FORAGE FISH SPAWNING IN THE ELWHA NEARSHORE:

ECOLOGICAL FORM AND FUNCTION IN A CHANGING ENVIRONMENT

by

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ABSTRACT

Forage Fish Spawning in the Elwha Nearshore: Ecological Form and Function in a Changing Environment

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Intertidal beaches within the Elwha nearshore are documented habitat for forage fish migration and spawning. Sediment processes of the Elwha drift cell, critical for forage fish spawning habitat, were historically altered by armoring of the shoreline, lower river alterations, and the in-river Elwha and Glines Canyon dams. The recent removal of these two dams, and the consequent release and transport of upwards of 2.5 x 10^6 m^3 of fluvial sediment to the Elwha nearshore, has begun a partial restoration of sediment processes within the drift cell and is changing the substrate characteristics of its beaches, potentially restoring nearshore function for forage fish spawning. We conducted egg surveys for two species of forage fish, surf smelt (*Hypomesus pretiosus*) and sand lance (*Ammodytes hexapterus*), over four years, including two years before dam removal (2007-8) and two years during the dam removal process (2012-13). Samples were collected from geomorphic habitat types (GMHTs) (embayment, bluffs, and spit) within the impaired Elwha drift cell and from comparative, intact Dungeness and Crescent Bay drift cells. In order to assess nearshore function, we compared spawning activity across impaired/intact drift cells, GMHT, and before/during dam removal time periods. While no sand lance eggs were found during the course of this study, our surf smelt results show that, overall, the intact Dungeness drift cell supports more-robust spawning activity than the impaired Elwha drift cell and that egg productivity did not differ significantly between the two time periods. We also conclude that egg abundance is highly variable across GMHT, with the greatest abundance in the intact bluffs site followed by the impaired embayment, where spawning habitat appears to have expanded during the dam removal period. Spit sites did not support any spawning activity. Understanding the implications of dam removal to the ecological functioning of the nearshore is important for full ecosystem restoration of the Elwha system, where shoreline armoring will remain an outstanding and long-term restoration issue.

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Chapter 1: Introduction and Literature Review

INTRODUCTION

Nearshore environments are complex and productive ecosystems that provide refuge, feeding, migratory, nursery, and spawning habitat to a diverse range of species. Because they occur at the interface between marine and terrestrial ecosystems, nearshore ecosystems are vulnerable to a wide range of anthropogenic activities (Fresh et al., 2011; Simenstad et al., 2011). The Elwha nearshore, located within the Strait of Juan de Fuca and along the north coast of Washington State's Olympic Peninsula, provides an example of an environment with historically impaired ecological processes that is currently undergoing massive and potentially restorative change. For over one hundred years, two dams on the Elwha River impounded fluvial sediment that would have otherwise been transported downstream to replenish nearshore beaches (Czuba et al., 2011a). Kilometers of the shoreline have also been armored, impairing the process of coastal bluff erosion that is responsible for most of the sediment input to the nearshore system (Finlayson, 2006). The result of these two developments has been severe sediment starvation of the nearshore, causing ongoing erosion of the coastline (Warrick et al., 2009) as well as coarsening of nearshore beach substrate to beyond the range necessary for successful forage fish spawning.

In 2011, a project to completely remove both dams on the Elwha River began. This will be the largest dam removal and sediment release in U.S. history (Draut & Ritchie, 2013). The project is now nearly complete and sediment has begun to be mobilized out of the former reservoirs and transported downstream (Kaminsky et al., 2014). This massive pulse of sediment delivered by the mouth of the Elwha River is transforming the sediment processes governing the creation and maintenance of nearshore habitat and has the potential to reestablish forage fish spawning habitat; however, significant impediments to full ecosystem restoration remain. Armored stretches of the shoreline will remain armored long after the initial pulse of Elwha River sediment has subsided and the river resumes its normal, much smaller, annual contribution of fluvial sediment to the nearshore system. Armoring will continue to impair feeder bluff erosion and sediment recruitment to nearshore beaches. While little is known about the exact quantity, timing, location, grain-size, or duration of sediment delivery, questions are raised as to which restorative actions will best optimize sediment arrival and retain it on nearshore beaches (MacDonald & Harris, 2013). As the sediment release is projected to last only 7-10 years, the time to act is now.

This thesis is comprised of three chapters. The chapters are interrelated and supportive of the others, but each chapter can also stand alone as a separate treatment with its own focus. The first chapter is a literature review, focusing on the Puget Sound nearshore environment and the sediment processes that form and sustain the spawning habitat of surf smelt and sand lance, two species of forage fish that are crucially important to the marine food web. The life histories and particular sediment composition and grain-size requirements of these forage fish are described in this review. The Elwha nearshore is also introduced in the first chapter, an area with impaired sediment processes that is located in the central

Strait of Juan de Fuca and within which the experimental portion of this thesis was conducted. The second chapter describes this experiment and has been formatted as a manuscript for publication in a journal of coastal research. It includes an abstract, introduction, and methods section, reports our results and conclusions, and includes a discussion of the findings of this study. The third and final chapter of this thesis examines the interdisciplinary nature of nearshore management issues, focusing on which actions might be taken to optimize both short and long-term ecosystem restoration within the Elwha nearshore and its implications for adjacent nearshore areas.

LITERATURE REVIEW

This literature review is composed of several sections, organized by topic. The first section, *the Puget Sound nearshore*, defines the nearshore environment within the larger context of the Puget Sound Basin, including the Strait of Juan de Fuca. The next section, *beach formation and sediment processes of the nearshore*, examines the sediment processes responsible for supplying, forming, and maintaining its nearshore beach habitat. The important role of *coastal feeder bluffs* is described in the following section because it is the erosion of these bluffs that contributes the majority of sediment to the nearshore system. After having described some of the physical and geomorphological conditions and processes of the nearshore, the next section, *forage fish*, describes the important biological role these fish play in the marine food web. The following two sections, *surf smelt* and *Pacific sand lace*, relate some of what is understood about the life histories of these two important forage fish. A lengthy examination of their specific habitat requirements is described in the subsequent section, *spawning habitat*. Some of the various ways in which *shoreline armoring* can degrade spawning habitat is reviewed next, followed by a closer examination of *the Elwha River and nearshore*, the specifics of its historical impairment, and how forage fish spawning in this area has been impacted. The final section, *management issues and nearshore restoration*, considers the major changes currently underway in the Elwha nearshore sediment regime and some of the ongoing management actions that might optimize nearshore restoration.

The Puget Sound nearshore

The Puget Sound is one of the largest estuaries in the United States, encompassing more than 8,000 square kilometers of marine waters and a watershed of more than 33,000 square kilometers. The physical and ecological complexity found within the Puget Sound region supports a rich and productive natural environment for plant, animal, and human communities alike. The nearshore zone is a complex ecosystem found within the narrow, contiguous ribbon of land and shallow water that rings the more than 4,000 km shoreline of Puget Sound. The nearshore is often defined as extending from the upland and backshore areas that directly influence shoreline conditions to the shallow offshore waters as far as the lower limit of the photic zone, where sunlight is no longer able to sustain marine vegetation (EnviroVision et al., 2007; Fresh et al., 2011). The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP), a collaborative effort between government agencies, universities, tribes, and environmental organizations, defines the nearshore as an area extending from the top of shoreline bluffs waterward to the deepest extent of the photic zone (Clancy et al., 2009). This photosynthetically-defined edge of the nearshore varies in its distance from shore according to water depth and clarity, but is often delineated around 30 meters below mean lower low water (MLLW) (EnviroVision et al., 2007; Shaffer et al., 2008). Occupying areas commonly known as the shore, beach, intertidal, and subtidal zones, the nearshore forms the transitional interface between three critical edge habitats: the edge between terrestrial and aquatic environments, the edge between the diverse and productive shallow waters and deeper water, and the edge between fresh water streams and the marine salt waters (EnviroVision et al., 2007). Interactions between various physical conditions such as coastal geomorphology, wave energy, sediment movement, sunlight, and salinity along these nearshore edges creates a mosaic of different habitats that support a wide diversity and abundance of life. The nearshore marine habitats of the Pacific Northwest are therefore critical components of our regional ecosystem. They provide nursery, migration, and feeding corridors for a number of fish, including several federally and state-listed salmon, and other wildlife (Fresh, 2006; Penttila, 2007). In fact, the nearshore environments are the most productive waters of Puget Sound; their condition, therefore, influences the productivity of the entire Puget Sound basin and many of the ecosystem goods and services important to human communities (EnviroVision et al., 2007; Fresh et al., 2011; Simenstad et al., 2006).

The Puget Sound nearshore has long attracted human activity. The area was home to about 50,000 native people when Captain Vancouver first sailed into Puget Sound more than 200 years ago but now sustains a population of 4.5 million people (Puget Sound Partnership, 2013), about 70% of the people living in Washington State. Large sectors of the northwest economy are tied to the Puget Sound and its nearshore environment, including shellfish and commercial fishing industries, ports, refineries, and trade activities, and a variety of recreational opportunities. This concentration of human population and intensity of activity within the nearshore makes it especially vulnerable to human impacts.

In recognition of this vulnerability, the Shoreline Management Act (SMA) of 1971 provides a framework requiring the evaluation of existing nearshore conditions and the establishment of policies and regulations that will protect nearshore ecological functions. As part of a required process to inventory and characterize shoreline conditions, local governments are directed to identify areas of critical saltwater habitat and designate them as "critical areas." In addition to kelp and eelgrass beds, mudflats, and areas associated with priority species, critical areas are defined to include, "spawning and holding areas for forage fish, such as herring, smelt and sand lance" (WAC 173-26-221(2)(iii)(A)). Critical habitats are also recognized as requiring a higher level of protection in order to preserve the important ecological functions they provide. The law calls for regulatory provisions for critical areas that protect existing ecological functions and ecosystem-wide processes (WAC 173-26-221(2)(B)(iv)) by integrating the management of shorelands and submerged areas (RCW 90.58.090(4) and WAC

173-26-221(2)(iii)(A)). As beaches are the primary feature that defines the landward edge of the nearshore zone, they provide important ecological functions but are often directly impacted by human activities in the nearshore. Beaches therefore, warrant a closer look at how they are formed, what processes sustain them, and what role they play in nearshore habitat form and function.

Beach formation and sediment processes of the nearshore

Beaches are formed by the accumulation of mobile material between the upland environment and an area of deeper water where substrate is not influenced by wave action and so is not active (EnviroVision et al., 2007). They occur along the shoreline where there is both an abundant supply of sand and gravel sediment and a sufficient degree of wave action to rework this material (Shipman, 2008). The erosion of coastal bluffs provides most of the sediment inputs into the Puget Sound nearshore system, with large rivers and small streams contributing additional inputs (Finlayson, 2006; Johannessen & MacLennan, 2007). It is this interaction between sediment input and sediment transport that controls the structure of beaches. The steady erosion of these bluffs, therefore, is critical for maintaining beaches and spits over the long term.

Beach substrate is in constant flux, mobilized by wave action and redistributed along the coastline in a process called longshore transport (Simenstad et al., 2011). Sediment redistribution occurs in a net direction according to prevailing waves, wind, and currents. The configuration and orientation of the coastline relative to these prevailing forces divides the shoreline into distinct areas with its own sediment source, area of transport, and area of deposition (Shipman, 2008). These semi-independent segments of the coast are called littoral cells, or drift cells, and 860 of them have been identified within Puget Sound (EnviroVision et al., 2007). The sediment processes that occur within drift cells result in a gradual change in beach size, shape, and structure, and are responsible for the present configuration of the shoreline. This link between geomorphological processes and the physical form of the nearshore creates habitats that are of critical importance to the survival of a multitude of marine creatures, including forage fish, juvenile salmon, marine birds and mammals, and aquatic vegetation such as eelgrass and kelp beds. Since bluffs contribute the majority of sediment sources into the nearshore system, it is important to understand their role in maintaining intact coastal sediment processes, as well as what might impact these processes.

Coastal Feeder Bluffs

Puget Sound’s coastal bluffs are geologic features that have formed since the last glacial period of the region ended 14,000 years ago, leaving behind an extensive layer of poorly consolidated sediment across the region at elevations above modern sea level (Shipman, 2004). Channels cut into this sediment layer by glacial meltwater became deep troughs and slowly filled with sea water until reaching the current sea level about 5,000 years ago, at which time bluffs developed and the modern shoreline to begin to evolve (Shipman, 2004).

Bluffs have a significant influence on the region's nearshore environment because they are found along more than 60% of Puget Sound's shoreline and are the primary source of recruitment for the sand and gravel that make up beach substrate (Johannessen & MacLennan, 2007). It is primarily through the erosion of these coastal feeder bluffs that sediment is delivered into the nearshore system to shape and maintain nearshore habitat. Bluff erosion often occurs through a process in which wave action removes material at the bluff toe, undercutting the slope and creating an unstable profile that eventually leads to mass-wasting of new material onto the beach (Shipman, 2004). The mobilization and distribution of this new material sustains the sediment processes within the drift cell. The rate of bluff recession depends on the bluff's exposure to wave action of sufficient energy to erode and remove sediment from the toe of the bluff, the geologic makeup of the bluff which determines its susceptibility to erosion and mass-wasting, and beach characteristics such as beach width and berm height which control how frequent and with what intensity waves reach the bluff toe (Shipman, 2004). Complex interactions between all of these factors combine to create a diversity of ecological forms and habitat types along the marine shoreline. Many nearshore species depend on habitat that is associated with beach substrate of a particular composition, size, degree of sorting, or other specific characteristic. For example, Forage fish require substrate within a particular range of grain-sizes for successful spawning (Moulton & Penttila, 2001; Penttila, 1995; Penttila, 1978). The habitat suitability of kelp forest and eelgrass beds, both important for providing productive refuge for a wide range of marine species, is also determined by sediment characteristics, although these factor differently for each (Mumford, 2007). Because bluffs are the primary source of sediment replenishing and maintaining beach substrate, they are indirectly responsible for ensuring that diverse habitats are available for species with a variety of sediment requirements. Bluffs, therefore, are a feature of the Puget Sound nearshore that are vital to the health of nearshore populations, and by extension, to the health of the Puget Sound region as a whole.

Having described some of the physical conditions and geomorphological processes shaping the nearshore, we now turn to examine one group of biological creatures inhabiting this unique environment. Forage fish display particular requirements for sediment size and composition and so are good indicators of the physical form and the health of ecological function in Puget Sound's nearshore environment.

Forage fish

Three species of forage fish, Pacific herring (*Clupea pallasi* (Valenciennes 1847)), surf smelt (*Hypomesus pretiosus* (Girard 1955)), and sand lance (*Ammodytes hexapterus* (Pallas 1811)) spawn in the nearshore zone of Puget Sound beaches (Penttila, 2007). Since all forage fish species rely on nearshore habitats for at least part of their life history and congregate in the nearshore in large numbers during spawning, the protection of these habitats is critical to the long-term sustainability of these species as well as to a number of other fish, mammal, and bird species which rely on forage fish as prey. Pacific herring spawn on marine vegetation in shallow subtidal regions of the nearshore, but surf smelt and sand lance spawning habitat occupies the upper intertidal region and so is particularly vulnerable to both changes in nearshore sediment processes and human activities which modify the shoreline. The following sections of this chapter will focus on the life histories of surf smelt and sand lance in particular, their importance to the marine food web of the Puget Sound region, and how their spawning activity is crucially linked to the sediment supply processes of the nearshore.

Surf smelt and sand lance are critically important to the structure of Puget Sound marine food webs (Cross et al., 1980; Penttila, 2007; Simenstad et al., 1979; Therriault & Schweigert, 2009). For instance, 35% of the diets of juvenile salmon (and 60% of the diets of juvenile Chinook salmon) in Puget Sound were found to be comprised of sand lance (Hershberger et al., 2006). Some have described forage fish as representing the primary energy bottleneck in the biological community of the nearshore, exerting both top-down control over primary and secondary tropic levels (phytoplankton and zooplankton) and bottom-up control over higher order predators such as salmonids, marine mammals, and sea birds (Rice, 1995; Simenstad et al., 1979). Variability in forage fish abundance and distribution, therefore, may have major consequences for determining the fitness of predator populations (Haynes et al., 2008). The Washington Department of Fish and Wildlife (WDFW) is charged with managing forage fish stocks in Washington State; yet, in spite of the apparent ecological significance of forage fish for other commercial or endangered species, the ecological variables that influence their populations remain largely understudied ((Penttila, 2007; Robards et al., 1999b). While herring stocks are regularly monitored, no monitoring strategy has been developed for surf smelt or sand lance and little is known of their life histories or geographic distribution. Nevertheless, observations of surf smelt and sand lance spawning behavior present in the literature afford some insight into their respective habitat requirements as well as ways in which anthropogenic factors can affect population abundance and demographics.

Surf smelt

Surf smelt occur from northern California to southern Alaska (Hart, 1973), but are particularly abundant in Puget Sound (Therriault et al., 2009) where they are also available much of the year, increasing their importance as a food source within the marine food web. Surf smelt feed primarily on calanoid copepods (Simenstad et al., 1979), a key herbivorous species of zooplankton that concentrate autotrophic carbon into particles of high-density plankton. Surf smelt thus serve as a crucial trophic link between primary consumers and higher order predators. Maturing and spawning at one year of age, few fish appear to survive beyond four years of age (Penttila, 1978). Little is known about the life history of surf smelt apart from their use of nearshore intertidal beaches for spawning.

Many questions remain unanswered as to the number of distinct surf smelt stocks, as well as their seasonal distribution and movement throughout the waters of the Puget Sound region (Penttila, 2007; Pierce et al., 2009). Spawning can occur year round, but in general surf smelt stocks are loosely divided into summer spawners and winter spawners. Summer spawning occurs in the northern Puget Sound region, including the Strait of Juan de Fuca, from May to October; winter spawning takes place in the southern Puget Sound region from September to March (WDFW, 2010). Spawning habitat has been documented along about 10% of the shoreline of the Puget Sound Basin (Penttila, 2007), including coastal areas of the Strait of Juan de Fuca (Moriarity et al., 2002a; Penttila, 1978), with a total of 259 lineal statute miles of Washington State shoreline known to be surf smelt spawning beach (WDFW, 2010). Spawning takes place in short intervals during high tides, in the few inches of water covering the uppermost one-third of the intertidal zone (Penttila, 2007). Surf smelt eggs are adhesive to particles of beach substrate and are often found with several grains of sand attached to them which acts to weigh down the egg and help it mix into the substrate below the beach surface (Penttila, 1978). Eggs can take from two to eight weeks to incubate, depending on seasonal temperature (Penttila, 2007).

