and tidal conditions, the nature and variability of the transition across the field boundaries in sediment type and current velocity, and changes in sediment supply (grain size and volume).

The San Juan Archipelago-Georgia Basin region of the central Salish Sea is an active tectonic province whose physiography and geomorphology reflect both Mesozoic to Cenozoic convergence (subduction/accretion) plate tectonic processes and Pleistocene glaciation (glacial scouring/deposition). These processes have fragmented, juxtaposed, and deformed Jurassic-Cretaceous metamorphic rocks with Tertiary-Quaternary sedimentary rocks producing a complex of fjords, grooved and polished bedrock outcrops, and erratic boulders and moraines (Orr and Orr, 1996). Banks of till and glacial advance outwash deposits have also formed and contribute to the variety of relief of substrate types within this marginal sea region. Present day tidal action has fashioned much of the relic glacial-marine sediments into dynamic bedforms consisting of sand and gravel waves and dune fields, many of which are static with a stable footprint on the seafloor but dynamic in the sense that the bedforms move back and forth during the tidal shifts. Modern day sedimentary deposits (sand and mud banks [e.g., "feeder banks"]) represent materials being eroded and supplied to the region along with sediment from the Fraser River of British Columbia, Canada.

1.4. Dynamic bedforms as a hazard

Sedimentary bedforms are geomorphic features of relief often formed by a fluid flow layer resulting from an unstable interaction between the flow and the bed material

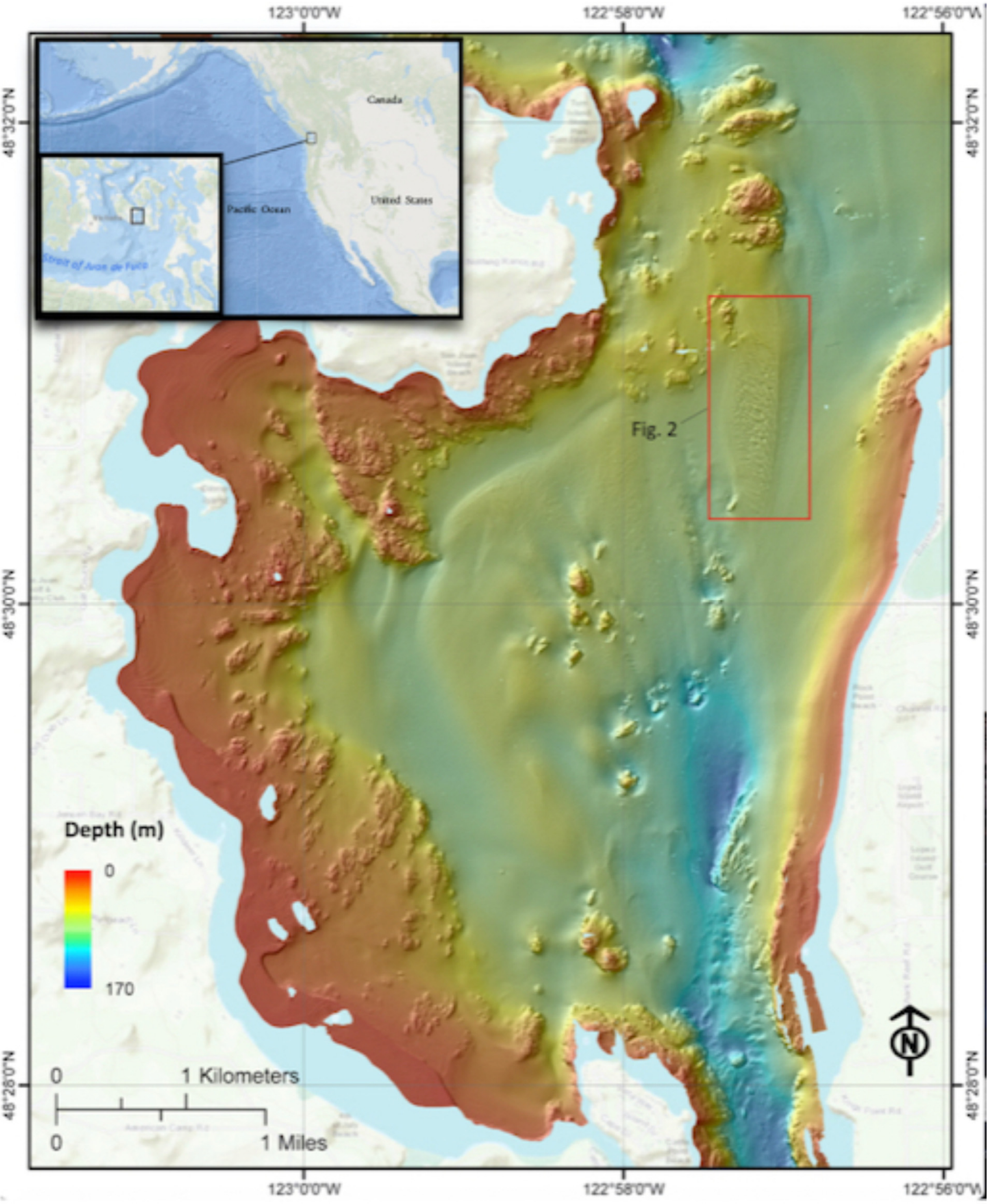

Figure 1 Location map showing the San Juan Channel sand wave field within the central part of the marginal Salish Sea. After Greene et al. (2017).

(Allen, 1968) and may be composed of loose grains, cohesive mud, and sometimes rock in the form of debris flows. Sedimentary bedforms consist of assorted morphologies, dimensions, and sediment types and can be classified and characterized based on their environment, process of formation, and grain size (Wynn and Stow, 2002). They can be observed in a variety of aquatic environments throughout the world including Monterey Canyon and San Francisco Bay, California; the Hudson Estuary, New York; the Danish Wadden Sea; the Cyclades Plateau in the northeastern Mediterranean; the Gulf of Cadiz in the Atlantic Ocean; and, in marginal seas such as the Strait of Juan

