

Impacts of Overwater Structures to Salmon and Kelp (22-1702)

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Cover photo:

University of Washington snorkelers conduct water column fish survey in Wollochet Bay, WA. Photo by UW Wetland Ecosystem Team.

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Abstract

Large overwater structures, such as ferry terminals, disrupt nearshore processes by adding vertical structures that interrupt sediment drift and by casting shadows to the benthos that impair vegetative growth and fish behavior; however, effects of small overwater structures (SOWS), like residential docks, are uncertain. Due to their smaller size, SOWS may have minimal or even positive effects to the ecosystem. We hypothesized that effects of SOWS will derive from two main causes: (1) reduction in light in the immediate vicinity of the SOWS and (2) altering sediment transport leading to measurable nearshore environment effects. We investigated SOWS effects on the nearshore environment by measuring a suite of metrics including sediment grain size, along-shore elevation, crabs, kelp, salmonids and other fishes, light availability, and SOWS structural dimensions. We also analyzed the NOAA overwater structure database to summarize SOWS density at various geographical scales of interest and compared these metrics to other shoreline features such as armoring and submerged aquatic vegetation. Overall, our study found limited evidence of SOWS effects on sediment, elevation, crabs, kelp, and benthic and water column fishes; however, some patterns did emerge, including positive and negative relationships between proportions of small (sand) sediment grain sizes to SOWS piling number, increased elevation near SOWS, greater abundance of crabs and benthic fishes near SOWS, and reduced abundance of kelp and eelgrass near SOWS. Light availability (photosynthetically active radiation - PAR) was reduced when shaded by SOWS. We found that grated decking, designed to increase irradiance, had no statistical effect in increasing irradiance under SOWS; however snorkelers noted more light at grated deck sites. Effects on juvenile salmonids and other water column fishes were highly variable with seasonal and regional effects appearing to drive patterns. While these results may seem to suggest that there are limited measurable effects of SOWS on the nearshore environment and that they offer some degree of habitat value for some species, we suggest that these results are more reflective of inherent spatial variability of these nearshore ecosystems and sampling logistics typified by high site to site variability in nearly all metrics. Therefore, identifying SOWS effects with high confidence may require intensive sampling of specific metrics or greatly increased sample size, or both. Furthermore, our study was designed to identify effects at the site scale; however, it is plausible that cumulative or drift cell-scale (5-20km) SOWS effects, or both, exist. Our results may indicate that removal of SOWS for shoreline restoration purposes would provide limited benefits. It is important to note that such removals would, at a minimum, enhance light penetration and therefore benefit kelps and other submerged aquatic vegetation. Additionally, the removal process has the potential to eliminate harmful materials, such as creosote pilings, which would contribute positively to the nearshore environment.

Introduction

Investments in Puget Sound's restoration necessitate actions that provide long-term benefits for habitats and species. Research indicates that large overwater structures, such as ferry terminals, negatively affect nearshore habitats, altering the ecosystem and hindering juvenile salmon migration (Shreffler & Moursund 1999, Simenstad et al. 1999, Williams et al. 2003, Munsch et al. 2014); however, the effects of small overwater structures (SOWS), such as residential docks, are less studied. While SOWS support recreational activities, concerns arise on their potential to impact nearshore habitats similar to the effects of larger overwater structures. Conversely, their smaller size may result in minimal or even beneficial effects. This uncertainty has led to their rarity in restoration discussions (Lambert et al. 2023).

SOWS are defined to have a total surface area (including pier, ramp, and float) less than 560m² (6027ft²) and dimensions that vary on the type of SOWS (NOAA 2018, Lambert et al. 2023). Under current permitting standards (WAC 220-660-380), residential piers cannot exceed 1.8m (6ft) in width, floats can only be up to 2.4m (8ft) wide, and construction of SOWS longer than 18m (60ft) is discouraged when feasible. Exact dimensions can vary and still be considered compliant if the design has been approved by the Washington Department of Fish and Wildlife (WDFW). Conversely, large overwater structures generally have lengths over 700m, widths over 200m, and surface areas that are greater than 560m² but are often tens of thousands of square meters, making them substantially larger than SOWS (Mulvihill et al. 1980, Haas et al. 202, Kelty & Bliven 2003, Toft et al. 2007, Able et al. 2013, Ono & Simenstad 2014).

Overwater structures cast shadows (i.e., reduce solar incidence) into the water column and onto the benthos that impair vegetative growth and stall fish outmigration. There is strong consensus that shadows cast by SOWS impair eelgrass growth (Fresh et al. 1995); however, there is little understanding about how kelps – many of which have lower light requirements than eelgrass – are influenced by SOWS shading. Similarly, juvenile salmonid behavior is light sensitive and, although we know that shadows cast by large overwater structures impede juvenile salmon migration (Munsch et al. 2014, Moore & Berejikian 2022), we do not know if shadows cast by SOWS have the same impact.

Understanding interactions between SOWS and nearshore processes is crucial to informing new SOWS project design, mitigation needs, and for prioritizing SOWS removal as a restoration strategy. For example, a study in Salmon Bay, WA showed SOWS removal significantly aided beach restoration for juvenile salmon (Toft et al. 2013). In this instance, without removing the SOWS, the broader beach restoration to remove shoreline armor would have provided fewer benefits to juvenile salmon. Conversely, SOWS might positively influence nearshore ecology in other ways. Divers have reported that some SOWS promote kelp growth (Tate, E., *pers. comm.*), which is vital given the region's kelp decline (Berry et al. 2023). SOWS could also mimic natural habitat features, providing migratory habitat for juvenile salmon. Thus, in certain contexts, SOWS may support restoration on impacted shorelines.

The present study builds off hypotheses that were originally conceptualized and studied with respect to large overwater structures and have yet to be formally addressed for SOWS. Our study aims to clarify the effects of SOWS on Puget Sound's ecology. Our goal was to further our understanding of how physical alterations and reduced light caused by SOWS influence juvenile

salmon abundance and kelp diversity and abundance. SOWS introduce physical structure in the nearshore, which we hypothesized can alter sediment transport, but also provide substrate for kelp, and serve as shelter for some fish species. Overwater structures in general are predicted to mediate sediment transport by interacting with currents (Nightingale & Simenstad 2001). Our conversations with regional experts suggest that substrates under and adjacent to SOWS are composed of more shell hash and finer-grain sediment compared to the adjacent beach (Lambert et al. 2021). These observations were not systematically collected but do suggest that SOWS interfere with normal sediment movement in drift cells.

We hypothesized that SOWS will affect nearshore ecosystems through two primary mechanisms that will in turn lead to measurable effects to sediment grain size and nearshore species including kelp and other submerged aquatic vegetation, crabs, and fishes. First, SOWS will alter sediment transport dynamics including local sediment accretion and substrate composition around the structures. In turn, changes in sediment composition may influence associated species. Second, SOWS will reduce light availability in the immediate vicinity of the structure. This may have negative effects of submerged aquatic vegetation, but potentially positive effects to mobile organisms that may seek refuge in shaded areas. If SOWS disrupt key nearshore processes, our findings will guide project planning and execution to bolster restoration outcomes. To address these hypotheses, we conducted a field sampling effort to measure key SOWS structural features and surrounding geomorphology, submerged aquatic vegetation, macroinvertebrates, and fishes. We also analyzed the NOAA overwater structures spatial database to build a better understanding of the current state of SOWS in Puget Sound and how they relate to shoreline features.

Methods

Study area

We identified two areas of Puget Sound to focus our data collection: Whidbey Island and Fox Island/Wollochet Bay (Figure 1). These study areas were selected for their high numbers of SOWS, input from project advisors, and logistics feasibility. In each study area, we identified multiple SOWS, defined as a total surface area of $\leq 560 \text{ m}^2$ (only two sites marginally exceeded this area constraint; Table 1), and contacted landowners to obtain permission to access their property. This resulted in a selection of 16 total sites, 8 in each region. Whidbey Island sites were located on the eastern shore of the island, spanning Saratoga Passage, Penn Cove, and Holmes Harbor. Fox Island/Wollochet Bay sites were within Hale Passage on the north and east ends of Fox Island and along the eastern and western shores near the mouth of Wollochet Bay.

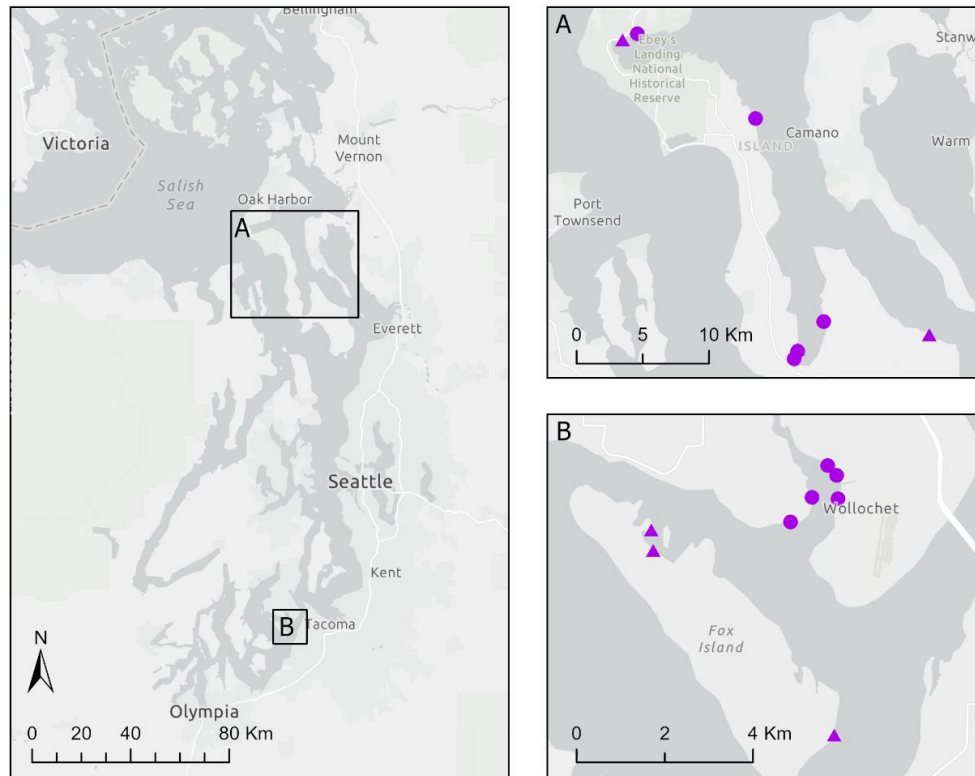


Figure 1: Study area and sampling locations (inset maps) in the regions of (A) Whidbey Island and (B) Fox Island/Wollochet Bay. Purple circles denote sites at which all data types were collected, and purple triangles denote sites where dive data were not collected.

Data collection

We collected a suite of data at each of our study sites including SOWS dimensions and building material, sediment grain size, beach elevation, fish community – including juvenile salmonids – kelp cover, benthic cover and invertebrates, and photosynthetically active radiation (PAR). These data were collected through three overarching collection methods: intertidal surveys, dive surveys, and snorkel surveys (Figure 2). Intertidal and snorkel surveys were conducted at all 16 sites (8 per region), while dive surveys were limited to a subset of 10 sites (5 per region).

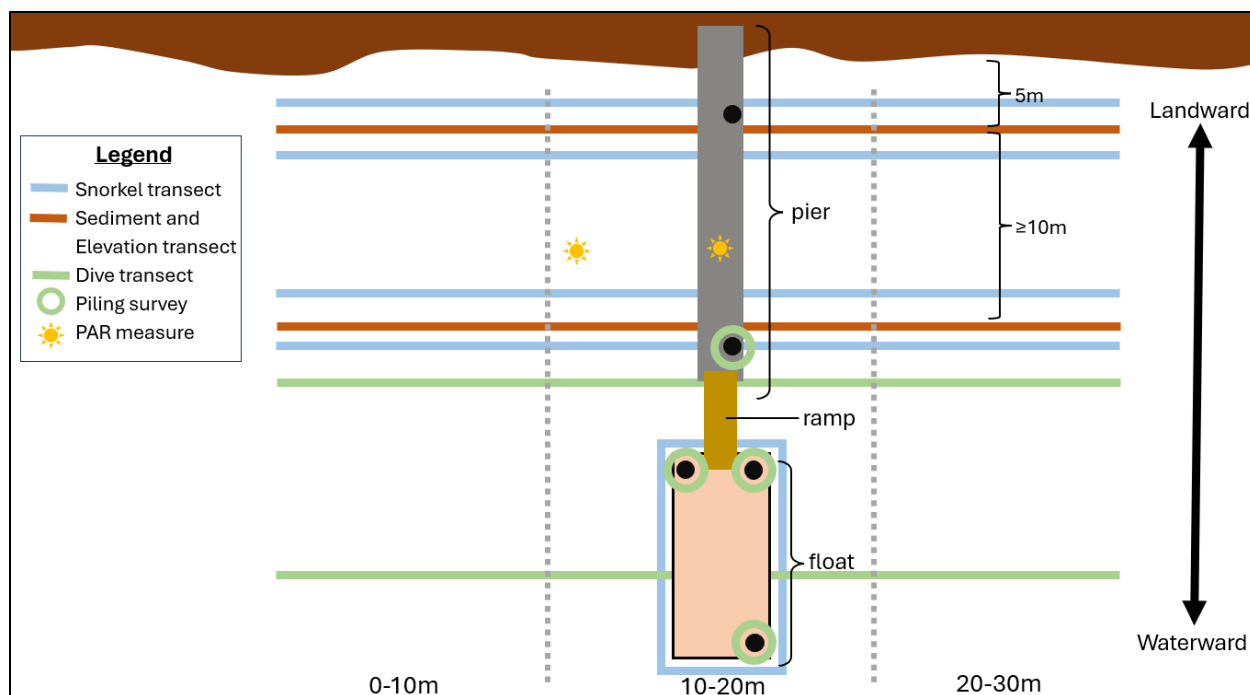


Figure 2: Sampling schematic for small overwater structures (SOWS) data collection. All shore parallel transects are 30m and centered on the structure. Dashed grey lines represent binning of transect sections considered near the dock (10-20m bin) and away from the dock (0-10m and 20-30m bins).