Pacific sand lance

The Pacific sand lance is a common and widespread species of forage fish found throughout the nearshore marine waters of the Puget Sound Basin. Like surf smelt, they feed primarily on calanoid copepods (Miller et al., 1980) and are in turn preyed upon by a broad array of marine mammal, bird, and fish species. As many as 31 species of birds, 9 marine mammals, and 27 fishes depend on sand lance for more than 50% of their diet (Robards et al., 1999b). Sand lance thus occupy an ecologically-important link in marine food webs similar to surf smelt.

Unlike surf smelt, however, sand lance often form dense surface schools, commonly called “bait-balls,” which attract a variety of predators including numerous alcid seabirds (Penttila, 2007). Sand lance are also unusual in that they actively burrow into beach substrate as a predator-avoidance mechanism and as part of diurnal and seasonal cycles of energy conservation (Quinn, 1999). The spawning season for sand lance appears to be shorter than for surf smelt, occurring exclusively in the fall and winter months. The greatest spawning activity has been detected in November and December, but extends to a lesser degree into January and February (Penttila, 1995b).

Although taxonomically unrelated, sand lance spawning habitat closely resembles that of surf smelt. Both spawn on upper intertidal beaches consisting of sand and fine gravel during high tides when the beach is covered with shallow water. While mapping the spawning activity of sand lance in beaches along the western Strait of Juan de Fuca, Moriarity et al. (2002b) found eggs deposited in a fluffy mixture of fine and coarse sands. This “fluffy” nature of the substrate is important because females will excavate shallow pits in which to deposit spawn (Penttila, 1995b; Robards et al., 1999a). The preference for uncompacted substrate, whether fluffy sand or a loose mixture of sand and gravel, is a characteristic shared by surf smelt. In fact, the same beaches are often used for spawning by both sand lance and surf smelt and the eggs of both can co-occur in the same beach substrate when their spawning seasons overlap in winter (Penttila, 1995a; Penttila, 2001). Since the spawning behavior so closely resembles each other, we will now examine the specific substrate requirements and other shared characteristics that define surf smelt and sand lance spawning habitat.

Spawning habitat

The upper intertidal zone is one of the most rigorous habitats in the marine environment. Few organisms have managed to adapt to its fluctuations in temperature, salinity, and submergence time, as well as to the grinding, abrasive nature of its shifting substrate (Penttila, 1995a; Penttila, 1978). Both the surf smelt and the sand lance have adapted their spawning activity to this zone and have been observed to seek out a specific type of substrate for spawn deposition. The characteristic beach substrate of an egg-bearing sample is often described as “pea-gravel,” “coarse sand,” or a “sand-gravel mix.” In one of the earliest measurements of substrate samples containing forage fish eggs, Penttila (1978) found that samples containing surf smelt spawn were composed mostly (80% by weight) of material in the size range of 1 to 7 mm in diameter. Another study found that the top one-inch surface of sand-gravel beaches used by spawning surf smelt was comprised mostly of material in the 1 to 10 mm size range (Penttila, 2001).

Sand lance utilize this same range of substrate sizes, but also spawn in finer classes of sand. Penttila (2001) analyzed the grain-sizes of spawn-bearing samples throughout Puget Sound and found that while 25% of the material containing sand lance eggs was characterized as “gravel-coarse sand” resembling the 1 to 7 mm grain-size range used by spawning surf smelt, the majority (67%)

of the material was medium sand between 0.2 to 0.4 mm. Others report spawning areas consisting of coarse sand and gravel, 20% of which consisted of shell fragments, with a slightly higher median particle diameter of 1.9 mm, concluding that the choice substrate for sand lance appears to be highly specific, characterized as well-washed, drained, and unpacked coarse sand with very little content of mud or silt (Robards et al., 1999a; Robards et al., 1999b). A controlled study in which sand lance were given a range of substrate sizes to chose from found that they preferred a coarse sand with grain-size from 0.5-1 mm (Summers et al., 2013). Since benthic areas and shorelines that lack sediment have been found to have no sand lance present (Haynes et al., 2007), it is clear that this species also displays specific substrate requirements in their spawning activity and use of the nearshore environment.

One of the more curious uses of the nearshore by sand lance is displayed in their habit of burrowing into beach substrate. The species has developed a number of adaptations, including the lack of a swim bladder, a slender body, and the ability to utilize oxygen-poor interstitial water, which allow them to bury themselves in loose sandy substrate (Quinn, 1999). This behavior appears to occur for a variety of reasons and at different times of the seasonal and diurnal cycle. For example, sand lance have been observed burrowing into sediment at night, as well as during the day while not foraging to escape from predators (Haynes et al., 2008; Haynes & Robinson, 2011). They may also burrow into sediment during winter for months at a time in a state of dormancy, and can remain buried above the waterline during low tide (Ciannelli, 1997; Quinn & Schneider, 1991). Sand lance may remain in the shallow depths of the coastal environment for much of their life history. Ostrand et al. (2005) found few sand lance located at depths of 40 m and none at 60 m. Their requirement for a highly specific type of spawning habitat, consisting of well-drained sand and pebbles without silt or mud, and their use of sediment as a refuge causes sand lance to be associated with shorelines that are plentiful in suitable substrate (Haynes et al., 2007).

Spatial and temporal factors also relate to substrate type and affect forage fish spawning. For example, shoreforms such as sandy spits and beaches at the far end of drift cells often support sand lance spawning habitat because those are the locations where the appropriate type of finer-grained sediment accumulates (Penttila, 2007). In their *Field Manual for Sampling Forage Fish Spawn in Intertidal Shore Regions*, Moulton & Penttila (2001) report that the upper third of the beach is the most likely area to contain eggs of both species. Because of wave energy acting to sort the substrate at this tidal elevation, this area is characterized by loose and well-mixed sand and small gravel that is devoid of the very-fine size classes of silt and mud. Forage fish, therefore, frequently spawn at high tide in order to reach this high position on the beach (Penttila, 1995b). After being deposited near the high tide line, some eggs are washed down the beach slope by receding waves and are distributed widely along the beach face for incubation (Moulton & Penttila, 2001). Eggs, along with smaller particles of beach material, are sifted into a lower strata of the beach by the sorting and resorting of the surface substrate by wave action, eventually coming to rest in a micro-environment providing both capillary moisture and sufficient aeration to maximize spawn survival (Middaugh et al., 1987; Penttila, 1978; Thompson & Associates, 1936). The spawning activity of these forage fish are thus well-adapted to the dynamics of the upper intertidal zone.

Spawning habitat is often not uniformly distributed, but found in a mosaic of substrate types representing various degrees of potential suitability. Depending on such factors as the source and composition of raw beach material, wave action regime, orientation of the shoreline, direction and velocity of sediment drift, and presence or absence of shoreline structures, the preferred sediment can be spatially patchy, occurring in limited areas (Haynes & Robinson, 2011), or in broad bands of material meters wide and kilometers long (Penttila, 1978; 2007). Geographical distribution can vary as well. Penttila (1995b) found that virtually every sandy-gravel beach in the series of bays of the northeastern sector of the Olympic Peninsula supported sand lance spawning activity. In contrast, the relatively rare pocket beaches of the San Juan Islands (Beamer & Fresh, 2012) and the protected cove beaches on the outer coast of the Olympic peninsula (Thompson & Associates, 1936) offer only small and discrete patches of suitable habitat.

Successful spawning habitat for forage fish depends on the presence of an adequate amount of beach substrate of the correct composition. Areas where the substrate of the upper beach is composed entirely of fine sand or large gravel and cobbles are rarely used by forage fish for spawning. When spawning does occur in such areas, for instance when located adjacent to heavily-used satisfactory spots, Penttila (1978) observed spawn of poor quality. Whether deposited on large-sized beach material or on fine pure sand, the light-weight eggs are unable to mix into the substrate below and so are left on the surface, suffering desiccation and thermal stress from the continuous exposure to sun and wind.

Further evidence that forage fish require substrate of a particular character comes from the observation that spawning sites are commonly used year after year. Haynes & Robinson (2011) found that sand lance exhibit site fidelity during their first year of life, re-using the same nearshore patch of sediment on time scales from weeks to months, and for a few sites, inter-annually. After discovering a suitable sediment patch, the fish stay nearby, presumably because of their high environmental specificity for substrate type and because of the risk of not finding another suitable sediment patch. Whether perennial use of isolated patches of habitat is evidence of a homing ability or of active searching behavior is not known (Penttila, 1995b)

Other investigations into how variations in the beach environment affect the suitability of spawning habitat have revealed annual spatiotemporal variations in the distribution of spawning activity in Puget Sound. Quinn et al. (2012) evaluated beach characteristics hypothesized to affect the suitability of surf smelt spawning habitat and found that aspect, fetch, solar radiation, and temperature were predictors of eggs abundance, but not of embryo mortality. Spawning activity appears highly variable, both spatially and temporally. Factors other than substrate characteristics, such as population density, behavioral dynamics, and other environmental conditions also determine whether a beach supports spawning. It has been estimated that, in any given year, perhaps as little as 30% of the known spawning beaches in Puget Sound actually support surf smelt spawning (Penttila, 2007; Quinn et al., 2012). The fact that most beaches with the suitable type of substrate are not used for spawning suggests that impacting those relatively few beaches that do support spawning could disproportionately affect surf smelt production.

The particular sediment requirements of forage fish spawning habitat makes them especially susceptible to alterations of sediment processes supplying the nearshore environment. Disruptions of these processes can change the physical characteristics of a beach, from coarsening the composition of substrate material to altering the beach slope and width (Fresh et al., 2011). Beaches that lose the continual inputs of sediment that sustain them can suffer loss of shoreline habitat. Wave action continues to suspend and carry away the fine sediments from the beach surface, over time leaving it as an area of hardpan mud, bedrock, and cobble, unsuitable for spawning forage fish (Middaugh et al., 1987; Moulton & Penttila, 2001). Changes in the distribution of sediment to size ranges outside those required by forage fish are likely to affect spawning site selection as well as egg mortality. Continual inputs of sediment are therefore required to sustain beach structure and forage fish habitat.

Shoreline armoring

The past 150+ years of development since Europeans began settling the region have profoundly changed the physical form of Puget Sound’s nearshore ecosystems with implications for the vitality of ecosystem functions, goods, and services. The modification of beaches and bluffs through the construction of shoreline armoring results in the reduction of sediment supply and the interruption of sediment transport processes. According to recent estimates, approximately 27% (about 1,070 km) of the shoreline of Puget Sound is armored (Puget Sound Partnership, 2013). Furthermore, while 27% of barrier beaches and 8% of pocket beaches have been armored, a full third of bluff-backed beaches have been armored along at least half of their length (Fresh et al., 2011).

Placing bulkheads or other armoring structures along a shoreline can result in forage fish habitat degradation in several ways. Armoring that extends low enough into the intertidal zone can cover over and physically eliminate the fine-grained substrates found on the upper beach that are necessary for forage fish (Penttila, 2007). By reducing bluff erosion and blocking sediment input to the beach, armoring can convert spawning areas of fine-grained substrate to coarser gravel and cobble material, unsuitable as spawning habitat (Fresh et al., 2011). Bulkheads may accelerate this process by reflecting wave energy back onto the beach, suspending and transporting away the fine grains of substrate and contributing to further coarsening (Carrasquereo-Verde et al., 2005). Armoring can also cause an increase in temperature on the upper beach through the removal of shade trees, thereby negatively impacting the survival of incubating embryos (Penttila, 2002). In fact, Rice (2006) demonstrated that anthropogenic shoreline modifications can create a brighter, hotter, and drier shoreline environment in which the proportion of surf smelt eggs containing live embryos was reduced in half.

Armoring can also have indirect effects on the abundance and distribution of forage fish spawning substrate. One study in Thurston County found that while woody debris on beaches provided structural support for the accretion and stabilization of sand, its presence or absence was the single most distinguishing factor between unarmored and armored shorelines (Carrasquero-Verde et al., 2005). They concluded that the loss of woody debris from armored beaches is likely to contribute to reduced forage fish spawning habitat (also see Clancy et al., 2009; Rich et al., 2014). Other indirect impacts to spawning habitat occur through activities that change the size and shape of the beach, and thus the area available for spawning, or the size and composition of beach substrate. Perhaps the most important indirect effect of shoreline armoring is to inhibit bluff erosion and thus reduce sediment inputs into the entire beach system. Changes in sediment supply directly affect the volume of sediment that is available for longshore transport within drift cells (Simenstad et al., 2011), and can lead to lower elevations and coarser sediments of beaches in the upper intertidal zone (Shipman, 2008). Longshore transport can be further impeded by groins and jetties or fill that extends onto or across a beach. Finally, the rate of transport may be altered by structures parallel to the shore, such as seawalls, which modify how waves interact with the beach (Simenstad et al., 2011). Armored shorelines are one important mechanism by which beach sediment processes are impaired. To adequately protect forage fish habitat requires not only protecting the beaches where spawning occurs, but also protecting the physical processes that form and maintain those nearshore habitats that support spawning (Schlenger et al., 2011).

Second to coastal bluffs, rivers are the other major input of sediment into Puget Sound and the Strait of Juan de Fuca. Rivers transport an estimated 6.5 × 10^6 t yr^{-1} of sediment to Puget Sound every year (Czuba et al., 2011b). Disrupting the delivery of sediment to nearshore beaches leads to changes in its structure and results in degraded ecosystem function (Schlenger et al., 2011; Simenstad et al., 2006). An example of impaired sediment processes resulting from the dual effects of shoreline armoring and in-river dams can be found within the Elwha River system and its nearshore environment.

The Elwha River and nearshore

The Elwha nearshore is located along a segment of coastline found within the Strait of Juan de Fuca, a body of water connecting the Pacific Ocean to the inland marine waters of Puget Sound which provides refuge, feeding, and spawning habitat for forage fish as well as a critical conduit for several migrating species of salmon (Shaffer et al., 2003). The Elwha nearshore follows a 21 km stretch of shoreline extending from the west end of Freshwater Bay east to the tip of Ediz Hook. Two large dams, built in the early 1900s, have disrupted the delivery of sediment into the Elwha drift cell, impacting the character of the substrate found on the beaches dependent on this supply. Over the course of their lifetime, the dams trapped an estimated 21 to $26x10^6$ m^3 of sediment within their reservoirs and reduced the Elwha River’s delivery of fluvial sediment to the coast to about 2% of the pre-dam load (Draut & Ritchie, 2013). With the dams in place, exposed bluffs along the lower Elwha River remained the only substantial source of sediment in the short section of river downstream of the lower Elwha Dam (Draut et al., 2011). The sediment supply to Ediz Hook, the spit at the terminal end of the Elwha drift cell, has been further impacted by the presence of approximately 5 km of bluff armoring located between the river mouth and the spit (Galster, 1989). The Elwha drift cell, with the two dams on the Elwha River and stretches of armored bluffs on the coast, provides an interesting case study on the effects that an impaired sediment delivery process has on the supply and composition of nearshore sediment, and the subsequent effects on forage fish spawning habitat.

Warrick et al. (2009) conducted a comprehensive study on the morphological changes ongoing in the Elwha delta and adjacent beaches and found that, between 1936 and 2006, the shoreline eroded at a rate consistent with the reduction in sediment supply from the Elwha River. Prior to dam construction, the river freely discharged sediment at a rate which maintained a steady shoreline position during the past ~7000 years. However, after dam construction and from 1939 to 2006, approximately 100,000 m^2 of coastal plain was lost to erosion as a result of the sediment reduction (Warrick et al., 2009). Not only did the shoreline recede in response to the reduced sediment input, but the intertidal zone substantially coarsened over the 20th Century, as evidenced by the cobbled low-tide terrace consisting of lag clasts that are stuck in place and rarely move (Warrick et al., 2009). This observation of change in the character of nearshore substrate is corroborated by oral histories of the Lower Elwha Klallam Tribe, predating dam construction, which describe a low-tide beach of soft sediment ideal for shellfish harvesting (Reavey, 2007). The storage of sediment behind the dams has impacted the river’s delta and the coastal beaches within the Elwha drift cell through increased erosion of the coastline and a dramatic coarsening of the beach substrate.

The long-term reduction in sediment inputs into the Elwha nearshore has caused diminished ecological function in a number of ways. Shaffer et al. (2012) compared fish abundance, density, and diversity between the nearshore environments of the sediment-impaired Elwha drift cell and the adjacent, intact Dungeness drift cell. They found that the degraded habitat in the Elwha drift cell had lower fish species richness and diversity than did the intact Dungeness drift cell. Interestingly, although surf smelt presence and diversity varied somewhat by geomorphic habitat type (embayments, bluffs, spits, and the lower reaches of rivers), they were consistently good indicators of habitat quality and ecological function at the overall drift cell scale. The higher surf smelt densities found in the intact drift cell may be due to the increased availability of substrate found there that meets their specific grain-size requirement (1-7 mm) for suitable spawning habitat (Shaffer et al., 2012). Since the researchers also found salmon from as far away as the Columbia River and Kalamath systems using the Strait of Juan de Fuca shorelines, they concluded that actions taken to restore and preserve nearshore ecosystem processes and ecological function are most appropriately designed at the scale of the drift cell, rather than targeted at single species or specific locations, and could thereby have cross-regional benefits.

Another study examining the dynamics of sediment supply and forage fish spawning activity within the Elwha drift cell found that adjacent, intact drift cells had both more sediment of the appropriate grain size for surf smelt spawning and significantly higher densities of surf smelt spawn than the impaired Elwha drift cell (Parks et al., 2013). Although sediment characteristics displayed seasonal variation with pulses of delivery in the spring and fall, all geomorphic habitat types within the intact drift cell consistently showed higher numbers of samples with grain sizes preferred by surf smelt (1-7 mm). In contrast, all geomorphic habitat types within the impaired Elwha displayed coarser size classes of sediment, with higher numbers of samples with grain sizes larger than 7 mm. The researchers conclude that disrupting the delivery of sediment into and across a drift cell causes the distribution of sediment size to be significantly more variable and significantly lowers the functional habitat required for forage fish spawning (Parks et al., 2013).

A project to remove both dams, the largest such project and sediment release in U.S. history, began in September 2011 and is expected to be completed by September 2014. Dismantling the dams, and the subsequent release of sediment trapped in the reservoirs, represents a unique and unprecedented opportunity to restore the sediment-starved and ecologically-degraded Elwha nearshore. However, significant impediments to full ecosystem restoration are present and require attention.

