Beach nourishment in Puget Sound: status, use, and habitat impacts

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Executive Summary

Beach nourishment is the purposeful addition of sediment to a beach. In Puget Sound, beach nourishment is used for a multitude of purposes including restoration, erosion control, and as mitigation for construction impacts or lost beach processes due to shoreline armoring. Regulators expressed a desire for a synthesis of the science surrounding beach nourishment's effectiveness, particularly for mitigation purposes. Here we review data from peer-reviewed publications and gray literature on the use and effectiveness of beach nourishment. In our review we integrate regional expert opinions in cases where data may not exist. Further, we contextualize this synthesis with an analysis of permits that use beach nourishment in Puget Sound to understand how and where the practice is used. We found that beach nourishment is often a highly effective component of beach restoration practices, particularly when associated with the removal of hard armor. Beyond its use in restoration, beach nourishment is poorly studied for other purposes. The limited data that do exist suggest that beach nourishment performs poorly in maintaining beach conditions when associated with structures like hard armor. This is because hard armor deflects wave energy that evacuates sediment from a beach quickly and most nourishment applications occur too infrequently (usually only once) and in insufficient volumes (one or more orders of magnitude too low). However, it is unclear whether more frequent nourishment or higher volumes of nourishment would adequately address issues of using beach nourishment in front of hard armor. We discuss the implications of these findings for existing local, state, and national regulations and restoration efforts.

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Introduction

Puget Sound is a culturally, economically, and ecologically significant estuary for Washington state and the United States more broadly. Puget Sound's nearshore habitats are particularly valuable given their important function for salmonids, forage fish, and shellfish. As such, there is an increasing need to synthesize available science underlying approaches to nearshore management ranging from mitigation decisions to restoration actions (Schlenger et al. 2011).

Over the ~4,000 km (2,500 miles) of shoreline in Puget Sound, roughly 1/3 is armored (MacLennan et al. 2017). This extensive armoring has led to a growing conversation about ways to mediate and reverse the impacts of existing and future armor or enhance the restoration benefits of armor removal given the undesirable physical and biological impacts to Puget Sound's nearshore environments (MacLennan et al. 2017, Dethier et al. 2020). Armoring limits sediment input from banks and bluffs that builds Puget Sound's beaches and increases transport of finer sediments offshore to deep water or accretion points (Johannessen and MacLennan 2007). Further, because it deflects wave energy, armoring makes beaches narrower, steeper, coarser, and capable of accumulating less wrack and logs which subsequently reduce invertebrate community diversity and abundance (Sobocinski et al. 2010, Heerhartz et al. 2014, 2016, Dethier et al. 2016). Armoring also reduces the amount of overhanging vegetation on beaches (Rice et al. 2006). Importantly, there are also data suggesting that armored beaches result in fewer forage fish eggs deposited and reduced forage fish egg survival (Rice et al. 2006). The effects of armoring are likely site-specific depending on placement below ordinary high water and amount of wave energy (Dethier et al. 2020).

One action that intersects with multiple efforts – particularly around armoring – in Puget Sound's nearshore is beach nourishment. Beach nourishment is the purposeful addition of sediment to a beach and can be used for a diversity of purposes including aesthetics, erosion control, restoration or habitat enhancement, and mitigation for shoreline development and construction impacts (Shipman 2001). In 2022, as part of the project "S*cience Sprints to Support Regulation*" funded by the Puget Sound Partnership, regulators from the National Oceanic and Atmospheric Administration (NOAA) and Washington Department of Fish and Wildlife (WDFW) – in consultation with other regional regulators – identified beach nourishment as a nearshore action that would benefit from a science synthesis that may inform the implementation of existing regulations and policy.

Although beach nourishment is widely used in Puget Sound, regulators and permitters expressed interest – particularly when implemented for compensatory mitigation purposes – in the habitat effects of nourishment, how frequently nourishment should be applied to maintain habitat conditions, and the appropriate volume or scale for each nourishment action. With respect to compensatory mitigation, beach nourishment is often intended as in-kind mitigation to offset lost sediment supply associated with new shoreline armoring. Further, regulators have noticed a cultural trend in Puget Sound where landowners, consultants, and contractors voluntarily include beach nourishment as components of nearshore development projects out of perceived benefits, even if nourishment is not required by regulations. As such, there is interest from regulators in understanding whether this voluntary placement serves an ecological function beyond perceived benefits by landowners and consultants.

In a process-structure-function framework, beach nourishment is intended to replace the lost process of sediment supply which would otherwise have been provided to beaches by natural bluff erosion, but which is impaired by shoreline structures like armor (Shipman 2001). The hypothetical structural and functional aspects of nourishment depend on the nourishment's intended use. For instance, Clancy et al. (2009) discuss nourishment for restoration and soft shore alternative armoring approaches. In these instances, nourishment is intended to have diverse structural benefits including improvements to beach profiles, sediment composition, backshore vegetation, and wood and wrack accumulation, all of which improve shoreline functions. In contrast, when nourishment is used as compensatory mitigation the sediment is expected to move away from the placement site, distributing sediment throughout the drift cell to maintain beach structure. In Puget Sound, nourishment sediment composition is typically designed to function as spawning substrate for forage fish [surf smelt (*Hypomesus pretiosus*) and Pacific sand lance (*Ammodytes hexapterus*), hereby referred to as sand lance] spawning substrate, although there are implications for submerged aquatic vegetation and invertebrates as well (Johannessen et al. 2014, Toft et al. 2021).

Before-after studies in Puget Sound have demonstrated that removing shoreline armor can restore habitat structure, function, and biodiversity (Lee et al. 2018, Des Roches et al. 2022). Even so, under current laws and practices, large swathes of Puget Sound are likely to remain armored, have armor repaired or replaced, or occasionally become newly armored, although recent regulations make installing new armoring difficult unless the threat of erosion to a structure is likely (Small et al. 2018). For nearshore projects in Puget Sound, various agencies use mitigation to sequentially avoid, minimize, and compensate for impacts to an ecosystem, species, or habitat. Compensatory mitigation refers to the final step of the mitigation sequence whereby unavoidable impacts are compensated for. Further, compensatory mitigation is generally prioritized by type and location in the following order: (1) in-kind, on-site, (2) in-kind, off-site, (3) out-of-kind, on-site, and (4) out-of-kind, off-site. Beach nourishment is typically the only tool available to permitters to compensate for the impacts of armoring on-site. Once avoidance and minimization considerations have been accounted for, regulators have found that there is a dearth of on-site, in-kind compensatory options available to mitigate impacts of hard armor, and beach nourishment has typically been identified as the only reasonable tool available (L. Bockstiegel, M. Curtis, K. Still, personal communications).

In Washington, an applicant for new, repair, or replacement armor must obtain a permit from the local municipality or county [through the regions' Shoreline Masters Programs via the Shoreline Management Act, Revised Code of Washington (RCW) 90.58], the state government [through WDFW's Hydraulic Project Approval (HPA) authority, Washington Administrative Code (WAC) 220-660, Revised Code of Washington (RCW) 77.55], and the federal government (US Army Corps of Engineers, in consultation with NOAA under the Endangered Species Act). In general, each relevant agency may approach the mitigation sequence differently depending on the limits of their authority and how that authority is implemented.

For instance, WDFW's jurisdiction is specific to protecting fish life in or near state waters and may not impose requirements that disproportionately optimize fish habitat conditions relative to baseline conditions when a permit is applied for and compared to anticipated post-project conditions. Notably, WDFW does not dictate the compensatory mitigation measures needed for a given project. Rather WDFW approves or denies mitigation actions that are suggested by the project applicant.

For comparison, NOAA and the United States Fish and Wildlife Service (USFWS) (together, the Services) are tasked, under the Endangered Species Act (ESA), to conserve endangered and threatened species and the ecosystems on which they depend. When actions may affect listed species or their habitat, the Services engage in formal consultation (culminating in a biological opinion pursuant to regulations at 50 C.F.R. § 402.14) determining whether the action is likely to jeopardize species (i.e., make species more likely to become extinct or prevent recovery) or destroy or adversely modify designated critical habitat. If a Service concludes that an action is likely to jeopardize a species or destroy or adversely modify designated critical habitat, the Service must include in its biological opinion a "reasonable and prudent alternative" to the action, if any are available. A "reasonable and prudent alternative" must be consistent with the intended purpose of the action, economically and technologically feasible, and avoid jeopardy and adverse modification of critical habitat. In addition, all biological opinions (concluding jeopardy or non-jeopardy) include "reasonable and prudent measures" appropriate to minimize the impacts (i.e., amount or extent of incidental take) (50 C.F.R. § 402.02). "Reasonable and prudent measures" can also include some project modifications to avoid and minimize impacts and, in some cases, offsets for impacts (mitigation). The Magnuson-Stevens Act also authorizes the National Marine Fisheries Service (NMFS) to identify mitigation for adverse effects on essential fish habitat.

Nourishment is frequently also a component of 'softshore' erosion control methods that are proposed as alternatives to hard armoring (Johannessen et al. 2014). Additionally, projects using NOAA's Nearshore Calculator currently receive credits for including nourishment (as one of eight current action types) in their project plans (Ehinger et al. 2023). NOAA's goal with the Nearshore Calculator is to provide comparisons of functions provided by nearshore projects, debiting projects that degrade habitat and crediting those which enhance habitat. Further, the idea of nourishing the beach has become a common cultural practice among Puget Sound's contractors, consultants, and landowners when doing construction in the nearshore, even if that beach nourishment is not required as compensatory mitigation or is not expected to improve beach conditions (M. Blair, personal communication). Thus, there is a need to understand whether the application of beach nourishment can functionally restore habitat and processes, control erosion, and compensate for the impacts of armoring and, if so, in what manner.

The overwhelming attention to beach nourishment in Puget Sound has been given to large projects where nourishment is used as habitat enhancement, erosion control, or aesthetics (Shipman 2001, Johannesen et al. 2014). These same projects also tend to be less impacted by nearshore development and so may not be comparable to nourishment along highly developed shorelines. This has left a large gap in our understanding of the science surrounding beach nourishment's role as a voluntary application or mitigation practice, particularly for armoring at the single-family residential scale. Here, we synthesize the state-of-knowledge on beach nourishment's application and efficacy in Puget Sound. To do so, we assessed information from three sources: (1) a review of published and gray literature from Puget Sound and on nourishment outside of Puget Sound, (2) an analysis of WDFW's permits, and (3) informal expert elicitation. Because we did not undertake a formalized expert elicitation process, we use expert insights only to contextualize the other analyses. Our goals were to synthesize quantitative data, if available, about the area (e.g., on-site, downdrift) of impact from beach nourishment projects, the duration of impact, intensity of impact, and the density of nourishment needed for impact.

Literature Review

We used the program *Publish or Perish* to query Google Scholar for any references containing "beach", "nourishment" and "Puget". This turned up 2,727 entries. Many of these entries were unrelated to the topic and so we only assessed the 140 entries with Google Scholar relevancy Ranks of 20 or better. Even so, the most pertinent references were related to restoration (see below) and most other entries contained little information about the efficacy of beach nourishment in Puget Sound or the practice's use in general. We supplemented this systematic literature search by obtaining relevant studies (primarily from the gray literature) that we encountered elsewhere, primarily in consultation with regional practitioners and researchers.

RCW 34.05.271 requires WDFW to categorize sources of information used to inform technical documents that directly support the implementation of a state rule or statute. Because our review may be referenced in regulations, such as for HPA permitting (e.g., WAC 220-660 and Shoreline Management

Act [e.g., WAC 173-26-221(5) (b)], we classify all references in the literature cited section into the following RCW 34.05.271 categories:

(i) Independent peer review: Review is overseen by an independent third party;
(ii) Internal peer review: Review by staff internal to the department of fish and wildlife;
(iii) External peer review: Review by persons that are external to and selected by the department of fish and wildlife;
(iv) Open review: Documented open public review process that is not limited to invited organizations or individuals;
(v) Legal and policy document: Documents related to the legal framework for the significant agency action including but not limited to: (A) Federal and state statutes; (B) Court and hearings board decisions; (C) Federal and state administrative rules and regulations; and D) Policy and regulatory documents adopted by local governments;
(vi) Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents reviewed under the processes described in (i), (ii), (iii), and (iv) of this subsection;
(vii) Records of the best professional judgment of department of fish and wildlife employees or other individuals; or
(viii) Other: Sources of information that do not fit into categories i - vii.

Below we organize findings from this review into two main sections focused on Puget Sound work or work elsewhere in the world. Within the Puget Sound section, we first summarize conclusions from two previous qualitative assessments of beach nourishment in Puget Sound, then summarize studies on restoration actions that use beach nourishment because most peer-reviewed research is related to restoration, and then present a series of case studies from the gray literature that assess beach nourishment used in association with structures (typically hard armor).

Puget Sound

We begin by summarizing two previously published qualitative assessments of beach nourishment in Puget Sound and then synthesize information from several case studies in Puget Sound that we encountered during our search. Shipman (2001) and Johannessen et al. (2014) qualitatively assessed beach nourishment projects in Puget Sound. Neither of these analyses included mitigation projects and typically did not discuss nourishment in association with hard armor. These works instead focused on larger projects, typically for restoration/habitat enhancement or erosion control.