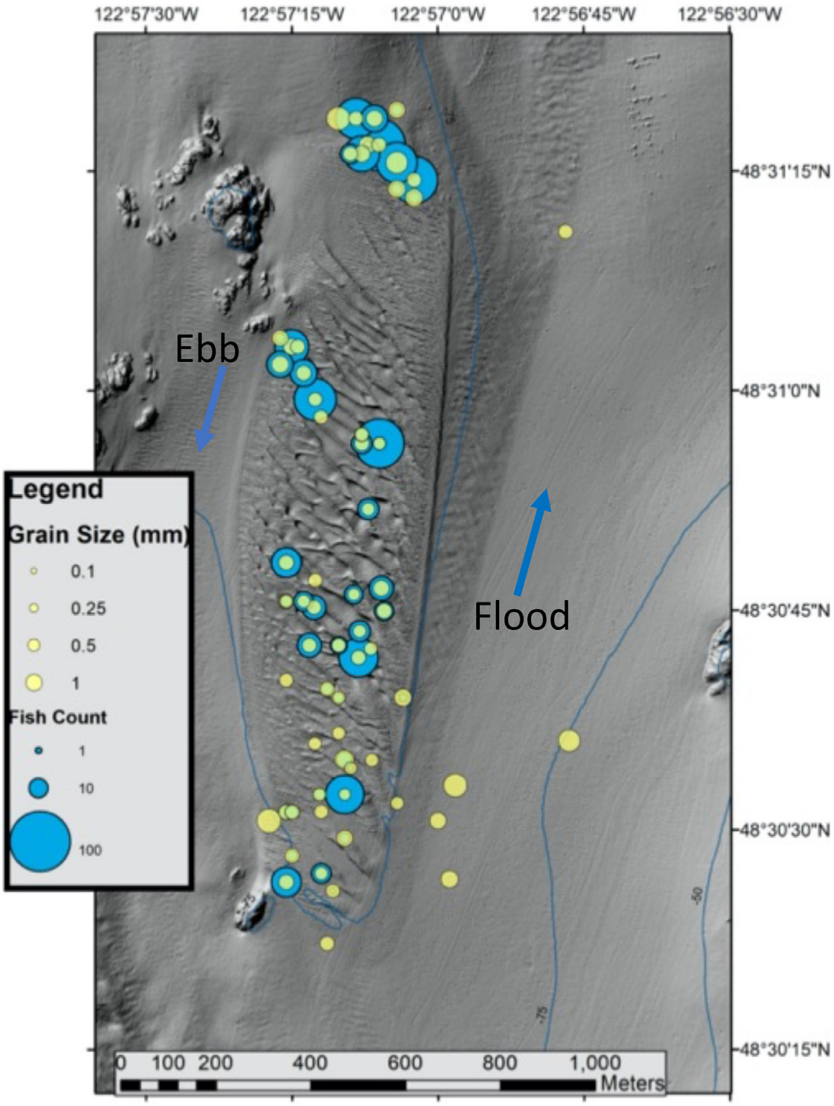

Figure 2 Wide swath multibeam bathymetric image of the San Juan Channel sand-wave field showing numbers of PSL sampled from July 2010 to June 2011 in relation to the sediment sample grain size analyses reported by Greene et al. (2011). Note that the largest number of fish recovered are clustered within the area of the largest sand-waves, an area where submersible observations detected plentiful amounts of PSL.

de Fuca, Washington State USA and Strait of Georgia, British Columbia (Barnard et al., 2012; Barrie et al., 2009; Greene et al., 2007; Hughes Clarke et al., 1996; Mosher and Thomson, 2000, 2002; Normark et al., 2002; Todd, 2005; Verhagen, 1989; Wynn and Stow, 2002).

Submarine sedimentary bedforms have been researched for the purpose of understanding sediment transport, deposition, and dynamics associated with bottom currents, turbidity currents, and gravity flows (Cattaneo, et al., 2004; Gutierrez et al., 2005; Habgood et al., 2003; Hoekstra et al.; 2004; Wynn et al., 2000), and for characterizing bedforms (Goff et al., 2005; Wynn and Stow, 2002). Studies have also been made describing associations where sediment waves were considered habitat for fishes (Auster et al., 1995; Gerstner 1998; Gerstner and Webb, 1998; Norcross et al., 1999; Stoner and Titgen, 2003). A field of well-formed submarine sand dunes was identified south of the junction of Haro Strait and the Strait of Juan de Fuca, British Columbia in the central Salish Sea, and was surveyed with sub-bottom profile, side-scan sonar, and multibeam MBES systems (Mosher and Thomson, 2000, 2002). The field included sand and fine gravel ($>$ 0.5 mm). The largest of the sand dunes were 25 m in height, 300 m in wavelength, 1,200 m in width and occurred in 97 m water depth. Based on grain size analysis, the dunes are composed of coarse sand (Mosher and Thomson, 2000).

The movement of sediment-waves across the seafloor can encroach upon infrastructures such as pipelines, cables, and foundations for wind and tidal turbines, resulting in abrading, scouring, and/or covering of such structures (Figure 3) with the risk to infrastructure increasing with high current velocity due to coarser sediment grain size that can be mobilized. As an example, although not a sand lance habitat because of high gravel concentration, proposals to

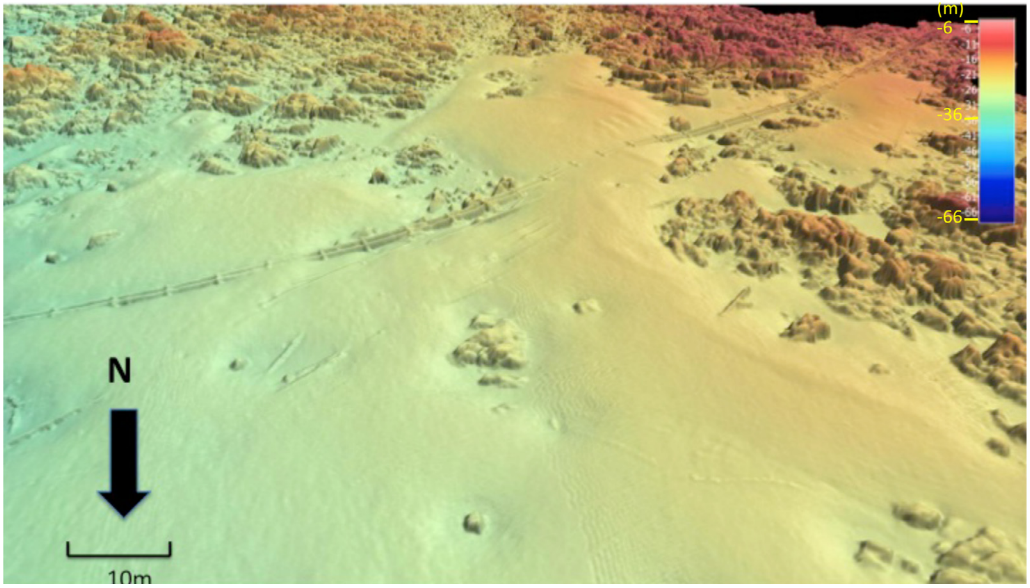

Figure 3 High-resolution multibeam echosounder bathymetric image of the seafloor offshore of the Monterey Peninsula showing encroachment, burial, and undermining of the twin seawater intake pipes for the Monterey Bay Aquarium. Other partially buried pipes associated with the historical sardine canneries in the area can also be seen in the image. Color bar represents depth in meters. Imagery courtesy of the Monterey Bay Aquarium.

extend several gas pipelines through the large gravel-waves of Boundary Pass of the Salish Sea — a common practice in marginal seas — near the southern Gulf Islands of Canada (Figure 4) was abandoned following analyses that concluded the pipelines would be adversely impacted and abraded by sediment movement (Mullan, 2017, page 38).

The disturbance of sand-waves resulting from the construction or installation of infrastructures, extraction for aggregate (as has occurred in San Francisco Bay; Figure 5), and the anchoring of vessels and structures, can also disturb critical habitat for forage fish such as PSL. Therefore, it is critical that these activities be considered as anthropogenic impacts to fisheries resources, and that potential risks to these resources (both short- and long-term) be thoroughly evaluated prior to their implementation. PSL constitute a large portion of the forage fish base for many top-order predators in the Salish Sea, including salmon, lingcod, diving birds, pinnipeds, and killer whales (*Orcinus orcas*). In this paper we describe the observations of a sediment wave-field with dynamic bedforms supporting a large population of PSL in order to evaluate the potential impacts of infrastructure development on this valuable prey resource. This is a qualitative (subjective) and not a quantitative study that adds value to previous quantifying investigations; a more statistical analysis is underway and will be reported upon at a later date (Baker et al., 2021).

2. Methods

The MBES bathymetric images and marine benthic habitat maps along with marine acoustical geophysical and geological data are used in this study for seafloor characterization and identification of seafloor geomorphology. Previously collected sediment grab samples are used for substrate identification and fish numbers obtained from sediment sampling is used for the comparison of fish presence and activity. Our primary tool and method for this study is the use of the five-person *Cyclops 1* submersible to observe in situ sedimentary and biological activity on the seafloor (Figure 6).

2.1. Multibeam echosounder data

Wide swath MBES bathymetry and backscatter acquired in cooperation with the Geological Survey of Canada, Canadian Hydrographic Service, and the Center for Habitat Studies, Moss Landing Marine Labs collected in the San Juan Islands, central Salish Sea were used to produce the seafloor images of sediment-wave fields within the region. These data along with side-scan sonar mosaics and 3.5 kHz sub-bottom seismic-reflection profiles were used to produce habitat types after Greene et al. (2007) and published in a marine benthic habitat map series (Greene and Barrie, 2011), which we draw upon for the characterization of our study area.