Management issues and nearshore restoration

Before the construction of shoreline armoring and in-river dams, feeder bluffs provided an estimated 70% of the sediment contribution to the entire Elwha drift cell (Parks et al., 2013) and 85% of the sediment that formed and sustained Ediz Hook (Galster, 1989). However, 68% of the entire length of these feeder bluffs are now armored (Flores et al., 2013; Kaminsky et al., 2014). Of the portion of bluffs within the Port Angeles city limits, 91% are armored, including a sea wall which was constructed at the city's landfill site in response to bluff erosion that had caused garbage to fall onto the nearshore beaches below (City of Port Angeles, 2012b; Neal, 2013). These armoring structures have significantly impaired the sediment processes within the Elwha drift cell by greatly reducing bluff erosion and its associated sediment input (Kaminsky et al., 2014), and will likely remain an issue for the long-term restoration of the Elwha nearshore. Still, some are optimistic that the sediment processes within the Elwha nearshore environment could be at least partially restored with the reestablishment of fluvial sediment sources (Parks et al., 2013; Shaffer et al., 2008; Winter & Crain, 2008).

With ongoing dam removal, sediment from the two reservoirs is moving downstream (Warrick et al., 2012) and deposited on Elwha nearshore beaches (Draut & Ritchie, 2013; Kaminsky et al., 2014). As of spring 2013, a total of 6.1×10^6 m^3 of sediment had been transported out of the two former reservoirs (Draut & Ritchie, 2013). Within the first two years, 2.5×10^6 m^3 of sediment had reached the nearshore environment (Kaminsky et al., 2014). Over the next five years, the natural flow of the Elwha River is expected to mobilize and transport downstream between one-third to one-half of the total volume of sediment stored within the two former reservoirs (Konrad, 2009; Randle et al., 1996). The large amount of sediment already delivered to the Elwha nearshore is changing the nature of its beach substrate and potentially creating habitat of the composition and grain size required for forage fish spawning.

The large pulse of sediment, however, will be short lived. After 7-10 years, the easily-erodible sediment in the reservoirs will be exhausted and the river will resume supplying its normal, much-lower amount of naturally-eroded sediment (Czuba et al., 2011a). Restoration of nearshore function, therefore, could be enhanced and perhaps prolonged by targeted action and management strategies. The Elwha Neashore Consortium (ENC), a group of scientists, managers, and citizens dedicated to understanding and promoting the restoration of the Elwha nearshore, advocates for an adaptive management approach to respond to the changing conditions, management needs, and best science as it becomes available (MacDonald & Harris, 2013). The presence of large woody debris (LWD) on nearshore beaches has been shown to reduce erosion and help stabilize beach substrate (Clancy et al., 2009; Rich et al., 2014). Deliberate placement of LWD, perhaps in combination with beach nourishment using large cobble, may be a useful strategy for capturing and retaining the new fluvial sediment as it arrives on sediment-starved beaches (Shaffer, 2013). Restoration will also depend on the continued preservation of unarmored coastal areas within the drift cell, such as Freshwater Bay near the mouth of the river, as well as adjacent areas with intact sediment processes. Ecosystem service valuation has been proposed as an additional management strategy, helping to justify investments in environmental restoration by revealing the economic value of intact areas of the shoreline as compared to impaired areas (Flores et al., 2013).

Such an approach could be useful for prioritizing restoration and conservation goals, and validating the need to ensure the continued protection of intact areas.

The ecological degradation of the sediment-starved, impaired Elwha drift cell may serve as a cautionary example to stewards of intact coastal regions, underscoring the detrimental consequences that shoreline armoring and impaired sediment processes have on nearshore function. Conversely, those nearshore areas with intact processes and robust ecological function can serve as an inspiration to guide effective and timely action in the Elwha nearshore. The rich diversity and biological activity found within intact coastal areas may also provide a baseline of healthy ecological function, to which we can calibrate our restoration goals and aspire to achieve in impaired nearshore areas. The dynamic changes now occurring in the Elwha nearshore offer an unprecedented opportunity to successfully restore this unique area. It is an opportunity that should not be squandered.

Chapter 2: Article Manuscript:

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Forage Fish Spawning in the Elwha Nearshore:

Restoring Ecological Form and Function in a Changing Environment

Abstract

Intertidal beaches within the Elwha nearshore are documented habitat for forage fish migration and spawning. Sediment processes of the Elwha drift cell, critical for forage fish spawning habitat, were historically altered by armoring of the shoreline, lower river alterations, and the in-river Elwha and Glines Canyon dams. The recent removal of these two dams, and the consequent release and transport of upwards of 2.5×10^6 m^3 of fluvial sediment to the Elwha nearshore, has begun a partial restoration of sediment processes within the drift cell and is changing the substrate characteristics of its beaches, potentially restoring nearshore function for forage fish spawning. We conducted egg surveys for two species of forage fish, surf smelt (*Hypomesus pretiosus*) and sand lance (*Ammodytes hexapterus*), over four years, including two years before dam removal (2007-8) and two years during the dam removal process (2012-13). Samples were collected from geomorphic habitat types (GMHTs) (embayment, bluffs, and spit) within the impaired Elwha drift cell and from comparative, intact Dungeness and Crescent Bay drift cells. In order to assess nearshore function, we compared spawning activity across impaired/intact drift cells, GMHT, and before/during dam removal time periods. While no sand lance eggs were found during the course of this study, our surf smelt results show that, overall, the intact Dungeness drift cell supports more-robust spawning activity than the impaired Elwha drift cell and that egg productivity did not differ significantly between the two time periods. We also conclude that egg abundance is highly variable across GMHT, with the greatest abundance in the intact bluffs site followed by the impaired embayment, where spawning habitat appears to have expanded during the dam removal period. Spit sites did not support any spawning activity. Understanding the implications of dam removal to the ecological functioning of the nearshore is important for full ecosystem restoration of the Elwha system, where shoreline armoring will remain an outstanding and long-term restoration issue.

INTRODUCTION

The nearshore marine habitats of the Pacific Northwest are critical components of our regional ecosystem. They provide nursery, migration, and feeding corridors for shore birds, marine mammals, and a number of fish species, including several federally and state-listed salmon (Fresh, 2006; Penttila, 2007; Shaffer et al., 2008). The nearshore environment also provides spawning grounds for small, schooling fishes known as forage fish. Surf smelt (*Hypomesus pretiosus*) and sand lance (*Ammodytes hexapterus*) are forage fish species that serve a crucial role in the complex marine food web of Puget Sound and the Strait of Juan de Fuca (Penttila, 2007; Robards et al., 1999b; Wilson et al., 1999). Forage fish represent a primary energy bottleneck in the biological community of the nearshore, exerting both top-down control over primary and secondary trophic levels as consumers of phytoplankton and zooplankton, and bottom-up control over higher order predators by serving as a prey species for other fish, birds, and marine mammals (Bargmann, 1998; Rice, 1995; Robards et al., 1999b). Surf smelt occur from northern California to southern Alaska (Hart, 1973), but are relatively abundant in Puget Sound (Simenstad et al., 1979; Therriault et al., 2009) where they are accessible for much of the year, increasing their importance as a food source within the local marine food web. Pacific sand lance are also an important prey species, constituting large portions of the diets of all life-stages of salmon, especially Coho (*Oncorhynchus kisutch*) and Chinook (*Oncorhynchus tshawytscha*) (Beacham, 1986; Brodeur, 1990; Hart, 1973). For example, sand lance were found to constitute, on average, 35% of the diet of juvenile salmon and

60% of the diet of juvenile Chinook salmon in Puget Sound (Hershberger et al., 2006). Consequently, variability in forage fish abundance and distribution may have major consequences for determining the fitness of these and other economically important predator populations (Wilson et al., 1999). This realization has led scientists and natural resource managers to become increasingly interested in forage fish conservation and protection (Penttila, 2007). The ecological functioning of nearshore habitats, therefore, are of special concern because forage fish rely on them for their spawning activity (Penttila, 2007).

Both the surf smelt and sand lance have successfully adapted their spawning activity to the habitat of the upper intertidal beach zone, rigorous for its fluctuations in temperature, salinity, submergence time, and to the harsh and grinding regime of shifting substrate (Penttila, 1978). Egg deposition occurs in the upper elevation of the beach, near the high tide line, in areas where waves and currents have sorted the substrate into a characteristic loose mixture of sand and fine-gravel, consisting mostly of material in the size range of 1 to 7 mm in diameter in the case of surf smelt, to finer size-classes of sand in the case of sand lance (Penttila, 2001; Quinn, 1999; Robards et al., 1999a). Such substrate allows wave action to work deposited eggs into the protective interstitial spaces below the beach surface where they are kept moist and aerated, and thus protected from desiccation and thermal stress (Middaugh et al., 1987; Penttila, 1978). Conversely, in areas where the substrate of the upper beach is composed of very fine sand or large gravel and cobbles, the lightweight eggs are unable to mix into the subsurface substrate and are consequently left exposed to the drying effects of sun and wind. Since successful spawning habitat for forage fish depends on the presence of adequate sediment, altering the sediment processes that supply coastal beaches can degrade the quality of forage fish spawning habitat and impair nearshore ecological function (Johannessen & MacLennan, 2007; Schlenger et al., 2011). The links between coastal sediment processes, nearshore function, and forage fish spawning makes the status of forage fish populations a useful indicator of the health and productivity of nearshore systems (Parks et al., 2013; Puget Sound Partnership, 2009; Simenstad et al., 2006).

The Puget Sound nearshore, including the nearshore of the Strait of Juan de Fuca, has been classified into geomorphic habitat types (GMHTs) that reflect the close relationship between sediment processes, coastal landforms, and habitat formation (Finlayson, 2006; Shaffer et al., 2012; Shipman, 2008). Nearshore ecological function is strongly influenced by the geomorphic processes that erode, transport, and deposit sediment across the coastal landscape and determine its physical form (Simenstad et al., 2006). Coastal bluffs and river estuaries are the two main sources of sediment responsible for the formation and maintenance of marine beaches within Puget Sound and the Strait of Juan de Fuca (Finlayson, 2006). Sediment processes in the nearshore occur within drift cells—semi-independent segments of the coastline that include both sources and sinks of sediment and within which net long-term sediment transport occurs (Shipman, 2008). The sediment processes within a drift cell are kept intact by the continual input of new fluvial and bluff sediment to replenish that which is lost to erosion, but can become impaired when anthropogenic activities, such as building dams and armoring shorelines, reduce these sediment inputs. Dams trap sediment within their reservoirs, disrupting fluvial sediment transport downstream (Finlayson, 2006; Johannessen & MacLennan, 2007). Shoreline armoring, designed explicitly to prevent the erosion of coastal bluffs, disconnects beaches from their major source of sediment nourishment (Shipman, 2010).

Armoring structures can have numerous additional direct and indirect detrimental effects on forage fish spawning habitat. Their placement in the upper intertidal zone covers-over and replaces the upper beach, directly reducing the area of available spawning habitat (Dugan et al., 2011; Penttila, 2007). Wave energy reflected from armored shorelines tends to suspend and transport away the finer-grained substrate, thereby converting the beach to unsuitable coarse gravel and cobble (Carrasquero-Verde et al., 2005; Fresh et al., 2011). By displacing shoreline trees, armoring structures can create a brighter, hotter, and drier shoreline environment that negatively impacts the survival of incubating embryos (Penttila, 2002; Rice, 2006) and disconnects the nearshore from terrestrial sources of food, nutrients, and organic matter, including woody debris which provides important structural support for the accretion and stabilization of beach substrate (Carrasquereo-Verde et al., 2005; Penttila, 2001; Rich et al., 2014). The disruption and impairment of nearshore sediment processes caused by the damming of rivers and construction of shoreline armoring can alter the physical characteristics of beaches and degrade important nearshore function, including that of forage fish spawning (Simenstad et al., 2006).

The Elwha nearshore provides an example of a drift cell with an historically-impaired sediment process that is currently undergoing massive change. Classified as including spit, bluff, and embayment GMHTs, the shoreline of the Elwha drift cell has been significantly degraded due to the disruption of habitat-forming processes from the construction of in-river dams and shoreline armoring (Schlenger et al., 2011; Shaffer et al., 2012). Two dams built on the Elwha River in the early 1900s trapped an estimated 21 to 26 x 10^6 m^3 of sediment within their reservoirs and reduced the Elwha River's delivery of fluvial sediment to the coast to about 2% of the pre-dam load (Draut & Ritchie, 2013). Consequently, evidence of sediment starvation has been documented in both the below-dam river channel and the Elwha nearshore (Draut et al., 2011; Warrick et al., 2009). Without the replenishing input of Elwha River sediment, approximately 100,000 m^2 of coastal plain within the Elwha delta was lost to increased erosion of the coastline between 1939 to 2006, and coastal beaches underwent a dramatic coarsening of their substrate (Warrick et al., 2009). This observation is corroborated by oral histories of the Lower Elwha Klallam Tribe which describe a low-tide beach of soft sediment ideal for shellfish harvesting prior to dam construction (Reavey, 2007). A project to remove both dams, the largest such project and sediment release in U.S. history, began in September 2011 and is expected to be completed by September 2014. During the ongoing dam removal, released sediment is washing downstream (Warrick et al., 2012) and arriving on Elwha nearshore beaches (Draut & Ritchie, 2013). Over the next five years, the natural flow of the Elwha river is expected to mobilize between one-third to one-half of the total volume of sediment within the two former reservoirs (Konrad, 2009; Randle et al., 1996). Although 93% of the feeder bluffs and spit within the impaired Elwha drift cell are currently armored and are likely to remain so (City of Port Angeles, 2012b), sediment processes within the Elwha nearshore environment may be at least partially restored with the complete removal of the dams and the reestablishment of fluvial sediment sources (Parks et al., 2013; Shaffer et al., 2008; Winter & Crain, 2008). The large pulse of sediment already delivered to the Elwha nearshore is changing the nature of its beach substrate (Figure 1) and is potentially creating habitat of the composition and grain size required for forage fish spawning.

This study examines changes in the amount and distribution of forage fish spawning activity within the Elwha drift cell since the dam removal process began in the fall of 2011. Our research quantifies this change and adds to the currently sparse literature on forage fish response to the rapid alteration of nearshore conditions due to a large river restoration project. We also report results for forage fish egg surveys that were conducted concurrently in the adjacent, comparative Dungeness and Crescent Bay drift cells, both of which retain intact sediment processes. By comparing spawning activity between before and during dam removal time periods, between impaired and intact drift cells as a whole, and between the various GMHTs within the drift cells, we hope to detect patterns in forage fish spawning behavior and start to determine the role that sediment processes play in forming favorable habitat conditions. We observe that the changes brought about by the influx of large quantities of sediment into the Elwha nearshore are changing the physical form of its habitat, thus potentially enhancing the long-term ecological function of forage fish spawning. Specifically, we pose the following hypotheses: a) forage fish spawning activity has significantly increased within the impaired Elwha drift cell during the dam removal phase; b) no significant changes between before and during dam removal have occurred

Figure 1. Freshwater Bay (impaired Elwha drift cell) has undergone dramatic changes in the composition of its beach substrate between the time period before dam removal (top) and during dam removal (bottom). Photo: Coastal Watershed Institute.

within the comparative, intact drift cells; c) the intact drift cells continue to support greater spawning activity than the impaired drift cell during the dam removal phase; and d) differences between GMHTs are significant, with bluffs supporting more forage fish spawning than embayments or spits. We believe that a better understanding of forage fish spawning activity on beaches within intact and impaired drift cells will highlight the close relationship between habitat-forming processes and habitat function, and will help scientists and resource managers implement successful long-term coastal management and restoration projects within the nearshore environment.

METHODS

This study describes the 2007-2013 forage fish component of the Coastal Watershed Institute-led long-term assessment of the Elwha nearshore. The nearshore study is intended to define nearshore ecological restoration response to dam removals, utilizing fish as the ecological metric and has three phases: before dam removal, during dam removal, and (in the future) after dam removal. To determine the role sediment plays in providing forage fish spawning habitat, we selected drift cells with impaired sediment processes (Elwha drift cell) and intact sediment processes (Dungeness and Crescent Bay drift cells). Habitat areas within these drift cells were categorized into the geomorphic habitat types (GMHTs) of embayment, bluffs, and spit in order to detect how different habitat types support forage fish spawning (Parks et al., 2013; Shaffer et al., 2012; Shipman, 2008). Forage fish data presented in this paper were collected over four years: 2007-2008 (pre-dam removal) and 2012-2013 (during dam removal).

Study Sites

The Elwha, Crescent Bay, and Dungeness drift cells lie adjacent to each other within the central Strait of Juan de Fuca and along the northern coast of Washington's Olympic Peninsula (Figure 2). The Elwha drift cell includes three impaired GMHTs: an embayment (Freshwater Bay), bluffs (Elwha bluffs), and a spit (Ediz Hook). Matching GMHTs were selected in the Crescent Bay drift cell, consisting of a single embayment (Crescent Bay), and the Dungeness drift cell, consisting of bluffs (Dungeness Bluffs) and a spit (Dungeness Spit), to serve as comparative study sites with intact sediment processes. Samples were collected from each GMHT within each drift cell, for a total of 6 sample areas (Table 1).

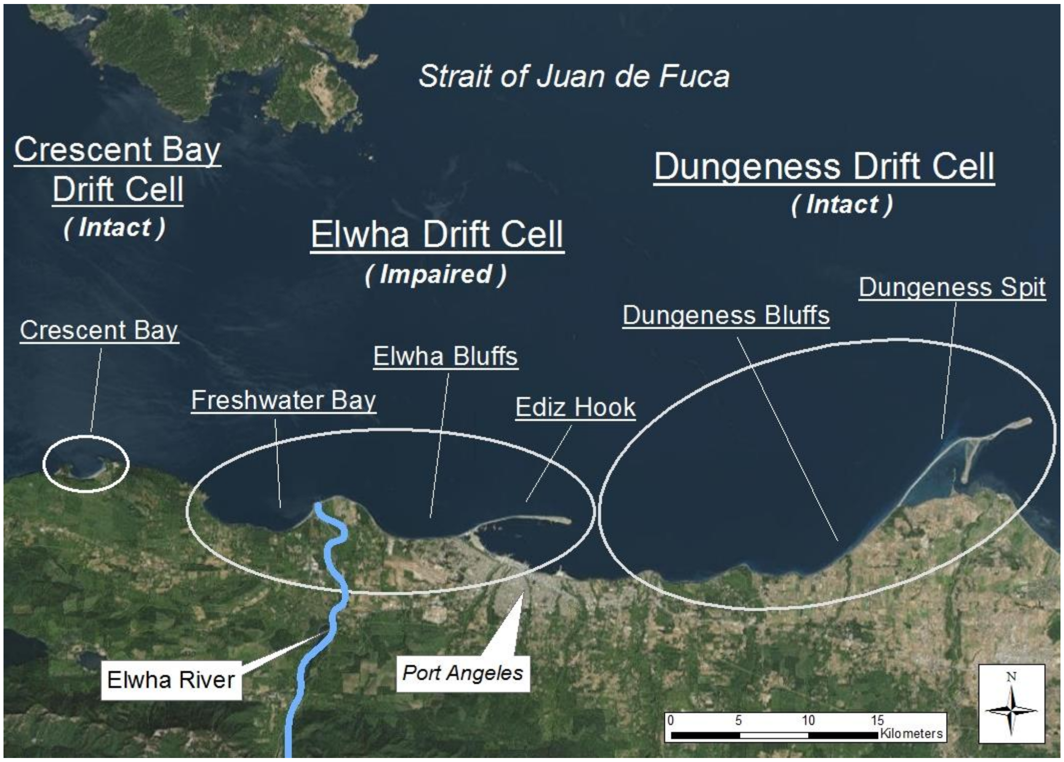

Figure 2. Study sites for surf smelt and sand lance egg surveys.