Shipman's (2001) goal was to synthesize how nourishment was used in Puget Sound and to outline factors contributing to a project's success or failure. In his report, Shipman reviewed 30 projects that were largely implemented in the 1980's and 1990's, used relatively large volumes of sediment (ranging from several hundred to several hundred thousand cubic yards of sediment), and all of which shared the goal of improving erosion control, recreational access, and habitat conditions. In reviewing these case studies, Shipman (2001) writes "*if erosion or chronic substrate changes are the result of sediment deficits within a littoral cell or due to human–induced changes in the local wave climate, nourishment may address a symptom without solving the underlying problem. Beach nourishment only addresses shoreline problems related to beach sediment. Nourishment can enhance the functions of a natural sand or gravel beach and in so doing, can reduce erosion or can restore appropriate-sized substrate...nourishment requires space...Nourishment projects may be inappropriate where concerns about short-term impacts cannot be balanced by expectations of long-term environmental improvement.*" Ultimately, Shipman (2001) concludes that nourishment can, at best, provide partial mitigation for lost nearshore sediment supply and is unlikely to be effective at mitigating the ongoing impacts of armoring on nearshore habitat (e.g., waterward erosion), particularly when only applied once and in small volumes.

Over a decade later, Johannessen et al. (2014) were commissioned by WDFW to produce the Marine Shoreline Design Guidelines (MSDG) to inform shoreline protections in Puget Sound. These guidelines were published the same year that our permit dataset (see below) began and so our permit analysis reflects permits given after guidance outlined in the MSDG. As part of this work, Johannessen et al. qualitatively assessed the effectiveness of shoreline stabilization techniques within 25 different case studies. Six of these 25 case studies used nourishment as a form of large-scale softshore protection and beach enhancement. The remaining 19 case studies did not use nourishment. Further, all nourished sites occurred on accretion shoreforms or areas with no appreciable drift which parallels findings in our permit analysis for softshore projects. However, the focus on accretion shoreforms and areas of no appreciable drift likely skew conclusions about the effectiveness of nourishment in slowing erosion or when used in association with structures as these projects typically occur on feeder bluffs and transport zones (see HPA analysis below). All but one of these nourished sites (Tolmie State Park) were in the northern half of Puget Sound and so may not necessarily reflect the breadth of conditions Sound-wide. Johannessen et al. concluded that all sites exhibited moderate-to-high effectiveness at slowing erosion and provided high overall benefits with few overall negative consequences.

For softshore applications of nourishment, one consequence was the need for renourishing the sites at various intervals which imposed additional costs and repeated beach disturbance. These guidelines note potential disturbances from equipment and sediment placement, smothering of meso/meiofauna, coarsening of substrates, buried portions of intertidal beach, and degraded salmonid migratory habitat as impacts from nourishment, although there was inconsistent evidence presented for these impacts. Smothering of invertebrate fauna was also relayed to us in reference to a voluntary residential nourishment project where the nourishment sediment caused a shellfish dieoff (C. Waldbillig, personal communication). Notably, the MSDG emphasized the Lummi Shore Drive project (detailed further below) in which nourishment was halted after the first five years because it was not economically sustainable given the need for constant renourishment and surf smelt habitat continuously declined over time despite the nourishment.

The MSDG was initially intended to be guidance for the single-family residential scale implementation (J. Johannessen, personal communication). Yet most of the case studies were larger in scale and applied in substantially higher volumes and densities than used for residential armoring projects. Additionally, in practice, the MSDG is applied to all relevant projects, regardless of size. Some projects occurred on residential beaches, but the nourishment was intended to provide shoreline stabilization rather than mitigate for hard armor or other impacts to habitat. Johannesen et al. further use the term “nourishment density” (in CY per lineal foot) to describe not only the volume of sediment placed but the length of beach over which that volume was placed. Given the lengths of beaches assessed, scale of nourishment applied, and other management actions taken during nourishment, the nourishment case studies in the MSDG contrast substantially from nourishment placed in association with residential structures like armor (see HPA permit analysis). For instance, these case studies often involved applying many hundreds or over 1,000 CY of nourishment at densities between 1-2 CY/foot, some involved additional actions such as adding large logs and plantings, and, if nourishment occurred in a residential context, it was typically placed in front multiple homes rather than a single-family residence. Based on our permit analysis, beach nourishment actions associated with a structure typically involve less than 10 CY of sediment (or sometimes 10’s of CYs), are applied at a density below 1.0 CY/ft, occur in isolation, and generally occur in front of a single property.

Across the MSDG case studies, some sediment typically moved downdrift, but forage fish habitat was often maintained on site and there were no impacts to eelgrass. Further, no or minimal offshore transport was noted, although surveys do not typically extend enough offshore to detect these effects. Ultimately, Johannesen et al. (2014) concluded that nourishment was a high-utility tool for erosion control and maintaining nearshore habitats when used in a softshore approach, at least for the particular shoreforms and minimal wind-wave conditions assessed. However, it was concluded that beach nourishment was not a recommended tool for mitigating the impacts of hard armoring, particularly in the small volumes and densities typically applied, although we note that none of the case studies assessed for the MSDG were actually compensatory mitigation projects or other similar small-volume, structure-associated nourishment applications.

Restoration Studies

Research in recent years has illustrated the value of beach nourishment when used as a restoration tool in conjunction with armor removal and other techniques like plantings and adding logs. In 2009, the Skagit River Systems Cooperative (SRSC) commissioned a restoration project at March's Point in Fidalgo Bay. This project aimed to improve conditions for forage fish (surf smelt) spawning by improving beach conditions and adding beach nourishment (Johannesen 2009). This represented an early attempt in Puget Sound to use beach nourishment as a restoration tool specifically to enhance forage fish spawning habitat. This restoration was motivated by surveys that found that riprap armoring that had been in place for decades had degraded beach conditions and left only small patches of surf smelt spawning habitat as of 1995 (Penttila 2012, 2013). These conditions were further exacerbated by the Texaco Refinery spill which contaminated the beach, and thus required the removal of forage fish spawning sediments. Surveys from August 2009 to June 2010 found that surf smelt spawning in late spring and summer was robust but that the fall-winter spawning had largely disappeared, largely due to coarsening of the beach compared to surveys in prior decades. The rock shore protection for the road next to the beach had to be maintained but roughly 229 CY of derelict, large angular rock was removed from the intertidal beach outside of the revetment's footprint. Ultimately, the project was designed to maintain as much sediment as possible on the beach to favor forage fish spawning on-site.

The restoration occurred in the fall of 2010 and included creating a wider upper beach where most of the sediment was placed to allow the sediment to slowly move downdrift and maintain habitat conditions for longer. 7,642 CY of nourishment was placed in two patches with a gap in between the patches to enhance approximately 2,000 lineal feet (3.8 CY/ft) of surf smelt habitat. Surf smelt spawning density and embryo survival (nearly 0% survival) were largely identical in the year before nourishment and the two years post-nourishment (Penttila 2012, 2013). Embryo mortality was relatively high in summer and declined towards the fall, likely due to the lack of shade on the beach, and the softening of the beach substrate did not cool or moisten the substrate sufficiently to increase survival. Despite minimal changes in spawning, the nourishment action vastly improved the amount of *potential* suitable surf smelt habitat, including an additional ~ 1,000 ft beyond where the sediment was placed due to longshore drift (Pentilla 2012). Interestingly, Pentilla (2012) noted that culvert effluent caused the most substantial cross-shore movement of sediment, interfering with longshore drift. Overall, nourishment improved potential forage fish habitat at March's Point but did not noticeably improve forage fish spawning density or survival. However, two years of surveys post-nourishment may have been insufficient for forage fish spawning to change.

Beyond these two unpublic case studies, several systematic studies have since occurred to compare restoration across multiple sites in Puget Sound. Unfortunately, the volume and density of nourishment were not reported in most of these studies, however, we can infer given the results of our permit analysis that restoration projects were substantially larger in scale than residential structure-associated projects. Lee et al. (2018) used opportunistic sampling at six sites across Puget Sound that were formerly armored, but which had armor removed. These sites also received additional restoration actions including nourishment. Macroinvertebrate abundance and richness increased after restoration, particularly at higher shoreline elevations. These responses occurred within a year of armor removal and restoration. Unsurprisingly, biotic changes increased in their effect size with the number of years post-restoration such that the effect size functionally doubled in year 10 relative to years 1-5 post-restoration. Wrack cover and the number of logs accumulated also increased post-restoration.

Another study evaluated 10 clusters of three sites distributed in a south-north gradient from south Puget Sound to the San Juan Islands (Toft et al. 2021). The three site types in each cluster included one "living" restored shoreline site, one armored control site, and one unarmored natural reference site. The living shoreline beaches had armor removed and beach restoration actions that included nourishment, log placement, and plantings in various combinations depending on a given site's needs. The majority of habitat or biotic variables of interest differed between beach treatments. Restored sites often mirrored natural control sites or were intermediate to naturally unarmored and armored control sites (armored sites consistently deviated from natural unarmored sites). For instance, wrack (terrestrial, eelgrass, and algae) accumulation and wrack invertebrate diversity were similar between restored and natural shorelines but were depauperate at armored sites. However, accumulated logs were nearly absent at armored sites and intermediate in abundance at restored sites compared to armored and natural controls, indicating more time was needed to restore log accumulation. Further, insect taxa richness increased as time-since-restoration increased, reaching a plateau after ~4 years.

Des Roches et al. (2022) expanded this work to 18 groups of sites across Puget Sound that included armored beaches, restored beaches (often with nourishment), and natural control beaches. This study used a before-after control-impact (BACI) analysis to test whether restoration improved beach habitat and biota. Wrack, the number of logs, and the length of the log line increased at the restored sites. Invertebrate density and family-level richness did not differ post-restoration, but order-level invertebrate richness did increase. This study also measured the *variability* in habitat and biotic variables and found that natural shorelines had higher variation than armored shorelines and that restored shorelines had wrack and invertebrate variances similar to natural shorelines. This work shows that armoring not only reduces the average value of habitat conditions and biological communities but also tempers the natural variability in conditions that characterize dynamic beach systems. Thus, removing armor and restoring beaches with nourishment and other treatments increases the habitat conditions and species diversity of these systems while also restoring their natural dynamism, although it is not possible to untangle the relative effects of armor removal and nourishment in this work.

Lummi Shore Drive

Perhaps the longest dataset on the effect of structure-associated beach nourishment in Puget Sound comes from 10 years of physical monitoring (including multiple pre- and post-implementation years) along the Lummi Shore Drive seawall (Johannesen 2008). This project was termed "mitigation" in that its goal was to mediate habitat and broader beach conditions on site that were lost to the new, large riprap revetment (hard armoring) (Shipman 2001). However, the nourishment did not constitute the mandatory, compensatory mitigation required for new armoring as it was a voluntary effort, although the intent was still to compensate for the impacts of hard armor. The ultimate goal of the nourishment was to repair and upgrade beach conditions along Lummi Shore Road and Lummi View Drive after the Army Corps of Engineers added a rock revetment to most of the 12,000 ft (the entirety) of Bellingham Bay and Portage Bay bluff toe along Lummi Shore Rd. Pre-implementation monitoring for this project began in 1996 and, in February of 1999, 4,000 CY of pit run gravelly sand was added with another 1,540 CY in February 2000, 500 CY of 1-8mm rich scalpings in 2001, and 2,000 CY of beach and bank sediment in 2003 that had been excavated during the revetment's construction. Not all of this material may have been suitable for placement as beach nourishment at this site. The final monitoring occurred from February 2008 through January 2009.

Multiple years of monitoring demonstrated that the elevation at the toe of the revetment continued declining after the revetment was constructed, despite the multiple years of nourishment. Further, the turnarounds which were installed to allow trucks to deposit nourishment interfered with sediment drift and caused some accretion. Although nourishment yielded immediate increases in beach sediment volumes, the entire shoreline showed a substantial decline in hundreds or thousands of cubic yards of sediment over the several years post-revetment construction. That decline in sediment volume on the beach was most pronounced in the first few years post-construction and nourishment addition did little to halt those declines.

The quality of the beach substrate for forage fish spawning was variable over time and space. The total potential surf smelt spawning area declined steadily over the duration of monitoring post-nourishment and shifted slightly northward in the direction of the net drift. This change in the spawning area indicated that continual, regular nourishment would be needed throughout the entire area to maintain forage fish spawning habitat. The goal of the project was to place most sediment in the southern portion of the beach and let it drift northward; this drift occurred but there was ultimately a net loss of sediment to the system, likely because the hard armoring evacuated sediment too quickly. The Lummi Nation was aiming to maintain at least 30,000 ft^2 of surf smelt spawning habitat (as defined by sediment texture) which was less than existed prior to the revetment installation. Spawning habitat continued to decline and, although this 30,000 ft^2 criterion was barely maintained throughout the duration of the monitoring, the continuous decline in habitat area showed that, given a constant rate of change, this criterion would not have been met four years after monitoring ended regardless of continued nourishment. Unfortunately, available data beyond 2002 do not exist. Surf smelt egg density data collected for pre-revetment and pre-nourishment (1996-1998) and afterwards (1999-2002) shows heterogeneity among sample sites and between years, however egg densities are largely similar before and after the project (personal communication from Devin Flawd on behalf of the Lummi Nation). Although nourishment appeared to maintain surf smelt spawning for several years post-nourishment, the continued decline in spawning habitat suggests a loss of spawning over time would also occur commensurately. Ultimately, the hard armoring continues to alter beach conditions at the Lummi Shore Drive site in a way that the volume, frequency, and elevation of nourishment was not able to mediate.