From 2001 through 2008 the Canadian Coast Guard vessels *Otter Bay, Revisor, Young* and *Vector*, under the direction of the Canadian Hydrographic Service (CHS), acquired extensive high-resolution bathymetric datasets of the waterways surrounding the Southern Gulf Islands and the San Juan Archipelago. The MBES Simrad EM 1002 (95 kHz frequency) and EM 3000-3002 (300 kHz frequency) systems were used for deep (>80 m) and shallow (<80 m) waters with resolutions 5 and 2 m. In most of the areas, the tracks were positioned so as to insonify 100% of the seafloor with a 100% overlap, providing 200% coverage. Positioning was accomplished using a broadcast Differential Global Positioning System (DGPS) and MBES data were corrected

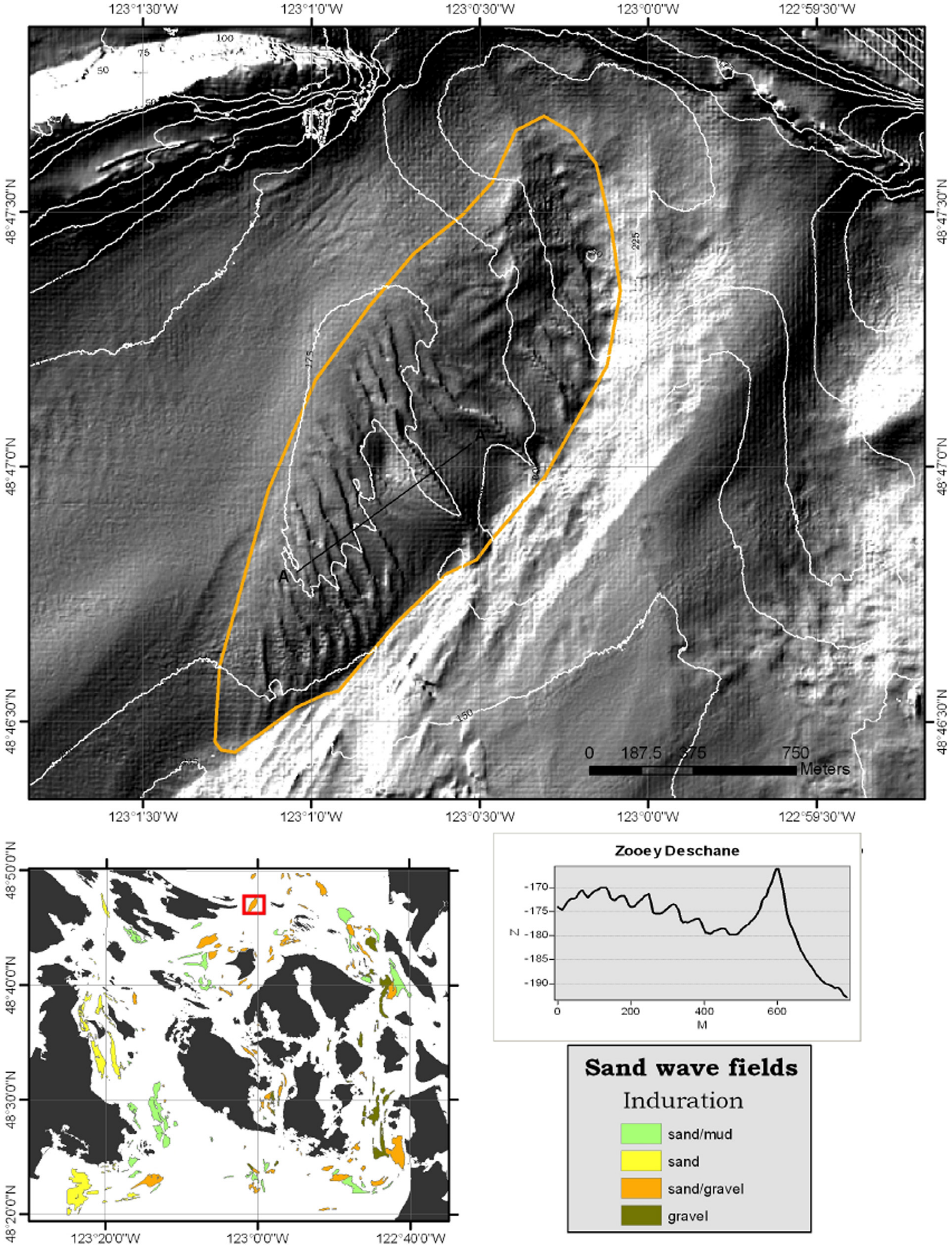

Figure 4 Mega-gravel-wave field in the Boundary Pass area of the San Juan Archipelago, central Salish Sea where gas pipelines have been proposed to cross from mainland British Columbia Canada to Vancouver Island. Amplitudes of sediment waves reach 30 m and are dynamic. Although not a sand lance habitat because of high gravel concentration, it nevertheless is a good example of a recent proposal to place infrastructure within a dynamic bedform. Location of field is shown by red-lined box in inset map, longitudinal profile along the field is shown in "Zooey Deschane" inset, and substrate types of all dynamic bedforms that may be potential PSL sub-tidal habitats within the San Juan Archipelago shown in "Sand wave fields Induration" inset box.

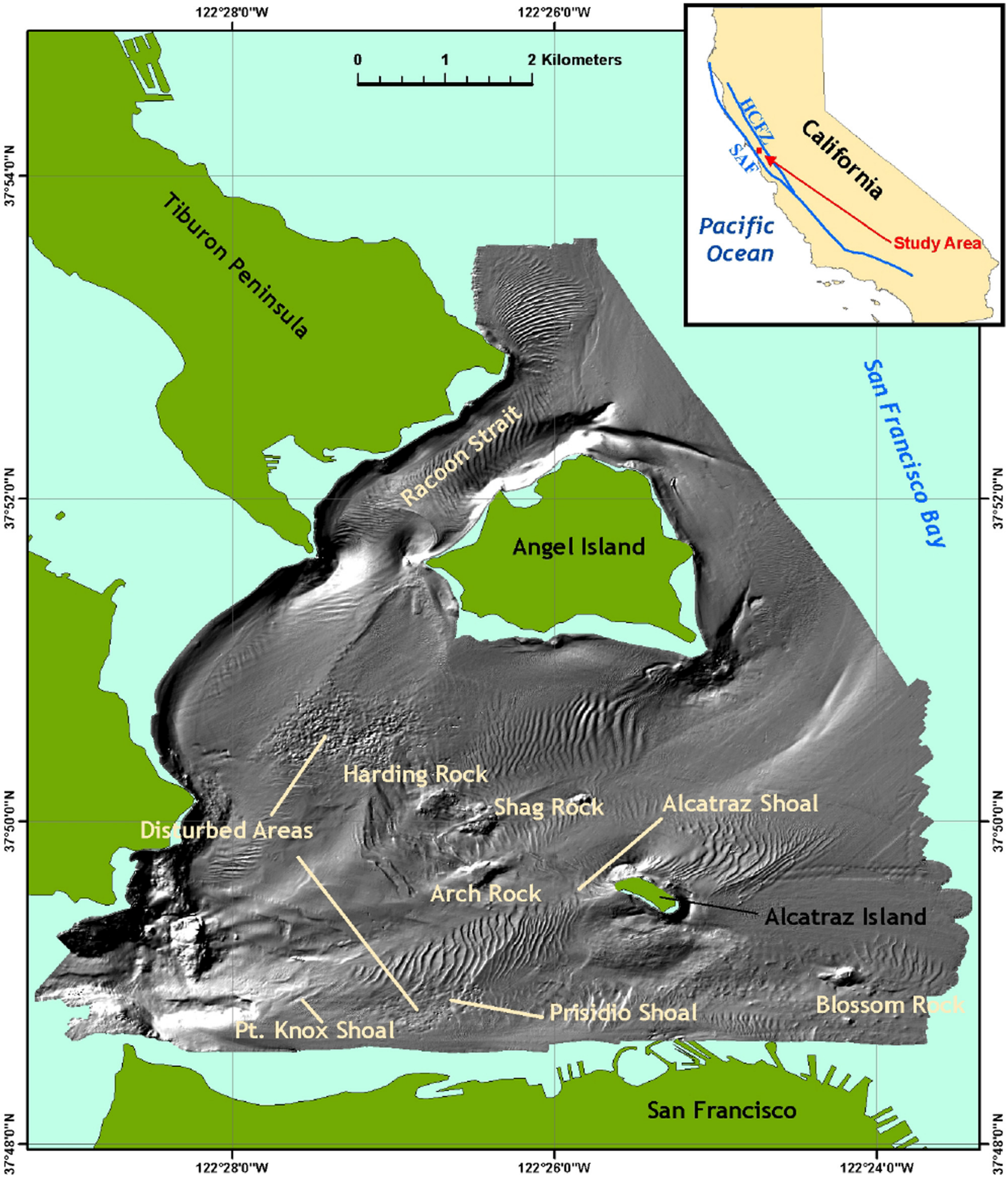

Figure 5 Dynamic bedforms in sediment-wave fields of San Francisco Bay with areas of disturbances caused by aggregate mining operations. After Greene et al. (2007, 2013).

for sound speed variations in the stratified water column using frequent sound speed casts. The San Juan Channel sand-wave field was surveyed multiple times and the comparison of the seafloor morphology (changes in depth) was determined between 2004, 2006, and 2007 (Figure 7).