Table 1. Sample areas designated by geomorphic habitat type (GMHT) and location within an impaired or intact drift cell. Samples were collected from three sample areas within the impaired Elwha drift cell and from matching GMHTs within the intact Dungeness (2 sample areas) and Crescent Bay (1 sample area) drift cells.

Sample Areas			
GEOMORPHIC HABITAT TYPE	Intact Drift Cells		Impaired Drift Cell
	Crescent Bay	*Dungeness*	*Elwha*
EMBAYMENT	Crescent Bay	----------	Freshwater Bay
BLUFFS	----------	Dungeness Bluffs	Elwha Bluffs
SPIT	----------	Dungeness Spit	Ediz Hook

Surf Smelt and Sand Lance Egg Sampling

Sampling for surf smelt and sand lance took place during their respective spawning seasons. In the Strait of Juan de Fuca, the documented spawning season for surf smelt is summer and for sand lance is winter (Moriarity et al., 2002a; Penttila, 2007). Surf smelt samples for this study were collected in the months of July, August and September, and sand lance samples were collected in the months October through January. Sampling for all forage fish eggs was conducted using a modified Moulton and Penttila (2001) technique. Bulk samples of beach substrate were collected using a hand scoop to skim from the top 2-3 cm of the beach surface at each sampling location. As forage fish spawning and incubation areas are normally in the +7 to +9 foot mean lower low water (MLLW) tide zone (Moulton & Penttila, 2000), samples were collected from the upper third of the beach, near the high tide mark, or 1 to 2 vertical feet below the driftwood log line. Between 5 and 8 scoops were used to collect about 15 kg of substrate from each sampling location and placed in a plastic bag, constituting one sample. A modified systematic random design was used to select 2 to 21 sampling locations spaced roughly equally across the length of sample area beaches. For each sample, a variety of metadata were collected, including the date, sample number, GPS coordinates of the sampling location, and geomorphological unit of the drift cell.

Once collected into plastic bags, the bulk samples were transported to Peninsula College in Port Angeles, WA for processing. Each sample was washed through a series of screens in order to sort the sediment grain sizes and collect the light fraction, thereby condensing the sample to a manageable size and concentrating the portion most likely to contain fish eggs. This was accomplished by placing a rack of Nalgene sediment screens, sizes 4, 2, and 0.5 mm, graded from the largest mesh size on top to the smallest on bottom, over a 5-gallon plastic bucket and thoroughly washing the sample through the screen set using water from a garden hose. Once washed, the sediment remaining on the top two screens was discarded while the material collected on the bottom (0.5 mm) screen was placed into a plastic dishpan and covered with 2-5 cm of water. The sample was then elutriated by hand in order to allow the relatively light eggs to migrate upward through the sediment towards the surface. After elutriation for 1-2 minutes, the lighter fraction was skimmed from the surface using a 235 ml plastic collecting jar. This winnowing process was repeated twice more on the remainder of the sample and added to the same jar, to which Stockard’s solution (50 ml formalin (37% formaldehyde), 40 ml glacial acetic acid, 60 ml glycerin, and 850 ml distilled water) was add to preserve the eggs. All processed samples were sent to Dan Penttila, of Salish Sea Biological, for examination under a dissecting microscope and to determine the presence or absence of eggs. All eggs were identified, counted, and their life-history stage was recorded.

Statistical Analysis

Treatments for analysis were defined as *before* and *during* the dam removal process, by each GMHT (*embayment*, *bluff*, and *spit*), and by drift cell as either *intact* or *impaired*. Because of the nature of the geographic location of our study sites and sampling schedule, our data are not independent but linked both physically and temporally. To control for unequal numbers of samples among different treatments, we calculated the average number of eggs found within each sampled beach on each date of collection. This average number of eggs served as a normalized metric of the egg productivity for each beach that could be combined with other beaches and dates of collection in order to compare spawning activity among different treatments and combinations of treatments.

Egg count data were analyzed to determine egg abundance within each drift cell and GMHT, both before and during the dam removal process. Because our data did not meet the assumptions of normality or equality of variance required by parametric ANOVA, Monte Carlo resampling methods were used to generate null distributions (10,000 random iterations) with which non-parametric analyses could be conducted. When comparing two treatments (i.e. impaired vs. intact drift cell), the absolute differences (DIF) between the two means were resampled. When comparing more than two variables (i.e. embayments, bluffs, and spits), the among treatment sums of squares (SSamong) were resampled. Bonferroni error corrections were used to control the familywise error rate arising from multiple hypothesis tests on all subsequent pairwise analyses. Statistical analyses were performed using the Resampling Stats 4.0 add-in for Excel. All figures show back-transformed means and standard error bars (±1 standard error).

RESULTS

We collected a total of 568 samples over the course of this study. Due to fluctuations in the amount of available volunteer hours, funding resources, and site conditions, the number of samples collected varied between years and sites. Sand lance sampling in the winter months was complicated by the difficulty posed by short daylight hours and evening low tides, especially for the bluff-backed beaches of the Dungeness Bluffs site, where the danger of being caught between the high bluffs and a rising tide at night prevented a more-extensive sampling regime. Sand lance surveys resulted in a total of 156 samples collected from across the study site over the course of this study (Table 2). Of this total, 30

Table 2. Sampling schedule for sand lance eggs in impaired and intact drift cells, before and during dam removal. Numbers in the table refer to the number of individual samples collected within the given treatment.

Sand Lance Sampling Schedule				
	Before Dam Removal	During Dam Removal	Total Samples	Samples containing eggs
Intact Drift Cells	17	28	45	0
Impaired Drift Cell	13	98	111	0
TOTAL	**30**	**126**	**156**	**0**

Table 3. Sampling schedule for surf smelt eggs by month and year. Numbers in the table refer to the number of individual samples collected within the given treatment.

Surf Smelt Sampling Schedule						
	Before		During		Total Samples	Samples containing eggs
	2007	2008	2012	2013		
July	11	33	0	70	114	31
August	20	39	0	71	130	35
September	19	35	9	72	135	20
TOTAL	**50**	**107**	**9**	**213**	**379**	**86**

samples were collected before dam removal and 126 samples were collected during dam removal (Table 2). All 28 samples collected from the intact treatment during dam removal were collected exclusively from the Crescent Bay drift cell. No sand lance eggs were found in any of the samples during the course of this study. Similarly, no eggs of either species were found in any of the 65 Crescent Bay samples (32 sand lance and 33 surf smelt). Accordingly, all of the sand lance data and all of the Crescent Bay samples have been excluded from the statistical analysis below, since conclusions about the relative strength of ecological function between treatments cannot be determined without any spawning activity with which to make comparisons. Our analysis, therefore, only includes surf smelt spawning data from the Elwha and Dungeness drift cells.

Summer sampling for surf smelt in the Elwha and Dungeness drift cells resulted in a total of 379 collected samples, 86 of which contained one or more surf smelt eggs (Table 3). Of the157 samples collected *before* dam removal, 26 were egg-bearing and yielded 457 eggs; of the 222 samples collected *during* dam removal, 60 samples were egg-bearing and yielded 617 eggs, resulting in a total

Table 4. Surf smelt sampling results by study site and phase of dam removal. Sites in italic are within the impaired Elwha drift cell.

Surf Smelt Survey Results

Site	Samples Collected	Samples Containing Eggs	Eggs Found	Samples Collected	Samples Containing Eggs	Eggs Found	Total Eggs Found
	Before Dam Removal			During Dam Removal			
Embayments							
Freshwater Bay	*27*	*8*	*64*	*33*	*5*	*21*	***85***
Bluffs							
Elwha Bluffs	*25*	*0*	*0*	*65*	*0*	*0*	***0***
Dungeness Bluffs	53	18	393	67	55	596	**989**
Spits							
Ediz Hook	*26*	*0*	*0*	*27*	*0*	*0*	***0***
Dungeness Spit	26	0	0	30	0	0	**0**
Total	**157**	**26**	**457**	**222**	**60**	**617**	**1074**

of 1,074 surf smelt eggs found during the course of this study (Table 4). Of the five beaches sampled, only two beaches were found to support surf smelt spawning activity: Freshwater Bay (impaired; 85 surf smelt eggs found) and

Table 5. Table of single dead surf smelt eggs not included in analysis because of their empty state and low number suggest that they may have drifted-in from another area.

Single Dead Surf Smelt Eggs Not Included in Analysis

Date	Location	Coordinates	Number of Eggs	Notes
9/25/2012	Elwha Bluffs	48.13457, -123.52144	1	Empty shell with sand grain attached
7/22/2013	Dungeness Spit	48.16743, -123.16096	1	Empty shell
7/23/2013	Dungeness Spit	48.16288, -123.16733	1	Empty shell
7/24/2013	Dungeness Spit	48.15796, -123.17378	1	Empty shell
8/18/2013	Dungeness Spit	48.1762, -123.1362	1	Empty shell with attached sand grains

Dungeness Bluffs (intact; 989 surf smelt eggs found) (Table 4). A small number of single dead surf smelt eggs were collected in the Dungeness Spit and Elwha bluffs locations that were not included in our analysis because their empty state and low number suggests they may have drifted-in from a different area (Table 5). For the purposes of statistical analyses below, the consolidation of all surf smelt samples from each given beach by each sampling date reduced the total number of surf smelt samples (n=379) to 41 data points (Table 6).

Table 6. Surf smelt data consolidated for statistical analysis. Numbers refer to the number of data points of the given treatment available for statistical analysis.

Consolidated Surf Smelt Samples for Analysis

Sample Site	Before Dam Removal	During Dam Removal	Total # of data points for analysis
Embayments			
Freshwater Bay	*5*	*3*	*8*
Bluffs			
Elwha Bluffs	*5*	*4*	*9*
Dungeness Bluffs	7	3	10
Spits			
Ediz Hook	*4*	*3*	*7*
Dungeness Spit	4	3	7
Total	**25**	**16**	**41**

Intact vs. Impaired Drift Cells

Overall, the intact Dungeness drift cell supported a significantly greater abundance of surf smelt eggs than the impaired Elwha drift cell (DIFF=4.267, p=0.018) (Figure 3). Surf smelt egg abundance in the intact treatment was almost 10 times greater than in the impaired treatment. Even though a greater number of samples were collected in the impaired Elwha treatment (n=203) than in the intact

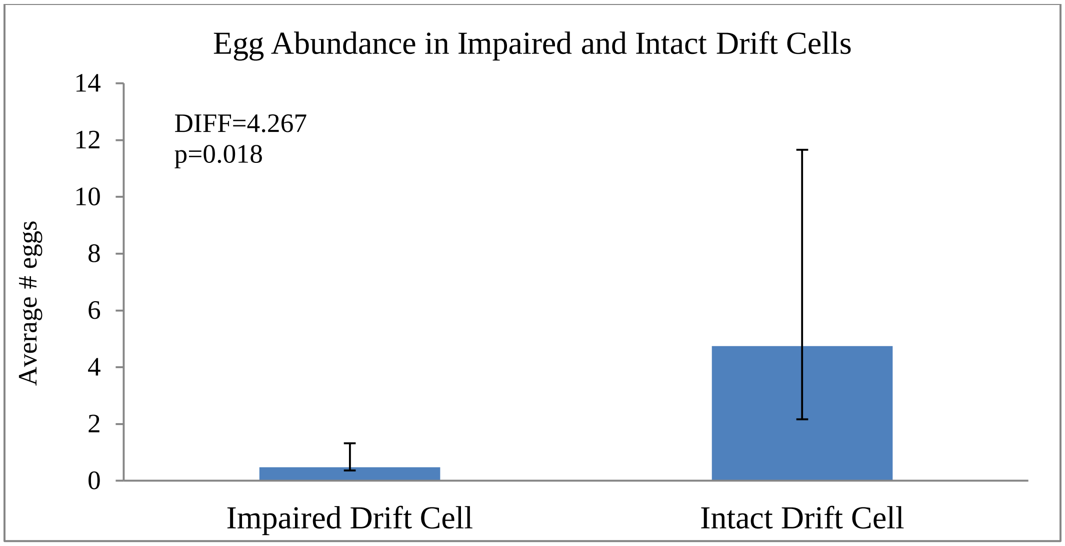

Figure 3. Surf smelt egg abundance in impaired and intact drift cells.

Dungeness treatment (n=176), only 13 (6%) samples from the impaired drift cell were egg-bearing, while 73 (41%) samples from the intact treatment were egg-bearing. The difference in the number of eggs is also striking, with a total of 85 surf smelt eggs found in the impaired drift cell compared to a total of 993 surf smelt eggs found in the intact drift cell. All eggs found in the impaired Elwha drift

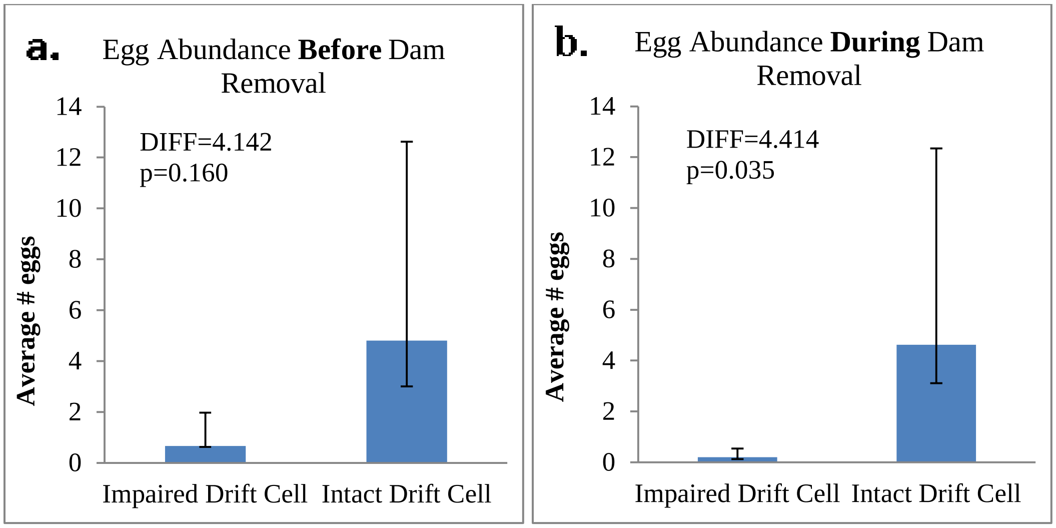

Figure 4. Surf smelt egg abundance in impaired and intact drift cells a) before and b) during dam removal.

cell were collected in the Freshwater Bay site, and all eggs found in the intact Dungeness drift cell were collected in the Dungeness Bluffs site. The Dungeness Bluffs site is the most productive beach within our study area and is the site responsible for causing the intact drift cell to consistently yield a greater abundance of surf smelt eggs than the impaired drift cell, both before and during the dam removal process (Figure 4).

Before vs. During Dam Removal

We compared all surf smelt samples taken before dam removal (n=157) to all samples collected during dam removal (n=222) and found that surf smelt egg abundance did not differ significantly between the two time periods (DIF=0.034, p=0.915) (Figure 5). Surf smelt egg counts seem to track sampling effort, with a total of 457 eggs found before dam removal and 617 eggs found during the dam removal time period. We also compared egg abundance between the two time

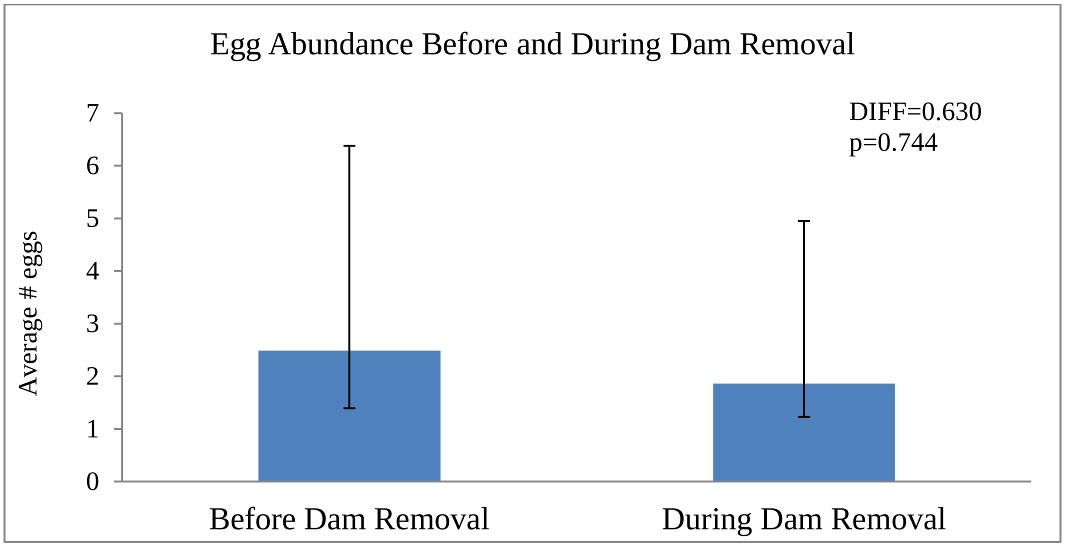

Figure 5. Surf smelt egg abundance across the combined impaired and intact drift cells before and during dam removal.