Site descriptions

Study sites and SOWS were selected based on specific size criteria available from the NOAA overwater structures geospatial dataset (NOAA 2018), with most structures falling within or closely meeting the requirements (Table 1). In this study, our measurements of structure dimensions often differed from those obtained from the NOAA dataset, with our estimates generally being lower. Total area of individual structures assessed in this study from our field measurements ranged from 59.5m² to 676.2m², whereas the NOAA estimates ranged from 66.6m² to 952.8m². These discrepancies are likely due to the inaccessibility of certain features of some of the SOWS in the field. The number of pilings associated with each structure varied greatly, ranging from 4 to 90 pilings, and were constructed from a variety of materials such as steel, creosote, and concrete. Decking material was also variable. Some structures had piers with solid decking made of wood planks or concrete, while others had plastic or aluminum grated decking. The height of piers above mean lower low water (MLLW) ranged from 2.8m to 7.4m. Dock dimensions, materials, and piling count observations were conducted during intertidal surveys (Table 1; described below).

Table 1: Characteristics of study sites and SOWS. Key: Region (WI = Whidbey Island; FI/WB = Fox Island/Wollochet Bay); Total SOWS Area m² Field/NOAA (includes all pier, ramp, and float segments); Drift Cell (indicator if SOWS occurred in a drift cell); Shoretype (FB = feeder bluff; TZ = transport zone; AS = accretion shoreform; NAD = no appreciable-drift, low energy); Armor Present (includes bulkheads or any other revetment type); Total Piling Count (includes all pier, ramp, and float segments); Pier/Float Decking (solid = planks or concrete; grated = plastic or aluminum; mix = combination of solid and grated material; Asterisk in Float Decking column indicates fixed/non-floating docks); Pier Height MLLW m (height of the pier relative to MLLW). Dashes indicated data when data was not collected.

Region	Total SOWS Area (m ²) Field	Total SOWS Area (m ²) NOAA	Drift Cell	Shoretype	Armor Present	Total Piling Count	Pier Decking	Float Decking	Pier Height MLLW (m)
WI	64.7	66.6	Y	FB	Y	8	grated	-	4.5
WI	96.8	135.4	Y	TZ	Y	9	grated	grated	5.3
WI	132.5	135.6	Y	FB	Y	45	solid	solid	6.9
WI	169.1	204.0	Y	FB	Y	21	grated	-	4.4
WI	-	271.6	Y	FB	N	57	solid	-	4.8
WI	361.8	476.8	Y	FB	Y	32	mix	mix	4.7
WI	644.8	952.8	Y	AS	Y	58	solid	solid*	4.9
WI	676.2	786.0	Y	TZ	N	90	solid	solid*	3.9
FI/WB	59.5	139.1	Y	TZ	Y	4	solid	mix	5.8
FI/WB	63.7	80.6	N	NAD	Y	8	grated	mix	5.4
FI/WB	69.2	92.7	Y	TZ	Y	12	grated	mix	5.2
FI/WB	69.3	97.0	Y	FB	Y	12	mix	mix	4.4
FI/WB	70.1	120.5	Y	TZ	Y	14	mix	mix	5.5
FI/WB	73.6	79.5	Y	FB	Y	10	mix	mix	6.3
FI/WB	117.7	144.9	Y	FB	Y	5	solid	solid	2.8
FI/WB	248.4	302.5	Y	TZ	N	11	solid	solid*	7.4

Intertidal surveys

We conducted intertidal surveys at low tides and measured various dimensions of the SOWS and collected sediment grain size and beach elevation data. Using transect tapes, we measured the length and width of the structures. If SOWS were comprised of multiple segments (e.g., pier, ramp, and float), the length and width of each segment was measured separately, and the total area of the SOWS was calculated by adding them together. Our field measurements were compared to NOAA's dimension estimates derived from their geospatial mapping dataset of overwater structures.

Sediment grain size distribution was estimated along two 30m shore-parallel transects centered on the pier of each SOWS at each site (Figure 2). One transect was placed approximately 5m waterward of the upland toe – denoted the ‘landward transect’ – with the second transect placed at least 10m waterward of the first – denoted the ‘waterward transect’. Along each transect we estimated surface and sub-surface sediment grain size percent cover in 21 0.5 X 0.5m quadrats. Sediment composition was categorized into five size classes: cobble (>6cm), pebble (4mm to 6cm), granule (2-4mm), sand (<2mm), and mud (smooth between fingers). Quadrats were spaced every 2 meters from transect distances 0m to 10m and 20m to 30m, and every one meter from transect distances 10m to 20m. This spacing created three distinct sampling bins, 0-10m, 10-20m, and 20-30m (n = 5 for both 0-10m and 20-30m bins and n = 11 for 10-20m bin), for which sediment data were parsed. After surface sediment grain size was estimated, we removed the quadrat and

dug away the top 5cm of sediment in the quadrat area. We then replaced the quadrat and estimated sub-surface grain size using the same size classes. Percent cover of shell hash (pieces of shell) was estimated separately. To address our hypothesis that SOWS will alter local sediment accretion, we collected position and elevation data using a real-time kinematic global positioning system (RTK GPS) at every meter mark (0-30m) along each transect. Elevation data were also parsed into the same three distinct sampling bins (i.e., 0-10m, 10-20m, and 20-30m). North American Vertical Datum of 1988 (NAVD88) values were converted to Mean Lower Low Water (MLLW) tidal datum for analysis using NOAA's VDatum conversion tool (NOAA, 2025).

Snorkel surveys

Snorkel surveys were focused on quantifying juvenile salmonids and other water column associated fishes following established protocols developed by the University of Washington (<https://www.shoremonitoring.org/fish/>). We snorkeled every site twice, once in the spring (May) and once in the summer (June-August), to span peaks of juvenile salmonid outmigration and juvenile salmon productivity. Surveys were conducted during high tides, when water levels were high enough to submerge most of the area beneath the pier of the SOWS. Snorkel surveys were conducted along at least four 30m transects parallel to shore (or more if space allowed), centered on the SOWS, with an additional survey encircling the floating dock at the end of the SOWS (Figure 2). During surveys, underwater observers recorded fish and crab abundance, size, distribution, and behavioral patterns, including feeding behaviors (Toft et al. 2007, Sawyer et al. 2020). Observations were standardized by transect length. Observations were coded as under the SOWS, adjacent (<1m) to the SOWS edge, or in open water away (>1m) from the SOWS. Fish identification was verified as needed by use of GoPro underwater videos, attached to clipboards during data collection. During snorkel surveys, two PAR ($\mu\text{mol photons m}^{-2} \text{s}^{-1}$) measurements were taken using a Li-Cor LI-192 sensor, one measurement was taken in the shaded area produced by the SOWS and another measurement in unshaded water both at 1m depth. Over the course of the study, 4 PAR measurements were made at each site (spring/summer, shaded/unshaded) at all sites except two (one in each study area).

Dive surveys

Subtidal SCUBA diving surveys were focused on quantifying submerged aquatic vegetation, macroinvertebrates, and benthic-associated fishes, and were based conceptually and taxonomically on Reef Check Washington protocols (<https://www.reefcheck.org/kelp-forest-program/training-tools/>), with some modifications. Two 30m by 1m shore-parallel swath transects centered on the pier were used to count fishes, benthic macroinvertebrates, and estimate benthic kelp cover (Figure 2). Each transect included three 10m subsample bins which allowed for comparison under (center segment: 10-20m) and adjacent to (end segments: 0-10m and 20-30m) the SOWS. The landward subtidal transect was placed to target a corrected depth of -2m to -3m MLLW, a zone anticipated to be high in submerged aquatic vegetation, if present. This placement aligned with the ramp (connecting the pier to the float) of the structure. The offshore transect targeted the center of the offshore float (Figure 2). At one site, an obstruction prevented surveyors from running the transect directly under the float, resulting in shifting the transect 1m waterward. We followed Reef Check's Kelp, Uniform Point Contact (UPC, targeting primary substrate or space-holding organism), and Fish survey protocols (<https://www.reefcheck.org/kelp-forest-program/training-tools/>). UPC measures three distinct layers: superlayer, cover, and substrate at 10 points within each transect bin. Superlayer is defined as upright species such as eelgrass and

stipitate kelps, cover includes prostrate algae such as *Ulva* sp., and substrate indicates the types of ground material such as sand, gravel, or cobble.

We also counted the dominant sessile and mobile organisms (macroinvertebrates and macroalgae) on up to four pilings at each site using a 1m vertical swath around the circumference. Similar to the onshore transect, piling surveys targeted a corrected depth of -2m to -3m MLLW. Reef Check's Kelp and Invertebrate survey protocols were performed on the pilings.

Field data analysis

Analyses for all data types focused on testing for SOWS effects. Additionally, site-specific covariates including total SOWS area and total number of pilings were sometimes tested, depending on the response variable. Total SOWS area and total number of pilings were positively correlated (Pearson's $r^2 = 0.8$, $p < 0.001$). We considered SOWS pilings to have a more direct effect on water and sediment movement, whereas SOWS area was more associated with effects on shading and biological communities. Accordingly, the more relevant covariate was used for each analysis depending on the response variable. We elected to not perform model selection as we wanted to compare the relative effects of explanatory variables to a given response; however, future analysis could explore model selection or model averaging techniques, or both, to focus results. Prior to analysis, all transect orientations were compared to the predominant along-shore drift direction (Washington Department of Ecology 2002), if defined, and re-oriented such that the 0m end was updrift and the 30m end was downdrift. The SOWS effect was tested using survey transect bin as the explanatory variable depending on the dataset of interest described below. Transect bin consists of three levels: (i) 10-20m, the section immediately under the SOWS; (ii) 0-10m, the section updrift relative to along-shore drift cell direction; and (iii) 20-30m, the section downdrift relative to along-shore drift cell direction. The 0-10m and 20-30m bins were treated separately to allow for detection of along-shore drift effects. While snorkel surveys were conducted along 30m transects, discrete bins were not assigned by distance. Rather, observers noted the position of fishes in relation to the structure as either (i) under the structure, (ii) adjacent to the structure (<1m away), or (iii) away (>1m) from the structure. All statistical analyses were conducted using the open-source R software (R Core Team, 2024).

To test for SOWS effects on sediment grain size and shell hash, percent cover data were arcsine square-root transformed to improve the normality of the data. Elevation data were normalized by subtracting the mean elevation from each site elevation aggregated by transect location. This centered the elevation differences around 0m, allowing for assessment of relative change along the transects, rather than analysis of absolute elevations, which were inherently variable among sites. Transformed sediment and shell hash data and normalized elevation data were used as the response variable in separate generalized linear models (GLMs) with Gaussian distributions and identity link functions to analyze their relationships with transect bin and total number of pilings. Model fits were separated by transect location (landward and waterward) and substrate layer (surface and sub-surface).

Abundance of crabs, kelps, and fishes from dive surveys were summed within each transect bin for each site and used as the response variable in GLMs testing the effect of SOWS adjacency via transect bin and total SOWS area. GLMs used Poisson distributions with log link functions to accommodate count data. Models were not fit for kelp abundance due to the lack of kelp at most sites, and very few kelps observed at sites where kelp was present. Benthic superlayer and cover data were averaged across sites and plotted. We tested for SOWS adjacency effects via transect bin

and total SOWS area effects on eelgrass percent cover (only recorded as a superlayer) on both the ‘under float’ and ‘under ramp’ transects. Percent cover was arcsine square-root transformed to improve the normality of the data.