Snohomish County Beach Nourishment Project

The most comprehensive, rigorous study to date on the physical and biological effects of beach nourishment comes from the Snohomish County Beach Nourishment Project (SCBNP) or the Railroad Grade Study (Dethier et al. 2020). This project included beach nourishment in discrete locations over a 42-km (26-mile) reach in front of the Burlington Northern Santa Fe railroad's armored shoreline. The goal of this work was to experimentally assess nourishment's habitat effects, particularly when associated with large stretches of armored beach.

The SCBNP added 16,879 CY of nourishment at an average depth of 2 ft by placing fine-grained dredged sediments (coarse sand) from the Snohomish River at discrete sites along the armored shoreline. The use of dredged sediment for nourishment is unique for Puget Sound where a "fish mix" of coarser gravel is typically used as nourishment. The study sites differed in fetch, initial substrate sizes, slope, the extent of railroad encroachment on the beach, and amounts of driftwood and vegetation on the back beach.

Howarth Park used 9,888 CY of coarse sand from the Snohomish River and imported larger beach gravel. This site also included armor removal, large wood placement on the backshore, and native plantings. In summer 2016, immediately after armor was removed but before nourishment, the SCBNP began monitoring four armored railroad sites, four nearby reference sites with natural shoreforms and beach vegetation waterward of the railroad, and four additional pairs of armored-unarmored sites in the region that were not nourished to document interannual variation. Four years of SCBNP monitoring included beach morphology, sediment sizes, wrack accumulation, logs, invertebrates, and forage fish spawning. For most data collection, the study used 50-m long transects parallel to the shore with data collected at various points along the transects depending on the measurement. The study also used perpendicular beach profiles from the backshore to mean low water (MLW) or mean lower low water (MLLW) using laser levels with stadia rods or RTK-GPS which provided data on the upland toe elevation (meters above MLLW; where the bank or armor face abuts the beach face) as well as beach width, slope, and waterward encroachment of the toe on mean higher high water (MHHW).

This study found that the nourishment sediment did not persist for long durations on-site at armored beaches, but instead moved offsite and downdrift quickly. At all sites but Howarth Park, placed material was expected to move downdrift and nourish sites far field from the placement location. In addition, material placed on all sites was expected to have a retention time of five-to-seven years upon which additional nourishment would be required to maintain habitat function (Anchor QEA, 2013 and 2014). At one site, all the added 2,284 CY of sediment was fully transported offsite of the placement site in 29 months, an average rate of 95 CY/month. Although it was assumed that sediment moved downdrift, monitoring was insufficient to detect how much sediment may have moved offshore. At a second site, nourishment material initially moved updrift for multiple months and then flowed downdrift but material was retained at the creek delta. By December 2018, all material had evacuated the nourishment area of a third site at a rate of 102 CY/month. Another site placed nourishment between two creek deltas on a low-slope beach in a subtle embayment. Within two months, sand started arriving downdrift but nourishment material remained on-site at the end of the study (44 months), resulting in a lower drift rate of 66 CY/month. At the final site, the nourished material persisted in thin layers for approximately three years but after 42 months, all material had evacuated at a rate of 103 CY/month and remained downdrift on a creek delta. These findings illustrate the rapidity at which nourishment material can move offsite along armored beaches and also how additional beach elements like small creek deltas can act as groins to retain sediment along shorelines. Sand drift rate was an interactive function of shoreform, beach width, slope, and elevation of drift placement which were determined by armor presence such that sand washed away faster at armored sites.

This study also included an unnourished "reference" region to the south to compare natural temporal variation at armored and unarmored sites. This comparison within unnourished areas exhibited marked impacts of armoring and these effects persisted over time. This included a more pronounced lower toe at armored sites than at unarmored sites. Armored beaches also had consistently narrower beaches and steeper slopes, unlike the nourished region where impacts were more variable among site pairs.

Substantial amounts of placed sediments moved to mean low water (MLW), moving down the shore. However, these did not persist. Wrack and invertebrate density responses were variable, and the effects of nourishment were not clear. Before nourishment, MLW invertebrate communities were similar between armored and unarmored sites, but nourishment caused heterogeneous changes, particularly by reducing ulvoid algae, barnacles, shore crabs, and periwinkles (which live on or under cobbles) and increasing Varnish clams, softshell clams, and ghost shrimp which rely on sediment. The before-after comparison however was not significant but there were many site-specific changes. In general, species richness declined post-nourishment at MLW but sometimes rebounded.

On-site sand lance spawning substrate almost immediately disappeared, and no nourished site saw increases in sand lance spawning substrate quality. However, the downdrift areas – which already had quality spawning substrate – experienced enhanced sand lance spawning substrate quality from the downdrift movement of nourished material. Over the next several years, some of these downdrift sites maintained higher forage fish spawning suitability whereas others declined to pre-nourishment conditions. Although the sandier nourishment substrate enhanced suitability for sand lance, these effects were relatively subtle given the large volume of material added to each nourished site. The increase in suitability downdrift presumably led to an observed increase in sand lance egg counts at those sites, although there was a decrease in sand lance spawning at the nourished sites. This result is interesting because the relationship between sand lance spawning was not always commensurate with improvements or lack of improvements in perceived suitable spawning habitats. In sum, the analysis found that nourishment enhanced sand lance spawning, but not on-site. Rather, spawning only increased down-drift, which was one expectation of the design, although increases in spawning were not always associated with increases in perceived substrate suitability.

For surf smelt, the fine sediment substrate did not improve habitat as the species prefers coarser substrate for spawning (Pentilla 2007). Variability in spawn count among years for surf smelt was also relatively high and so no effects of nourishment were obvious. Interestingly, annual differences in egg counts could not be readily associated with substrate suitability. Surf smelt spawning substrate suitability declined post-nourishment at some sites, but spawning remained similar. This suggests that spawning was related to other factors and/or that smelt had high site fidelity that was not particularly impacted by substrate suitability. In tandem with the sand lance results, these findings call into question the degree to which we understand the relationship between substrate conditions and forage fish spawning in Puget Sound.

Ultimately, this study found that nourishment’s structural and functional effects are not likely to persist for more than several years (or potentially months), particularly if nourishment is not continued at set intervals outlined during the design process, occurs at smaller scales than was implemented here, and/or is associated with armor. However, a caveat of this work is that the study used finer material than is typically applied to Puget Sound beaches and thus may be more prone to movement. An important conclusion from this study was that the effects of nourishment (increase in toe elevation and width, slight decreases in slope) – if detected – were largely seen on armored beaches due to their highly degraded conditions. However, habitat responses were highly site-specific and so the impacts of nourishment may be detectable sometimes but may be strongly dependent on each site’s conditions. This site-level variation complicated making robust conclusions about the effects of armor, nourishment, and temporal changes in beach profile. This high degree of site-level variability overwhelmed the detection of any consistent nourishment impact to habitat conditions at either armored or unarmored sites and the only lasting toe elevation effect was at Howarth Park where nourishment occurred in conjunction with armor removal. Indeed, most of the benefits of nourishment (e.g., improvements to wrack conditions, log accumulation) appear to last when nourishment occurs in conjunction with armor removal. Further, the impacts of nourishment are unlikely to be felt on-site but rather downdrift, particularly in areas impacted by deltas from creeks which facilitate accretion. Finally, this study did document some nourished sediment moving cross-shore (perpendicular to the shore) which reduced the biotic community’s diversity.

Mt. Baker Terminal

As mitigation for the Mount Baker Terminal (constructed in 2005 and 2006), the Port of Everett nourished 1,100 ft of shoreline and included two years of pre-construction baseline monitoring for forage fish spawning from 2003-2004 and three years of post-construction monitoring from 2006-2008 (Pentec Environmental 2009). Impacts of the new Terminal were expected to include those from pier construction and operations, shading to eelgrass, softbottom habitat loss in piling footprints including documented sand lance spawning habitat, and potential delays to salmon migration. The habitat enhancement work (also called “restoration” here) occurred over 2.3 acres of intertidal habitat and included 7,850 tons of beach core gravel, 7,300 tons of beach face material (mixture of sand, granules, and pebbles), 2,950 tons of backshore sand, 6 inches of topsoil added and mixed with the sand, and backshore plantings. Unfortunately, we are unable to convert tonnage to cubic yards of nourishment applied. The project also included preemptive compensation for eelgrass lost due to shading by transplanting eelgrass shoots to expand eelgrass area coverage.

The before-and-after monitoring included field surveys of substrate (sorting, recruitment, and migration) in addition to changes in slope and substrate at 10 transects on the restored beach and adjacent beaches. Pentec Environmental also compared epibenthic biota at one reference transect and three project-impact transects for three years post-construction. Further, there was seine sampling for nearshore fishes at the restored and reference beaches. In winter 2007-2008 (two- and three-years post-construction), four 33m survey transects were added in suitable forage fish spawning substate and sampled following WDFW protocols.

Sediment volume increased from 2007 to 2008 in the downdrift end of the nourished area but decreased elsewhere. From construction to the end of monitoring, the beach face angle persisted with little obvious downslope sediment transport despite some coarsening of the nourished material. Most erosion at the west end of the constructed area already occurred by 2007. Further, the reference area’s cross-sectional area functionally did not change. These observations illustrated the dynamic nature of the beach because the nourishment sediment gradually moved downdrift from the nourished area to the reference beach. Specifically, the eastern end of the nourishment area fed the reference beach further to the east. Ultimately, this dynamic change in sediment led to considering further nourishment and modifying the project area to stabilize sediment. Additionally, this project identified interactions between the longshore transport of sediment from the west to east ends and the Japanese Gulch Stream outfall’s culvert. This outfall caused an accretion delta over the lower sandy beach and halted the movement of material that would have otherwise drifted further east. The nourished area had a rock wall and rail line at the back beach, but it was unclear how much wave action interacts with this armoring and influences sediment dynamics.

Three years post-construction, the nourished beach and nearby reference beach had similar densities of copepods and other epibenthic biota. The densities of species assumed to be juvenile salmonid prey (e.g., harpacticoid copepods, amphipods) were higher at the reference site but the effect size was relatively small. There was a negative impact to epibenthic biota from the project, but that impact declined over time. Prior to construction, there was moderate sand lance spawning but this spawning activity was largely absent post-construction. In large part this was likely due to the declining suitability of sediment grain size which coarsened from 2006 to 2008. This coarsened substrate may be suitable for surf smelt but this species is not known to spawn in this region. Impacts to eelgrass were less clear given that there was some evidence that eelgrass may have been declining prior to the construction, and nearly 6,000 square feet of eelgrass were lost post-construction. The translocated eelgrass beds had mixed success and one bed that was translocated lost nearly all eelgrass by the end of monitoring, likely due to sediment accretion from Japanese Gulch Creek which mobilized the drifting nourishment material, pushing it into the eelgrass zone.

Ediz Hook

Another project involved ~14,388 – 18,311 CY of nourishment material over 500 m of beach inside of Ediz Hook near Port Angeles in late summer 2015 by the Lower Elwha Klallam Tribe. The goal of this work was for restoration and erosion control for the adjacent road which abutted the beach. Before the increased erosion control project, there was long-term but slow erosion occurring and some undercutting of the road. The sediment was placed as a mass and left to passively erode, sort, and spread. The beach elevation at mean lower low water (MLLW) increased with nourishment as expected and persisted through at least the two winters when monitoring ended (Miller et al. 2017). Finer material was sorted by waves and moved down the beach face where it persisted. West (down drift) of the nourishment site also saw changes in beach sediment composition including a reduction in sediment grain size in the lower, middle, and upper intertidal. Although sediment composition shifted downdrift, there was only a minor shift in beach profile. No biotic data were available for this case study, and it remains unclear how habitat conditions shifted over longer time scales.

Custom Plywood Remediation

This project was a Washington Department of Ecology Toxics Cleanup Program project site on Fidalgo Bay in Anacortes over a 23-acre area (HartCrowser 2016). The work represented multiple phases of toxics cleanup remediation with in-water cleanup completed in 2013. The project included removing contaminated sediment and in-water and overwater structures, dredging contaminated sediments over 7.1 acres and backfilling with clean sediment, removing 1,465 creosote-treated piles, derelict structures (e.g., bulkhead) and debris over 13,500 square feet, nourishment and grading, eelgrass plantings, and riparian vegetation plantings. Monitoring began upon completion of the clean-up and lasted for two additional years. This monitoring included nine beach profiles from the edge of eelgrass beds to 15 feet (~5 m) above MLLW to assess physical conditions including substrate sorting and migration, large wood accumulation, and riparian vegetation development. The monitoring also included four transects (three at the impacted site and one at a nearby reference beach) for epibenthic substrate-associated zooplankton at ~1.3 and 2 m above MLLW. Nearshore fishes were sampled at three seine locations at the impacted site and one location at the reference site south of the project location. On year two of monitoring, the project assessed forage fish spawning using the WDFW protocol in addition to sediment-associated epibenthic invertebrates. The beach profile changed minimally since the project's interventions, although the nourishment sorted into distinct bands of gravel and sand. The reference beach was similar but also had larger cobbles. Invertebrate abundance and species richness did not differ between the restored beach and the reference beach. Surf smelt eggs were found at both the reference and restored beach but were not quantitatively analyzed. The data from this study are not robust enough to conclude whether nourishment maintained or enhanced habitat conditions.