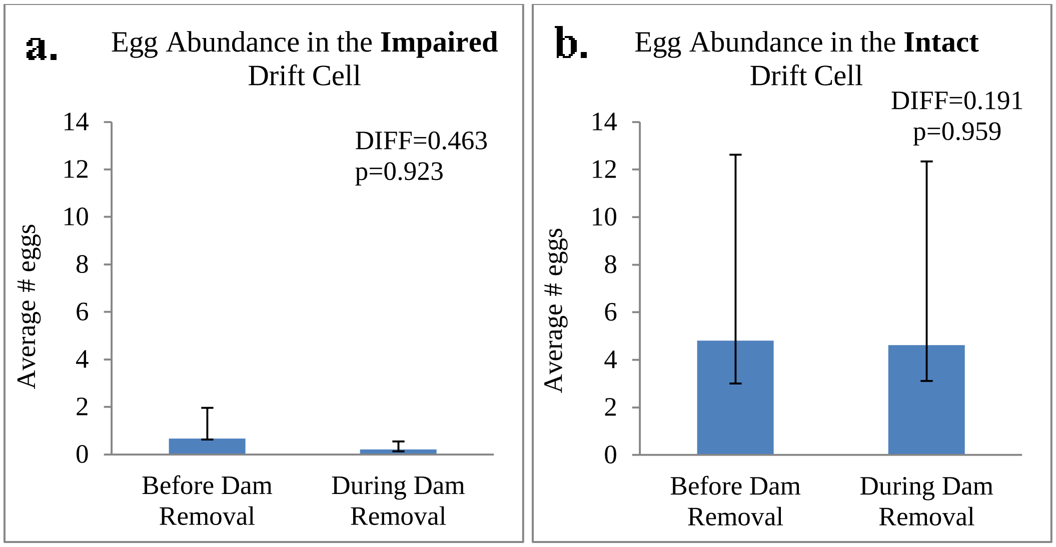

Figure 6. Surf smelt egg abundance before and during dam removal in the a) impaired and b) intact drift cells.

periods in both the impaired and intact drift cells (Figure 6). The change in surf smelt egg abundance between before and during dam removal is not significant for either drift cell treatment. This might be expected for the intact drift cell since the nearshore sediment processes, by definition, remained intact between the two time periods. However, the dam removal project has apparently not yet had the expected boosting effect on surf smelt spawning activity in the impaired Elwha drift cell despite the changes this process has brought to the nearshore sediment supply and beach composition. Instead, surf smelt egg abundance within the impaired drift cell appears to have decreased (~30% less), although not significantly, during the dam removal process (Figure 6a).

Freshwater Bay remained the only beach within the impaired drift cell to support surf smelt spawning activity throughout the duration of this study (Figure 7). Although egg abundance decreased by about 38% in the during dam removal

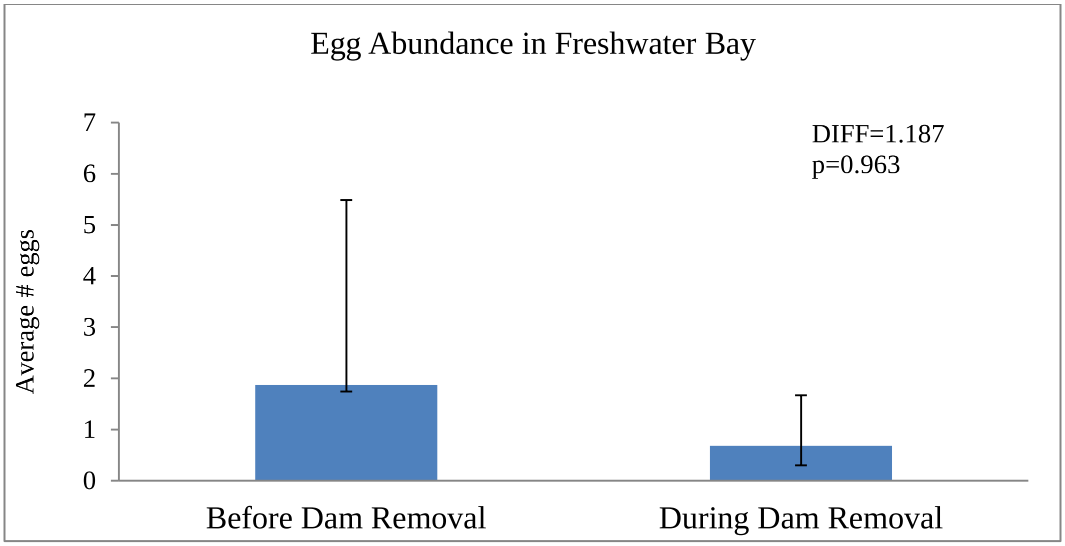

Figure 7. Surf smelt egg abundance in the impaired Freshwater Bay before and during dam removal.

phase, spawning not only continues to occur in those areas we documented as surf smelt spawning habitat prior to the beginning of dam removals, but appears to have expanded during the dam removal time period (Figure 8). Surf smelt are now using areas further to the east, close to the Elwha River mouth, where there was

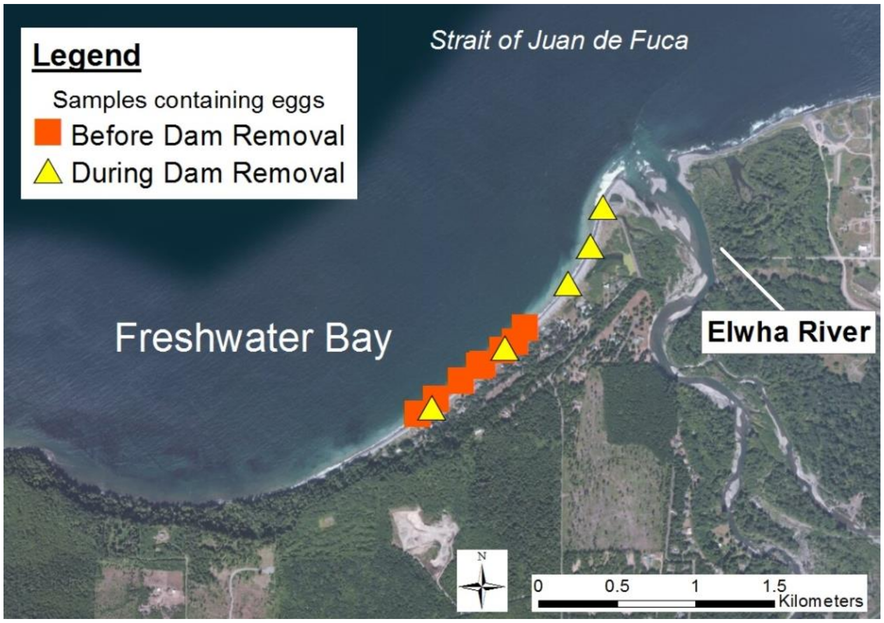

Figure 8. Freshwater Bay samples containing surf smelt eggs before and during dam removal.

no suitable habitat prior to dam removal (see also Figure 19 and 20 in the Appendix).

Geomorphic Habitat Type

The differences in surf smelt egg productivity by geomorphic habitat type (GMHT) were not significantly different between embayment, bluff, and spit sites (SSamong=151.814, p=0.132) (Figure 9). Bluff sites, as a whole, supported the greatest surf smelt egg abundance, almost three times that of embayments. Spit sites did not appear to support surf smelt spawning activity.

Surf smelt spawning activity occurred within different GMHTs between the impaired and intact drift cell treatments (Figure 10). Within the intact drift cell, only the bluff GMHT (Dungeness Bluffs) supported surf smelt spawning activity; intact *embayment* and *spit* sites did not support any spawning activity. In contrast, within the impaired Elwha drift cell, only the *embayment* (Freshwater

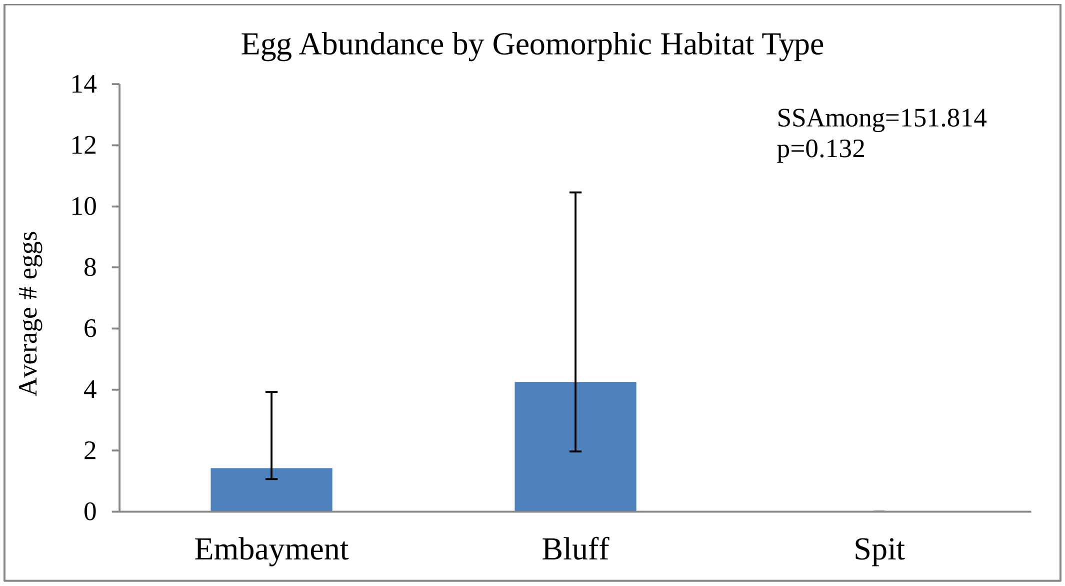

Figure 9. Surf smelt egg abundance by geomorphic habitat type (GMHTs).

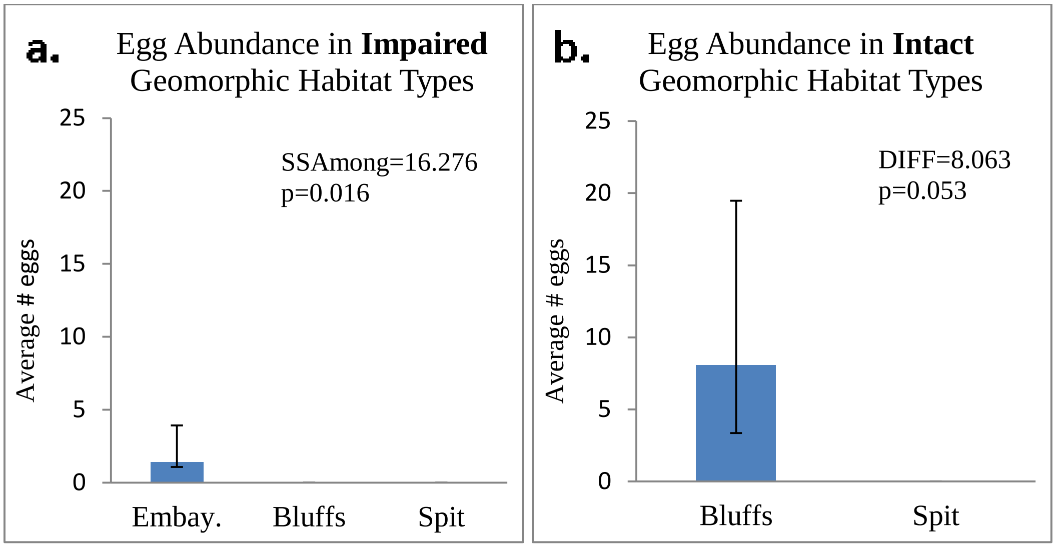

Figure 10. Surf smelt egg abundance by geomorphic habitat type (GMHT) within a) impaired and b) intact drift cell treatments.

Bay) supported surf smelt spawning activity; none of the samples taken in the Elwha's *bluff* or *spit* GMHTs contained any eggs. Egg abundance between these two GMHTs differed greatly, with intact bluffs yielding more than 5.6 times greater egg abundance than impaired embayment. Given the productivity of the intact Dungeness Bluffs site, it is striking that no surf smelt eggs were found in any of the 90 samples collected at the Elwha Bluffs site (see Figure 15 in the Appendix). Surf smelt spawning activity also differed in its magnitude among the two productive GMHTs. Of the 60 samples collected in the impaired Freshwater Bay site, only 13 (22%) samples contained one or more surf smelt eggs, while in the in intact Dungeness Bluffs site, 73 (61%) of the 120 samples were egg-bearing.

DISCUSSION

Despite the documented presence of abundant juvenile sand lance in the Elwha and Dungeness drift cells (Shaffer et al., 2012), we were unable to find any sand lance eggs at any of our sites during the course of this study. Other surveys have succeeded in finding sand lance spawning activity within our study area, as well as along adjacent portions of the Strait of Juan de Fuca shoreline (Moriarity et al., 2002b; Penttila, 1995b; WDFW, 2014). However, unlike our sites, these spawning areas were located within sheltered embayments, such as along the inner margins of Dungeness Spit and Ediz Hook, and within Sequim Bay, Discovery Bay, and a protected embayment near the Pysht River. It may be that sand lance prefer a low-energy beach spawning habitat and that the beach sites within our survey area are too exposed to tidal and wave energy, thus discouraging their spawning behavior. It may also be simply too early in the nearshore restoration process as beaches rapidly change in response to the influx of Elwha River sediment, and that sand lance will begin spawning in upcoming years. Previous work documenting forage fish spawning habitat has shown spatial and temporal variability in habitat conditions and unpredictable fluctuations in spawning behavior, revealing the necessity to conduct multiyear surveys to accurately define spawning areas (Moriarity et al., 2002b; Parks et al., 2013; Penttila, 2007; Quinn et al., 2012). The Coastal Watershed Institute will continue to survey these beaches during the post dam removal time period.

The results of our surf smelt surveys show that areas of the central Strait of Juan de Fuca are actively used by this species as spawning habitat. Spatial patterns of surf smelt spawning activity reveal preferences for habitat type and illustrate the important role that sediment processes play in forming favorable habitat conditions. The greatest abundance of surf smelt eggs was consistently found at the Dungeness bluffs site. Importantly, these bluffs remain unarmored. Placing armoring at the base of coastal feeder bluffs in this region has been shown to reduce bluff recession rates by 50-80% (Kaminsky et al., 2014), significantly decreasing the amount of new sediment delivered to nearshore beaches of the size and composition required by surf smelt as spawning habitat. It is significant that the Elwha bluffs site, which is mostly armored, appears not to provide any surf smelt spawning habitat as none of our samples collected at the site yielded eggs. The Elwha bluffs only produce half as much sediment per alongshore distance as the Dungeness bluffs (Kaminsky et al., 2014), resulting in beaches which are relatively starved of sediment and unfavorable as spawning habitat. We conclude that the greater supply of sediment provided to coastal beaches by unarmored bluffs is connected to our observations of favorable surf smelt spawning habitat along unarmored stretches of bluffs.

Comparing surf smelt egg abundance between impaired and intact drift cells as a whole demonstrates the importance of sediment processes operating at a larger scale. We found that, overall, the drift cell with intact sediment processes (the Dungeness) clearly supports a significantly greater abundance of surf smelt eggs than the impaired drift cell (the Elwha). While this result is obviously connected to the relative egg abundances found in the Dungeness bluffs and Freshwater Bay sites as mentioned above, it has important implication in its own right. Because sediment is continually entering and moving through a drift cell system, efforts to restore specific beach locations may be thwarted if they cannot be linked to larger-scale, intact sediment processes. Having intact sources of sediment, and shorelines free of impediments to its movement, is important for maintain longshore sediment drift and crucial for sustaining nearshore habitat along the entire length of the drift cell. As Chinook and coho salmon from as far away as the Columbia and Kalamath River systems have been found utilizing Strait of Juan de Fuca shorelines (Shaffer et al., 2012), nearshore habitat within intact drift cell systems can have both regional and cross-regional benefits. Defining priorities for the preservation and restoration of nearshore processes and ecological function is therefore most appropriately accomplished at the drift cell scale.

The differences between spawning activity within different GMHTs were not surprising since GMHTs can function differently for different species and in different sites (Shaffer et al., 2012). Accretionary shore forms such as sandy spits that form at the distal ends of drifts cells are known to support sand lance spawning habitat in other locations within Puget Sound, but may limit surf smelt spawning by their overly fine, sandy character (Penttila, 2007). The spit GMHTs encompassed within this study appeared to be used very sparsely for spawning, or possibly not at all since the origin of the few eggs found on Dungeness Spit are uncertain and no eggs were found on Ediz Hook. The four dead eggs that were each found in separate samples from Dungeness Spit were all empty surf smelt egg shells that were likely spawned on the Dungeness Bluff beach to the west and transported to the spit by currents. This drift of eggs may indicate that beaches with prolific spawning activity could provide a source of “seed eggs” to newly-formed beaches with suitable habitat where they could incubate and hatch to form new surf smelt populations.

Surf smelt have continued to use the impaired Freshwater Bay as spawning habitat during the dam removal phase. Not only are we are seeing continued use in the areas we documented as surf smelt spawning habitat prior to the beginning of the dam removals, but, interestingly, it appears that the spawning area in Freshwater Bay may be expanding to the east, adjacent to the growing river delta. Surf smelt are now using areas where there was no suitable spawning habitat prior to dam removal; however, overall egg abundance within this embayment has not yet changed significantly since the beginning of dam removal.

The event of two dam removals on the Elwha River and the subsequent, ongoing delivery of fluvial sediment into the Elwha nearshore system have not yet had a strong effect on spawning behavior on the beaches of the impaired Elwha nearshore. However, the dam removal process is still ongoing and the post-dam removal response and restoration of the nearshore has not yet begun. It is therefore too early to determine the response in surf smelt (and sand lance) spawning to this dam removal event. The effects of the dam removal process on the Elwha nearshore environment will clearly be a long-term process and will require continued monitoring to detect trends and outcomes in the ongoing ecological response.

Surf smelt spawning activity in both the impaired (Elwha) and comparative intact (Dungeness) drift cell varied considerably between the two time periods. The nearshore is inherently a variable system and these findings are consistent with other observations that the abundance of forage fish in a localized region can fluctuate from year to year in response to factors such as inter-annual variations in beach substrate composition (Parks et al., 2013) as well as factors such as ocean conditions, recruitment success, pressure from predators and fisheries, and habitat quantity and quality (Liedtke et al., 2013). Variability in year to year forage fish use of the same beaches has also been observed within the Puget Sound region where only a small fraction of beaches with appropriately-sized sand and gravel substrate are used for spawning in any given year; in fact, the majority of Puget Sound beaches that appear to have the suitable substrate and habitat structure to support spawning are not documented surf smelt spawning sites (EnviroVision et al., 2007; Moulton & Penttila, 2000; Quinn et al., 2012). Further research into habitat selection and inter-annual and longer-term cycles of forage fish usage could expand our knowledge of this poorly-understood phenomenon.