Snorkel survey transects were aggregated by their orientation to the SOWS. Fish abundance by species was summed on all transects arranged perpendicularly to the pier and the remaining survey conducted around the float was treated separately. Within these two groupings we calculated the mean abundance of all fish species by season, study area, and SOWS adjacency. SOWS adjacency was defined in three categories (i) under the SOWS (‘yes’), (ii) within 1m of the SOWS (‘adjacent’), or (iii) not in close proximity to the SOWS (‘no’). Salmonid (family = Salmonidae) and non-salmonid species were plotted separately to highlight patterns of these groups. We elected not to fit statistical models for the effect of SOWS adjacency due to low or highly variable abundance, or both.

We tested for the effect of SOWS grating on PAR irradiance with a t-test. We elected to treat each PAR measure at each unique site and data independently; however, three sampling instances were removed due to instrument malfunction. First, raw PAR measures made under the SOWS (in the shaded portion of the water column) were converted to a proportion of PAR measured away from the SOWS (in the unshaded portion of the water column). Second, we observed multiple different types of SOWS decking and degree of grating. We elected to define SOWS as grated if any portion of the structure used grated decking.

NOAA overwater structures analysis

We aimed to increase understanding of SOWS effects in Puget Sound by summarizing and analyzing the NOAA overwater structures geospatial dataset (NOAA 2018). This is a rich dataset with many possible explorations and uses but our investigation had two primary goals. One, summarize SOWS counts, size, spacing, and density at the Puget Sound, drift cell and sub-basin scales. Two, relate summary metrics (above) with existing shoreline/nearshore features including shore type (MacLennan 2014), shoreline armoring, Beach Strategies Phase 2 data (Coastal Geologic Services 2020), submerged aquatic vegetation including floating kelp and eelgrass, and known forage fish spawning beaches.

We computed summary metrics directly from the NOAA overwater structures geospatial dataset in ArcGIS Pro. First, we filtered data to only consider structures with a total surface area $\leq 560\text{m}^2$. Summary metrics were then related to existing spatial layers from publicly available sources. We summarized metrics in relation to four existing Puget Sound spatial features, sub-basins used in the Floating Kelp Vital Sign (Berry et al. 2023), Washington State Counties, and Beach Strategies drift cells, and shoretypes (Coastal Geologic Services 2020). Detailed methods are available in Appendix A. For the purposes of this report, we report summary metrics including SOWS area, count, density, and inter SOWS distance at the drift cell scale. We compared these metrics of all Puget Sound to the drift cells in our two study areas: Whidbey Island and Fox Island/Wollochet Bay.

Results

Overall, our study found limited evidence of strong SOWS effects on sediment grain size, crabs, kelp, and benthic and water column fishes; however, some patterns did emerge including the relationship between proportion of smaller sediment grain sizes and shell hash to SOWS piling

number, increased elevation near SOWS, greater abundance of crabs and benthic fishes near SOWS, and reduced abundance of kelp and eelgrass near SOWS. Sites with grated decking allowed slightly more solar irradiance at 1m depth but irradiance was not significantly different than sites with solid decking ($t = 0.76$, $df = 15.303$, $p = 0.459$; Figure 3). Effects on juvenile salmonids and other water column fishes were highly variable with seasonal and regional effects appearing to drive patterns.

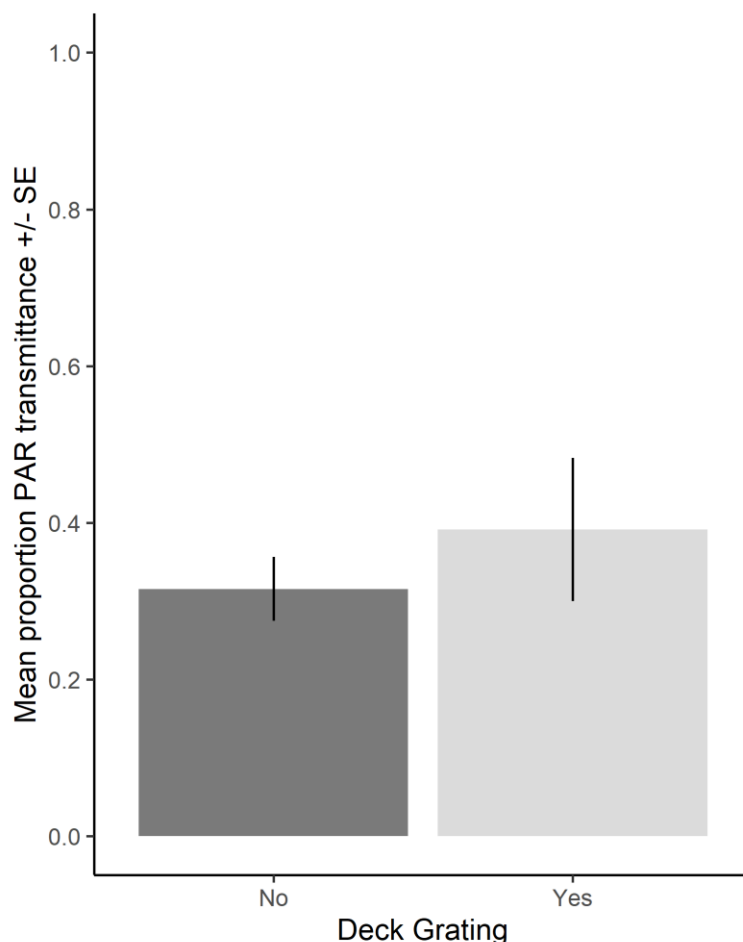


Figure 3: Proportion of photosynthetically active radiation (PAR) measured at 1m depth in the shaded portion of the water column at sites with grated and not grated decking. PAR proportion is calculated as the proportion of light measured in the shaded region of the SOWS compared to PAR measured unobstructed by any structure.

Sediment grain size, shell hash, and elevation

Sediment grain sizes did not respond to differences across transect bins for any combination of transect locations and layers, except for inconsistent changes in mud percent cover in the 20-30m bin and a slight decrease in cobble percent cover in the 10-20m bin (Supplementary Tables S1-S4; Supplementary Figures S1-S8). Since the pilings themselves were expected to be more representative of any direct impacts to sediment composition, to avoid collinearity between predictor variables, total number of pilings were included as a predictor variable rather than SOWS area. With sand and mud representing the light fraction material that we expect to have any response to SOWS influence, both grain size proportions variably responded to the total number of pilings associated with SOWS. The sub-surface layer of the landward transect showed moderate

negative correlations between sand proportion and number of pilings ($\beta = -0.002$, $p = 0.014$; Figure 4; Supplementary Table S2). Conversely, sand proportions increased with the number of pilings in the surface layer of the waterward transect ($\beta = 0.008$, $p < 0.001$). Following a similar pattern, mud percent cover decreased in both surface ($\beta = -0.003$, $p = 0.022$) and sub-surface ($\beta = -0.002$, $p < 0.001$) layers of the landward transect and increased in the surface layer of the waterward transect ($\beta = 0.001$, $p < 0.001$). As for the larger grain sizes, cobble percent cover consistently decreased in response to the number of pilings (Supplementary Tables S1-S4).

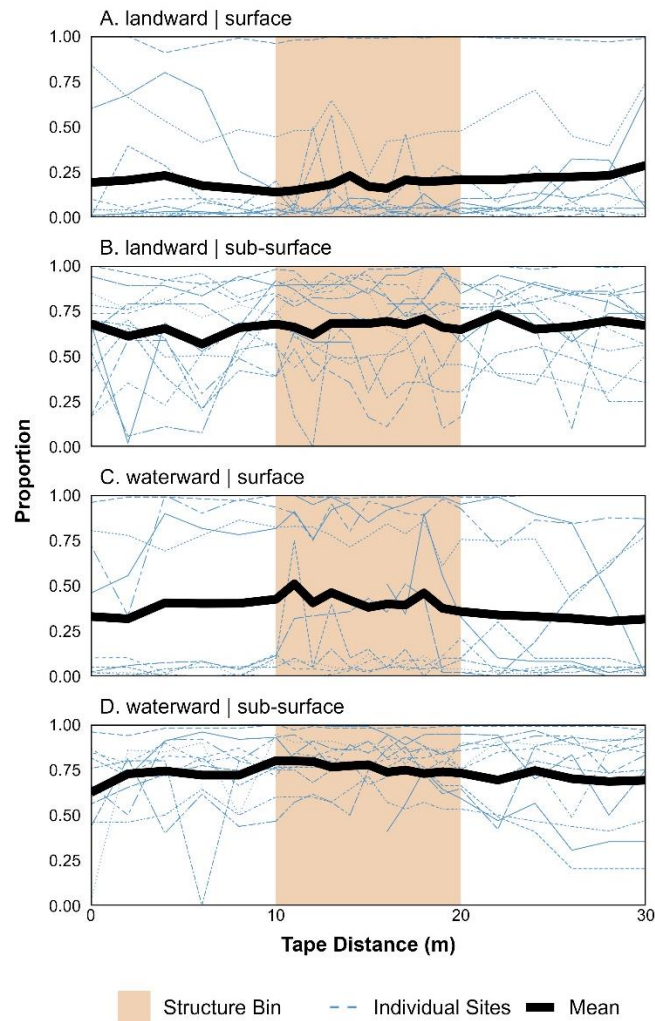


Figure 4: Sand (<2mm) proportion across (A) landward surface, (B) landward sub-surface, (C) waterward surface, and (D) waterward sub-surface transects. In each panel, dashed blue lines represent individual sites, and the solid black line indicates the mean sand proportion across all sites. The orange shaded area denotes the transect bin under/immediately adjacent to structure (10-20m bin). Tape distance (m) on the x-axis is oriented from upstream to downstream along the prevailing drift cell flow direction, when known (left to right).

Shell hash was another variable we expected to respond to the structural effects of SOWS, based on input from regional experts and its light fraction properties. Shell hash proportions did not respond to changes across transect bins for all combinations of transect locations and layers (Supplementary Tables S1-S4; Supplementary Figure S9-S13); however, shell hash proportions

increased with number of pilings at the landward sub-surface layer ($\beta = 0.004$, $p < 0.001$) and both waterward surface ($\beta = 0.001$, $p = 0.001$) and sub-surface ($\beta = 0.001$, $p = 0.002$) layers.

Shore-parallel profiles of elevation were significantly variable across transect bins in both landward and waterward transects (Figure 4; Table 2; Supplementary Figure S14); however, the number of pilings did not affect elevation (Table 2). Normalized elevation relative to MLLW in the landward transect increased under the SOWS structure ($\beta = 0.027$, $p = 0.024$; Table 2). In the waterward transect, normalized elevation increased both under ($\beta = 0.032$, $p < 0.001$; Table 2) and downdrift of the SOWS ($\beta = 0.028$, $p = 0.002$; Table 2). Increased elevations under and downdrift of the SOWS suggests accretion effects.

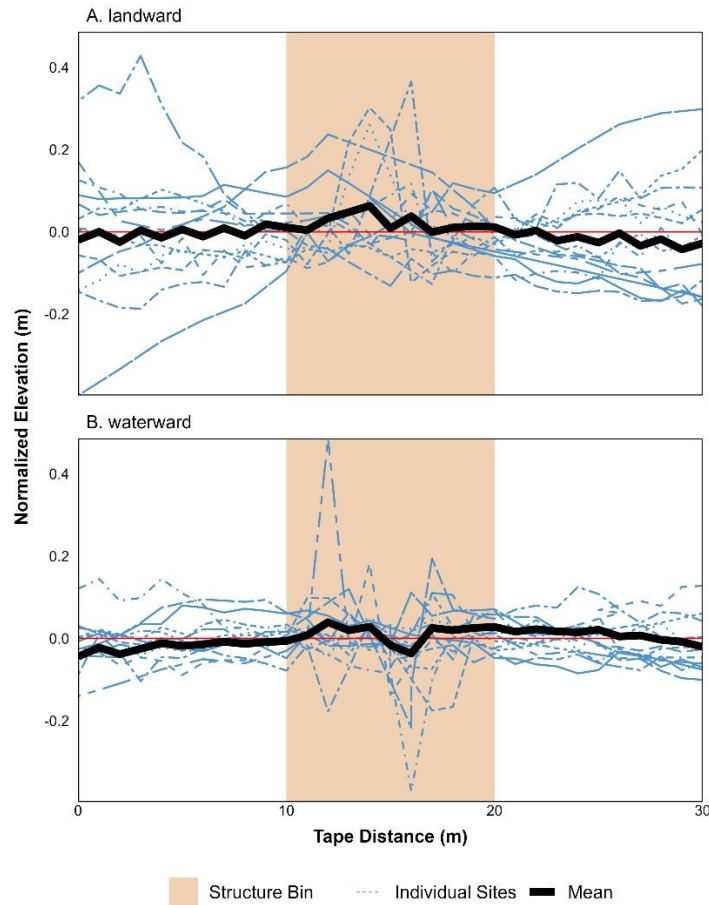


Figure 5: Profiles of normalized elevation (m) relative to MLLW along (A) landward and (B) waterward transects. In each panel, dashed blue lines represent individual sites, and the solid black line indicates the mean normalized elevation (m) across all sites for each transect. The solid horizontal red line indicates the y-intercept at 0m. The orange shaded area denotes the transect bin under/immediately adjacent to structure (10-20m bin). Tape distance (m) on the x-axis is oriented from upstream to downstream along the prevailing drift cell flow direction, when known (left to right).