Hood Canal DOT

In the winter of 2013-2014, the Washington State Department of Transportation (WSDOT) initiated a pilot study aimed at using coastal bluff landslide material on State Route 106 as beach nourishment. Typically, WSDOT removes landslide material from the road surface and disposes of it far offsite. However, prior to road construction, slide material would have naturally deposited on the beach. In April 2014, a cliff deposited a series of sloughs to the roadside ditch and WSDOT placed that material at 20 sites on the beach. The permit allowed no more than 10 CY of sediment volume to be placed at any site. Because the material was wet, much of it flowed from the dump area at the edge of the road prism to the upper intertidal. Within several weeks, much of the fine material had completely eroded and the coarser gravel and cobbles spread out in a fan. Roughly 25% of the placement sites were high enough on the beach that they did not interact with the water and remained largely intact and did not contribute to the beach. However, these higher-beach piles were colonized by plants and so may contribute somewhat to bank stabilization. The majority of the placement sites had continued erosion at the toes and likely continued eroding with rain and wave action.

Evidence From Other Regions

Although beach nourishment has been employed as a restoration and mitigation tool for some time within Puget Sound, we uncovered relatively little systematic research on the biological effects of these actions on nearshore habitat and associated species for the region, particularly when used for mitigation associated with hard armor, although the above case studies include multiple examples of large nourishment projects associated with hard armor. Where possible, we leveraged information from other regions and locations to enhance our understanding of the potential benefits and impacts of beach nourishment actions on Puget Sound biota. We note that our review of non-Puget Sound research focused solely on biological responses to beach nourishment and does not represent a thorough assessment of associated physical processes and changes. Several aspects of this broader literature review are noteworthy. Foremost, empirical evidence for direct *benefits* to biota provided by beach nourishment are rare. The overwhelming majority of studies indicate negative impacts or, at best, no change to biotic conditions after nourishment actions (see reviews by Speybroeck et al. 2006, Wilber et al. 2009, de Schipper et al. 2021, Kindeberg et al. 2022). Invertebrates were widely studied while little to no information exists on impacts to submerged aquatic vegetation (Kindeberg et al. 2022). However, these impacts are largely species-specific, magnitude-related, and depend on species recruitment dynamics and life history. We explore direct and indirect impacts to nearshore biota and the potential mediating factors in brief below.

Direct impacts to species are those where the cause (beach nourishment) can be explicitly tied to the biological effect in nearshore habitats. The most commonly identified impacts occurred during sediment placement and construction phases of particular projects (Peterson et al. 2000, Manning et al. 2014, Wooldridge et al. 2016, Schooler et al. 2019). Burial of organisms during sediment placement reduced abundances of key invertebrate species by 35-65% (Peterson et al. 2000) and was linked to changes in species diversity and community assemblage (Wooldridge et al. 2016, Schooler et al. 2019). While these changes were not typically permanent, recovery times varied from months to years (Wooldridge et al. 2016, van Egmond et al. 2018). Direct impacts on benthic invertebrates appeared mediated by timing the placement of sediment prior to recruitment in the spring (Manning et al. 2014) and by minimizing the use of mechanical placement from the beach (e.g., bulldozing, trucking, etc.). Reduced invertebrate abundance was observed in both small- and large-scale projects (van Egmond et al. 2018). Direct impacts to fish communities were studied infrequently compared to benthic invertebrates (Peterson and Bishop 2005) though shifts in species dominance and reduced foraging success in some species of surf fish were observed and hypothesized to be driven by increased turbidity after nourishment actions (Wilbur et al. 2003, Manning et al. 2013).

Indirect impacts to nearshore biota were generally observed via changes to beach habitat characteristics. Changes to sediment composition after nourishment actions had broad, and potentially lasting, impacts on nearshore biota. Altered sediment composition impeded or increased burrowing time for benthic species thereby increasing stress levels or subjecting organisms to displacement by erosion and transport off the beach (Peterson et al. 2000, Peterson et al. 2014, Viola et al. 2014). These effects were linked to reduced abundance and diversity of invertebrate species and the duration of impacts lasted for multiple years after nourishment (Peterson et al. 2014). Several studies also identified correlated reductions in abundance at higher trophic levels (e.g., fish, birds, etc.) presumably as a function of reduced prey resources and foraging success related to sediment composition (Manning et al. 2013, Peterson et al. 2014, Wooldridge et al. 2016). Turbidity was also observed to increase with increasing fine material in the sediment resulting in constant resuspension of material impacting fish as outlined above (Manning et al. 2013). Changes to beach slope and profile after nourishment also influenced spawning behavior in some fish species. For instance, large deposits of sand during nourishment created steep scarps that disconnected the upper beach spawning habitat for grunion in southern California (Martin and Adams 2020). Similar profile changes reduced nesting success for green and loggerhead sea turtles (Brock et al. 2009). However, some profile changes were observed to benefit species, particularly backshore vegetation where beaches were widened offering protection from erosion and more sediment for dune formation (Nordstrom et al. 2009). As with direct impacts, many of these indirect impacts via changes to habitat characteristics were mediated by timing, design, and location. Avoiding placement during spawning seasons and minimizing the disturbance period (during sediment placement or through re-nourishment) may reduce observed impacts. Site-specific characteristics may dictate the amount of change that occurs on-site but may also directly influence changes off-site (due to sediment movement) which should be considered for any project (Davis et al. 2000).

When and how can we use evidence from other regions?

Information from regions outside Puget Sound further develops and supplements our understanding of ecological responses to beach nourishment. However, there are limitations to comparing the results of these studies to the habitat, species, and environment of Puget Sound. Furthermore, there is consensus in the broader literature that considerable uncertainty remains regarding the biological impacts from beach nourishment practices (Peterson and Bishop 2005); this may represent the greatest limitation of extrapolating between studies and regions and reinforces the need for further research.

There are several differences between the species and habitats that are synthesized in the published literature and those of Puget Sound. Most studies on beach nourishment have focused on coastal sand beach environments and involve volumes from 64,090 to 27.5 million cubic yards of material; far greater than what is typically used within Puget Sound. Rocky coastlines and gravel/cobble-dominated beaches as found within Puget Sound are not represented within the greater literature on beach nourishment which focus on sandier beaches. In addition, many of the projects in the broader literature are intended to bolster barrier beaches (southern Atlantic and Gulf coasts) or improve/support recreational opportunities (Europe, Asia, and southern California). While these differences are considerable, the themes and lessons of the research regarding impacts to nearshore biota are likely comparable and informative for Puget Sound. Sediment composition plays a large role in determining impacts to many species and while the exact composition may vary between Puget Sound and elsewhere, matching natural sediment composition is typically preferable for reducing potential impacts or promoting potential benefits. We may assume that processes driving sediment movement, erosion, and transport operate under similar principals despite the differences in location and habitat such that the dynamics of a beach nourishment project in Puget Sound would behave accordingly given certain factors or characteristics (i.e., wave activity, shoreline condition, shore type, etc.)

Species differences between Puget Sound conditions and those in the broader literature are also pronounced. Yet, we can largely extrapolate inferences based on similarities among species that share comparable behaviors or functional relationships with nearshore environments including recruitment dynamics (i.e., seasonality), habitat preferences (i.e., benthic), or foraging types. Benthic invertebrates were commonly impacted by nourishment and, though species identities may differ, benthic invertebrates in Puget Sound may also be vulnerable. Although some of the data reviewed above suggest that nourishment may enhance invertebrate abundance and diversity within a year of placement, particularly in large-scale restoration projects. Fish responses to nourishment are sparse but implications for the foraging and spawning success of surf fishes in the broader literature are likely applicable to Puget Sound despite species differences. Several species of salmon and forage fish commonly use nearshore habitats for rearing/foraging (Duffy et al. 2010, Davis et al. 2020) and spawning (Pentilla 2007). These species may therefore be exposed to positive or negative impacts from beach nourishment. The roles of mediating factors such as timing and location, as outlined in the broader beach nourishment literature, are also applicable to actions within Puget Sound. Avoiding nourishment prior to or during recruitment and spawning – as is common practice in the Puget Sound case studies and permits we reviewed – likely mediates impacts to susceptible species.

Lastly, general uncertainty in the literature regarding the ecological impacts from beach nourishment remains considerable and persistent. Uncertainty surrounding study design and unquantified background variation has been a common criticism. Peterson and Bishop (2005) present a useful review of studies assessing the impacts on biota from beach nourishment actions. Many of the studies that have attempted to address such questions suffer from poor design and lack rigorous content review. Research on beach nourishment would likely benefit from a standardized methodological framework for assessing impacts to organisms. Such a framework would rely heavily on understanding conditions before and after the action occurs and comparing results with the intended outcomes of the project (e.g., compensatory mitigation, restoration). Long-term or cumulative effects of single actions or multiple/repeat nourishment actions also remain largely unknown and deserve greater attention in future studies (Peterson and Bishop 2005, Speybroeck et al. 2006).

HPA Permit Analysis

To characterize current nourishment practices, we assessed all WDFW Hydraulic Project Approval (HPA) permits in the Aquatic Protection Permitting System (APPS) database that include nourishment as part of the project or as a condition of the project (i.e., for mitigation). We assessed HPA permits rather than permits from other relevant entities (e.g., Army Corps of Engineers, counties, cities) because these other permits are not readily quarriable. Importantly, WDFW reviews and conditions proposed projects, and, although they may provide technical assistance and guidance, they do not design projects or mitigation plans for applicants. Rather, WDFW ensures that the mitigation sequence has been considered, including compensatory mitigation as needed, to achieve no net loss of fish life. Further, a project applicant typically receives permits for shoreline projects from multiple agencies; as such, actions permitted in the HPA may also include work that is required by federal or local jurisdictions but is not required by WDFW. Such stipulations may be contained in the permit language, but the wording for a given permit may not clarify the reason beach nourishment is included in the project (e.g., voluntary desire vs required mitigation).

We requested a query from the APPS' company – enfoTech – for all permits containing "nourishment" as an authorized activity or condition of their permitted project. This original query produced 713 permit IDs. After removing duplicate permit IDs, non-marine projects, permits on the outer coast, permits for which the application of nourishment could not be discerned from the permit language, and projects which did not actually implement nourishment, our final dataset included 421 HPA permits from 2014 (when the APPS database was established) to 27 June 2022 which included beach nourishment. We manually reviewed each permit to obtain project category, sediment volume applied, and other details. If information was absent from the permit itself, we attempted to find that information in associated permit documentation (e.g., email correspondence, project design plans). For our purposes, we categorized projects as using nourishment for habitat restoration, softshore erosion control, a one-time application associated with a structure, renourishment associated with a structure, hybrid combinations of hard and soft approaches, or “Other”. The category “Other” included various, typically larger, applications of nourishment such as dredging marinas and placing the sediment on the beach.

Of the 421 permits which included nourishment, 280 (66.5%) were for one-time structure-associated nourishment actions, eight (1.9%) were for structure-association renourishment at some regular frequency for the life of hard armor, 37 (8.8%) were for softshore erosion control, 22 (5.2%) were for hybrid purposes that included a mixture of hard and soft methods, 27 (6.4%) were for restoration purposes, and 47 (11.2%) were for “Other” purposes. For trends analyses below, we removed the 28 permits from 2022 because these do not reflect an entire year’s permitting cycle. Permits in each category were distributed throughout Puget Sound, albeit unevenly for some categories (**Figure 1**). For instance, permits with structure-associated nourishment tended to be concentrated in south Puget Sound whereas permits with restoration nourishment were sparse in this region but more prevalent northward.

Permit frequencies were relatively static over time for each project category, although permits with structure-associated nourishment suggest a general decline Sound-wide (**Figure 2**). Further, for frequencies of permits with structure-associated nourishment as mitigation, we found significant county-level variation in changes in permitting frequencies from 2014-2021[1]. Most counties had relatively stable trends over time with notable exceptions such as increases in Island County and decreases in Pierce County (**Figure 3**)[2]. Interestingly, of the 288 permits with structure-associated nourishment (one-time and re-nourishment), only 29 (10.1%) were for new armor. The majority were for armor repairs (n = 66, 22.9%; fixing damaged or dilapidated armor) and replacement armor (n = 151, 52.4%; replacing portions of the entirety of armoring). The remainder of permits were for placing nourishment as part of projects associated with other structures (docks, culverts, outfalls, ramps, stairs) that were built, maintained, repaired, or replaced.

We found that nourishment sediment volume was inconsistently recorded. Volume may not have been discernable from a permit because relatively small volumes were used to “dress” construction impacts or because of errors. Because of the heterogeneity in how volume was reported in permits, we only recorded volume if the exact volume was provided (in cubic yards; CY) or if the length, width, and depth of volume of sediment applied were explicitly detailed. Because of this inconsistency, we could only obtain volume data for approximately half of all permits across project types (**Figure 4**).

Nourishment volumes generally varied by project category. Our analysis of permits with quantifiable nourishment volumes found that one-time structure-associated placement had the lowest applied volumes, and project category “Other” had the highest. All remaining nourishment project categories were variable and statistically indistinguishable from both one-time structure-associated nourishment (**Figure 5A**). If “Other” permit types are excluded from the same analysis, both types of permits with structure-associated nourishment (one-time and renourishment), permits for softshore stabilization, and hybrid permits were all statistically indistinguishable and all used significantly smaller volumes than permits for restoration (**Figure 5B**)[3]. Puget Sound-wide, the cumulative volume of applied nourishment attributable to each project category varied from year-to-year (**Figure 5C, D**).

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[1] We used a generalized linear model (GLM, Poisson family distribution) to analyze trend data. A likelihood ratio test found support for a significant County*Year interaction ($p < 0.0001$) which indicates that 2014-2021 trends vary in their direction (increasing, decreasing, static) by county.

[2] Because of the county interaction, we performed intendent GLMs for each county. Most counties had relatively stable trends over time ($p \geq 0.05$) with notable exceptions such as increases in Island County ($p = 0.001$) and decreases in Pierce County ($p < 0.0001$).