It is still very early in what will surely be a long-term nearshore restoration of the Elwha system. The composition and timing of sediment mobilization depends on the rate and stage of dam removal, local morphology, the driving riverine and marine hydrology during and in the years following the removal, and the amount and grain size of the sediment, particularly in the reservoirs (Czuba et al., 2011a; Draut & Ritchie, 2013; Randle et al., 1996). As of spring 2013, a total of 6.1 x 10^6 m^3 of sediment had been mobilized downstream from the deposits in both reservoirs (Draut & Ritchie, 2013), representing only about 20% of the total 13 to 20 x 10^6 m^3 projected sediment load to be released into the Elwha system over the next several years (Randle & Bountry, 2012). Much of this early-stage sediment release has been very fine-grained material which has formed ubiquitous mud deposits along the Elwha River channel margins and floodplain instead of being exported to the coast as was expected. This was largely due to an unusual lack of winter flood flows in the winters of 2011 and 2012 resulting in unusually low fluvial transport capacity (Draut & Ritchie, 2013). As dam removal progresses, the coarser sand and gravel sediment fractions are expected to be increasingly mobilized and released downstream over the next 7-10 years (Czuba et al., 2011a). The potential volume of sand and gravel is substantial; 50% of the total sediment (21.6 ± 3.0 x 10^6 m^3) in the upper Lake Mills reservoir and 32% of the lower Lake Aldwell reservoir total sediment (4.6 ± 1.5 x 10^6 m^3) is estimated to be sand and gravel (Czuba et al., 2011a; Draut & Ritchie, 2013). The delivery of this sand and gravel sediment to the Elwha nearshore will change the abundance and distribution of suitable surf smelt spawning habitat. These changes present an opportunity to investigate and better understand shifts in habitat form and function and associated spatial and temporal patterns of surf smelt usage in the Elwha nearshore.

The bulkheads at Elwha bluffs represent an outstanding and long-term restoration issue. Historically, feeder bluffs provided an estimated 70% of the sediment contribution to the entire Elwha drift cell (Parks et al., 2013) and 85% of the sediment that formed and sustained Ediz Hook (Galster, 1989). Currently, 68% of the entire length of these feeder bluffs are now armored with bulkheads (Flores et al., 2013; Kaminsky et al., 2014). The prevention of the sustained erosional input of sediment from these bluffs has significantly impaired the sediment processes of the Elwha nearshore in the past; their persistence will likely continue to impair long-term sediment processes as long as they remain in place.

After the initial pulse of fluvial sediment into the Elwha nearshore system resulting from dam removal, the delivery of sediment from the Elwha River is expected to reduce and equilibrate around the pre-dam rate of 120,000 to 290,000 m^3 of sediment annually (BOR, 1996; Czuba et al., 2011a). While this sediment input will benefit the unarmored beaches near the river mouth, including the unarmored Freshwater Bay, the feeder bluffs of the Elwha drift cell will still remain armored. It is unclear whether this sediment will accumulate along the armored portion of the Elwha Bluffs beach. The Army Corps of Engineers, the City of Port Angeles, and The Coastal Watershed Institute are currently working to determine what may occur in this regard. Sediment accumulation along armored areas has been shown to be limited to the shorter beach face below the base of the armoring structure and is less likely to accumulate and persist in the high-energy beach environment associated with armored shorelines (Johannessen et al., 2014; Johannessen & MacLennan, 2007; Rice, 2006). In order to take advantage of the restorative pulse of Elwha River sediment arriving on nearshore beaches, an adaptive management approach is needed to respond to changing conditions, management needs, and best scientific information as it becomes available. Specific actions to enhance nearshore restoration may include the placement of large woody debris and beach nourishment with cobble in order to capture and retain the Elwha sediment as it arrives (Clancy et al., 2009; Rich et al., 2014; Shaffer, 2013). The preservation of Freshwater Bay, which remains unarmored, as well as intact adjacent bluff areas will be important restoration and conservation actions for the entire coastal region.

Healthy nearshore ecosystems support sustainable economic activity and can provide a wide variety of valuable public benefits. The value of nearshore ecosystem services along the Strait of Juan de Fuca, such as carbon storage and sequestration as well as habitat creation for fish and wildlife, including for forage fish, has been estimated to contribute more than $15 million annually to the local and regional economies (Flores et al., 2013). The sediment transfer value of feeder bluffs within the Dungeness and Elwha drift cells contribute between $99,000 to $506,000 every year, with intact, unarmored bluffs providing more value than armored sections of the shoreline (Flores et al., 2013). However, nearshore ecological function depends on maintaining those processes that shape its physical form. Intact sediment processes are crucial for sustaining beaches that provide forage fish spawning habitat. Documented sites of forage fish spawning habitat are currently protected from net loss through Washington State’s Hydraulic Code (WAC 220-110) and by shoreline master programs and critical area ordinances, but widespread privatization of tidelands throughout Puget Sound may necessitate further regulations in order to ensure effective stewardship of the public’s forage fish resources. Interest is also growing in armor removal projects in the region (Johannessen et al., 2014). However, the amount of new armoring constructed in Puget Sound continues to outpace the amount of armoring that is removed every year (Puget Sound Partnership, 2013). The persistence of armored shorelines within the Elwha drift cell represents a continued and long-term impairment of nearshore sediment processes and thus, of ecological function. The massive influx of sediment to the Elwha nearshore resulting from the dam removal project represents an unprecedented opportunity to promote ecosystem restoration at a drift cell scale. However, this opportunity will be short lived, so the time to take advantage of it is right now.

Chapter 3: Restoration and Management of the Elwha Nearshore

Introduction

The Strait of Juan de Fuca is a critical migratory corridor for federally threatened Chinook and Hood Canal summer chum salmon, as well as a number of other culturally and economically important marine fish and wildlife species that migrate to and from the Pacific Ocean. This region's nearshore environment, often defined as extending from the upland coastal bluffs and riparian forests to the shallow offshore waters of about 30 meters depth (Shaffer et al., 2008), is an important zone that provides spawning, rearing, and forage habitat for a number of bird, fish, and marine mammal species. The susceptibility of the nearshore environment to anthropogenic impacts, combined with its great ecological value, make it an important area for heightened measures of protection as well as for efforts at restoration and stewardship. The nearshore of the central Strait of Juan de Fuca offers a unique location for learning about the relationship between coastal geomorphic processes, physical habitat form and ecological function. The sediment recruitment and transport processes of the Dungeness drift cell remain largely intact and support the creation and maintenance of functioning nearshore habitat, including that which supports forage fish spawning. In contrast, the sediment processes of the Elwha drift cell have been impaired for over a century by ongoing industrial and urban development, including extensive shoreline modifications by the armoring of bluffs and spit, and the construction of two in-river dams and lower river dikes on the Elwha River. These alterations, and the consequent sediment starvation of the Elwha nearshore, have caused the erosion and coarsening of beaches and the degradation of nearshore habitat.

The stark contrasts in ecological form and function evident between these two adjacent segments of the central Strait of Juan de Fuca coastline offer lessons for coastal management practices as well as for restoration actions. The ecological health and function of those coastal areas with still-intact ecological function can serve as an example of potential function achievable by the proper restoration of degraded areas. In turn, areas of impaired ecological processes and degraded function can serve as a cautionary tale, an example to be avoided by proper management practices. In order to pursue both ecological restoration in the Elwha nearshore and management recommendations in areas of intact ecological processes requires an interdisciplinary approach. Sound science must inform policy decisions and the wide range of stakeholders must be considered and incorporated into the decision process. Historical and present conditions of nearshore areas must be considered with the best available science and used to inform our calculations of the consequences of proposed actions. Collaborations between scientists and local governments are enhanced with input from the local residents and property owners that would be affected by management decisions. The present conditions in the nearshore of the central Strait of Juan de Fuca vary from degraded urban shorelines and armored feeder bluffs to drift cells with intact sediment processes supplying and maintaining beach and spit habitats. This range in ecological function spans both a spatial scale as well as a temporal one since conditions are changing fast and action must be taken immediately. The potential to optimize the sudden influx of 100 years of Elwha River sediment to the nearshore offers an unprecedented restoration opportunity that requires the unusual blend of careful consideration and speedy action from the perspective of a wide range of disciplines. Making the best ecological and community decisions necessitates weighing how management decisions will affect not only the ecology of the nearshore, but also the impacts to the region's economic activity and its affect on people's lives in both the short-term as well as the long-term. Good management decisions occur at the intersection of science and policy. Coastal geomorphology, ecology, and technology can intersect with such disciplines as history, economics, law, and anthropology to inform and equip policy makers with a vision of management that can be effective and respond adaptively to the needs of the environment and the community.

This chapter is about nearshore management in the Elwha and Dungeness drift cells. The release of 100 years worth of fluvial sediment into the Elwha nearshore as a result of the dam removal project represents a unique and unprecedented opportunity to restore the sediment-starved and ecologically-degraded Elwha nearshore. However, a number of challenges exist. Lessons learned from unwise management practices of the past, as well as the attempts at ecological restoration in the present and near future, can offer a cautionary tale and insight into how to approach questions of management in other areas of the nearshore. This chapter begins with an assessment of nearshore conditions in the central Strait of Juan de Fuca. Our attention then focuses on the degraded ecological conditions of the Elwha nearshore and the history of how its feeder bluffs and Elwha River sediment input processes became so impaired. We then turn our attention towards the removal of the two Elwha River dams and what the release of long-trapped reservoir sediment could mean for Elwha nearshore restoration. Shoreline armoring in long stretches of the Elwha drift cell pose a number of challenges to full restoration of its nearshore. We illustrate some of these challenges with an examination of the unusual situation at the City of Port Angeles Landfill site and its associated seawall at the base of the Elwha feeder bluffs. We then examine some of the restoration questions and actions that have been proposed to address these challenges, such as the role that large woody debris might play in recruiting and stabilizing the influx of sediment. Ecosystem service valuation can also be a management tool that is useful for prioritizing restoration and conservation goals, and help justify investments in environmental restoration. We look at the findings of a report on the value of ecosystem services of the Elwha nearshore, including its feeder bluffs, before comparing these values to nearshore function in the intact Dungeness drift cell. Such a comparison reveals the great ecological (and economic) value of intact areas of the shoreline and illustrates the need to ensure the continued protection of these areas.

Nearshore conditions of the central Strait of Juan de Fuca

The Strait of Juan de Fuca’s nearshore environment appears to be in a generally healthy and unaltered state, although a few important exceptions require attention. Clallam County’s Inventory and Characterization Report (ESA et al., 2012)) states that the processes shaping and maintaining the nearshore ecosystem along its shoreline are some of the least altered in the entire Puget Sound basin (see also City of Port Angeles, 2012a). An extensive assessment by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) supports this assertion when ranking the level of degradation for a number of ecosystem processes within the various sub-basins of Puget Sound. In their assessment of sediment processes, they found generally low levels of degradation for sediment input and transport, and for the erosion and accretion of sediments along the Strait of Juan de Fuca shoreline (Schlenger et al., 2011). For instance, while shoreline armoring cumulatively occurs along 27 percent of the entire Puget Sound Basin (and as high as 63% of the south central Puget Sound sub-basin), the Strait of Juan de Fuca sub-basin was among those with the least shoreline armoring (16%), and had one of the longest average length of shoreline reach with no shoreline armoring (17.2 km; an average of the 10 longest reaches within the sub-basin) (Schlenger et al., 2011). The Strait of Juan de Fuca also had long portions of shoreline characterized as “Less Degraded” or “Least Degraded” by environmental “stressors”; a suite of 12 quantifiable anthropogenic modifications known to impair nearshore processes. The average length of the 10 longest shoreline reaches in the Strait of Juan de Fuca sub-basin with no stressor was 12.8 km (compared to an average of 2.9 km found in the south central sub-basin), and the longest reach with no stressor in the entire Puget Sound study area was a 38.2 km reach also found in the Strait of Juan de Fuca sub-basin (Schlenger et al., 2011). While much of the Strait of Juan de Fuca shoreline remains in an un-degraded state, anthropogenic alterations to the shoreline have occurred in a few areas and have impaired the ecological function of its nearshore.

The Elwha Drift Cell

The Elwha drift cell is a glaring exception to the relatively unaltered shoreline environment of the north Olympic Peninsula. Located in the central Strait of Juan de Fuca, the Elwha drift cell spans approximately 21 km of shoreline from the western extent of Freshwater Bay to the eastern tip of Ediz Hook and encompasses a mosaic of shoreline habitats including 6 km of embayment (Freshwater Bay), the Elwha River estuary, 4.9 km of feeder bluffs (Elwha Bluffs), and a 5.5 km spit (Ediz Hook) (Figure 2 in previous chapter). However, years of urban and industrial development in the area have impacted the shoreline of the central Strait, severely impairing the sediment processes of the Elwha drift cell and degrading its ecological function. For instance, the beach habitats of the Elwha nearshore have been documented to be less suitable for forage fish spawning than comparative beaches in the adjacent Dungeness drift cell (Parks et al., 2013). In fact, the only process units in the entire 329 km Strait of Juan de Fuca sub-basin classified as “Most Degraded” encompass the City of Port Angeles and Ediz Hook, areas with highly modified shorelines that are almost completely armored (Schlenger et al., 2011; USCOE, 1971). Intact sediment processes are crucial components of a healthy nearshore. However, disruption to the sediment processes in the Elwha drift cell has occurred primarily from extensive armoring of the Elwha feeder bluffs. In addition, the construction of two in-river dams on the Elwha River has contributed further to the sediment starvation observed on the beaches of the Elwha nearshore.

The Elwha feeder bluffs are critically important to the overall sediment budget of the Elwha drift cell, but their contribution has been impacted by a series of shoreline armoring projects over the past 80 years or so. Large volumes of continually-eroded sediment from the Elwha bluffs are largely responsible for the formation and maintenance of Ediz Hook, a long spit lying to the east of the bluffs at the distal, depositional end of the Elwha drift cell. When the sea level essentially stabilized about 5,000 years ago (Downing, 1983), the Elwha bluffs lay 900 to 1,500 meters to the north of their present position (Galster, 1989). The steady erosion of these bluffs supplied an estimated 70% of the sediment contribution to the Elwha littoral system (Kaminsky et al., 2014; Parks et al., 2013) and 85% of the sediment that formed and sustained Ediz Hook, even allowing a progressive extension of the spit by about 1.5 m/yr (Galster, 1989). The remainder of sediment influx to the Elwha drift cell was furnished by the fluvial sediment of the Elwha River until the construction of two dams in the early 1900s largely curtailed its transport and delivery to the Elwha nearshore. In 1930, an industrial waterline was buried along 5.3 km of the toe of the Elwha bluffs, and a series of armoring projects were completed in 1961 to protect over 2 kilometers of the pipeline. By 1961, the cumulative effect of dam construction and bluff armoring had reduced the sediment budget sustaining Ediz Hook by 89% (Galster, 1989; USCOE, 1971). The dramatic reduction in the supply of littoral sediment to Ediz Hook caused an alarming rate of erosion of the spit itself, prompting the

Army Corps of Engineers to design a massive revetment and beach nourishment project to protect the spit (and the Port Angeles harbor sheltered behind it), which was completed in 1977-78 (Galster, 1989). Almost the entire length of the spit remains armored today but continues to erode and requires periodic nourishment with sand and gravel (USCOE, 2002). At present, 68% of the entire length of the Elwha feeder bluffs are armored (Flores et al., 2013; Kaminsky et al., 2014). Of the approximately 3 km of bluffs within the Port Angeles City limits, 91% are now armored with a rock revetment (City of Port Angeles, 2012b). Armoring has dramatically slowed the processes of bluff erosion (Kaminsky et al., 2014) and severely starved the Elwha nearshore of its replenishing sediment supply.

Adding to the Elwha nearshore sediment starvation was the dramatic reduction in the fluvial sediment contribution of the Elwha River. Two in-river dams on the Elwha River impounded an estimated 21 to 26 × 10^6 m^3 of sediment in their reservoirs and reduced fluvial sediment transport to the coastal waters to about 2% of the pre-dam load (Draut & Ritchie, 2013). Without the replenishing input of Elwha River sediment, approximately 100,000 m^2 of coastal plain within the Elwha delta was lost to increased erosion of the coastline between 1939 to 2006, and coastal beaches underwent a dramatic coarsening of their substrate (Warrick et al., 2009). While shoreline armoring has had the most significant impact on Elwha nearshore sediment processes, the construction of the two in-river dams contributed to the dramatic sediment starvation observed throughout all the beaches of the Elwha drift cell. The combined effect of these two impacts has been to significantly impair the sediment delivery processes to the Elwha nearshore and highlights the role that intact coastal geomorphic processes play in creating and sustaining nearshore ecosystem structure and function.

Disrupting the continual input of sediment into a drift cell can change the physical characteristics of downdrift beaches, from changing the composition of substrate material to altering the beach slope and width (Fresh et al., 2011). A drift cell is a segment of the shoreline along which sediment moves at a measureable rate and direction depending on wave energy and currents and includes sources of sediment (such as bluffs and river mouths), a zone of transportation, and an area of deposition. Modifying the shoreline to interfere with sediment input or its transport can affect the structure of downdrift beaches. Observed effects of reduced sediment supply in the Elwha drift cell include the steepening of the beach profile of Ediz Hook (City of Port Angeles, 2012a) as well as the coarsening and higher variability in grain-size of beach substrate throughout the Elwha nearshore beaches (Parks et al., 2013). Such dramatic changes to the physical structure of beaches reduces or degrades habitats for a wide variety of marine plants and animals that require the presence of fine sediment, including forage fish, shellfish, eelgrass, and birds (Penttila, 2007; Schlenger et al., 2011). Indeed, the Elwha drift cell, with its degraded habitat-forming sediment processes, was found to have lower fish species diversity and richness than comparative areas with intact processes (Shaffer et al., 2012). The Elwha nearshore has also been starved of deposits of large woody debris (LWD), an important component of the nearshore ecosystems which provides structure and stability to beaches and spits by helping to trap and retain sediment, buffer wave energy, and prevent erosion of nearshore habitat (Clancy et al., 2009; Rich et al., 2014). In addition to impounding sediment, the two dams on the Elwha River prevented LWD delivery to the nearshore, and shoreline armoring has prevented the recruitment and retention of large woody debris entering the Elwha drift cell from riparian forests or from other bodies of water (Rich et al., 2014). While shoreline armoring has been, and will continue to remain, a significant impediment to restoration efforts, the dam removal project, and its associated mobilization and delivery of sediment and LWD, represents an unprecedented opportunity to restore ecosystem function to the Elwha nearshore.

Dam removal and the potential for nearshore restoration

A project to remove both dams on the Elwha River commenced in September of 2011 and is expected to be completed by the end of 2014. The two dams on the Elwha River impounded an estimated 21 to 26 × 10^6 m^3 of sediment in their reservoirs since their construction (Draut & Ritchie, 2013). As of spring 2013, a total of 6.1 x 10^6 m^3 of sediment had been mobilized downstream from the deposits in both reservoirs (Draut & Ritchie, 2013), representing only about 20% of the total 13 to 20 x 10^6 m^3 projected sediment load to be released into the Elwha system over the next several years (Randle & Bountry, 2012; Ritchie, 2013). Much of the early-stage sediment release has been very fine-grained material but as dam removal progresses, coarser sand and gravel sediment fractions are expected to be increasingly mobilized and released downstream over the next 7-10 years (Czuba et al., 2011a). The potential volume of sand and gravel is substantial; 50% of the total sediment ($21.6 \pm 3.0 \times 10^6$ m^3) in the upper Lake Mills reservoir and 32% of the lower Lake Aldwell reservoir total sediment ($4.6 \pm 1.5 \times 10^6$ m^3) is estimated to be sand and gravel (Czuba et al., 2011a; Draut & Ritchie, 2013). Large amounts of sand have already made their way down to the river's mouth and are moving into the Elwha drift cell (Ritchie, 2013; Warrick & Gelfenbaum, 2013). The physical structure of beaches adjacent to the river mouth, such as Freshwater Bay, is changing dramatically. Sandy substrate now lies where coarse cobble made up the beach. As sediment continues to be delivered to the Elwha nearshore, the volume and trajectory of its distribution throughout the drift cell is unknown; however, its arrival to nearshore beaches downdrift could potentially, even if partially, restore nearshore form and function.