Table 2: GLM output for the effect of transect bin and total number of pilings on normalized elevation (m) relative to MLLW. 0-10m transect bin serves as reference group.

Response	Effect	Estimate	Std. Error	t value	p
Elevation – landward transect	Intercept	-0.004	0.010	-0.387	0.699
	10-20m	0.027	0.012	2.266	0.024

	20-30m	-0.014	0.012	-1.135	0.257
	Total pilings	-0.0001	0.0002	-0.251	0.802
Elevation – waterward transect	Intercept	-0.020	0.078	-2.877	0.004
	10-20m	0.032	0.008	3.911	<0.001
	20-30m	0.028	0.009	3.191	0.002
	Total pilings	-0.00003	0.0002	-0.191	0.848

Benthic flora and fauna

Crab abundance varied among sites and SOWS adjacency (Figure 6a). On average, crab abundance was greatest near the SOWS (10-20m transect bin; $p = 0.002$), however, this pattern is strongly driven by a single site (Figure 6a, S15a). Furthermore, we found a strong positive relationship between crab abundance and total SOWS area ($p < 0.001$; Figure 6b; Table 3). Kelps were rarely observed among sites, and when they were observed, they were present in very low abundances (Figure 6c). Benthic observed (dive transects) fishes varied among sites and SOWS adjacency with a general trend of greater fish abundance near the SOWS (10-20m bin) and the end of the transect surveyed first (0 – 10m bin; Figure 6e). Total fish abundance was greater in these bins compared to the end surveyed last (20-30m bin; $p < 0.001$). Fish abundance also had a positive relationship with SOWS area ($p < 0.001$; Figure 6f; Table 3).

Table 3: GLM output for the effect of transect bin and structure total area on crab and benthic fish abundance. 0-10m transect bin serves as reference group.

Response	Effect	Estimate	Std. Error	Z value	p
Crab abundance	Intercept	0.118	0.194	0.611	0.511
	10-20m	0.511	0.168	3.049	0.002
	20-30m	0.100	0.183	0.547	0.584
	Total area	0.0115	0.0008	14.805	< 0.001
Benthic fish abundance	Intercept	2.139	0.080	26.708	<0.001
	10-20m	0.066	0.063	1.046	0.2696
	20-30m	-2.133	0.140	-15.226	<0.001
	Total area	0.012	0.0001	34.308	<0.001

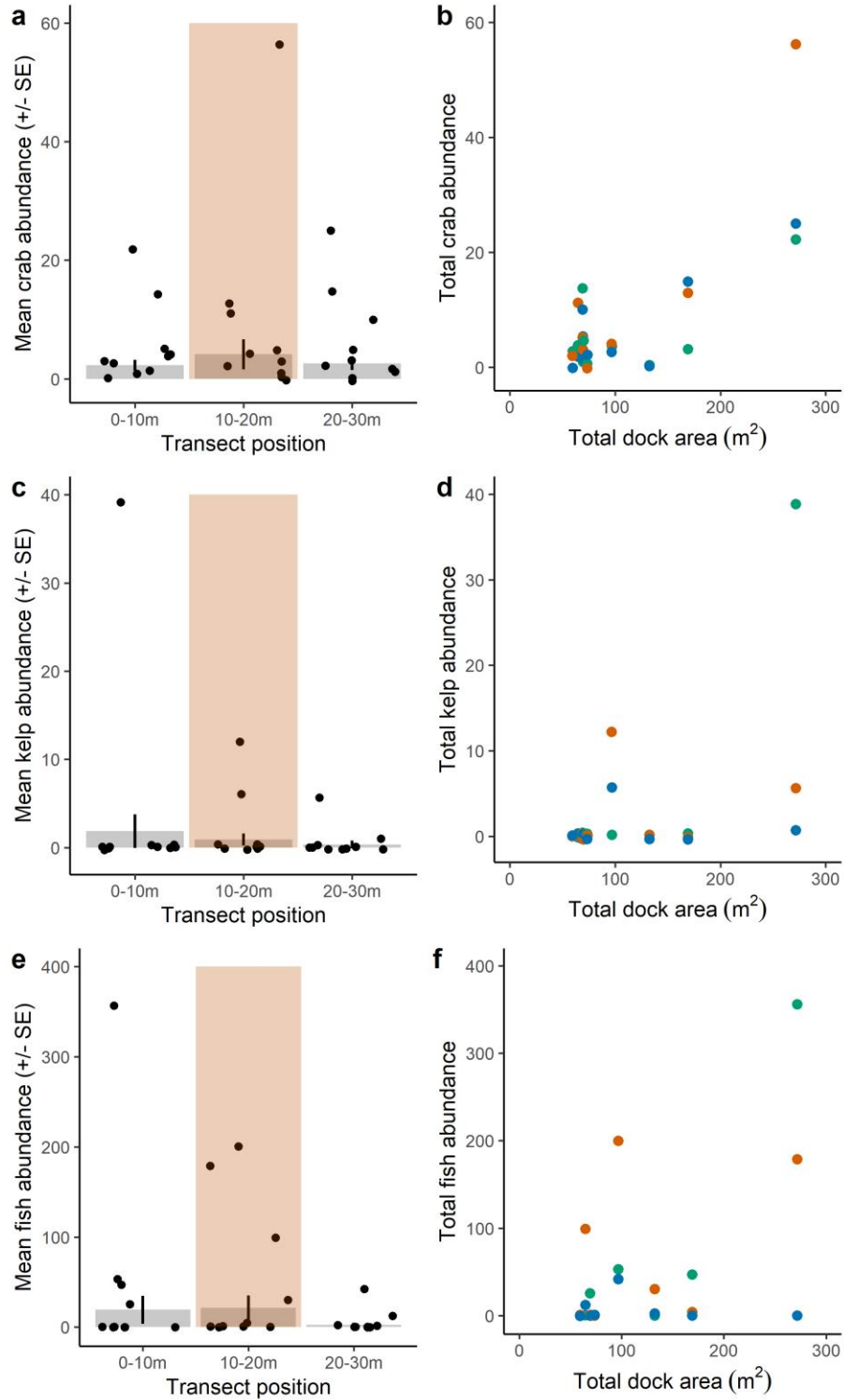


Figure 6: Mean total crab (a), kelp (stipe counts) (c), and benthic fish (e) abundance by transect position (counts per bin) and total dock area (b, d, f). Shaded region in a, c, and e denote bins near structure. Points indicate site level totals. Transect bin under/immediately adjacent to structure (10-20m) is highlighted with orange shading. Transect bin location in b, d, and f is noted as color 0-10m (teal), 10-20, (orange), 20-30m (blue). Points are jittered for clarity.

Benthic cover

Benthic cover varied by layer (cover and superlayer), largely dominated by bare substrate and green algae with occasional eelgrass, especially in the superlayer (Figure 7). Tests for an effect of SOWS adjacency and total SOWS area on eelgrass percent cover did not identify any significant effects (Table S5). Interestingly, the few observations of brown algae, including kelps, were all made upstream of or beneath SOWS.

Species diversity and abundance on SOWS pilings varied by site. At all but three sites invertebrates were observed, but only two sites had pilings with algae. In general, cover was dominated by invertebrates including mottled sea stars (*Evasterias troschelii*), plumose anemones (*Metridium* spp.), and ochre sea stars (*Pisaster ochraceus*). When present, algae cover was dominated by sugar kelp (*Saccharina latissima*) with acid weed (*Desmarestia* spp.) observed at one site.

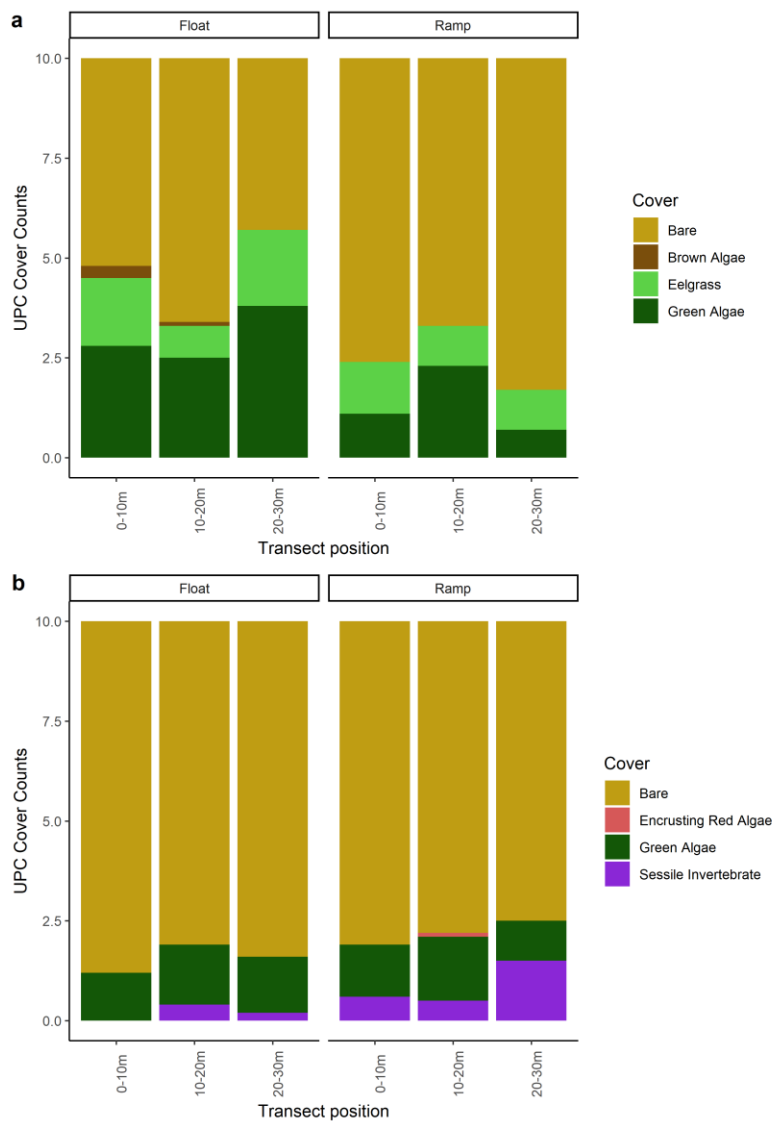


Figure 7: Mean UPC cover counts of benthic superlayer (a) and cover (b) among transect bins grouped by the transect placed perpendicular to the structure float or ramp. Transect position 10-20m is centered under the structure and positions 0-10m and 20-30m are adjacent to structure.