[3] If “Other” permits are excluded from the same analysis, both types of structure-associated permits (one-time nourishment and renourishment), shoftshore permits, and hybrid permits are statistically indistinguishable ($p > 0.05$) but all use statistically smaller volumes than restoration permits ($p < 0.0001$).

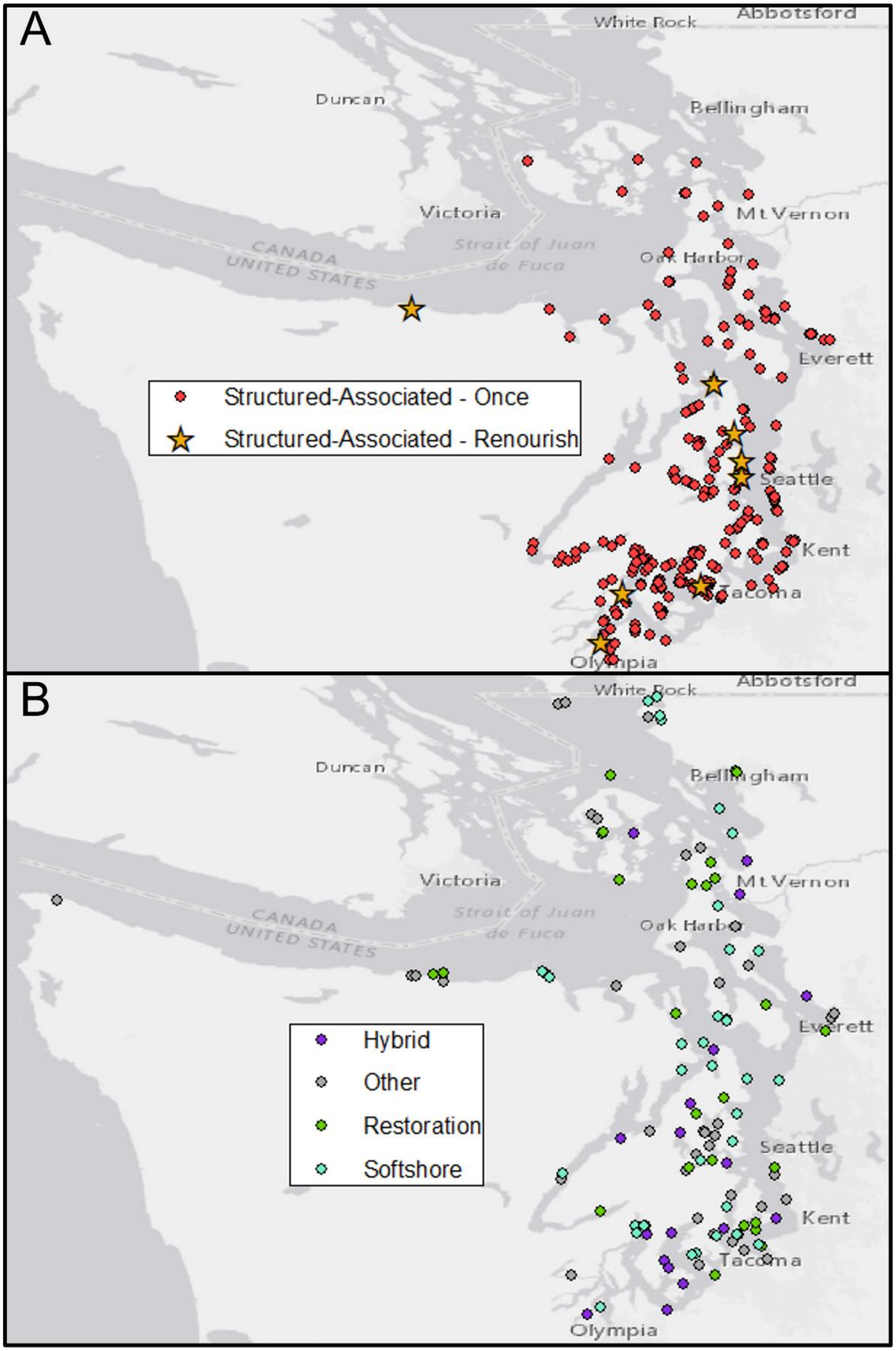

Figure 1 – *Distribution of HPA permits using beach nourishment for various uses across Puget Sound from 2014-2022.*

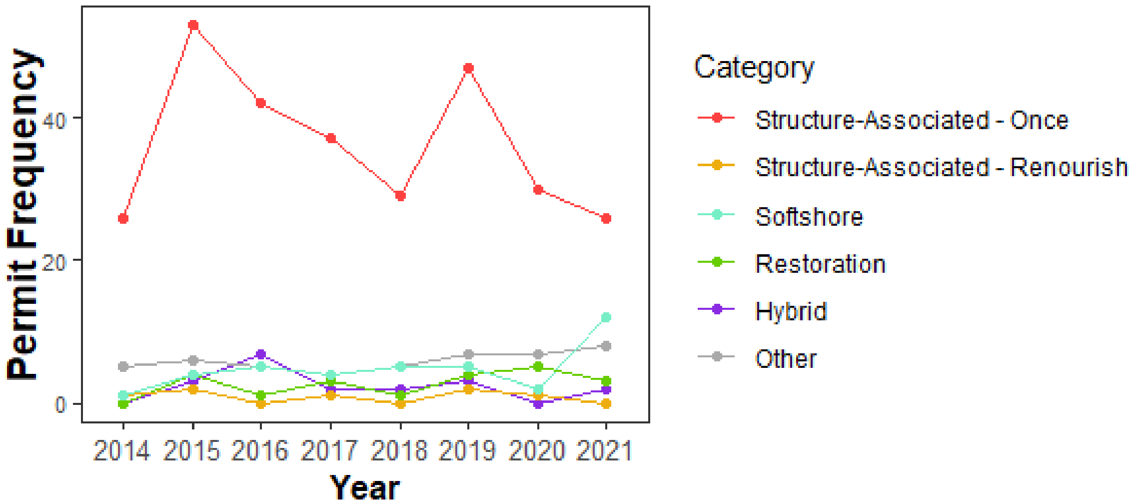

Figure 2 – *The frequency of each project category per year over time across Puget Sound.*

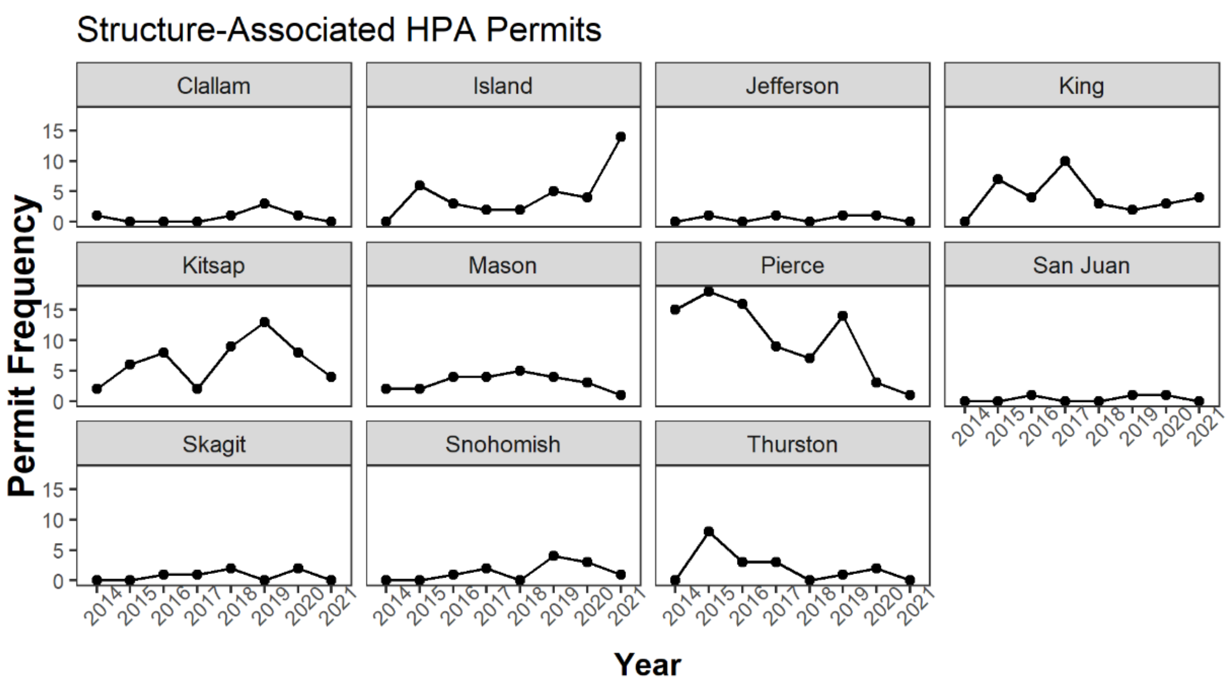

Figure 3 – *The frequency of HPA permits using beach nourishment in associated with structures over time by county in Puget Sound. Most counties show relatively static permit frequencies over time but other show changing trends such as increasing frequencies in Island County and decreasing trends in Pierce County.*

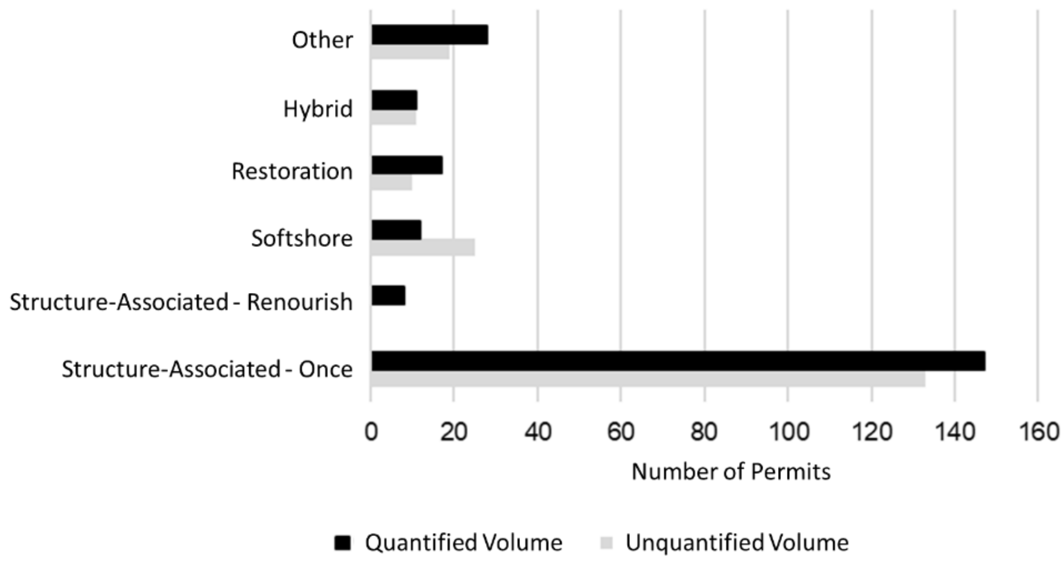

Figure 4 – *The number of permits that use beach nourishment across project categories where the volume of beach nourishment applied was explicitly quantified and those where volume was not readily quantifiable*

Next, we converted these data into an ESRI shapefile in ArcMap and joined each project with Beach Strategies GIS data (Coastal Geologic Services 2020) to extract the amount of shoreform that is armored at a project site, the shore type, and the presence of documented forage fish spawning habitat (surf smelt and sand lance). A shoreform typically describes larger shore features that are hundreds or thousands of meters in size (e.g., coastal bluffs or barrier beaches) whereas shore type typologies include local scale features which, in this case, are accretion shoreforms, feeder bluffs, areas of no appreciable drift, pocket beaches, and transport zones (MacLennan et al. 2017).

Permits with one-time structure-associated nourishment tended to occur on shoreforms with the highest armoring coverage (**Figure 6**). Permits with "Other" project categories occurred on shoreforms with variable - and typically lower - percentages of armoring. One-time structure-associated projects tended to occur on feeder bluffs or transport zones, as did hybrid projects that employed a mixture of hard and soft techniques. All permits with structure-associated renourishment were on feeder bluffs (**Figure 7**). Nearly half of the permits with nourishment as softshore stabilization were on accretion shoreforms and the rest occurred in transport zones, feeder bluffs, areas with no appreciable drift, and some pocket beaches. With subtle differences, permits for restoration projects occurred on shoreforms in similar distribution to softshore projects.

With respect to forage fish, roughly a third of projects - including one-time structure-associated projects - occurred on shorelines that had no known forage fish spawning (**Figure 8)**. Forage fish data are derived from intensive sampling efforts[4] and thus are relatively comprehensive, meaning that forage fish spawning classifications likely reflect true conditions. Of those projects located within known forage fish

[4]https://wdfw.maps.arcgis.com/home/webmap/viewer.html?webmap=19b8f74e2d41470cbd80b1af8dedd6b3&extent=-126.1368,45.6684,-119.6494,49.0781

spawning habitats, relative frequencies were similar across project categories with restoration projects most often associated with documented spawning habitats.