The restoration of fluvial sediment inputs will occur in two phases. The first phase is the delivery of large quantities of sediment released by the dam removal project. As the Elwha River carves through and mobilizes the abundant supply of unvegetated and unstable sediment in the former reservoirs, it will deliver a multiple-year-long pulse of sediment to the nearshore that constitutes the largest sediment release from a dam removal project in history (Draut & Ritchie, 2013).

The second phase will come after the supply of easily-mobilized reservoir sediment is exhausted and the river resumes equilibrium with its supply of normal, naturally-eroded sediment. Estimates of the pre-dam sediment load are 160,000 m^3yr^{-1} of fine and coarse sediment (Randle et al., 1996), or ~217 000–513 000 t/year (Czuba et al., 2011a). The restoration of river sediment inputs to the Elwha nearshore is an opportunity to promote restoration of nearshore ecological function, but represents a temporary and only partial restoration of sediment processes. The pulse of sediment associated with the dam removals will be short-lived (7-10 years); the subsequent, normal annual fluvial sediment inputs represent only a small fraction (~15%) of the total (bluff and fluvial) volume of sediment that was historically delivered to the Elwha drift cell each year. The Elwha bluffs, representing the bulk of sediment historically supplied to the nearshore, will remain armored after the dam removals and therefore will continue to deliver only a minor fraction of their pre-armoring volume (Kaminsky et al., 2014). In the long run, with much of the bluffs (68%) and almost the entire spit armored, ecological function in these areas of the Elwha nearshore will likely remain impaired. Full restoration of the Elwha nearshore will be challenged by these and other ongoing management issues.

Port Angeles landfill and other nearshore management issues

Even while the Elwha dams come down and restoration of the watershed begins, large portions of the Elwha nearshore remains heavily managed. The Nippon paper mill, located at the base of Ediz Hook, armors their shoreline regularly. The Army Corps of Engineers performs routine maintenance work on an erosion control project for Ediz Hook which consists of nourishing the spit’s beach with gravel and cobble and re-keying revetment rocks that have fallen onto the beach (USCOE, 2002). Lower Elwha River alterations, such as estuarine diking, will also limit restoration of portions of the Elwha nearshore (Shaffer et al., 2008).

Another major management issue involves the future management of the Port Angeles landfill site which is located atop the Elwha bluffs west of the city center and managed by the City of Port Angeles.

The landfill was originally privately owned, predating the City, and was purchased in 1947, becoming operational as a publicly owned city dump in 1979 (Figure 11). A number of pits, (referred to as East 304 cell, valley cell, and West 304 cell) were constructed near the edge of the bluff and filled with approximately 575,000 cubic meters of raw garbage in the East and West 304 cells alone (Neal, 2013; Puntenney et al., 2013). The thin bluff wall acting as the

Figure 11. Looking west along the base of the Elwha bluffs towards the City of Port Angeles landfill in the distance, 1947. The photo shows a portal (center) for the industrial water line buried along the toe of the Elwha bluffs and protected by shoreline armoring (right). Photo courtesy of Coastal Watershed Institute.

sole barrier between the Strait of Juan de Fuca and large quantities of garbage (~18 m deep) is highly unstable and is thinning at a rate of 0.6 to 1.8 m per year due to wave action undermining the toe of the bluff and causing mass wasting events (Neal, 2013). A 140 m long seawall was installed, without federal permits, in 2006 to protect the West 304 and Valley cells but the installation increased bluff erosion immediately down drift. Waste from East 304 cell became exposed at the edge of the bluff in June of 2011, triggering concern that bluff failure could result in landfill waste once again collapsing onto the Strait of Juan de Fuca shoreline (Parks et al., 2014; Shaffer, 2013). This event sparked a number of proposed design alternatives to address the problem. The city eventually decided on a $21.2 million plan to dig up and transfer 202,600 m^3 of waste in stages from the East cell to another cell within the landfill located further inland, as well as taking action to augment the ends of the existing seawall at the base of the bluff with transitional energy-defusing scour protection in order to reduce erosion to the adjacent unarmored shoreline (City of Port Angeles, 2013; Neal, 2013; Schwartz, 2014). With the waste removed from East 304 cell, the bluff at that location would be allowed to erode naturally onto the shoreline while city managers continue to adaptively manage the site with continued monitoring of bluff erosion rates and shoreline processes over the next 25 to 100 years. Future management actions could include additional waste removal to allow continued bluff erosion as well as seawall removal and replacement with softer shoreline stabilization material if the wave energy and environment permit (Neal, 2013). Future management decisions will depend, in part, on those actions taken today at the landfill site. One of the important decisions facing managers today regards what actions to take in order to best optimize the arrival of Elwha River sediment to nearshore beaches. Actions that enhance the capture and retention of substrate on the sediment-starved beaches of the Elwha drift cell, including the beach below the landfill, will help to stabilize them as well as take a step towards restoring ecological function.

Elwha nearshore restoration: questions and actions

The delivery of Elwha River sediment to the beaches of the Elwha drift cell could potentially restore nearshore ecological function to its impaired bluffs and spit, but little is known about the exact quantity, timing, location, grain-size, or duration of sediment delivery. Additional questions remain as to whether, and for how long, sediment would remain on beaches with armored shorelines, and whether management actions could be taken to assist its capture and retention on these beaches. Another unknown is whether the arrival of sediment to the beaches below the city landfill would help ameliorate the ongoing issue of erosion at that site. Answering these questions could help the city of Port Angeles define specific restoration actions they could take in order to optimize the arrival of Elwha River sediment and restore ecological habitat function to their hardened shoreline. The Elwha Nearshore Consortium (ENC), a group of scientists, managers, and citizens dedicated to understanding and promoting the restoration of the Elwha nearshore, has pledged to help the city answer these questions and assist them in making the best management decisions for the environment and the community. The ENC advocates for an adaptive management approach that responds to the changing conditions, management needs, and best science as it becomes available. Specific actions may include the placement of large woody debris and beach nourishment with cobble in order to capture and retain the Elwha sediment as it arrives (Shaffer, 2013). The ENC also advocates for the preservation of Freshwater Bay, which remains unarmored, and the restoration of portions of the lower Elwha River which has undergone channelization and diking, resulting in restricted fish use of parts of the tidal influenced estuary (Shaffer et al., 2008). Long-term feeder bluff erosion rate studies should also be undertaken and incorporated into bluff management decisions.

In addition to releasing large amounts of sediment, the removal of the dams is also releasing LWD which could potentially help stabilize eroding Elwha beaches and trap the new inputs of sediment as it arrives. However, if LWD is prevented to recruit to beaches by the presence of riprap, the structural habitat improvements may not be realized (Figure 12). To augment Elwha River LWD inputs, active protection of intact riparian areas within the Elwha drift cell, such as Freshwater Bay, and adjacent areas could help optimize restoration efforts and create a more resilient and natural nearshore habitat for forage fish and other wildlife. Increasing the amount of LWD on nearshore beaches, especially along Elwha Bluffs and Ediz Hook, with root wads and branches, and limiting and reducing shoreline armoring would be first steps of active restoration practices in the nearshore (Rich et al., 2014). Adding LWD and nourishing the beach with appropriate-sized gravel has been successful elsewhere as a “soft shore” approach to replace hard armoring while still offering protection from wave energy (Rich et al., 2014).

The Elwha River Ecosystem and Fisheries Restoration Act (Elwha Act, Public Law 102-495) of 1992 calls for “full restoration of the Elwha River ecosystem and the native anadromous fisheries” (Section 3(c)). The restoration of the Elwha nearshore is a crucial component to achieving the successful realization of this goal because the nearshore is a bottleneck for salmon recovery. Salmon depend on nearshore habitat as an important migration and forage corridor, and as a crucial transition point between the freshwater of the river and saltwater of the marine environment. However, Elwha nearshore restoration presents unique

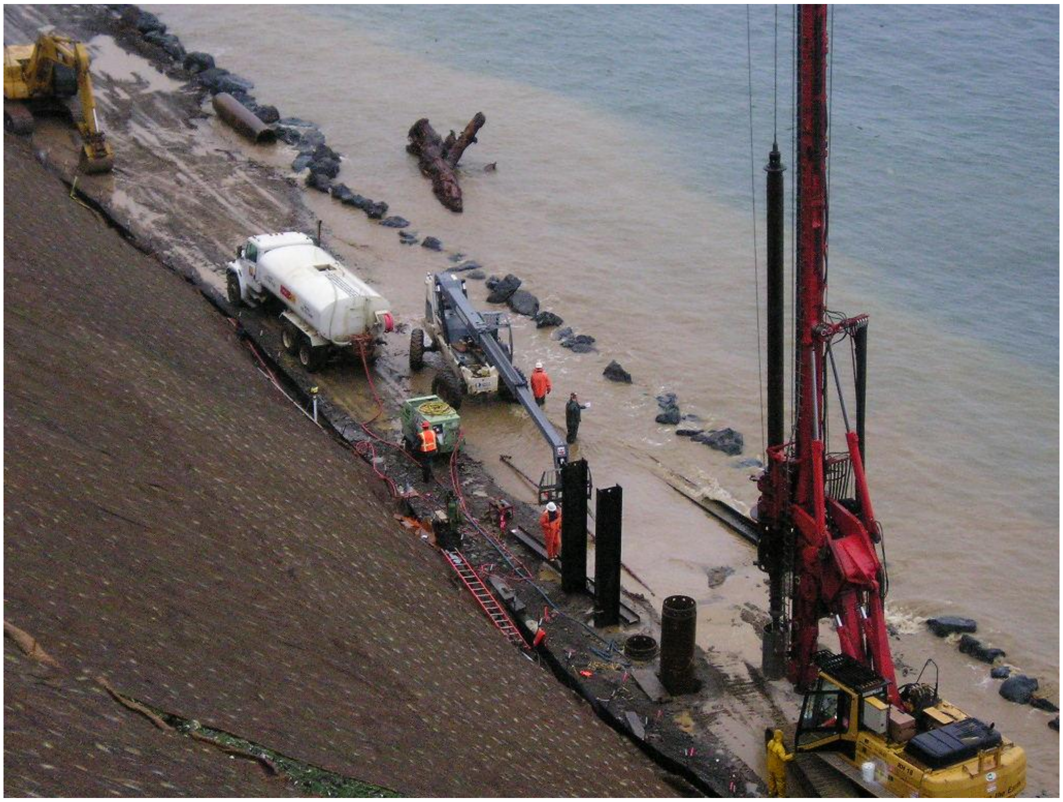

Figure 12. City of Port Angeles installing landfill sea wall in 2005. Note large wood unable to recruit to the beach due to newly installed riprap at base of Elwha bluffs. Photo by Darlene Shanfeld.

management complexities as compared to the restoration of the Elwha River watershed. While over 80% of the Elwha watershed lies within the Olympic National Park (ONP), the Elwha nearshore lies entirely outside the ONP and is owned instead by a complex mosaic of private, city, county, state, tribal, and federal landowners. This matrix of various stakeholders makes decision-making and coordination of restoration activities much more complex than that within the watershed. Since 68% of the feeder bluffs within the Elwha drift cell will remain armored long after the initial pulse of Elwha river sediment enters the nearshore system, the mosaic of shoreline property owners, natural resource managers, research scientists, and other stakeholders will have to consider which actions to take in order to optimize the temporary pulse of sediment delivery, as well as to minimize future continued degradation of the Elwha nearshore as the amount of fluvial sediment drops to normal annual levels. Education of the local citizenry as to the importance and benefits of intact nearshore processes will undoubtedly be an essential component of building awareness and support for nearshore restoration as a crucial part of full ecosystem recovery of the entire Elwha system. Education could take place through workshops, presentations, newspaper announcements and articles, and community college classes.

Another tool that can be used to both help promote and guide restoration and management decisions is a consideration of the economic value of ecosystem services that are provided by nearshore processes and features. Earth Economics, a non-profit organization providing science-based, economic analysis of ecosystem services released a report on the value of natural capital in Clallam

County focusing on nearshore processes, including feeder bluffs. They found that the nearshore ecosystem services of carbon storage and sequestration, creation of habitat, and forage fish supportive value contribute over $15 million annually to the local and regional economies; commercial and recreational fishing provides a minimum of $20 million annually; and feeder bluffs contribute on average between $99,000 to $506,000 annually, the range depending on the health of the shoreline processes and the presence or absence of shoreline armoring (Flores et al., 2013). The difference in the value of sediment inputs between armored and unarmored sections of feeder bluffs is striking; within the Elwha drift cell alone, armored portions of bluffs had an estimated value of $2.97 to $5.94/foot/year, while unarmored portions had an estimated value of $9.45 to $18.90/foot/year. Ecosystem services valuation can be used to help managers prioritize restoration and conservation goals, better understand the connections between the environment and the economy, and help justify investing in environmental outcomes within the context of pressure for economic development.

The Elwha as cautionary tale

The extent to which the Elwha drift cell's sediment processes have been impaired becomes apparent when compared to adjacent drift cells with intact sediment processes. The Dungeness drift cell serves as an appropriate comparison because it shares many of the same GMHTs and geomorphic processes, but is not influenced by the presence of armoring along its feeder bluffs or by in-river dams. Differences in nearshore processes and measures of ecological function make powerful arguments not only for the restoration of impaired areas, but also for the preservation of those areas that remain intact. For example, our finding of increased surf smelt spawning in the intact drift cell can serve both as an example of what might be achievable with restoration of the Elwha drift cell, as well as a reason to ensure the continued preservation of the functioning Dungeness nearshore. The degradation of nearshore function in the Elwha drift cell can serve as a cautionary tale, illustrating to coastal managers a scenario of what to avoid replicating in intact stretches of the nearshore environment.

Other measures of nearshore function, such as bluff retreat rates and volumes of sediment inputs, can also support preservation efforts. The Dungeness bluffs have been found to erode faster and contribute greater volumes of sediment to the Dungeness drift cell than do the Elwha bluffs to the Elwha drift cell. Kaminsky et al. (2014) estimate that the unarmored Dungeness bluffs produce twice as much sediment per alongshore distance as the mostly-armored Elwha bluffs (avg. 7.5 m3/m/yr vs. 4.1 m3/m/yr, respectively). The broad, flat, self-maintained beaches of the Dungeness drift cell, supportive of surf smelt spawning, are testament to the intact habitat forming processes of this portion of coastline, and should be recognized as such when considering management decisions. Coastal managers can use bluff recession rates in planning future land use zoning and growth rates, and regulating setback distances from bluff edges for new construction.

Conclusions

The project to remove both dams on the Elwha River, the largest project of its kind in U.S. history, presents a unique opportunity for the restoration of the impaired Elwha nearshore. The pulse of sediment released from the former reservoirs is currently making its way down the river and entering the nearshore environment, changing the character of its beaches and restoring the sediment processes that shape and maintain nearshore habitat. However, this pulse of Elwha River sediment is projected to be short-lived. After the un-consolidated, easily-erodible reservoir sediment has been washed out of the system within 5 to 10 years, the river will likely resume its natural, but much lower, rate of sediment contribution to the nearshore (Czuba et al., 2011a). The opportunity to take action and optimize this event, therefore, is time sensitive.

A major obstruction to restoration, however, will persist in the Elwha nearshore. Much of the Elwha Bluffs, which historically contributed the majority of sediment to the Elwha drift cell, will remain armored with bulkheads and a sea wall, thereby greatly reducing their rate of recession and sediment contribution, and potentially interfering with the capture and retention of fluvial sediment as it arrives on nearshore beaches. Nearshore restoration associated from dam removals may therefore be temporary, and only partial. Coordination between scientists, natural resource managers, and the various private, tribal, and government stakeholders is required to address this and other problems, as well as to plan and implement the best possible stewardship of this valuable resource.

Understanding the links between sediment processes and the impairment of nearshore function should also be applied towards the preservation of those areas of the nearshore environment that remain intact.

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Appendix

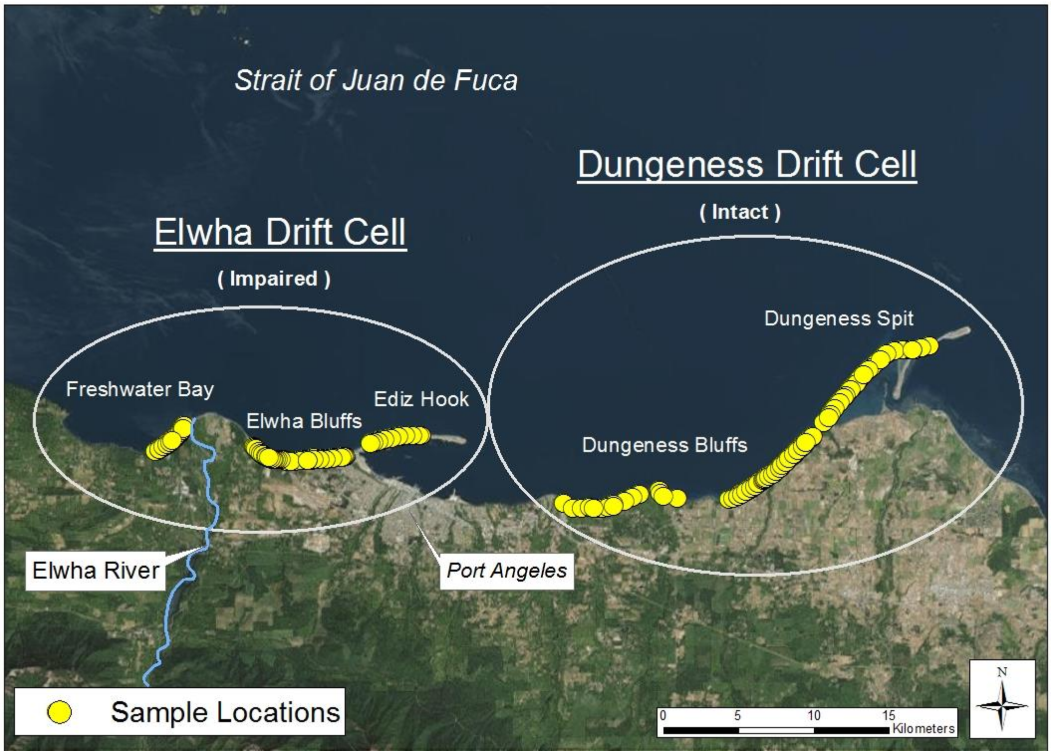

Figure 13. All surf smelt sample locations in the Elwha and Dungeness drift cells.