2.2. Sediment Sampling, Video, and Fish Collection

Building upon the work of Blaine (2006), we conducted a comprehensive sediment sampling effort of the central San Juan Channel sand-wave field prior to 2011

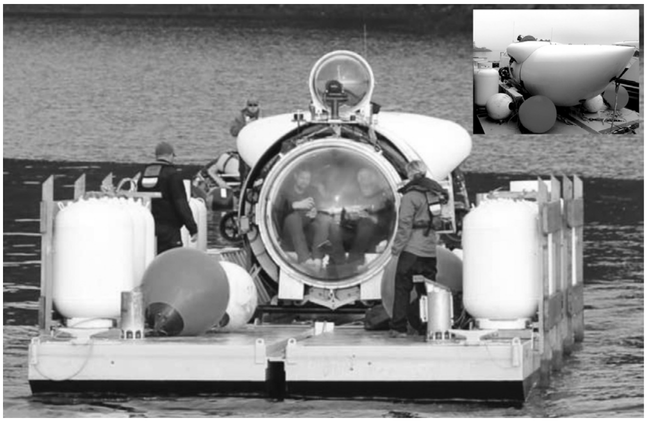

Figure 6 Main image: photograph of *Cyclops 1* submersible (fore perspective) with two of the authors (Baker and Greene) onboard being towed to the dive site on the Ocean Gate deployment and recovery barge; photo courtesy of OceanGate. Inset image: photograph of aft perspective; photo by M.R. Baker.

Table 1 Estimated density of fish in the San Juan Channel sand-wave field sampled from July 2010 to June 2011 showing seasonal and annual variability of fish population within the total area of the field. (After Greene et al., 2011, 2017).

CRUISE	POPULATION DENSITY BY AREA
C1-10 (JUL 2010)	400,000
C2-10 (OCT 2010)	34,000,000
C3-10 (NOV 2010)	72,000,000
C1-11 (JAN 2011)	58,000,000
C2-11 (FEB 2011)	38,000,000
C3-11 (APR 2011)	5,000,000
C4-11 (JUN 2011)	5,000,000

(Greene et al., 2011), using Van Veen and Poner grab samplers. The USGS eyeball sediment camera was used to selectively sample the crest and troughs of the sand waves to determine grain size distribution throughout individual sand-waves and to randomly sample the field as a whole (Greene et al., 2017). Sediment analyses were undertaken with a RoTap™ sieving machine using screens that sieved sediment ranging from silt to coarse gravel at 1φ sieve intervals (see Table 1 of Blott and Pye, 2001). We used these experimental results to assist us in refining the substrate characteristics preferred by PSL in this study.

Our methods included collection and comparison of sediment samples across individual sand-waves, across the sand-wave field boundary, and outside the sand-wave field. Sediment grain sizes were measured and compared within, included the USGS eyeball sampling method (Figure 8), and outside of PSL habitats in order to determine the range of size distributions favorable for sand lance occupation.

2.3. Submersible observations

The five-person submersible *Cyclops 1* was used for collecting video and stereo-camera images of the seafloor within the San Juan Channel sand-wave field (Figure 6). Observations and video recordings using iPhones™ from inside of the submersible were made by close up viewing through the single forward optically corrected Plexiglas hemisphere. *Cyclops 1* measures 6.7 m long by 2.8 m wide by 2.5 m high and has a maximum depth rating of 500 m. The vehicle is equipped with four Innerspace™ 1002 electric thrusters (two horizontal and two vertical) that provide depth control and a maximum speed of 2 knots over the seafloor. The primary observation port is a forward-facing, optically corrected Plexiglas hemisphere approximately 2 m (˜6 ft.) in diameter, allowing for unobstructed observation of the marine environment enabling video recordings from inside the submersible.

We made two dives into the field, one of approximately three hours duration during the morning hours (1020 to ˜1300 h local; 1720 to 2000 UT) on Monday, 10 September 2018 and the other one of approximately two and half hours duration during the afternoon hours (1354 to 1434 local; 1954 to 2134 h UT) of Thursday, 13 September 2018. The Monday dive was primarily concentrated along the eastern margin of the sand-wave field while the Thursday dive was along the central and western margin of the field (Figure 9).

Positioning and recording the track of the submersible was problematic due to a malfunction of the acoustic tracking system on the first dive, requiring us to use a dead reckoning approach with assistance from the surface vessel. To accomplish this, we gridded the high-resolution imagery of the sand-wave field with 10-m-squares (inset map Figure 9) and kept the surface vessel positioned nearly directly over the submersible allowing the submersible to be located within any given grid cell throughout the dive.

Comparison of submersible fixes with the morphology observed from the submersible allowed for a fairly accurate (within ˜2—5 m) tracking and a reasonable reproduction of the dive route.

3. Results

Extensive sampling of our proto-typical PSL sub-tidal habitat type (the San Juan Channel sand-wave field) on a regular basis through the summer, fall, and winter seasons of 2010—2011 allowed for documentation of PSL occupancy and their relative abundances (Greene et al., 2011). Comparative evaluation of the results from a tank experiment study (Bizzarro et al., 2016) and in situ sampling support our hypothesis that PSL prefer grain sizes of 0.5—1.0 mm (medium- to coarse-grain sand) to any other grain sizes and that dynamic bedforms can act as preferred habitats for the fish.

From our previous (2010—2011) sediment and fish sampling study we determined that a large number (Table 1) of PSL occurred in the San Juan Channel sand-wave field, which has a distinct sand-wave morphology (Figure 7). In addition, in comparing sediment types recovered from the crests and troughs of sand waves within the San Juan Channel sand-wave field with the USGS eye-ball camera photographs (Figure 8) and grain size measurements (Greene et al., 2017), we found that a higher number of fish were sampled in the well sorted sand where distinct well-developed sand-waves existed (Figure 2). While PSL