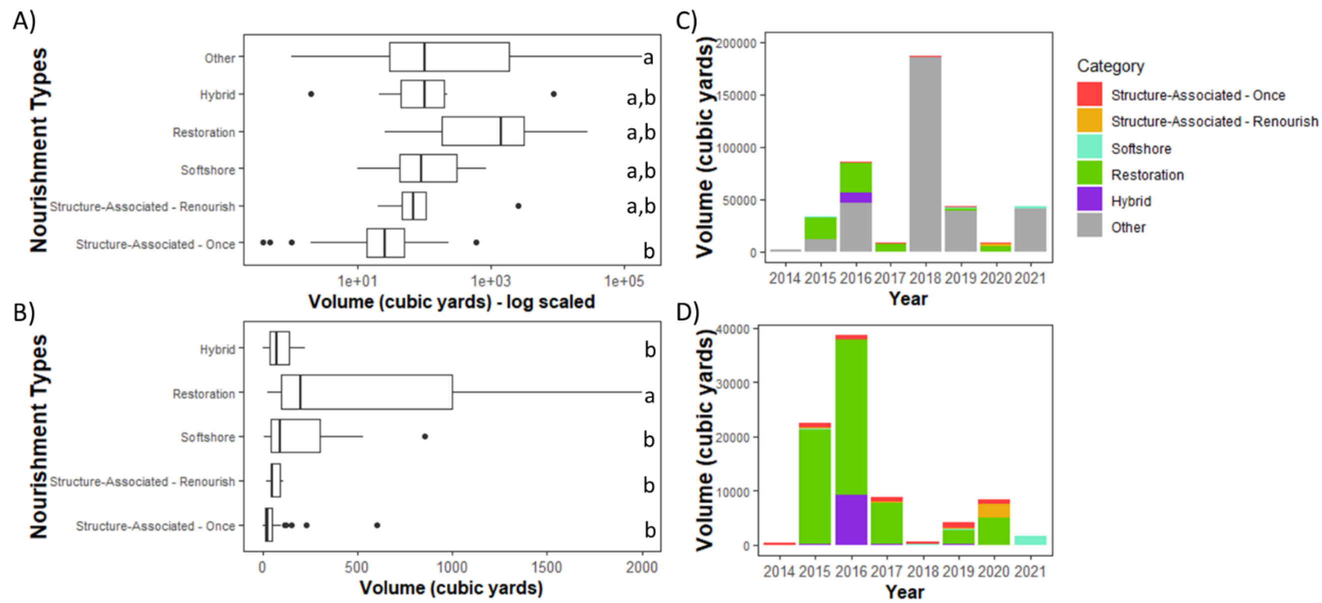

Figure 5 *– Beach nourishment volume are presented log-scaled to show multiple order of magnitude differences between structure-associated projects and larger projects like restoration (A). Volumes are also displayed unscaled at a maximum volume of 2,000 cubic yards and without the "Other" category (B). Note in (B) that two restoration and one hybrid project are not shown due to their much larger volumes. Lowercase letters in (A) and (B) are statistical groupings. Cumulative volumes over time by project type with (C) and without (D) "Other" projects which occur in high volumes that obscures trends.*

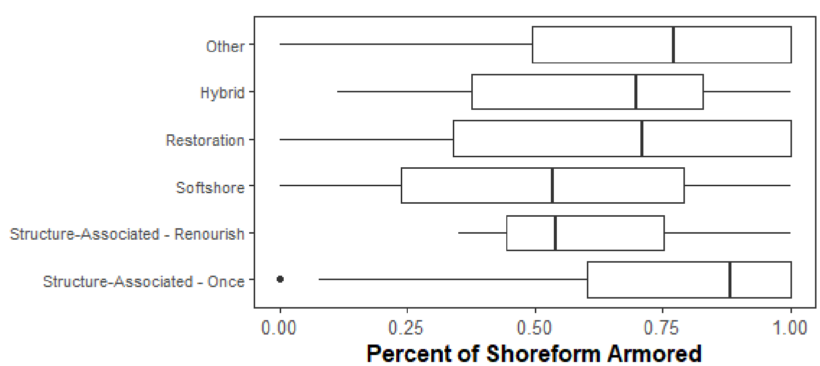

Figure 6 – *The percentage of shoreform that is armored where a permitted project takes place. One-time structure-associated projects take place on the most-armored shorelines.*

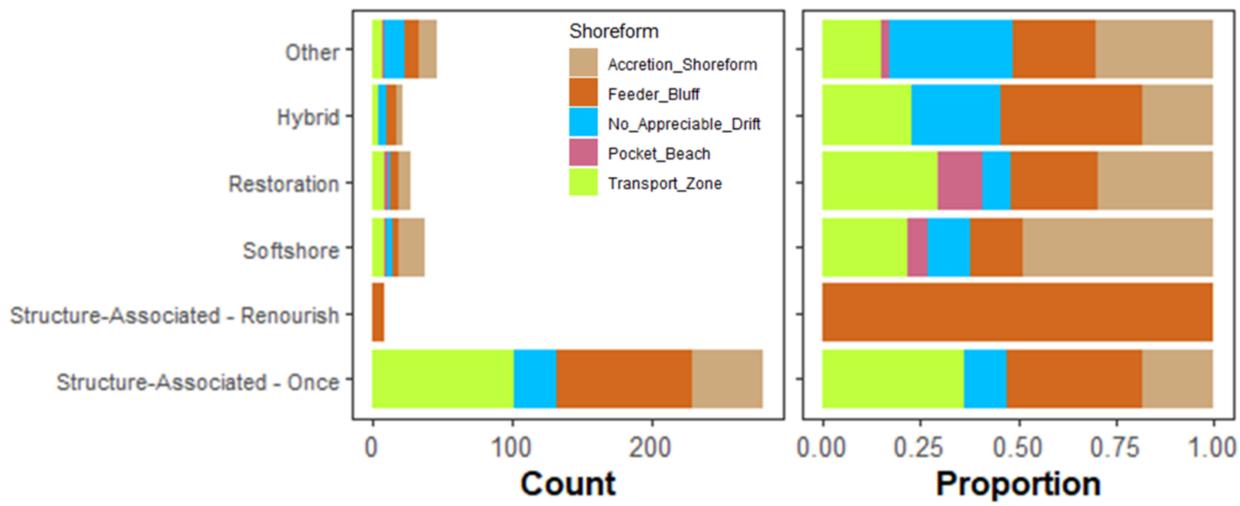

Figure 7 – *The frequency of shoreform types that each permitted project type occurs at displayed as raw count data as well as proportions of all permitted projects from 2014-2022. In general, project types that use at least some hard armoring (structure-associated, hybrid) have higher occurrences on feeder bluffs and transport zones. Notably, projects on pocket beaches or accretion shoreforms tend to be restoration or softshore projects.*

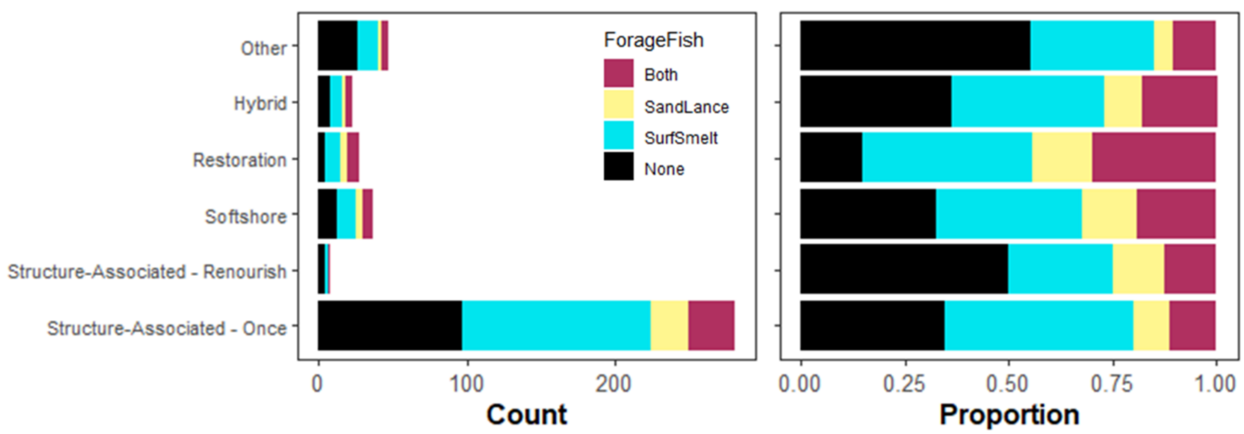

Figure 8 – *The frequency of shorelines with forage fish spawning presence that each permitted project type occurs on displayed as raw count data as well as proportions of all permitted projects from 2014-2022.*

Conceptual Model

With the data available, we sought to derive a conceptual model (**Figure 9**) that organizes the potential process-based impacts of beach nourishment to organisms in Puget Sound. Biological and ecological endpoints are often the product of changes to, or relationships between, physical processes and habitat structure within the environment, and thus we use a process – structure – function framework as our foundation. Though we acknowledge the integrated paradigm, we leverage previous work to describe the complex physical processes associated with beach formation and the role or influence of beach nourishment in nearshore ecosystems within Puget Sound (Shipman 2001, Clancy et al. 2009, Johannessen et al. 2014).

The success of beach nourishment as a tool for compensatory mitigation or restoration depends upon the biological response to the habitat conditions altered by the nourishment. Changes to species assemblages, abundances, or biomass patterns, or modifications to habitats that support rearing and spawning activities are important indicators for determining the success or application of beach nourishment techniques. Our conceptual model considers the duration (short- or long-term) and the pathway (direct/indirect) of benefits or impacts as important measures towards inferring the influence of nourishment on local biota and habitat function. The duration of potential negative and beneficial impacts, including recovery times of species and habitat features, can inform mitigation timelines and requirements. Direct and indirect impacts (i.e., via changes to habitat structure) can isolate specific disturbances (e.g., burial) from latent effects (e.g., reduced foraging function from loss of invertebrates). Lastly, nearshore beach ecosystems are inherently dynamic and complex environments characterized by overlapping physical and biological processes. Though we describe linear associations between process, structure, and biological response, we also acknowledge the potential complexities that exist. The potential feedback loops both within and among the biological and physical components are undoubtedly important, yet evidence to support these relationships as a function of beach nourishment is lacking and therefore not directly included in our model.

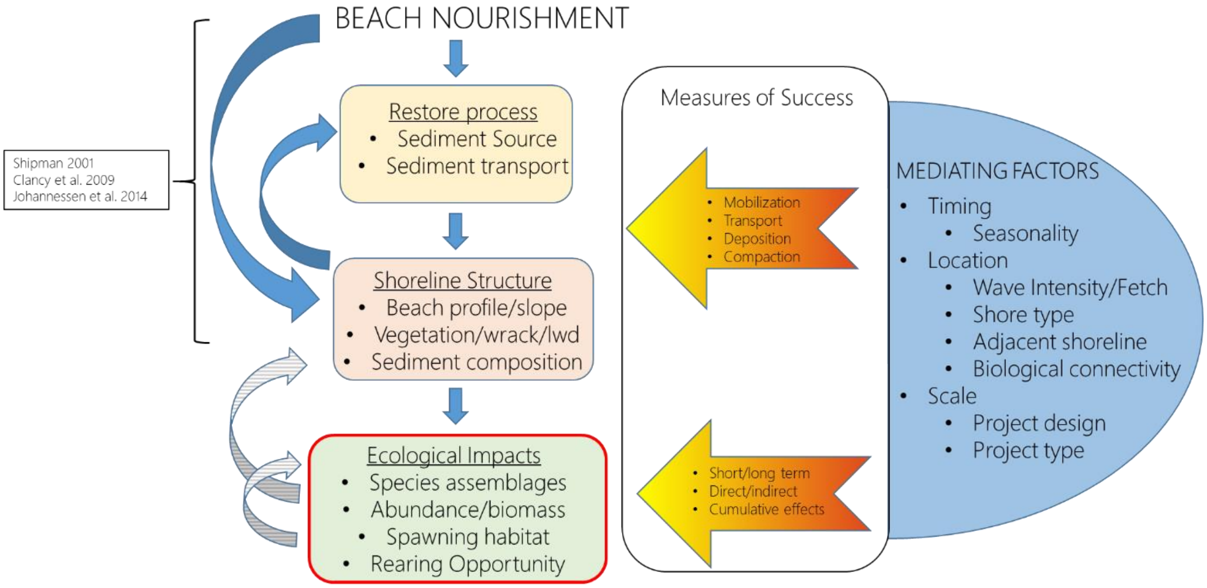

Figure 9 – *Conceptual model for the role of beach nourishment in Puget Sound.*

Finally, the best available science undergirds the ecological impacts and benefits from beach nourishment in our model. However, we recognize that decisions regarding nourishment actions are often made with minimal direct information about the biological communities or physical attributes of a particular site, and the data we reviewed illustrate how nourishment's consequences are highly site-dependent (e.g., Dethier et al. 2020). We identify mediating factors – timing, location, and scale – that may influence, or promote, certain physical and biological outcomes and which may be accessed through regional datasets or project planning documents. Biological communities within nearshore habitats often exhibit seasonal patterns in their life histories, behavior, and use of these environments. Nourishment activities that avoid, or work within, seasonal patterns may promote a more desirable outcome. The location of a particular nourishment action likely significantly influences the likelihood of success. Attributes such as wave direction and height, shore type, and adjacent shoreline conditions (e.g., armoring, groins, streams) likely influence the physical changes that may be expected after nourishment occurs while biological connectivity (e.g., known spawning locations, eelgrass/shellfish beds) may help identify the most vulnerable species/populations. The scale, design, and type of project will also have some bearing on the expected outcome(s) of nourishment activities. Project size may dictate the impact but may also dictate the expectation for potential benefits while project designs (e.g., re-nourishment included, on-site vs. up-drift action) may increase the period of impact and/or influence recovery and response times.