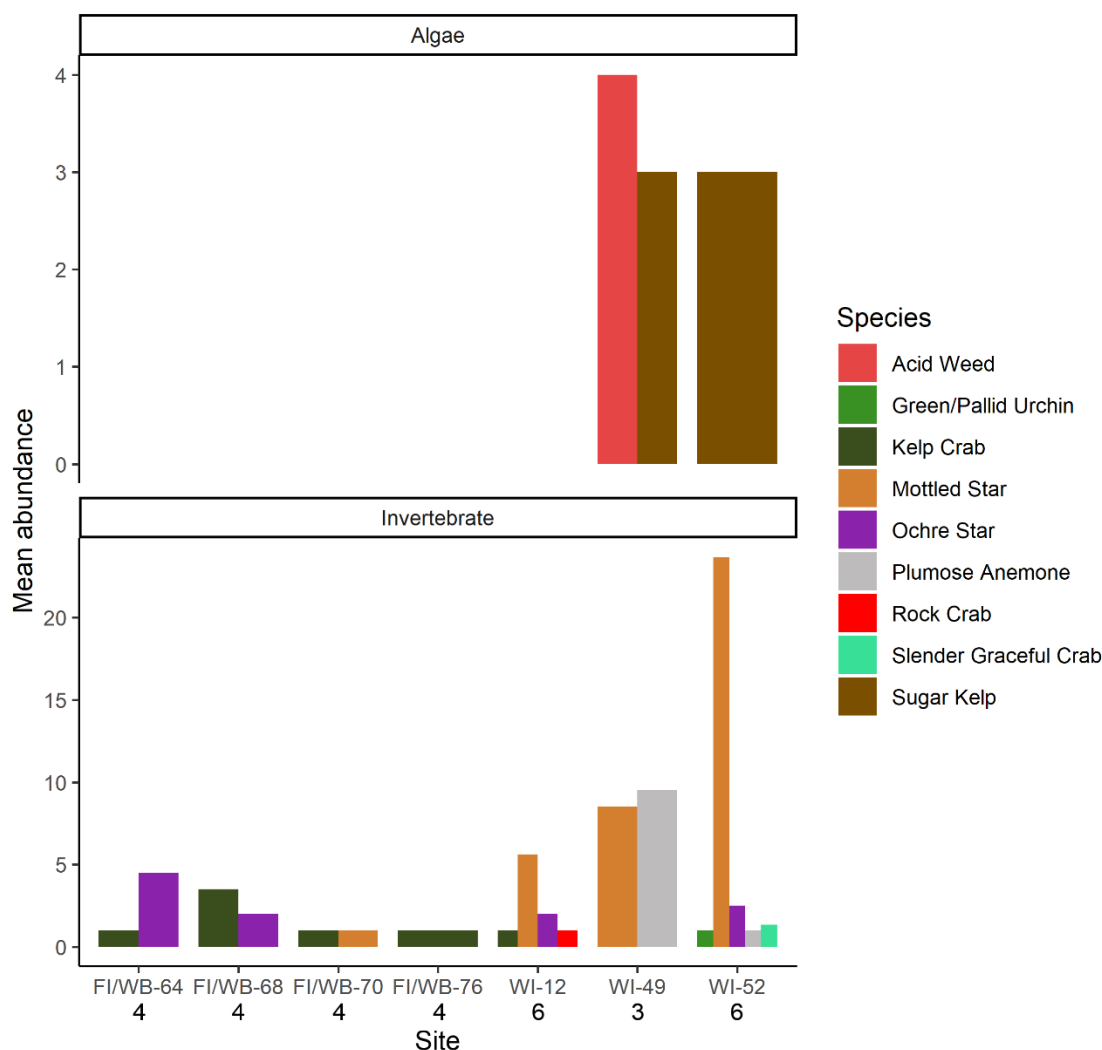


Figure 8: Mean abundance (counts) of algae and invertebrates observed on SOWS pilings. Numbers below each site name indicate the number of pilings surveyed. Three sites (not shown) were surveyed but no algae or invertebrates were observed.

Water column fishes

Juvenile salmonid abundance was variable among species and sites, with 9 out of 16 sites observing at least one salmonid. When salmonids were observed, they were mobile, mostly in the transect adjacent the shoreline, and typically schooling (chum/pink) or solo (Chinook; Figure 9). During and post transect surveys, we regularly observed salmon schools passing through snorkel transects and under piers. Salmon observed under piers were typically in large schools that were present along a shoreline that included a survey pier. While our data do not support a strong link between salmonids and SOWS adjacency, we understand that juvenile salmon are mobile, transient, and will frequently encounter SOWS in Puget Sound. While SOWS effects appear weak, we did observe strong seasonal and regional patterns in salmonid abundance. Salmonids were observed in the greatest abundance in the Fox Island/Wollochet Bay study area during spring surveys. In contrast, very few salmonids were observed during summer surveys and in the Whidbey Island study area at all (Figure S16a, b).

Non-salmonid fish abundance varied among species, sites, and SOWS adjacency (Figure S16c, d). In contrast to salmonids, all sites observed non-salmonid fishes. Shiner perch (*Cymatogaster aggregata*), when observed, were found in relatively high numbers compared to other species. Forage fishes – Pacific herring (*Clupea pallasii*) and Pacific sand lance (*Ammodytes personatus*) – were occasionally observed but at relatively low abundance. Pile perch (*Rhacochilus vacca*) and striped seaperch (*Embiotoca lateralis*) were associated with the float and pier pilings (Figure S16c, d).

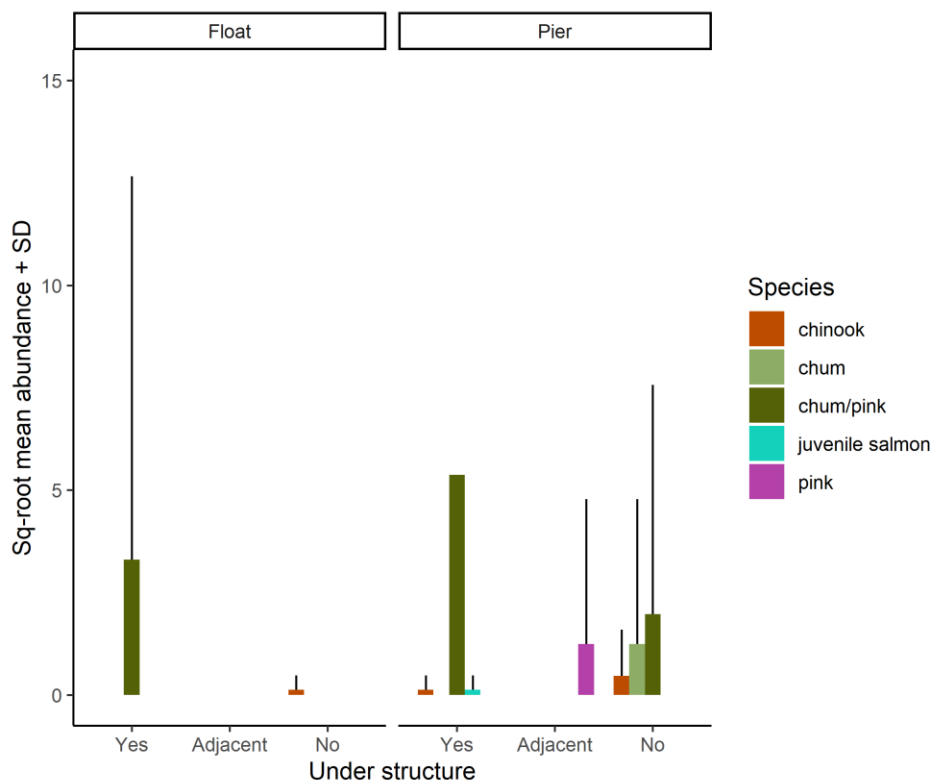


Figure 9: Square-root of mean salmonid abundance observed under (yes), adjacent, or not (no) under the SOWS. Abundance is summarized as observations near the float or most waterward portion of the structure or the mean of 4 or 5 transects (depending on site) that bisected the pier of the structure.

NOAA overwater structures analysis

Data summary statistics and spatial joins of NOAA overwater structure data provide a useful tool for investigating patterns and features of SOWS in Puget Sound. Detailed results are presented in Appendix A. Here we summarize results as they apply to drift cells and specific locations where we conducted fieldwork (results above; Figure 10). A total of 1,619 drift cells from Cape Flattery east to the main basin of Puget Sound were assessed for the presence and features of SOWS. Of these, 842 (52%) drift cells contained at least one SOWS. Our study regions of Fox Island/Wollochet Bay and Whidbey Island represented a very small proportion of the total number of SOWS in Puget Sound; however, are representative of the range of SOWS area, counts, density, and distance between SOWS (Table 5). The Fox Island/Wollochet Bay study area drift cells are representative of the upper end of SOWS surface area, counts, and density and lower end of distance between adjacent SOWS compared to all drift cells. Alternatively, the Whidbey Island study area drift cells

represent the opposite; characterized by lower SOWS counts and density and greater distance between SOWS.

Table 2: Summarized SOWS metrics from GIS analysis of NOAA overwater structure database grouped by drift cell. Area, density, and distance calculations omit drift cells with zero SOWS. Whidbey Island and Fox Island/Wollochet Bay study area drift cells all had at least one SOWS.

Metric	All drift cells (N = 1,619)				Whidbey Is. (N = 5)				Fox Is. / Wollochet Bay (N = 5)			
	Min	Mean	SD	Max	Min	Mean	SD	Max	Min	Mean	SD	Max
SOWS area - m ²	49.3	88.9	44.8	165.9	75.8	129.0	63.8	258.4	13.9	90.6	74.2	334.5
Count SOWS	0	4.3	1.9	149	1	9.2	9.1	20	16	38.4	28.5	83
Density SOWS - n/km	0	2.4	5.0	47.2	0.1	1.4	2.1	5.1	5.9	15.0	6.9	25.1
Mean distance between SOWS - km	<0.1	0.5	1.2	22.9	<0.1	0.1	<0.1	2.2	<0.1	<0.1	<0.1	0.2

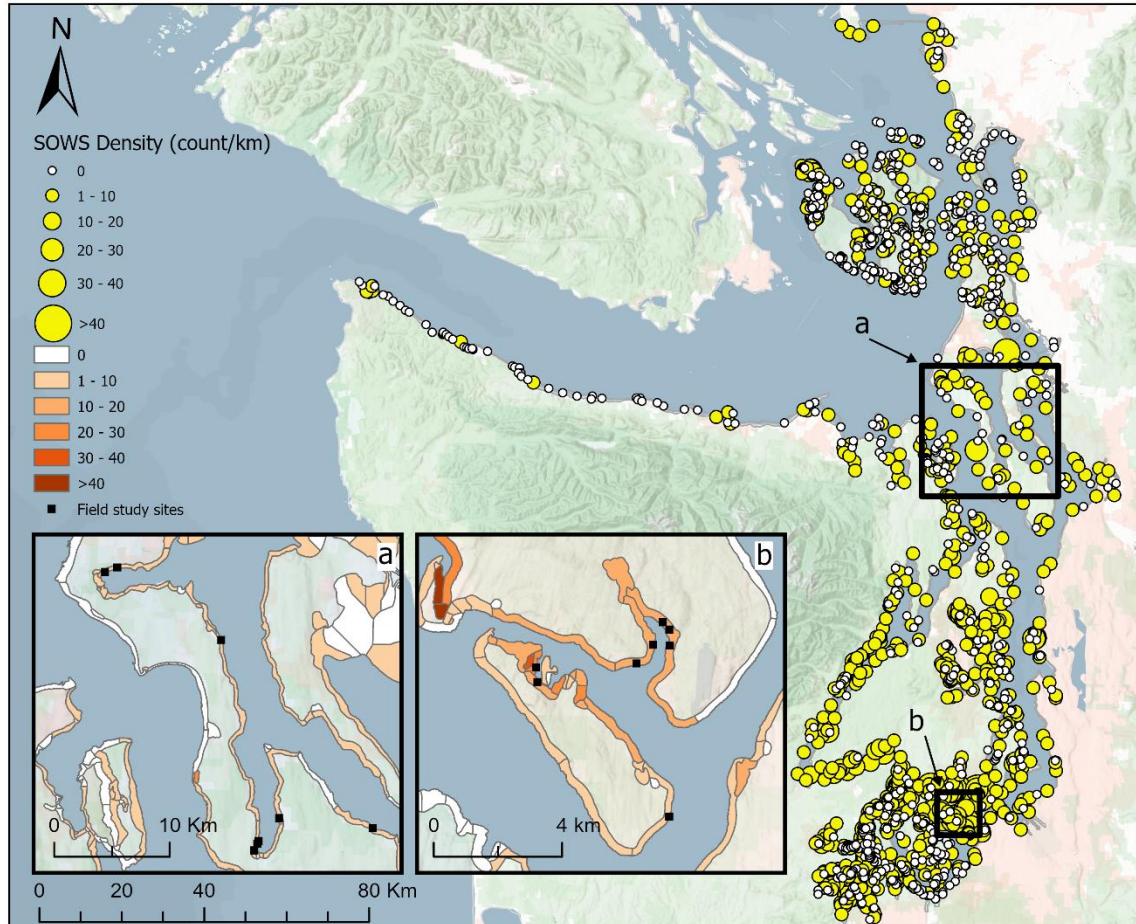


Figure 10: Puget Sound drift cells coded by density of small overwater structure (SOWS) density as count per kilometer of shoreline. Whidbey Island (a) and Fox Island/Wollochet Bay (b) study areas shown in detail with field study sites (black squares).

Discussion

Our results suggest that ecological effects of SOWS on the immediate nearshore environment may be limited, with some positive relationships to crabs and fishes that are possibly confounded by other factors. Positive effects of piling counts with sand and shell hash proportions may indicate SOWS influence along shore drift by slowing water movement and increasing the deposition of smaller sediment grain sizes. SOWS decking material had no effect on light irradiance under the structure and was considerably less than unshaded areas. However, PAR samplers noted that light subjectively appeared greater at sites with grated decking. We found some negative effects of SOWS on kelp and eelgrass – likely due to reduced light availability near and under SOWS; however, these data were highly variable and many sites had no eelgrass or kelp at all. Juvenile salmonids and other water column fishes were highly variable among sites and in relation to SOWS adjacency but did show strong regional and seasonal patterns.