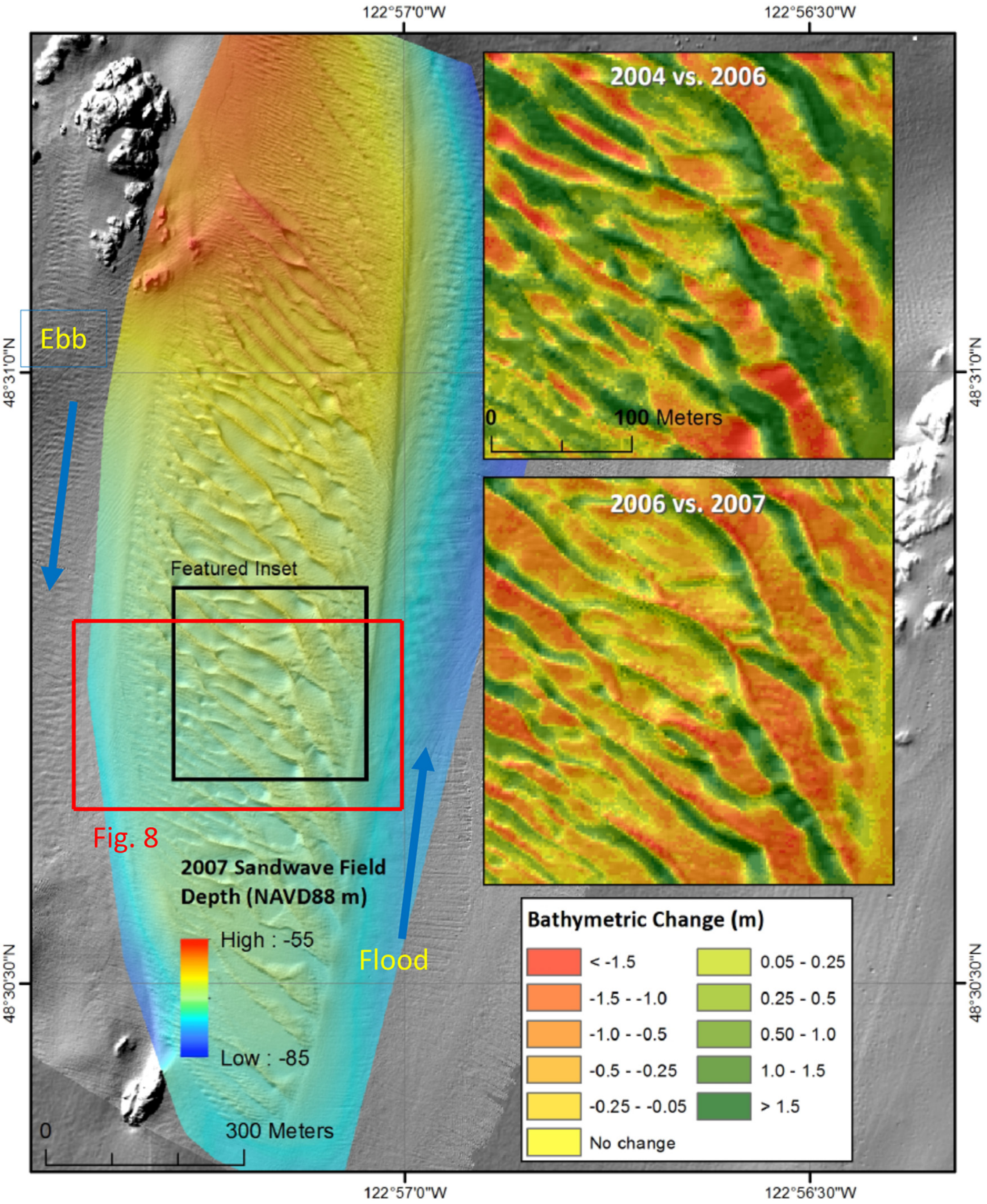

Figure 7 Multibeam echosounder bathymetric images of the San Juan Channel sand-wave field illustrating changes in depth and morphology between the years 2004, 2006, and 2007. Warmer colors in insets represent areas of erosion while cooler colors represent areas of deposition. After Greene et al. (2017).

were observed exiting flat rippled sandy substrate during our dives and seen entering the water column from coarse-grain sand, gravel, and shelly substrate, as observed before (Figure 10) they were not in the numbers observed in the larger, cleaner and well sorted sand-waves. This observation fits with laboratory experiments that examined PSL substrate type preferences and found that the fish preferred well-sorted sand for burrowing (Bizzarro et al., 2016).

3.1. Submersible observations

In the present study the two transects along the length of the San Juan Channel sand-wave field (Figure 9) were undertaken to investigate sediment dynamics in relation to the concentration of fish along various parts of the field, and to observe the reaction of fish to the submersible. In addition, we selectively picked sites to set down and stati-

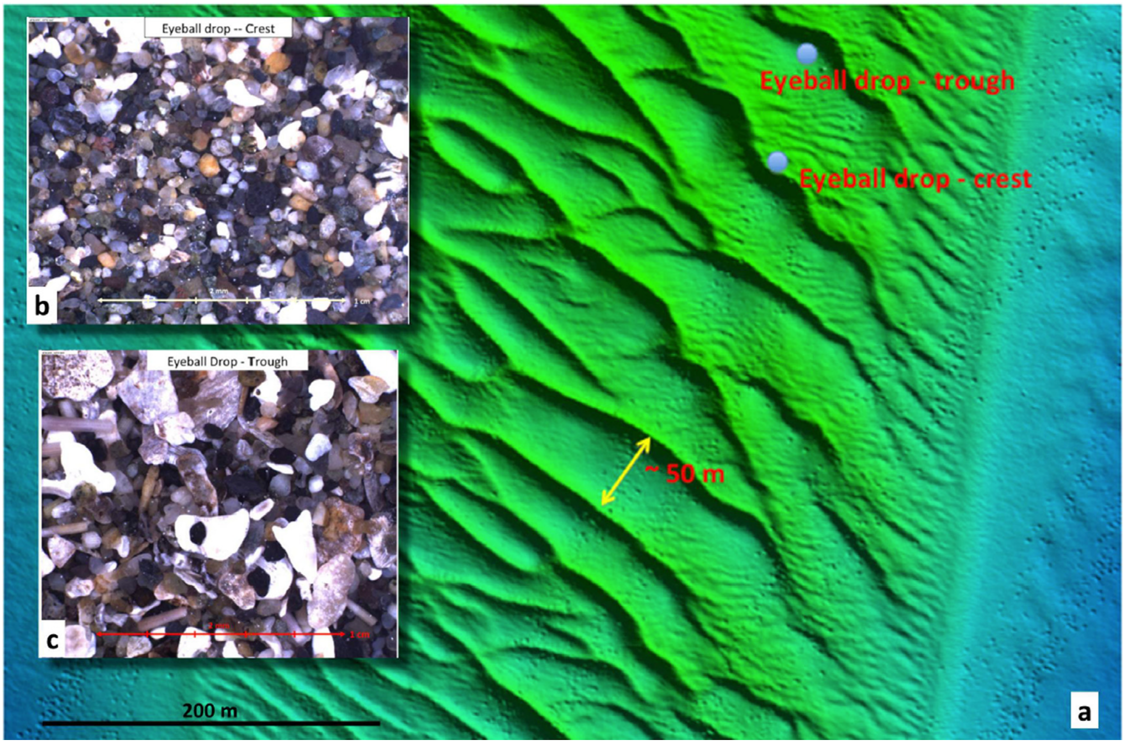

Figure 8 Sediment measurements using USGS eye-ball camera in the San Juan Channel sand wave field; a) high resolution multi-beam echosounder bathymetric image showing location of sample points at crest and troughs of sand waves, b) well sorted sand at crest of wave, and c) poorly sorted sand in trough of wave. After Greene et al. (2017).

cally observe activity within the sand-waves. The two transects revealed a considerable amount of fish associated with the crest areas of the larger sand-waves in the field (Table 2). In traveling into the flood tidal current we observed, and video-taped (see supplemental video 1) large numbers of PSL exiting from the upper lee (near crest) sides, crests, and upper stoss sides, in that order, of approximate 2 to 3 m high sand-waves (Figure 11). A large number of the fish were observed generally to be exiting towards the up current direction, although others exited in various other directions, but all generally coming from the crest areas of the sand-waves (Figure 12).

The fish were obviously disturbed by the transit of the submersible and upon entering the water column began to concentrate around the submersible (Figure 12), then followed the vehicle for a considerable distance away from where they exited the sand-waves. During the static observation periods we turned off the submersibles lights and observed that the seafloor at about 75 m depth was bathed in dim ambient light (Figure 9). This is counter to previously reported light meter measurements taken at 60—80 meters depth in the sand-wave field where light was not detectable by a light meter (Greene et al., 2011). However, little fish activity was observed, and no fish emerged from the substrate during the quiet times we spent setting on the seafloor with lights and motors off.