Discussion

Beach nourishment is widely used in Puget Sound with our synthesis documenting hundreds of uses of beach nourishment in the past decade at a variety of scales and diversity of purposes including restoration, mitigation, and erosion control. Interestingly, this analysis and our conversations with regional regulators suggests that the broader Puget Sound community – particularly shoreline landowners and consultants – readily and eagerly place beach nourishment voluntarily when conducting shoreline development projects because it is believed that doing so will benefit Puget Sound. At this time, we cannot provide quantitative inferences about the impacts of nourishment to beach processes and structure because of the variation in how data were collected. Even so, our synthesis has yielded multiple important conclusions for the use of beach nourishment in Puget Sound.

Feed or Build a Beach?

"*Nourishment is an important tool in addressing shoreline problems on Puget Sound, but that effective application requires improved engineering and regulatory guidance, systematic monitoring, and increased knowledge of the geomorphologic processes acting on individual sites*" (Shipman 2001).

When designing or recommending beach nourishment as a tool for mitigation it is important to consider the project site and project design in the context of the environment where nourishment will occur. Beach nourishment can address shoreline processes and habitat structure directly or indirectly and must be aligned with project goals. Such actions may be summarized broadly into two categories: "feed a beach" and "build a beach" (Leventhal et al. 2021). To "feed a beach" is to focus on using beach nourishment to restore, supplement, or initiate natural processes along shorelines (e.g., adding sediment to a drift cell to replace sediment supplies lost to armoring). The restored process(es) then influences the habitat structure and putatively provides some ecological benefit. At project sites with no natural supply of sediment to the project shorelines, beach nourishment must be repeated on some time interval to maintain the benefits of the "feed a beach" approach.

To "build a beach", nourishment is used to add sediment directly to a site with the goal of directly changing/restoring the physical structure of that location for aesthetic, recreational, or ecological purposes. For example, sediment additions at a site could replace lost sediment (erosion) and thus alter/restore the beach profile and/or improve sediment composition. Army Corps of Engineers regulations make this approach more complicated in Puget Sound because nourishment may count as "fill" and thus require mitigation. Direct changes to local habitat structure may provide biological benefits but may also influence shoreline processes creating feedbacks in the process-structure-function relationship. Examples of this feedback could be reduced erosion from the restoration or enhancement of the beach profile or changes to habitat structure that are more substantial (e.g., groin construction) to promote sediment retention on the project site.

In using beach nourishment as compensatory mitigation for nearshore development projects, nourishment's role is often considered by regulators as a "feed a beach" approach whereby nourishment mediates the lost process of sediment supply in a drift cell rather than providing on-site habitat (L. Arber, N. Siu, K. Still, and C. Waldbillig, personal communications). Nearshore development projects also – and likely more commonly – use nourishment as a "build a beach" approach when minimizing impacts from construction and using sediment as a dressing. For comparison, the restoration and softshore projects we reviewed use nourishment both for on-site physical alterations ("build a beach") as well as to supply sediment to sediment-starved areas ("feed a beach"), however, on-site effects are often the primary goal. Although part of the philosophy behind nourishment as compensatory mitigation is that sediment will move in the drift cell naturally, armoring itself makes it such that sediment is displaced more quickly than is natural and also continues to degrade beach conditions. For instance, Dethier et al. (2020) found that sediment removal rates tended to be higher at armored beaches (~60-100 CY/month) than unarmored ones and on beaches where armor encroachment was greater. The volumes removed from each site per month in Dethier et al. (2020) were equal to or typically much greater than the amount of sediment typically placed in Puget Sound in association with armor and other structures. This aligns with regional experts' observations that nourishment used as compensatory mitigation is often rapidly evacuated – either downdrift or into deeper water – from a project site, often within several weeks or months but occasionally within days (although it can occasionally last for several years; L. Arber, J. Johannessen, N. Siu, D. Small, C. Waldbillig). This rapid sediment evacuation is something that can frustrate project applicants when the costly nourishment applied as compensatory mitigation disappears from their beaches faster than anticipated (J. Johannessen personal communication).

Nourishment and Armor

"*Beach nourishment can be effective at partially mitigating for armor; however, the benefit will be much shorter in duration than the impacts since the lifespan of hard armor is typically 30 years or more. Nourishment cannot effectively mitigate for lost forage fish spawn area due to direct loss via burial. Additionally, mitigation using (re)nourishment would be required every 5 years, indefinitely, resulting in considerable cost and disturbance and, perhaps more importantly, these types of ongoing mitigation requirements are often not adequately tracked or carried out. This type of ongoing mitigation requirement is therefore not recommended*," (Johannessen et al. 2014)

Beach nourishment is effective as a component of restoration or softshore erosion control in Puget Sound (Johannessen et al. 2014, Lee et. 2018, Des Roches et al. 2022). Typically, a common condition that is central to the success of restoration and softshore projects in Puget Sound is the absence or removal of armor. This success is contrasted by several case studies (Mt. Baker Terminal, Lummi Shore Drive, and Snohomish Rail) where nourishment occurred at relatively large scales in front of armored shorelines. The application of nourishment in these examples represents "best case scenarios" for nourishment associated with armoring because of the large scale of nourishment volume and density used. However, in these cases where nourishment occurred in front of armor, nourishment was insufficient to compensate for the effects of armoring. Rather, sediment moved off-site quickly, and beach habitat conditions continued to degrade in front of the armoring. Evidence from these Puget Sound case studies suggests that armor-associated nourishment typically moves off-site faster than would occur on unarmored shorelines and thus does not maintain habitat conditions. These findings indicate that, when associated with armoring, nourishment's structural and functional effects are not likely to persist for more than several years and often only a few months, particularly if renourishment does not consistently occur and nourishment is applied at comparatively small scales. Further, evidence to-date across case studies does not suggest that beach nourishment consistently maintains or improves forage fish spawning or spawning habitat on-site or downdrift.

For new armor, beach nourishment is unlikely to be an effective action for on-site compensatory mitigation except, perhaps, in some situations where nourishment may function along an armored shoreline depending on site conditions (e.g., shoreform) and project design features (e.g., waterward encroachment), but that remains to be explored. It is likely that substantially higher volumes (i.e., increased by at least an order of magnitude from what is currently practiced, *sensu* Johannessen et al. 2014) would be needed to better compensate for impacts from residential hard armor that interacts significantly with waves (J. Cote, J. Johannessen, personal communications). Per the agency's hydraulic code rules, WDFW assesses project impact and mitigation needs relative to baseline conditions at the time of a permit's application. Consequently, the repair and replacement of existing shoreline armor may not require compensatory mitigation, particularly if the structure's repair or replacement is in-kind (not moved waterward, not expanded, etc.). However, NOAA, under the Endangered Species Act, may consider the impacts resulting from extending the design life of existing structures. Thus, NOAA's analysis considers the impacts that would not occur but for the proposed repair or replacement. Such impacts from extending the functional existence of a structure in the environment include delaying the establishment of habitat forming processes (NMFS 2022). Our data suggests that project applicants are applying beach nourishment for repair and replacement structures which could be voluntary or used as a minimization measure to dress temporary construction impacts. Beyond these applications of beach nourishment for repair and replacement structures, local or federal agencies may be requiring beach nourishment as mitigation, although the HPA permit language often does not distinguish the reason for applying nourishment.

Issues related to sediment retention and beach erosion are compounded by multiple findings in our review that nourishment sediment can be displaced not only downdrift but also cross shore when associated with armor (e.g., in the Snohomish Rail study). There is concern – albeit with uncertainty – from regional geological science experts that nourishment in front of residential armor will result in the loss of the placed sediment offshore (i.e., not necessarily retained in the drift cell) (J. Cote, J. Johannessen, and H. Shipman, personal communications). This process would conflict with the articulated goal of permitters in using nourishment as compensatory mitigation for armor such that the supplied sediment in a drift cell is transported by longshore drift. Thus, beyond an insufficient volume of placed sediment that reflects the lost sediment supply, the amount of sediment available for habitat may be further reduced due to losing sediment offshore from wave interactions with armoring, particularly in high-energy areas (J. Cote, personal communication).

The permitters we spoke to about beach nourishment understand that beach nourishment's habitat function is not necessarily on-site but rather as part of a process where sediment moves downdrift in a drift cell (L. Arber, M. Reaves, N. Siu, C. Waldbillig, personal communications). Thus, under this philosophy, any realized habitat benefits would not occur on-site. Therefore, the typical preference for "on-site" and "in-kind" compensatory mitigation may be of little functional value for habitat because the habitat consequences of nourishment are not necessarily anticipated to be on-site anyways (beyond dressing construction impacts). Therefore, other compensatory actions for new armor that are explicitly off-site from the armor impacts may be worth exploring. This has been used for residential compensatory mitigation purposes where nourishment material is placed updrift and allowed to drift towards the project site and elsewhere (J. Cote, H. Shipman, N. Siu, C. Waldbillig; personal communications). However, the habitat impacts from armoring extend beyond lost sediment supply and include a reduction in wrack, beach substrate coarsening, and loss of connectivity with upland vegetation. As such, sediment nourishment at armored sites cannot be an effective compensatory tool.

Beyond sediment supply

Importantly, armoring does not solely block the natural erosion of sediment that feeds a drift cell. Rather, armoring changes the physical structure and processes of beaches and the nearshore environment, particularly in high-energy areas and where the armoring is placed waterward of the ordinary high-water mark. This means, that more sediment than would naturally be eroded would be necessary to maintain sufficient suitable nearshore habitat. Therefore, substantially higher volumes and densities of nourishment sediment and/or more frequent nourishment may be needed to adequately resupply sediment to Puget Sound's shorelines. However, beach structure and processes are perpetually disturbed by armoring in dynamic nearshore environments and so nourishment is fundamentally insufficient as *in-kind* and *on-site* compensatory mitigation for sediment supply and other impacts of new hard armoring that is placed waterward. Even so, recent policy changes make it challenging for applicants to build new armor low on the beach (D. Small, personal communication) which means that armoring placed sufficiently landward will reduce impacts like toe erosion due to wave interactions with the armor but will still cause a loss of sediment supply or riparian connectivity.

Because lost sediment supply is not the only or dominant consequence of armoring to nearshore processes, using nourishment to compensate for new armor does little to address the continued degradation of beach habitat conditions resulting from the indefinite placement of armor (H. Shipman, personal communication). Specifically, armoring can degrade beach conditions (narrows, steepens, and coarsens), reduces the ability of shorelines to accumulate wrack, supports depauperate invertebrate communities, reduces connections to riparian zones, and impairs forage fish spawning habitat, spawning density, or embryo survival (Rice 2006, Sobocinski et al. 2010, Heerhartz et al. 2014, 2016, Dethier et al. 2016). Beyond lowering beaches, armoring can itself also disrupt sediment drift by causing accretion if oriented in a way that blocks normal drift. The relative impact of armoring will depend on its location to the ordinary highwater mark and the energy dynamics of a beach (e.g., lower impact higher on the beach and in lower energy areas).

Although placing nourishment sediment elsewhere in the drift cell may at least partly accomplish the goal of replenishing sediment to a sediment-starved drift cell, it does not address the broader habitat conditions that are lost from the armor's presence. Beyond the avoidance and minimization measures associated with mitigation for structures, beach nourishment is typically the only tool available to Washington state permitters for compensatory mitigation associated with new armoring on-site (L. Bockstiegel, M. Curtis, K. Still, personal communications) and this may explain the dominant philosophy of using nourishment to "feed a beach" rather than "build a beach". Given the limitations of nourishment and paucity of other tools, there may be a need to consider "out-of-kind" and/or "off-site" compensatory mitigation actions like armor removal elsewhere or *in lieu* feels to address the effects of new armoring.

Further, the composition of material used for nourishment actions should be considered carefully and match natural conditions or conditions that support the intended goal. Often the goal of nourishment is mitigation to support habitat for fish use, including forage fish (surf smelt and Pacific sand lance) spawning, and juvenile salmon rearing functions (Ehinger et al. 2023). The evidence we reviewed from Puget Sound and other regions suggest sediment composition can have considerable influence on spawning success and invertebrate production and diversity which directly affect prey resources for target fish species. Puget Sound forage fish species tend to spawn at the same beaches annually and substantial habitat that is putatively "suitable" never receives spawning (Pentilla 2007). Yet roughly one-third of the structure-associated permits we analyzed do not occur on shorelines where Pacific sand lance or surf smelt breed. In these cases, it is unclear what the intended nourishment was addressing beyond construction impacts but adding nourishment should not be expected to encourage new spawning.

Interestingly, observations by Dethier et al. (2020) and Pentilla (2012, 2013) from nourishment projects suggest that associations between substrate conditions and forage fish spawning are less clear than previously assumed and may warrant further investigation. It may also be worth considering whether promoting habitat for forage fish spawning also adds value for other species like juvenile salmonids and the habitat functions they rely upon (e.g., prey production). Therefore, nourishment used as mitigation for habitat to support target species should be considered carefully and in the context of where the action occurs. Improving clarity about what nourishment is intended to mitigate for would be useful for understanding the conditions under which it may be effective for some species.

Improving current practices for using nourishment with armor

One form of mitigation that nourishment accomplishes is to fill in disturbances on a beach that occur from heavy equipment during armor maintenance or installation. This minimization measure, or "dressing", is likely to be a generally useful form of mitigation as it immediately mitigates the disturbed sediment incurred during construction (H. Shipman, personal communication). The degree to which beach nourishment is used solely to minimize or rectify construction impacts as dressing versus compensate for impacts to sediment supply and other continuous habitat impacts from a structure's presence is unclear. Some of the permits we reviewed explicitly dictate beach nourishment solely as dressing (without a volume given), as needed for dressing in addition to a quantified volume as mitigation for a structure, or just as compensatory mitigation for armoring. But the language in most permits is vague as to whether the nourishment is used to minimize and/or compensate for the activity, or to advance another unstated voluntary goal.