The lack of a statistical effect of deck grating on PAR was not expected, however, we suggest that this result should be viewed with caution. First, PAR data are the result of point measurements. Light can vary widely in short periods of time due to weather and water conditions which could easily affect data. Second, due to our measurement approach we are not able to put PAR data in the context of biological relevance, that is the amount of total light available to photosynthetic organisms. Third, there is clear evidence that overwater structures limit the growth of eelgrass, and other submerged aquatic vegetation, from other studies (e.g., Fresh et al. 1995, 2006). Future efforts should focus on extended deployments of light loggers in and out of the shade of SOWS and relate these integrated light measures to physiological limits of submerged aquatic vegetation.

Although beach elevations sometimes increased near the SOWS, suggesting accretion, and either reduced or increased sand content, our dataset does not clearly demonstrate whether the pilings are directly affecting elevation values. At higher elevations in the intertidal, proportions of light fraction material, such as sand and mud, is reduced by piling intensity, aligning with the expectation of fixed structures (e.g., shoreline armoring) to decrease smaller sediment grain sizes through scouring. At the lower intertidal transects, and consistently for shell hash, increased sand and mud deposition around SOWS contrasts with expected sediment patterns on armored shorelines, where armoring tends to decrease the abundance of small sediment grain sizes on the waterward section of the structure (Dethier et al. 2016). Given that 13 of our 16 sites were on armored shorelines, this introduces an interesting paradigm of how armoring structures and SOWS may interact. While these patterns may suggest that SOWS could moderate the negative effects of armoring on sediments and accretion, the SOWS may be limiting smaller-grained sediment transport in the drift cell, potentially starving downdrift beaches of these sediments. Addressing these patterns would require baseline data on sediment and elevation prior to installation of SOWS and high frequency spatial and temporal sampling within a drift cell.

In the absence of baseline data, we found that SOWS may influence sediment accretion, especially lower in the intertidal where higher elevations were positively associated with transect bins under or downdrift (relative to drift cell flow direction) of the SOWS. Shore-parallel profiles indicate that elevations around SOWS were more variability underneath SOWS than in adjacent portions of the transect. Our interpretation is that the observed variability is meaningful, given that the precision of the RTK GPS measurements ranged from 0.010m to 0.094m vertically and 0.010m to 0.172m horizontally, meaning potential measurement error is much smaller than the observed variability along the transect. These changes in elevation further suggest that SOWS may be altering sediment dynamics across the shoreline in some capacity.

Our results suggest that crabs and some fishes may benefit from the structural habitat SOWS create in the nearshore environment. This is expected given that many studies describe strong relationships between structure and invertebrate and fish abundance (Huston 1979, Kovalenko et al. 2012, Strain et al. 2021). Our study design assessed species abundance on a gradient of SOWS adjacency, and we did not survey any adjacent habitat (>15m away) for the presence of crabs and fishes. Adjacent habitat, and the species assemblages therein, could have a large effect on the species presence in our transects. Future research could consider surveying adjacent, non-SOWS, habitats to address this question. One interpretation of our result may be that SOWS are ‘good’ for crabs and fishes; however, this perspective should be taken with caution. First, as described above, our study design did not survey adjacent habitats for crabs and fishes. Second, SOWS may be attracting organisms rather than fundamentally increasing crab and fish abundance in the ecosystem. This topic has been heavily studied in relation to artificial reefs, and in most cases

artificial structures appear to (i) be attractors more than producers of new biomass and (ii) their communities tend to differ from natural counterparts (Brickhill et al. 2005, Bracho-Villavicencio et al. 2023). Similarly, we did not survey kelp and eelgrass at non-SOWS sites or record measurements of flow despite the a priori assumption that SOWS would likely be constructed at sites protected or semi-protected from high flows that would commonly be associated with kelp abundance (Mann 1973).

Previous research on the effects of large overwater structures (e.g., ferry terminals) found that juvenile salmonids actively avoid going underneath these structures. Researchers observed juvenile salmonids altering their movement to not go under the structure, but swim along the outer (waterward) edge, potentially exposing them to increase predation risk (Shreffler & Moursund 1999, Simenstad et al. 1999, Williams et al. 2003, Munsch et al. 2014, 2017). These patterns and observations did not transfer to our study on smaller docks. While variable, salmonids were observed throughout our survey transects, seemingly independent of SOWS adjacency. Furthermore, we regularly observed salmonids and other fishes passing under all parts of the SOWS even though some of these instances were not part of survey transects. These results suggest that salmonids may not perceive shade lines of 1-3m as a threat compared to large shade swaths of 10-100s of meters created by large overwater structures.

A challenge for this work was balancing knowing what we wanted to measure but not understanding the optimal scale and resolution to go about doing so. This was unavoidable for a first-time study, and we did benefit from adapting existing methodologies with a strong track record from the Shoreline Monitoring Toolbox, Reef Check, and others; however, in hindsight we recognize that some methods, and our overall study design may not have been the best approach to address our questions given the capacity we had for this initial study. There are multiple aspects of the study that could be modified that may decrease variability and increase certainty, but for the purposes of SOWS effects of salmonids, kelp, and drift cell dynamics we suggest the following. One, including reference sites without SOWS present to provide a comparison where local (within 15m) SOWS effects are removed. Two, sediment traps could directly measure sediment movement and accretion in association with SOWS and reference areas. Three, higher frequency salmonid sampling may reduce variability and build a more complete picture of salmonid use. This could be accomplished with more frequent snorkel surveys, time-lapse video, or a combination of both. Four, a before – after, control – impact (BACI) study design could be a powerful approach to isolate time and SOWS effects; however, this may be logistically challenging and may not address cumulative SOWS effects.

Our study design focused on identifying SOWS effects at the local (within 15m) scale. This approach was driven by a goal to describe effects at the scale of the permit, which in most cases is the adjacent landward parcel. As discussed above, improvements could be made to increase sampling rigor at this scale; however, larger spatial and temporal scale SOWS effects deserve further attention. Much of Puget Sound has numerous SOWS with some drift cells holding 47 SOWS per km of shoreline or one SOWS every 22m on average (Figure 10; Table 3). In places with high or even moderate SOWS density, the potential for cumulative or interactive effects of SOWS, or both, in the nearshore environment seems plausible, even if local effects are absent or undetectable. There is strong evidence from armoring studies in Puget Sound that the drift cell context in which a site is located can change interpretation of results (e.g., Dethier et al. 2016). For example, if the sediment supply in a drift cell is 100% armored that may mask the effects of SOWS because there is less sediment in the system to begin with. This perspective is ripe for future research and could

consider multiple interactive effects including shoreline armoring, shoretype (e.g., bluff), drift cell size, water residence time, upland development, relative location of SOWS within a drift cell (e.g., are SOWS in the sediment supply, transport, or accretion zone), and others. This perspective may identify thresholds where SOWS effects on nearshore processes and species become more or less pronounced. Identifying these types of relationships may be particularly useful for restoration planning and prioritization as it could highlight SOWS or drift cells that would be impacted by new SOWS construction or restoration.

Small overwater structures are a ubiquitous feature of Puget Sound shorelines and their effects on nearshore processes and species have only recently gained attention. Our study is the first in the region to assess the effects of SOWS in the marine environment, focusing on potential impacts to kelp and salmon. In general, our results suggest weak effects, but this should not be mistaken as a lack of effect. As described above, elements of our data collection and study design may have precluded detecting of SOWS effects but were only apparent after sampling. Despite this, our data confirm that SOWS, like large overwater structures, reduce light availability to primary producers and therefore lead to reduced abundance; however, SOWS built with grated decks have less of a negative effect on light. Limited effects of SOWS may also be indicative that current regulations are working, i.e., limiting the size and shading of SOWS minimizes the impact to fish and kelp. From a broader perspective, our data confirm that many species of interest occur near SOWS including juvenile salmonids, kelp, and eelgrass. This should encourage natural resource managers, restoration practitioners, and scientists to continue to consider and research SOWS effects on these species and the nearshore ecosystem in general. While the results of this study may provide limited understanding on the effects of SOWS on nearshore processes and species, SOWS and adjacent shorelines should still be considered for restoration action. The clearest effect of SOWS removal would be increased light availability which will have positive effects on submerged aquatic vegetation. SOWS removal would also likely coincide with removal of shoreline armoring as 13 of out 16 study sites included shoreline armor and armor removal has a variety of benefits to nearshore processes and species (Des Roches et al. 2022). Depending on the materials used, SOWS removal may have the additional benefit of removing harmful materials such as creosote pilings from the environment which have detrimental effects to fish life (Vines et al. 2000).

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References

Berry H, Raymond WW, Claar DC, Dowty P, Spaulding E, Christiansen B, Ferrier L, Ledbetter J, Naar N, Woodard T, Palmer-McGee C, Cowdrey T, Oster D, Shull S, Mumford T, Dethier MN (2023)

- Floating Kelp Monitoring in Washington State: Statewide Summary. Washington Department of Natural Resources.
- Bracho-Villavicencio C, Matthews-Cascon H, Rossi S (2023) Artificial Reefs around the World: A Review of the State of the Art and a Meta-Analysis of Its Effectiveness for the Restoration of Marine Ecosystems. *Environments* 10:121.
- Brickhill MJ, Lee SY, Connolly RM (2005) Fishes associated with artificial reefs: attributing changes to attraction or production using novel approaches. *Journal of Fish Biology* 67:53–71.
- Coastal Geologic Services C (2020) Beach strategies for Puget Sound, Phase 2 Summary Report.
- Des Roches S, LaFuente JR, Faulkner HS, Morgan JR, Perla BS, Metler M, Dethier MN, Toft JD (2022) Shoreline armor removal can restore variability in intertidal ecosystems. *Ecological Indicators* 140:109056.
- Dethier MN, Raymond WW, McBride AN, Toft JD, Cordell JR, Ogston AS, Heerhartz SM, Berry HD (2016) Multiscale impacts of armoring on Salish Sea shorelines: Evidence for cumulative and threshold effects. *Estuarine, Coastal and Shelf Science* 175:106–117.
- Fresh K, Williams B, Penttila D (1995) Overwater structures and impacts on eelgrass (*Zostera marina*) in Puget Sound, Washington. In: *'Puget Sound Research '95 Proceedings.'* Puget Sound Water Quality Authority, Seattle, Washington, p 537–543
- Fresh KL, Wyllie-Echeverria T, Wyllie-Echeverria S, Williams BW (2006) Using light-permeable grating to mitigate impacts of residential floats on eelgrass *Zostera marina* L. in Puget Sound, Washington. *Ecological Engineering* 28:354–362.
- Huston M (1979) A General Hypothesis of Species Diversity. *The American Naturalist* 113:81–101.
- Kovalenko KE, Thomaz SM, Warfe DM (2012) Habitat complexity: approaches and future directions. *Hydrobiologia* 685:1–17.
- Lambert MR, Ojala-Barbour R, Jr RV, McIntyre AP, Quinn T (2021) Small overwater structures: a review of effects on Puget Sound habitat and salmon. Washington Department of Fish and Wildlife, Olympia, Washington.
- Lambert MR, Ojala-Barbour R, Vadas Jr. R, McIntyre A, Quinn T (2023) Do small overwater structures impact marine habitats and biota? *Pac Conserv Biol*.
- MacLennan AJ (2014) Coastal Landforms.
- Mann KH (1973) Seaweeds: Their Productivity and Strategy for Growth: The role of large marine algae in coastal productivity is far more important than has been suspected. *Science* 182:975–981.
- Moore ME, Berejikian BA (2022) Coastal infrastructure alters behavior and increases predation mortality of threatened Puget Sound steelhead smolts. *Ecosphere* 13:e4022.
- Munsch SH, Cordell JR, Toft JD (2017) Effects of shoreline armouring and overwater structures on coastal and estuarine fish: opportunities for habitat improvement. *Journal of Applied Ecology* 54:1373–1384.
- Munsch SH, Cordell JR, Toft JD, Morgan EE (2014) Effects of Seawalls and Piers on Fish Assemblages and Juvenile Salmon Feeding Behavior. *North American Journal of Fisheries Management* 34:814–827.
- NOAA (2018) Puget Sound Over Water Structures: Salmon Habitat Status and Trend Monitoring Program Data.
- Shreffler D, Moursund R (1999) Impacts of ferry terminals on juvenile salmon migrating along Puget Sound shorelines. Phase II: field studies at Port Townsend Ferry Terminal. Washington State Department of Transportation.
- Simenstad CA, Nightingale BJ, Thom RM, Shreffler DK (1999) Impacts of Ferry Terminals on Juvenile Salmon Migrating Along Puget Sound Shorelines. Phase I: Synthesis of State of Knowledge. Washington State Department of Transportation.