During transects over the sand-waves at the beginning of flood tidal flow we observed the transport of lighter grains of shell hash being swept up and over the sand-waves and down the lee sides into the troughs (Figure 11). The crests of ripples were composed of these light colored (white) grains of shell hash as well. As the tidal flow increased in strength we observed fine sand-size silicaclastic grains being swept up and over the sand waves. The peaks of the sediment wave appeared stable, not moving in a lateral position, although this was difficult to ascertain as we were transiting slowly over the field and not in a fixed position where we could evaluate changing morphology. Unfortunately, we were unable to observe sediment transport and fish reaction during the peak of tidal flow as the submersible was unable to keep steerageway or to be located in a position that would allow it to sit on the bottom in a stable position at current speeds greater than three knots (˜1.54 m/s; 154 cm/s).

Power and communications cables lie within the San Juan Channel sand-wave field (Figure 9; Table 2) and during our western transect we observed exposed cables, apparently unarmored lying on the sand substrate. One of the power cables was cut and dragged across this field in the past, but the cause of the disruption was never determined. However, trawl marks are visible as expanding and contracting parallel lines in the MBES imagery (Figure 9) collected in 2007, indicating that trawling has occurred in the area previously.

3.2. Grain size measurements

Grain-size measurements previously reported (Greene et al., 2017) were used for evaluating the concentration of PSL in the sediment we observed from the submersible. These samples collected by a van Veen grab were analyzed as follows: after being dried with flood lamps and weighed (in whole), the sub-samples were

Table 2 *Cyclops 1* Dive Video Logs — San Juan Channel Sand-Wave Field

10 September 2018

Local (UT-Z)	Comments
1051 (1751)	On bottom, no current, some PSL emerging from sand
1053	Moving, sand-wave, ˜6 PSL
1056	Moving, mixed sand and shell hash
1057	Above bottom, some PSL in water column
1058	Near rippled sand bottom, drift kelp, small school (˜50) PSL coming off bottom
1100 (1800)	Medium (˜100+ fish) school following sub, increased to over ˜200 with fish aggregating and scattering in front of sub
1110	On bottom, lights off, observed ambient light
1126	Sitting on bottom, rippled sand
1127	Good sand waves, few PSL at start but increased in numbers coming out of rippled sand waves
1128	Off bottom, few fish observed
1131	Transiting south
1132	Small school PSL in water column preceding sub, over rippled sand waves
1135	Over coarse-grain sediment substrate
1142	Over rippled sand, small school of PSL above bottom
1146	Over bottom of sand and fine shell hash
1148	Crab crossing shell hash area, no fish
1204*(1904)	Coarse ripples on large (˜2.5 m) medium-grain size sand-waves — observed many PSL exiting from upper front face (stoss side), crests and back (lee side) of waves; occurred over multiple waves
1207*(1907)	Crossing large (˜3 m high) sand waves, lots of fish exiting crest areas, primarily stoss face, coarse shell hash and shells in troughs
1210*(1910)	Large school of PSL rising from bottom
1217	Coarse-grain bottom of shells, gravel, live clams — out of sand-wave field, setting on bottom
1233	Coarse-grain bottom (71 m depth), Coarse sand with shells, near edge of field, lots of PSL exiting flat substrate
1234	Back in field, current picking up
1241	Sand-waves, few PSL, crest of ripples composed of fine shell hash
1242	Large amplitude (˜3 m high) sand-waves, steep stoss slopes
1243	Strong current, shell hash concentrated on lower stoss sides, migrating up and over crests
1244	Observed exposed cable on bottom in trough of sand wave — not moving because of strong currents
1249	Over crest of sand-wave, heavily rippled with shell hash
1250	Over rippled sand-wave crest, not moving
1251*	V(1951)Transiting up-current over multiple large sand-waves with fish emerging from upper lee and stoss sides and crests (good video)
1253	Over rippled sand-waves, PSL in water column
1255	Not moving, over rippled sand bottom
1257	Stopped on crest of sand-wave, turning
1305 (2005)	Transiting down current, PSL exiting stoss face of sand-waves
1308*(2008)	Sand bottom, lots of shell hash and PSL emerging from substrate
1310	Much shell hash being swept up and over crest of sand-waves
	End Video

13 September 2018

Local (UT-Z)	Comments
1309 (2009)	On rippled medium-grain sand bottom with shell hash
1319*	Off bottom, moving, lots of PSL (>100+) in water column
1321*	On bottom, rippled medium-grain sand, PSL in water column
1322*P	Near crest of sand-wave, fish coming out of upper lee side of sand-wave and lots of PSL rising up into water column (good photo)
1324	Off bottom, few PSL
1326	Rippled sand bottom, no fish
1331	Well sorted, medium-grain sand (dark gray) with shell hash stripes (light, white) along ripple crests
1340*	Lots of PSL in water column above well-sorted, medium-grain sand and fine shell hash
	End Video

Note: See Figure 9 for general locations of observations; * = lots of PSL, V = Video of fish exiting sand, P = Photo of fish rising up into water column.

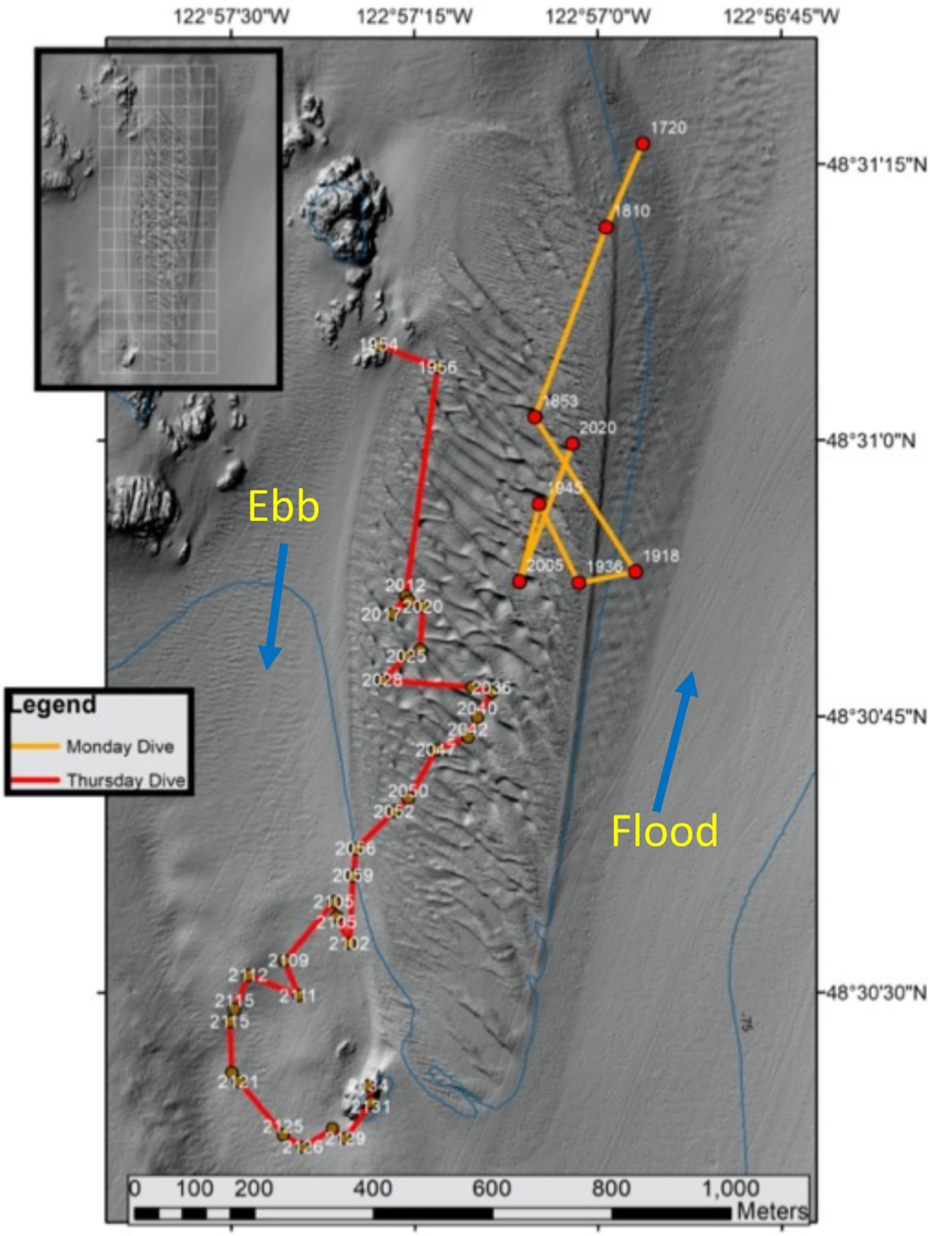

Figure 9 A bathymetric image of the San Juan Channel sand wave field overlaid with the *Cyclops 1* submersible tracks where PSL were observed. Inset image shows grids that were constructed for locating the submersible from a surface vessel and observational seafloor related morphology. Solid blue lines represent direction of flood and ebb tidal bottom currents.