For structure-associated nourishment that is intended for compensating for impacts of new armor, one improvement could be to increase the density of nourishment applied. The MSDG describes "nourishment density" as the volume per linear foot of beach that is nourished and suggests that nourishing at 1-2 CY/ft leads to better project success. Currently, NOAA's Puget Sound Nearshore Habitat Conservation Calculator recommends applying a density of 4.5 cubic feet (not cubic yards) of nourishment per foot of armoring (0.17 CY/ft) (Ehinger et al. 2022). This number is an order of magnitude lower than recommended in the MSDG. Current compensatory mitigation practices often use aerial imagery to estimate background erosion rates and apply a volume of sediment as nourishment that is commensurate (C. Waldbillig, personal communication). However, aerial imagery is not accurate enough to calculate typical erosion rates and may not accurately capture stochastic erosion events that feed Puget Sound (J. Cote and H. Shipman, personal communications). It may be advisable to nourish with more material than would naturally erode from a site because armoring increases the rate at which sediment is displaced from a shoreline, including potentially moving sediment offshore, thereby enhancing beach erosion (J. Cote, personal communication). Although the MSDG recommended a higher density of nourishment than is typically applied for new armor projects, it remains unclear how much more nourishment and over how many repeated applications would be useful for successfully compensating armoring impacts.

Further, although the current goal with using nourishment as compensatory mitigation is to replenish a drift cell's sediment supply, there may be value in actions that help retain sediment on-site for longer periods of time (i.e., "build a beach") given that armoring displaces sediment more quickly. Incidental findings from several case studies (Lummi Shore Drive, Mt. Baker Terminal, SCBNP) found that structures or effluent from streams and culverts can slow or halt longshore drift of nourishment materials. Potentially adding sills or groins at the residential scale may help stabilize mitigation nourishment, however these structures can have negative impacts to downdrift shorelines by starving beaches and research would be needed to understand groin design (logs vs artificial) and effects. Alternatively, if one goal of nourishment as compensatory mitigation is to keep more sediment on-site, then renourishing may be necessary. However, nourishing and subsequently renourishing is costly and logistically challenging to implement and enforce. Further, renourishment would increase the frequency of disturbance to sites and potentially cause further degradation to nearshore biota (Johannessen et al. 2014).

Nourishment in Puget Sound is largely effective when it is coupled with other actions like removing armor (i.e., restoration). It is likely also more effective on beaches with less encroachment from hard armor and at beaches with lower wave energy. An important conclusion from this synthesis is that site-specific conditions influence the success of nourishment. As such, there may be potential for more "hybrid" projects that incorporate some softer approaches like adding large wood or vegetation if site conditions allow for it. This hypothetically is the goal of RCW 77.55.231 implemented in 2021 which requires applicants to consider the least impacting technically feasible alternative, including softer approaches, when proposing to replace an existing shoreline armor structure. Additionally, there may be other opportunities for compensatory mitigation that involve coordinating efforts among multiple property owners (including potentially with larger volumes of beach nourishment) to realize larger-scale benefits. Such opportunities, however, would be voluntary and proposed by the project applicant, rather than required. There are several examples of softshore erosion control efforts where multiple homeowners worked together to apply high volumes and densities of nourishment including at a high-energy site (Zelo 2000, Johannesen et al. 2014). Such approaches also recognize that beaches are dynamic, and that sediment moves. To our knowledge, such an effort has not been conducted with compensatory mitigation but doing so could provide a more comprehensive mitigation attempt that has added longevity and benefit due to scale. Even so, such an approach would be more logistically cumbersome.

Implications for repair and replacement armor

It is notable that only a small percentage of the permits we analyzed from 2014 through 2021 were for new armor. This highlights how infrequently new armoring is being permitted and so the scale of compensatory mitigation for new armor is a relatively small component of the nourishment portfolio in Puget Sound. As a corollary, a surprising finding from our permit analysis was that most permits with structure-associated nourishment are not for new armor, but rather for replacement armor (n = 151 permits, 52.4% of structure-associated HPA permits that use nourishment) or armor repair (n = 66 permits, 22.9% of structure-associated permits that use nourishment). Our results mirror those from similar analyses. For instance, Shipman (2017) reviewed HPA data for the year 2015 for all marine shoreline stabilization projects, finding that 20 were for new armoring, 10 for armor removal (but 366 m [1200 ft] more armoring was removed than newly added), and 150 were for a cumulative 579 m (1900 ft) of repair and replacement armoring. Similarly, Small et al. (2018) traced armor patterns over time and found that the rate of replacement armoring is still outpacing the combined extent of Puget Sound shorelines that are having armor removed or new armor added, although armor removal becoming more prevalent than new armor. This underscores that the impacts of historical armoring are ongoing and remain largely unmediated.

These findings are interesting because WDFW evaluates impacts caused by a project by comparing the condition of the habitat before project construction or work to the anticipated condition after project completion. Therefore, for repair or in-kind armor replacement, the baseline condition on which to measure impact is altered. Mitigation is always required, but *compensatory* mitigation is only required if avoidance and minimization measures are insufficient (WAC 220-660). As such it is unclear from the HPA permits we reviewed if the large number of repair and replacement armor permits that used nourishment did so because the project applicant elected to apply nourishment or if nourishment was required by another permitting agency like a county or the Army Corps of Engineers and NOAA. Anecdotally, there does appear to be an established culture in Puget Sound where landowners, consultants, and contractors include beach nourishment as part of shoreline construction projects for perceived benefits, even if the nourishment is not required by any agency (M. Blair and K. Still, personal communications). The nourishment associated with these permits may also simply be dressing for construction impacts, but it is difficult or impossible to discern this in many cases.

In 2021, RCW 77.55.231 required that applicants wishing to replace shoreline armor must employ the least impacting, technically feasible alternative (in these cases, nourishment as a softshore tool rather than compensatory mitigation for hard armor) for the protection of fish life. Unless WDFW exempts the project, the applicant must conduct a site assessment to consider removing the structure and restoring the beach, replacing the structure with softshore approaches (*sensu* Johannessen et al. 2014), or moving the structure landward. In these applications, hard armoring can only be used as replacement if no less-impactful alternative is identified. However, given decades of land use practices that permitted structures to be built waterward by several meters, there are likely few situations where project applications for replacement armor can use softshore approaches or move armor sufficiently landward to be less impactful, although the exact number is hard to quantify (D. Small, personal communication). As such, substantial amounts of shoreline armoring around Puget Sound are likely to persist indefinitely (H. Shipman and D. Small, personal communications). Indeed, the last third of the 20th century was marked by an explosion of new armor construction and armor repair or replacement because for decades regulations around Puget Sound severely limited restrictions on armor construction and even encouraged unnecessary bulkheads and the construction of bulkheads substantially waterward (D. Small, personal communication). It was not until recent years that WDFW had substantive authority over new armor or repair and replacement armor siting and design. Similarly, federal authority surrounding shoreline armoring did not begin until the turn of the millennium with the listing of Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*) and Hood Canal summer chum (*O. keta*).

The indefinite legacy and long duration of hard armor may represent an arena for further restorative actions or policy development. WDFW and the Army Corps of Engineers do not require nourishment for replacement or repair armor. However, NOAA accepts beach nourishment, where deemed beneficial by NOAA and WDFW biologists, as a conservation offset for such projects. For example, NOAA's consultation on the Corps' proposed action for the Salish Sea Nearshore Programmatic (SSNP) includes four options for conservation offsets and beach nourishment, where appropriate, may be used under one of those options. Under SSNP, options for conservation offsets for all action categories that propose mitigation include off-site mitigation. Further, regardless of whether nourishment is required as mitigation for repair and replacement armor, our analysis makes it clear that most project applicants are using nourishment as part of their armor projects, potentially beyond minimizing construction impacts.

As such, developing alternative off-site compensatory mitigation actions could be a fruitful opportunity for Puget Sound. For example, rather than the cost of applying nourishment, fees for new, replacement, or repair armor could be used for opportunistic beach enhancement projects that may better offset the beach habitat lost to armoring (in conversation with D. Small and H. Shipman). Without addressing existing armor that is repaired or replaced, Puget Sound's nearshore habitats will remain deficient in habitat value. This situation is expected to be exacerbated by rising sea levels associated with anthropogenic climate change. Rising sea levels will shrink intertidal environments and shoreline armoring – even armoring placed further landward – will further reduce the amount of intertidal habitat available. (Krueger et al. 2010).

Remaining uncertainties and research needs

The research on beach nourishment, particularly in Puget Sound, is relatively depauperate. This is evidenced by the fact that only 52% (23 of 44) of our cited references come from the peer-reviewed published literature and the remainder come from technical reports and expert opinion. Of the peer-reviewed studies we reference, most are from geographies outside of Puget Sound or focused on nourishment used for restoration in Puget Sound. If nourishment continues to be used for mitigation, more research is needed to measure and improve its efficacy. Specifically, that research could be targeted to understand:

(1) the area impacted from nourishment,

(2) where and how long before the benefits from nourishment are realized,

(3) how long the benefits last,

(4) how often renourishment is needed,

(5) what volume/density is needed,

(6) what sediment composition is ideal, and

(7) how long negative impacts remain for

Further, it remains unclear to what extent armoring contributes to the movement of sediment offshore and out of a drift cell and how much armoring accelerates the displacement of sediment in longshore drift. Other uncertainties remain around the effectiveness of nourishment – for various purposes – as a function of different shoreforms, what the recovery time of organisms is post-nourishment, and where most impacts from nourishment occur (on-site, downdrift, offshore).

Conclusions

Here, we synthesized evidence from the peer-reviewed literature, gray literature, expert opinions, and an analysis of Puget Sound permits to understand the effectiveness of beach nourishment. From this synthesis, we present five key conclusions below. One overarching takeaway from this body of work is that nourishment is most effective when synergistically paired with armor removal, yet this synergy also means that nourishment is of little value when placed in association with armor. Unfortunately, we are unable to quantify the degree of impacts from beach nourishment given the heterogeneity in how existing data were collected. Even so, the peer-reviewed studies and case studies we evaluated provide important lessons.

- **Beach nourishment is an effective restoration strategy when included in a suite of tools**.
    - Research in Puget Sound demonstrates that nourishment can be effective at maintaining beach habitat conditions as part of larger-scale restoration and soft shore erosion control projects, particularly when paired with armor removal, backshore plantings, and the addition of logs. While it is challenging to separate the effects of each tool within the suite of actions, it appears the likelihood of success is related to the sum of all actions rather than each independently.
- **Effectiveness of beach nourishment actions is sensitive to the volume of sediment placed.**
    - Globally, beach nourishment actions typically involve sediment volumes several orders of magnitude great than what is generally used within Puget Sound. Yet, even using sediment volumes of such magnitude the effectiveness of beach nourishment is inconsistent and not generalizable.
    - Within Puget Sound, nourishment is generally ineffective at addressing the negative impacts to sediment processes from new single-family residential hard armor. This is largely because the density of sediment used in such practices is likely too small. When

beach nourishment is associated with hard armor, and because hard armor fundamentally alters beach structure and function, conditions rapidly displace nourishment and continues eroding beach conditions, particularly when armor is placed further seaward.

- **Ecological benefits of beach nourishment are largely inconsistent and remain generally unknown; further directed research activities are warranted.**
    - Both within Puget Sound and across a broader geography, the ecological benefits of beach nourishment are mixed and inconsistent. Though the timing of sediment placement did mitigate some impacts to benthic species in particular, there was no clear and consistent benefit to target species as a result of beach nourishment.
    - Within Puget Sound more long-term monitoring of nourished sites will be critical to developing our understanding of potential ecological benefits for nearshore marine species. Monitoring should include pelagic and benthic species as well as impacts/benefits to submerged aquatic vegetation.
    - Beach nourishment is often cited as a tool to enhance forage fish spawning habitat in Puget Sound. Again, the efficacy of beach nourishment and relationship to forage fish spawning habitat remain tentative. Additional research is warranted including refining habitat suitability metrics for forage fish species as it relates to sediment conditions.
- **Project design requirements for beach nourishment should include better accounting of sediment loss due to natural processes**.
    - Case studies of beach nourishment actions in Puget Sound consistently found loss of sediment within the first several years after placement. Both longshore (parallel to the beach) and cross-shore (perpendicular to the beach) processes may move sediment from the nourished site. While in some cases this movement may be intentional (e.g., feeding sediment to the drift cell), many beach nourishment actions are intended to benefit sediment conditions at the site and losses may be detrimental to success.
    - Given the low volumes of sediment commonly used in beach nourishment activities throughout Puget Sound, improved accounting of site-specific conditions and local processes – either from longshore or cross-shore movement – could be included in project designs to ensure placement of sediment (and associated volumes) are sufficient for the intended goal(s).
- **Cost/benefit of beach nourishment may warrant alternative strategies**
    - Finally, given the costs of initial nourishment actions and recurring costs of potential nourishment, coupled with the inconsistent and inconclusive ecological benefits, this practice may not be the most cost-effective form of habitat compensatory mitigation. While the use of beach nourishment as part of a suite of restoration tools is promising, the use of nourishment as a stand-alone action is not well supported and suggests alternative forms of addressing armoring impacts may be worth exploring.

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