- Strain EMA, Steinberg PD, Vozzo M, Johnston EL, Abbiati M, Aguilera MA, Airolidi L, Aguirre JD, Ashton G, Bernardi M, Brooks P, Chan BKK, Cheah CB, Chee SY, Coutinho R, Crowe T, Davey A, Firth LB, Fraser C, Hanley ME, Hawkins SJ, Knick KE, Lau ETC, Leung KMY, McKenzie C, Macleod C, Mafanya S, Mancuso FP, Messano LVR, Naval-Xavier LPD, Ng TPT, O'Shaughnessy KA, Pattrick P, Perkins MJ, Perkol-Finkel S, Porri F, Ross DJ, Ruiz G, Sella I, Seitz R, Shirazi R, Thiel M, Thompson RC, Yee JC, Zabin C, Bishop MJ (2021) A global analysis of complexity–biodiversity relationships on marine artificial structures. *Global Ecol Biogeogr* 30:140–153.
- Toft J, Cordell JR, Levey C, Morgan E, Armburst E (2013) Salmon Bay Natural Area: Restoration Monitoring. Prepared for Seattle Public Utilities, Seattle, Washington.
- Vines C, Robbins T, Griffin FJ, Cherr GN (2000) The effects of diffusible creosote-derived compounds on development in Pacific herring (*Clupea pallasii*). *Aquatic Toxicology* 51:225–239.
- WAC 220-660-380 (no date) Residential and public recreational docks, piers, ramps, floats, watercraft lifts, and buoys in saltwater areas.
- Washington Department of Ecology (2002) Shoreline Sediment Driftcells.
- Williams GD, Thom RM, Shreffler DK, Southard JA, O'Rourke LK, Sargeant SL, Cullinan VI, Moursund R, Stamey M (2003) Assessing Overwater Structure-Related Predation Risk on Juvenile Salmon: Field Observations and Recommended Protocols. Washington State Department of Transportation.

Supplementary Material

Supplementary Table S1: GLM output for the effect of transect bin and total number of pilings on sediment grain size and shell hash percent cover in the surface layer of the landward transect. 0-10m transect bin serves as reference group. Sediment grain size and shell hash are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), mud (smooth between fingers), and shell hash (pieces of shell).

Response	Effect	Estimate	Std. Error	t value	p
cobble	Intercept	0.130	0.020	6.545	<0.001
	10-20m	-0.023	0.022	-1.071	0.285
	20-30m	-0.018	0.025	-0.690	0.490
	Total pilings	-0.001	0.0004	-2.680	0.008
pebble	Intercept	0.999	0.045	21.996	<0.001
	10-20m	0.038	0.050	0.756	0.450
	20-30m	-0.069	0.058	-1.196	0.232
	Total pilings	-0.001	0.001	-1.330	0.184
granule	Intercept	0.176	0.024	7.390	<0.001
	10-20m	-0.004	0.026	-0.142	0.887
	20-30m	0.026	0.031	0.847	0.398
	Total pilings	0.003	0.0004	7.532	<0.001
sand	Intercept	0.409	0.049	8.361	<0.001
	10-20m	-0.002	0.053	-0.033	0.974
	20-30m	0.069	0.062	1.098	0.273
	Total pilings	-0.002	0.001	-1.833	0.068
mud	Intercept	0.007	0.007	1.000	0.318
	10-20m	0.0002	0.007	0.025	0.980
	20-30m	0.035	0.008	4.260	<0.001
	Total pilings	-0.0003	0.0001	-2.296	0.022
shell hash	Intercept	0.118	0.012	9.975	<0.001
	10-20m	0.005	0.013	0.381	0.703
	20-30m	0.005	0.015	0.321	0.748
	Total pilings	-0.0002	0.0002	-0.072	0.942

Supplementary Table S2: GLM output for the effect of transect bin and total number of pilings on sediment grain size and shell hash percent cover in the sub-surface layer of the landward transect. 0-10m transect bin serves as reference group. Sediment grain size and shell hash are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), mud (smooth between fingers), and shell hash (pieces of shell).

Response	Effect	Estimate	Std. Error	t value	p
cobble	Intercept	0.089	0.017	5.227	<0.001
	10-20m	-0.042	0.019	-2.259	0.025
	20-30m	-0.012	0.022	-0.540	0.590
	Total pilings	-0.001	0.0003	-2.080	0.038
pebble	Intercept	0.440	0.028	15.641	<0.001
	10-20m	-0.047	0.031	-1.517	0.130
	20-30m	-0.055	0.036	-1.506	0.133
	Total pilings	-0.001	0.001	-1.316	0.189
granule	Intercept	0.203	0.028	7.247	<0.001
	10-20m	-0.003	0.031	-0.106	0.916
	20-30m	-0.034	0.036	-0.938	0.349
	Total pilings	0.003	0.001	6.458	<0.001
sand	Intercept	0.975	0.036	26.954	<0.001
	10-20m	0.050	0.039	1.264	0.207
	20-30m	0.064	0.047	1.373	0.171
	Total pilings	-0.002	0.001	-2.484	0.014
mud	Intercept	0.134	0.018	7.266	<0.001
	10-20m	-0.010	0.020	-0.472	0.637
	20-30m	0.005	0.024	0.192	0.848
	Total pilings	-0.002	0.0003	-4.511	<0.001
shell hash	Intercept	0.121	0.018	6.746	<0.001
	10-20m	-0.019	0.019	-0.971	0.332
	20-30m	-0.002	0.023	-0.108	0.914
	Total pilings	0.004	0.0003	11.974	<0.001

Supplementary Table S3: GLM output for the effect of transect bin and total number of pilings on sediment grain size and shell hash percent cover in the surface layer of the waterward transect. 0-10m transect bin serves as reference group. Sediment grain size and shell hash are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), mud (smooth between fingers), and shell hash (pieces of shell).

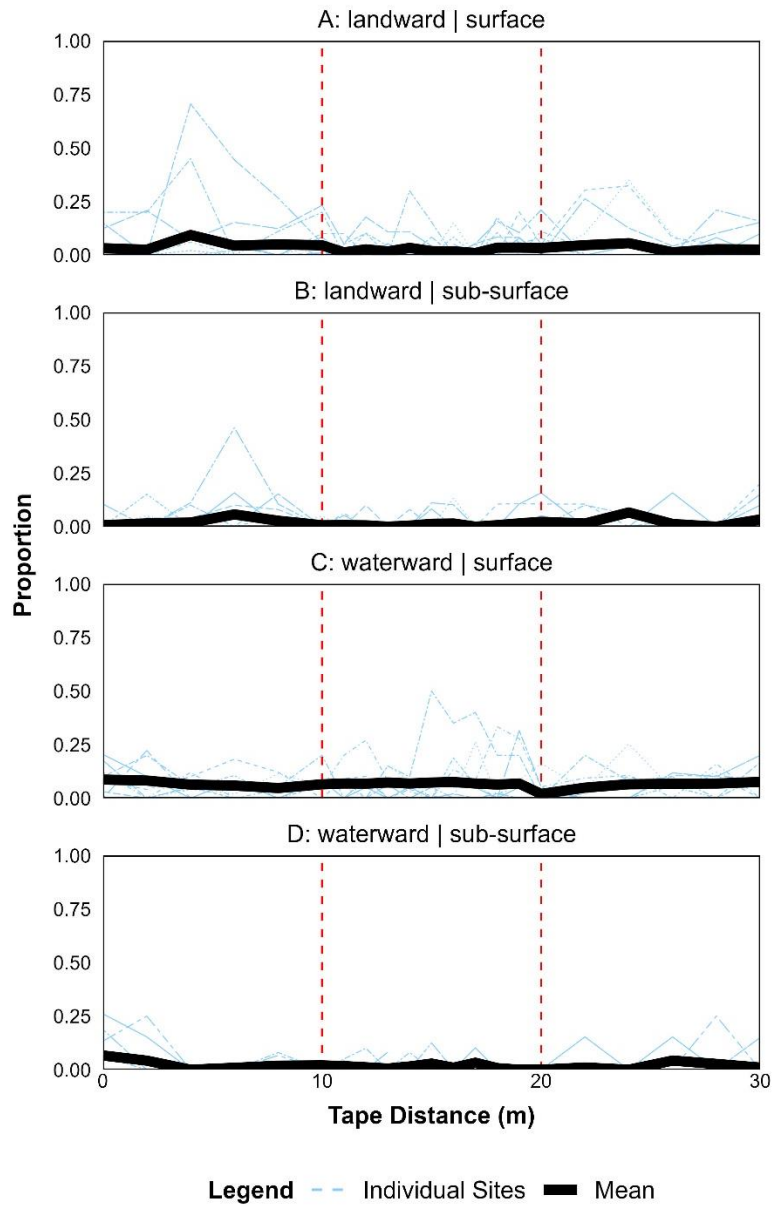
Response	Effect	Estimate	Std. Error	t value	p
cobble	Intercept	0.208	0.027	7.611	<0.001
	10-20m	-0.015	0.030	-0.509	0.611
	20-30m	-0.018	0.035	-0.519	0.604
	Total pilings	-0.002	0.001	-4.316	<0.001
pebble	Intercept	0.922	0.061	15.201	<0.001
	10-20m	-0.038	0.066	-0.570	0.569
	20-30m	0.083	0.077	1.071	0.285
	Total pilings	-0.007	0.001	-5.983	<0.001
granule	Intercept	0.189	0.024	7.900	<0.001
	10-20m	-0.024	0.026	-0.936	0.350
	20-30m	-0.016	0.031	-0.511	0.609
	Total pilings	-0.001	0.0004	-1.498	0.135
sand	Intercept	0.417	0.063	6.614	<0.001
	10-20m	0.067	0.069	0.982	0.327
	20-30m	-0.053	0.080	-0.662	0.508
	Total pilings	0.008	0.001	6.742	<0.001
mud	Intercept	-0.008	0.008	-1.071	0.285
	10-20m	0.004	0.008	0.533	0.594
	20-30m	-0.002	0.010	-0.233	0.816
	Total pilings	0.001	0.0001	5.945	<0.001
shell hash	Intercept	0.157	0.022	7.180	<0.001
	10-20m	-0.004	0.024	-0.187	0.852
	20-30m	0.010	0.028	0.370	0.712
	Total pilings	0.001	0.0004	3.393	0.001

Supplementary Table S4: GLM output for the effect of transect bin and total number of pilings on sediment grain size and shell hash percent cover in the sub-surface layer of the waterward transect. 0-10m transect bin serves as reference group. Sediment grain size and shell hash are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), mud (smooth between fingers), and shell hash (pieces of shell).

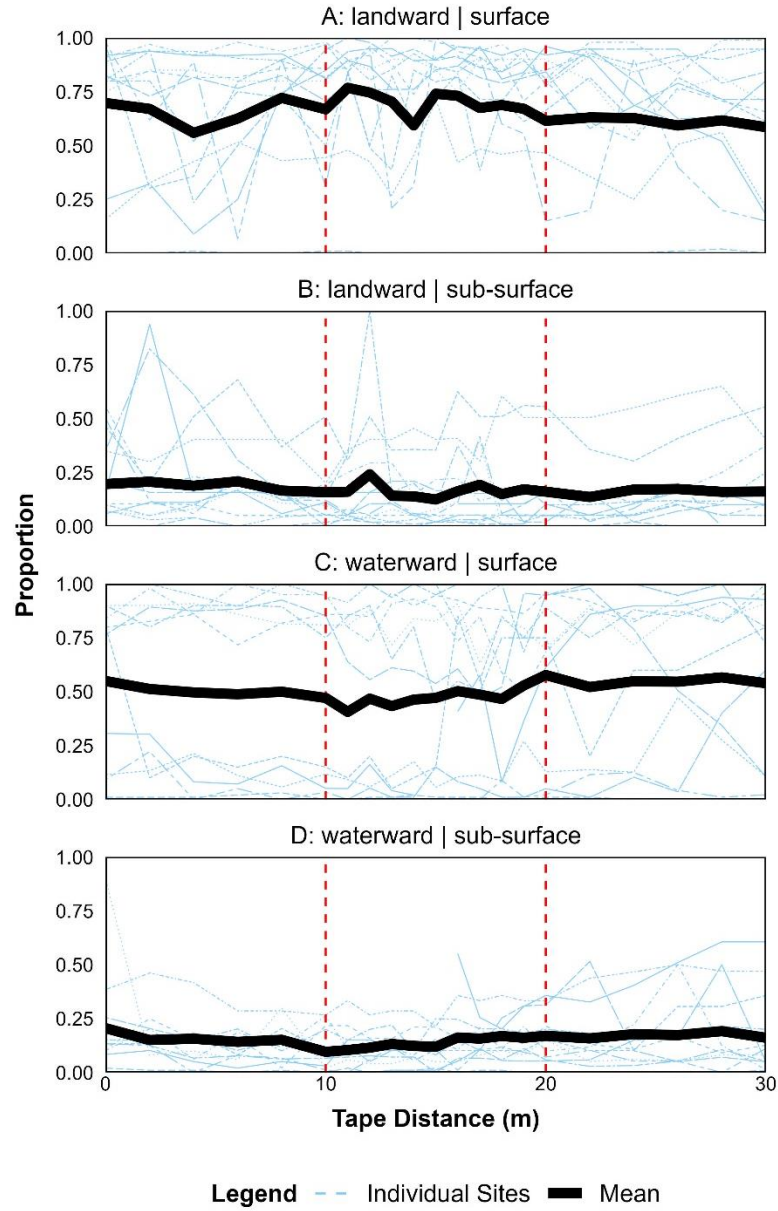
Response	Effect	Estimate	Std. Error	t value	p
cobble	Intercept	0.086	0.017	5.023	<0.001
	10-20m	-0.035	0.019	-1.888	0.060
	20-30m	-0.027	0.022	-1.231	0.219
	Total pilings	-0.0004	0.0003	-1.403	0.162
pebble	Intercept	0.382	0.028	13.646	<0.001
	10-20m	-0.020	0.031	-0.659	0.510
	20-30m	0.036	0.036	1.005	0.316
	Total pilings	-0.001	0.001	-1.613	0.108
granule	Intercept	0.152	0.019	8.199	<0.001
	10-20m	-0.011	0.020	-0.545	0.586
	20-30m	-0.009	0.024	-0.363	0.716
	Total pilings	0.0003	0.0003	0.905	0.366
sand	Intercept	1.011	0.036	28.461	<0.001
	10-20m	0.071	0.039	1.828	0.069
	20-30m	0.011	0.045	0.250	0.803
	Total pilings	0.001	0.001	0.962	0.337
mud	Intercept	0.147	0.025	5.861	<0.001
	10-20m	-0.049	0.027	-1.777	0.077
	20-30m	-0.082	0.032	-2.580	0.010
	Total pilings	0.0004	0.001	0.958	0.339
shell hash	Intercept	0.221	0.024	9.376	<0.001
	10-20m	-0.013	0.026	-0.490	0.624
	20-30m	-0.025	0.030	-0.824	0.411
	Total pilings	0.001	0.0004	3.155	0.002