shaken through a series of sieves (2, 1, 0.5, 0.25, 0.125, 0.063, 0.038 mm) for 15 minutes on a Ro-Tap® sieve shaker machine. Each size fraction preserved on each sieve was transferred to a pre-weighed weigh-boat and weighed in total. The proportions of gravel, sand, and silt of the samples, according to the Wentworth Grain-size Classification Scheme (Wentworth, 1929) was calculated from the fraction weights and plotted as graphs and histograms. Using the San Juan Channel sand-wave field as the geomorphologic and sediment type proto-type for a preferred PSL sub-tidal habitat (Figure 1) we see from the results of grain size analyses that well-sorted sediment, with little skewness, and a mean near 1 φ (0.5 mm) in clast size contained the highest number of fish sampled.

4. Discussion

The results of this study are far-reaching (e.g., applies to other marginal seas) and multidisciplinary. We investigated the dynamics and stability of the sand-wave field in central San Juan Channel of the marginal inland Salish Sea using the submersible *Cyclops 1*. Our major objectives were to observe dynamic conditions in situ and to assess the

Figure 10 Photograph of a Pacific sand lance from the study location, extending above the surface of mixed carbonate and siliciclastic coarse-grain sediment substrate extracted from the study site. Photo by M.R. Baker.

hazard associated with the installation of infrastructure in sand-waves that could impact sustainability of these physical features and important habitats.

Observationally we documented that PSL bury themselves within sediment wave crests of well sorted, unconsolidated, medium- to coarse-sand where they have been seen emerging from the upper lee sides, crests, and upper stoss sides of the larger waves within the San Juan Channel sand-wave field (Figures 11, 12). The PSL appeared to be less numerous outside of the field. Our results are consistent with those studies conducted elsewhere showing PSL prefer areas where sediment has a high proportion of sand-size grains (˜2—0.62 mm) and a near absence of fines (silt and clay sizes, <0.062 mm) because this sediment type (“clean sand”) is easily penetrated and has an adequate supply of oxygen (Haynes et al., 2007; Holland et al., 2005; Pinto et al., 1984; Robinson et al., 2013; Wright et al. 2000).

Bedforms that appear as important habitats for such forage fish species as PSL need to be studied elsewhere in marginal seas to protect a valuable resource from anthropogenic impacts. In addition, global warming and sea level rise may have an adverse impact on such features as the bottom current regime may change the sediment dynamics and could alter the grain size distributions and transport of sediment (see Greene et al., 2017).

4.1. Sand-waves stability

The San Juan Channel sand-wave field (Figure 1) contains sand-waves with wavelengths up to approximately 100 meters and approximately 3—5 m in height within the central

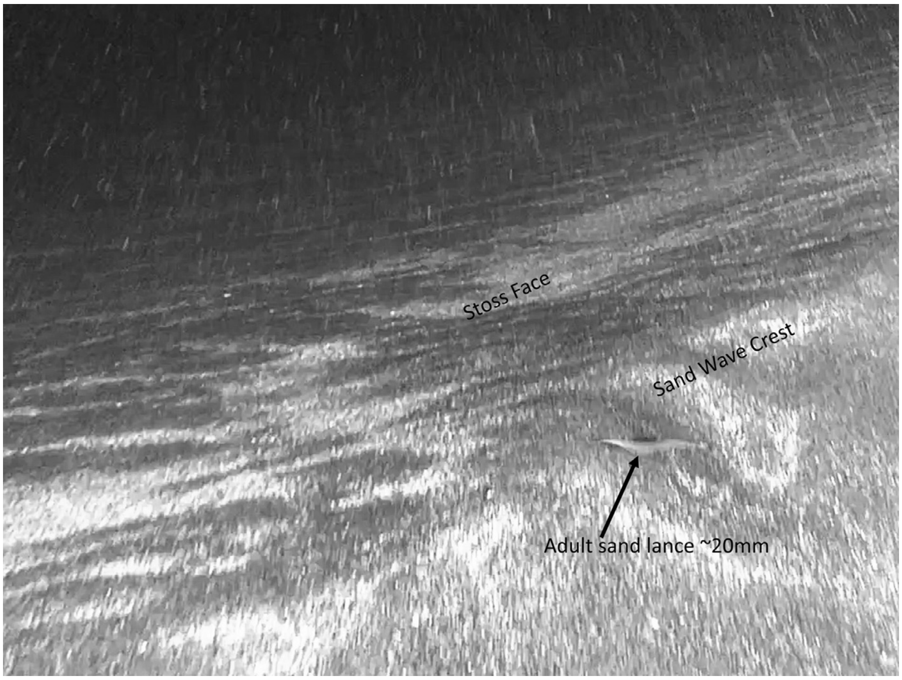

Figure 11 Photograph of crest, stoss slope, and trough of an approximate 2-m-amplitude sand-wave within the central eastern part of the San Juan Channel sand-wave field where a video (see supplemental video 1) recording shows a large number of fish exiting multiple sand-waves (see “V” in Figure 13 for location). Note concentration of light-colored carbonate shell hash in stringers perpendicular to stoss slope and on the crest of the sand-wave. PSL can be seen merging from the substrate (white streaks above bottom) and swimming up into the water column. For scale see PSL shown in photo (length ˜20 mm). Photo taken from inside *Cyclops 1* submersible by M. Baker.

Figure 12 Photograph of PSL rising above a sand-wave observed along the western margin of the San Juan Channel sand-wave field (see "P" in Figure 13 for location). Note sharp form of crest in the background of the photo and the well-sorted medium-grain sand in the foreground. Photo taken from inside the *Cyclops 1* submersible by H. G. Greene.

area. From examination of the sand-waves within the field using the USGS eyeball camera it was shown that the grain size at the crest of a wave is significantly finer (median ˜0.5 mm) than that in the trough (˜2.0 mm), a typical occurrence (Greene et al., 2017; Figure 8) and observations from the submersible supports these analyses (see Figure 11). Furthermore, biogenic shell material dominates in the trough and was observed to flow up and over the crests of sand-waves during tidal flow. Our observations indicate that less dense calcium carbonate material composed of fine shell hash are easily swept up from the troughs and over the crests of the sand-waves during the early stages of tidal flow (Figure 11).

It is well known that sediment transport in the form of migrating dynamic bedforms of dunes and waves can impact seafloor infrastructures through abrasion, burial, and undermining (scouring). The sand-wave field we report upon, and those in other marginal seas are no different and are a hazard to the cable infrastructure present today. However, as far as we can tell the reverse situation has not been addressed, that is, how installation of seafloor infrastructure, trawling, and anchoring can lead to the disturbance of dynamic bedforms through creating an impact on a vulnerable valuable biological resource. We show that a sand-wave field within the marginal central Salish Sea is a critical habitat for PSL and that this fish can easily be disturbed by anthropogenic activity as demonstrated during our submersible investigation. Physical disturbance of sand-waves may be a strategy employed by predators to PSL. For example, Coho Salmon caught by hook-and-line in sand-waves that harbor PSL had striations along their sides (Greene et al., 2017) suggesting that the salmon may be diving into or brushing along the edges of the sand-waves to flush prey out of the sediment. In the case of infrastructure, the unnatural disturbance resulting from the installation of submerged structures in PSL habitat may increase predation risk to PSL and could have short-term and/or long-term impacts on local populations, especially if the local population represents a unique genetic component of the meta-population. Further, the installation of infrastructure may alter the size and extent of the sand-wave fields by changing the natural geomorphologic processes that control the stability of the field. Should the installation of infrastructure result in a net negative loss of habitat, PSL populations could decline, with possible negative implications arising higher in the food chain. Therefore, consideration for protecting such habitats from infrastructure development needs to be assessed and addressed as a hazard to a marine resource, not unlike the consideration of constructing infrastructure on an unstable seafloor.