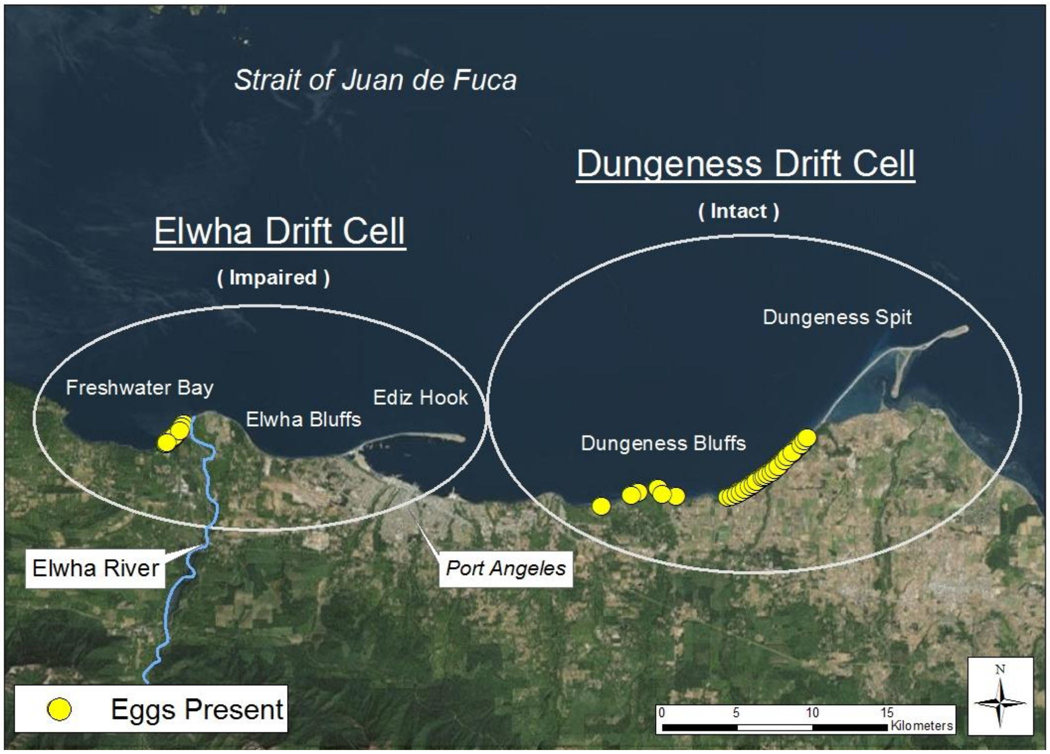

Figure 14. All surf smelt samples containing eggs.

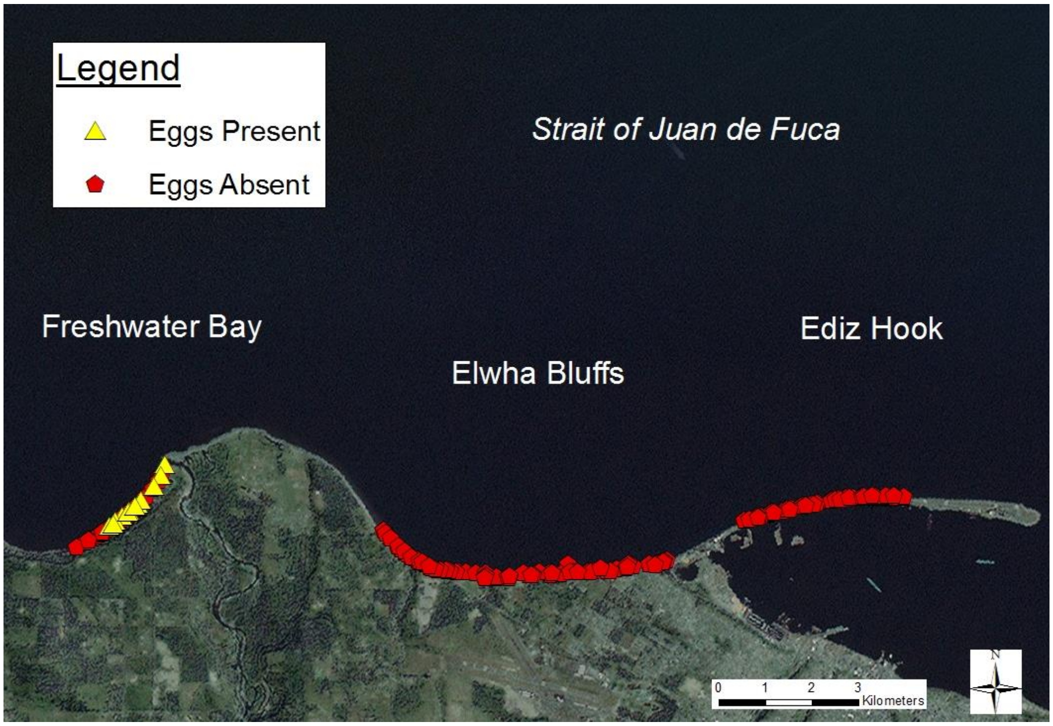

Figure 15. Surf smelt survey results for all samples collected in the impaired Elwha drift cell.

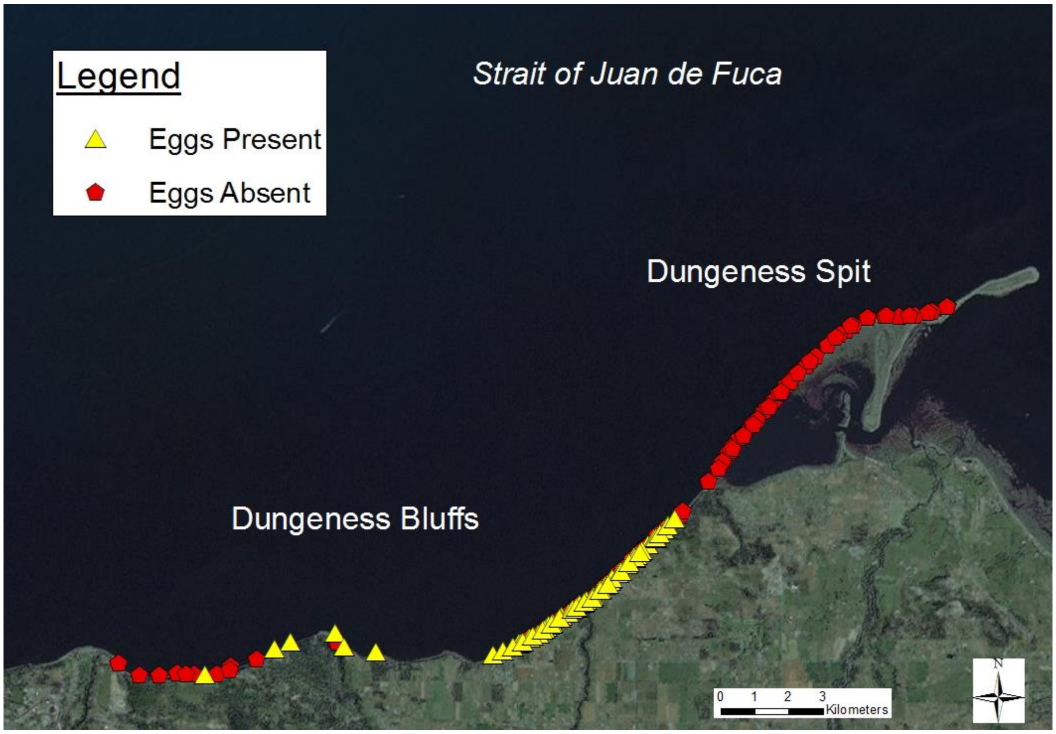

Figure 16. Surf smelt survey results for all samples collected in the intact Dungeness drift cell.

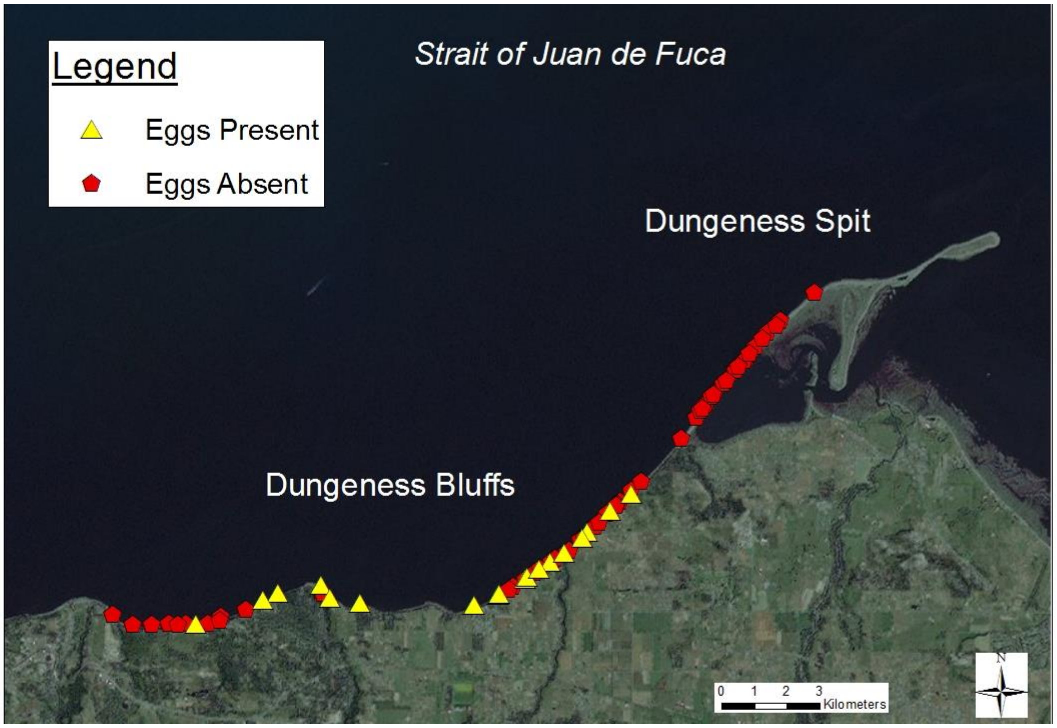

Figure 17. Surf smelt survey results in the intact Dungeness drift cell before dam removal (2007-2008).

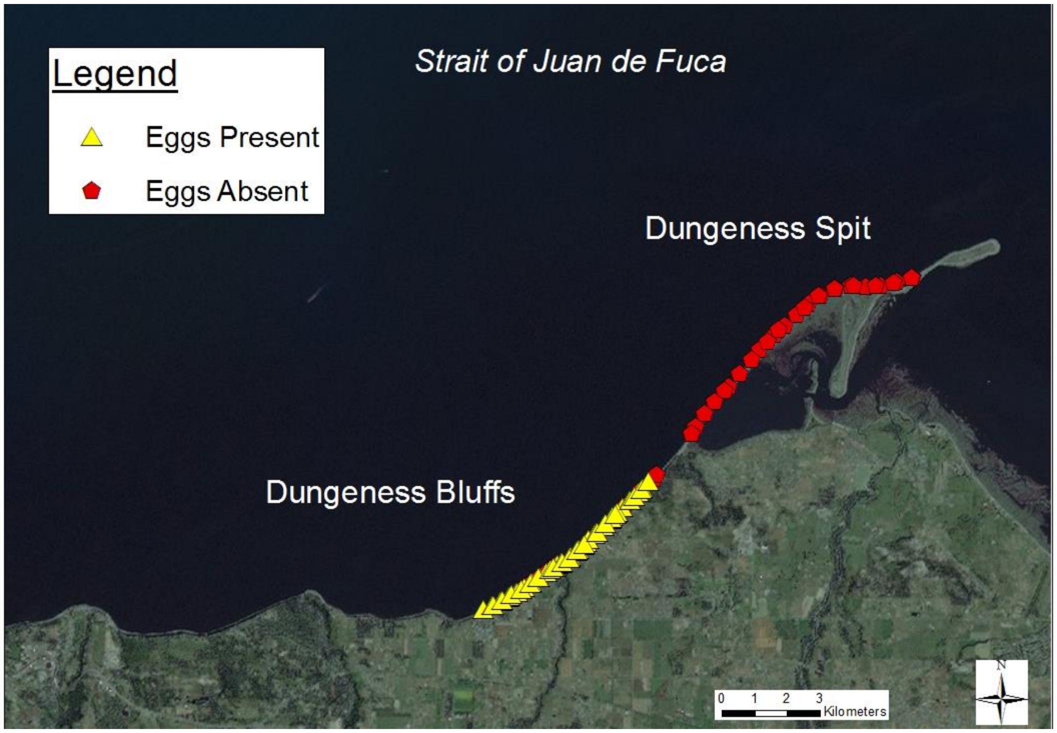

Figure 18. Surf smelt survey results in the intact Dungeness drift cell during dam removal (20012-2013).

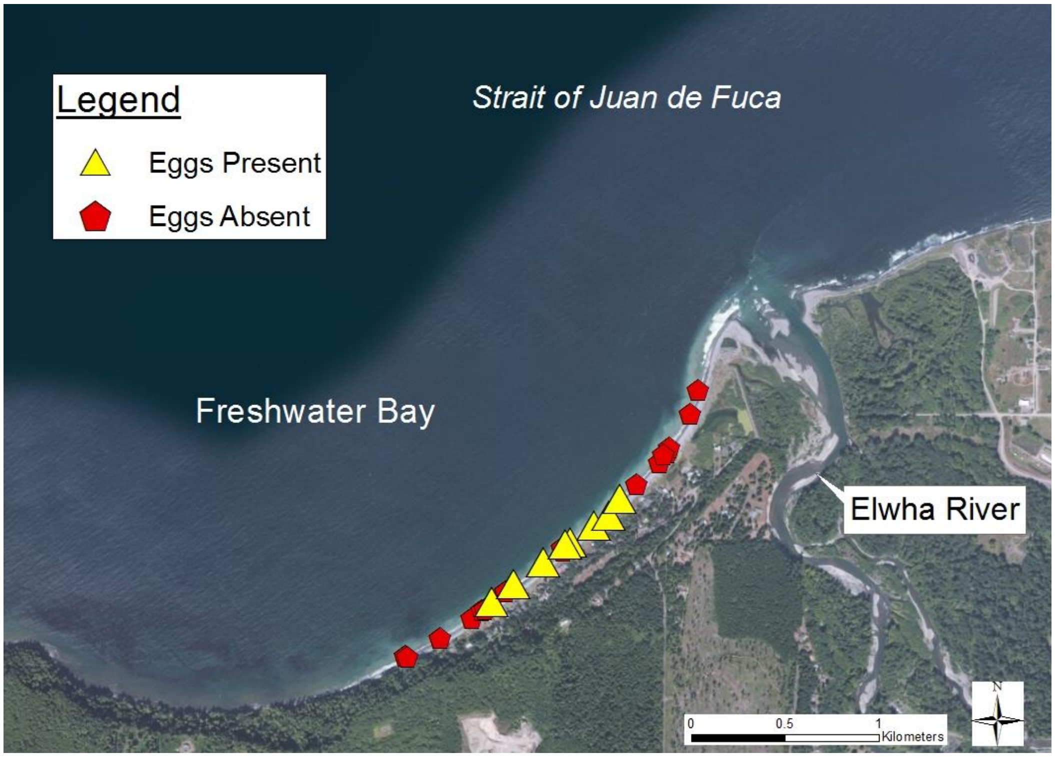

Figure 19. Surf smelt survey results in Freshwater Bay (impaired Elwha drift cell) before dam removal (2007-2008).

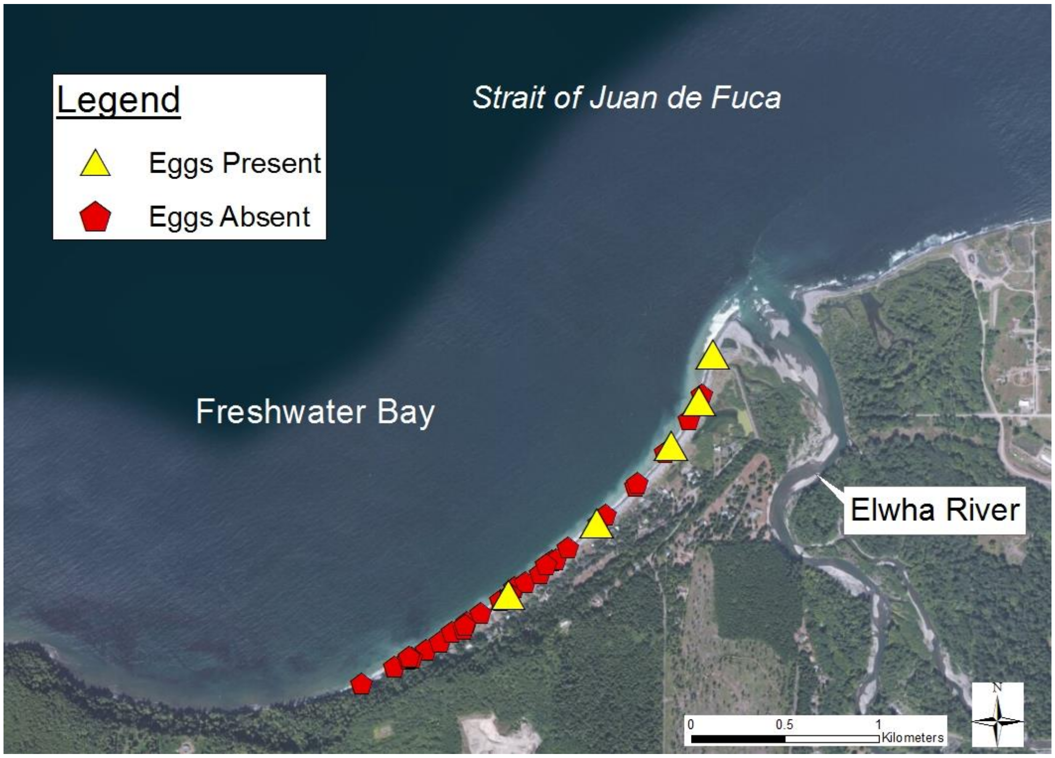

Figure 20. Surf smelt survey results in Freshwater Bay (impaired Elwha drift cell) during dam removal (2012-2013).