On Figure 13 we plot the approximate positions along the submersible transects (Figure 9) where the largest numbers of PSL were observed exiting the sand-waves and video recorded (Table 2; supplemental video 1). In comparison to the geomorphology of the sand-wave field (Figure 13), the previously reported large number of fish recovered from sediment sampling (Figure 2; Greene et al., 2017), and photographs and sediment analyses obtained by the USGS sediment eyeball camera (Figures 7, 13; Greene et al., 2017), we are able to show that these fish are associated with the largest and best defined sand-waves in the San Juan Channel sand-wave field, although further statistical analyses are needed to confirm this. Based on this information we outlined the geomorphology that we believe best defines an ideal PSL deep-water sub-tidal benthic habitat (Figure 13), which is well-sorted, medium- to coarse-grain, well-aerated, loosely packed sands formed into 2-3 m amplitude wave bedforms that are swept back and forth from tidal motion but without loss of sediment (Figure 7; Greene et al., 2017). The silicaclastic sediment that make up the bedforms appear to be statically positioned glacial lag deposits that are well winnowed and continuously supplemented by locally produced calcium carbonate shells and shell hash that are swept into the field by tidal action. Parts of these carbonate deposits are incorporated into the bedforms but from our observations much appear to be transiting through the area by being swept up and over the sand-waves with short residence time in the wave's troughs and crests where they concentrate during slack tides. This sediment equilibrium where the winnowed glacial lag deposits are stable and contained within the field, along with the carbonate supply appear critical to the maintenance of a PSL preferred sub-tidal habitat.

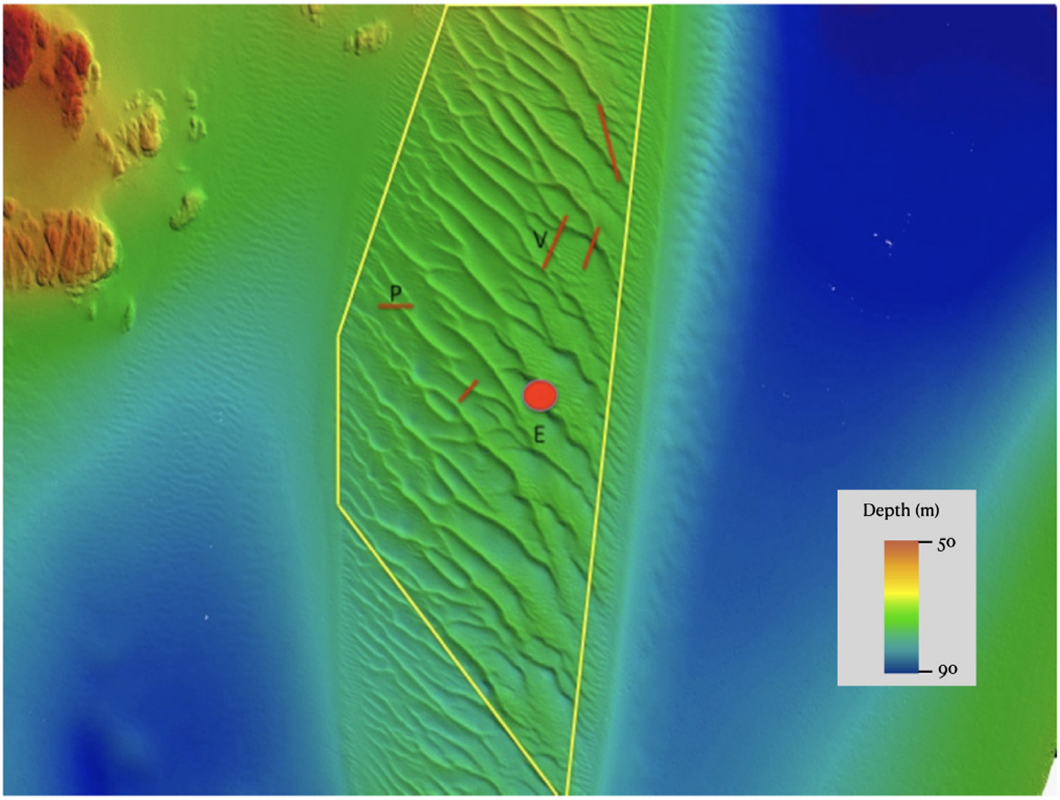

Figure 13 High-resolution (2 m) wide swath multibeam echosounder bathymetric image of the central part of the San Juan Channel sand-wave field showing well-defined dynamic bedforms. Solid red lines represent the approximate locations where large numbers of PSL were observed exiting sand-waves; large red dot with "E" denotes approximate location of USGS sediment eyeball camera photos and grain size analyses shown in Figure 8; "V" is approximate location where video description of PSL exiting the stoss, lee, and crest parts of multiple sand-waves were observed (see Table 2; Figure 9); "P" is location of where PSL were observed and photographed rising above a sand-wave on the western side of the field (see Figure 12); yellow line outlines the distinct dynamic bedforms geomorphology that is considered ideal deep-water sub-tidal benthic habitat preferred by PSL.

5. Conclusions

From sampling of the San Juan Channel sand-wave field in the marginal central Salish Sea it is apparent that PSL prefer to burrow into medium- to coarse-grain (˜0.5-1 mm) size sand. Observations from dives made with the *Cyclops 1* submersible in the field support the sampling results and the hypothesis that PSL concentrate in the crests of sand-waves. We observed that PSL disturbed by the presence of the submersible emerge from the upper lee and stoss sides, and crests of sand-waves, which have an amplitude of 2 to 3 m and wavelength of ˜50 to 100 m. Thus, the seafloor conditions found at our proto-typical habitat type in San Juan Channel exhibited the highest concentrations of PSL observed during our investigation (Table 2; Figure 13). Disturbances from seafloor infrastructure construction and installation could have short-term and/or long-term adverse impacts on PSL and similar species' sub-tidal benthic habitats. Comprehensive evaluation of such impacts is recommended in order to protect such valuable vulnerable biological resources. Fewer numbers of PSL were observed outside of the sand-wave field (Table 2) suggesting that the fish prefer the well-sorted, well-defined sand-waves for refuge and overwintering.

Based on this work we conclude that a predictive and promising potential PSL sub-tidal habitat model can be based on a geomorphology similar to the well-formed sand-waves observed in the San Juan Channel sand-wave field (Figure 13). Metrics for this predictive model include grain size (0.5—1.0 mm, ˜1 φ), depth (30—80 m), wave amplitude (3—4 m), wavelength (50—100 m), and current strengths of ˜0.06 m/sec. However, PSL are known to occur in different types of bedforms (e.g., ripples, sand and gravel flats) and further study needs to be undertaken to place limits and threshold conditions for the habitat attraction of these fish within the Salish Sea and quantitative analyses are needed to support these observational conclusions.

Sediment wave fields and dynamic bedforms are a common potential marine benthic habitat for valuable, vulnerable foraging fish within the marginal inland Salish Sea. Seafloor conditions that shape and maintain such habitats in the Salish Sea are common in other high-latitude marginal seas. In the past many marginal seas including the Salish Sea were shaped by glaciation. With glacial retreat and melting transgression of the sea inundated areas previously covered by ice, allowing the concentration of relic glacial deposits along with forming dynamic bedforms from increasing tidal flows. The substrate habitat type preferred by PSL, resulting from the winnowing influence of the tides, is also valuable as granular resources for the construction industry (e.g., production of concrete), from which resource extraction may be detrimental to the fish habitat. In the future, continued sea level rise and sediment extraction within marginal seas may have adverse impacts on critical marine benthic habitats, thus future multi-disciplinary studies are necessary to understand the relationship of ecology and geology as addressed by the GeoHab community.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.1016/j.oceano.2021.06.002.

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