Supplemental Table S5: GLM output for the effect of transect bin and total SOWS surface area on eelgrass cover on the under dock and under gangway transect.

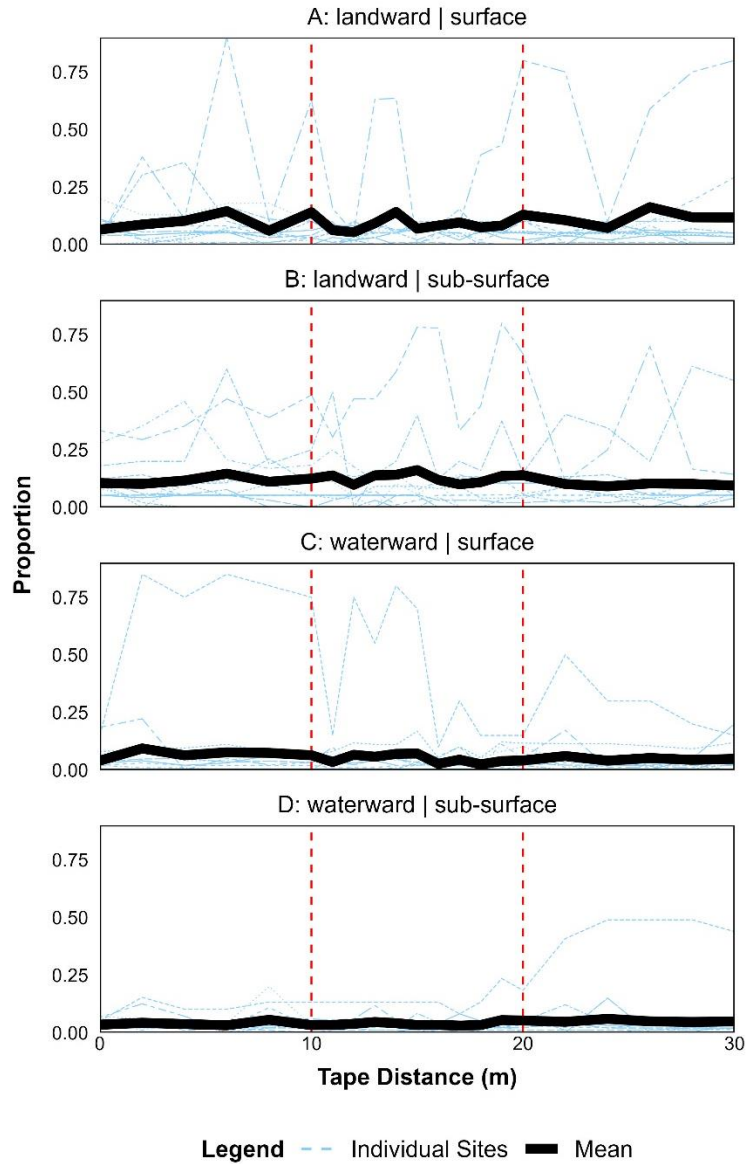
Response	Effect	Estimate	Std. Error	Z value	p
Eelgrass cover – under float transect	Intercept	0.176	0.230	0.768	0.450
	10-20m	-0.145	0.233	-0.624	0.538
	20-30m	0.026	0.233	0.111	0.913
	Total area	0.001	0.001	0.500	0.621
Eelgrass cover – under ramp transect	Intercept	0.229	0.225	1.016	0.319
	10-20m	-0.058	0.228	-0.254	0.802
	20-30m	-0.058	0.228	-0.254	0.802
	Total area	-0.000	0.001	-0.086	0.932



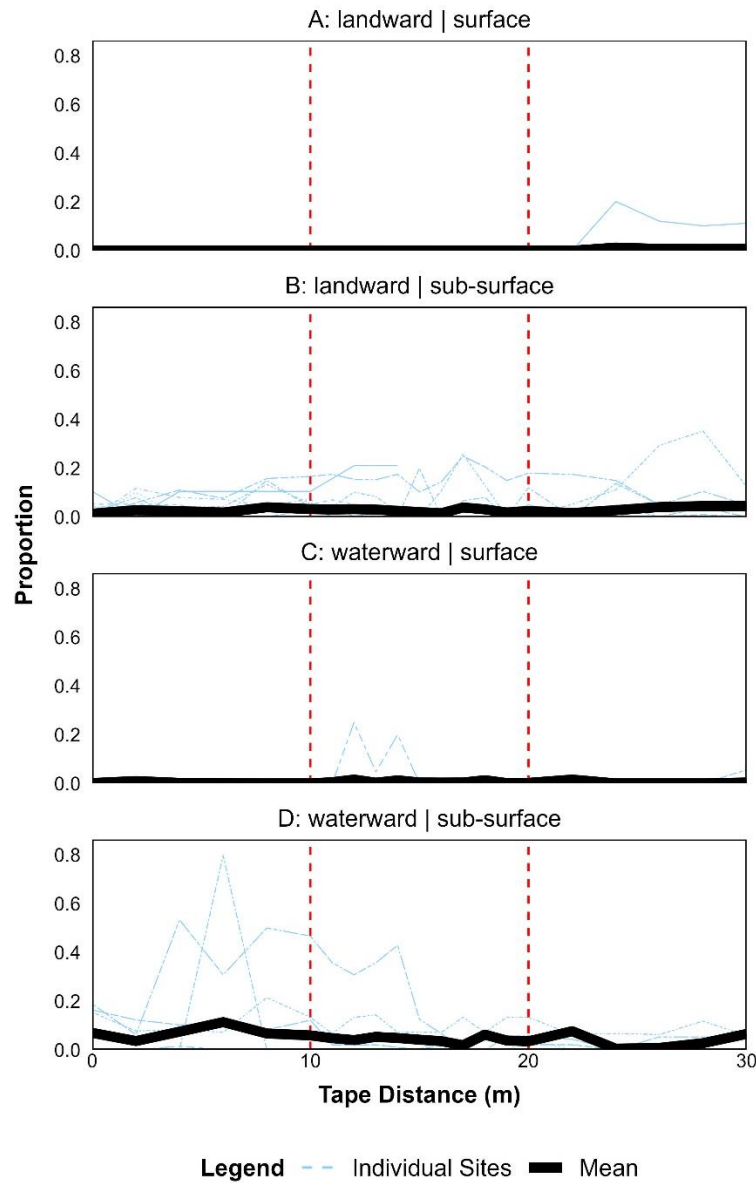
Supplementary Figure S1: Cobble (>6cm) proportion across (A) landward surface, (B) landward sub-surface, (C) waterward surface, and (D) waterward sub-surface transects. In each panel, dashed teal lines represent individual sites, and the solid black line indicates the mean cobble proportion across all sites. The two red dashed vertical lines delineate the separation of transect bins (0-10m, 10-20m, and 20-30m). Tape distance (m) on the x-axis is oriented from upstream to downstream along the prevailing drift cell flow direction, when known (left to right).



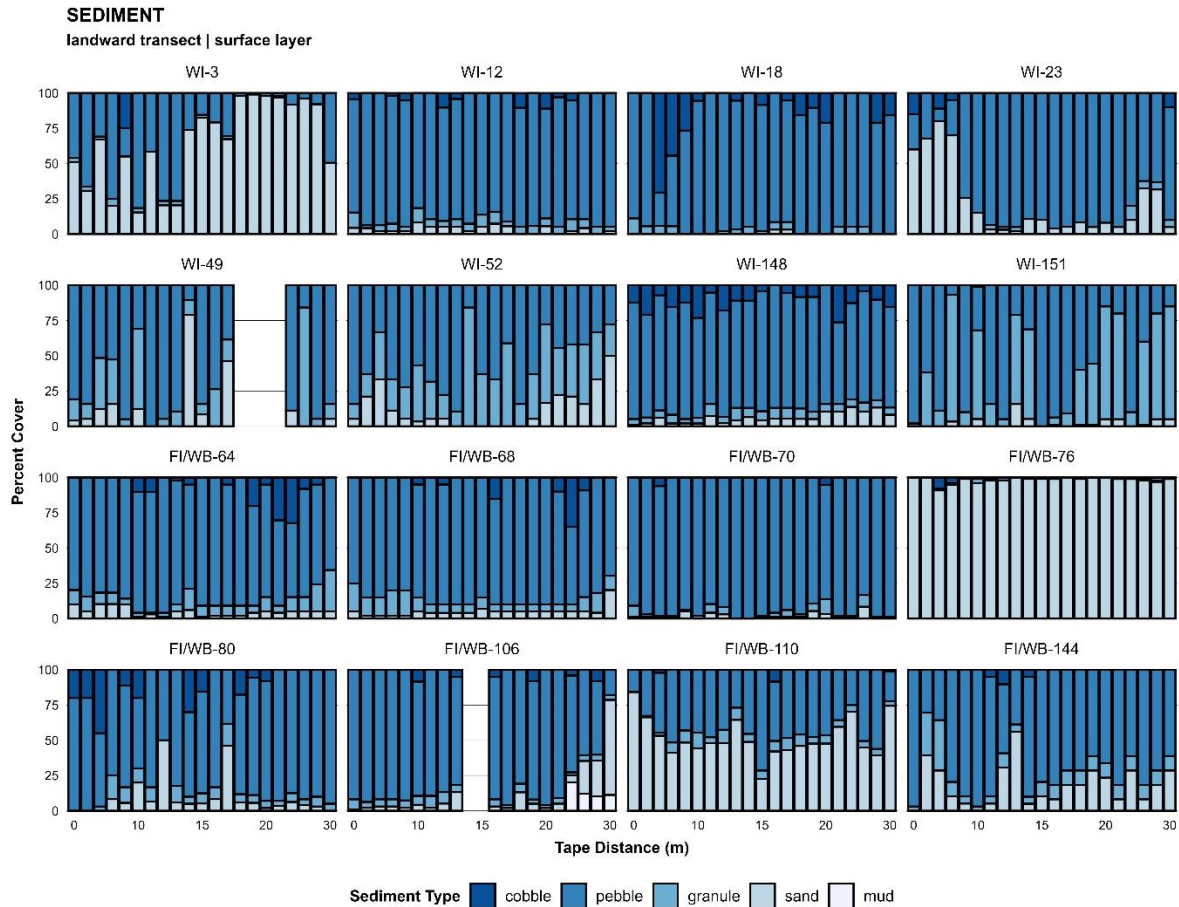
Supplementary Figure S2: Pebble (4mm to 6cm) proportion across (A) landward surface, (B) landward sub-surface, (C) waterward surface, and (D) waterward sub-surface transects. In each panel, dashed teal lines represent individual sites, and the solid black line indicates the mean pebble proportion across all sites. The two red dashed vertical lines delineate the separation of transect bins (0-10m, 10-20m, and 20-30m). Tape distance (m) on the x-axis is oriented from upstream to downstream along the prevailing drift cell flow direction, when known (left to right).



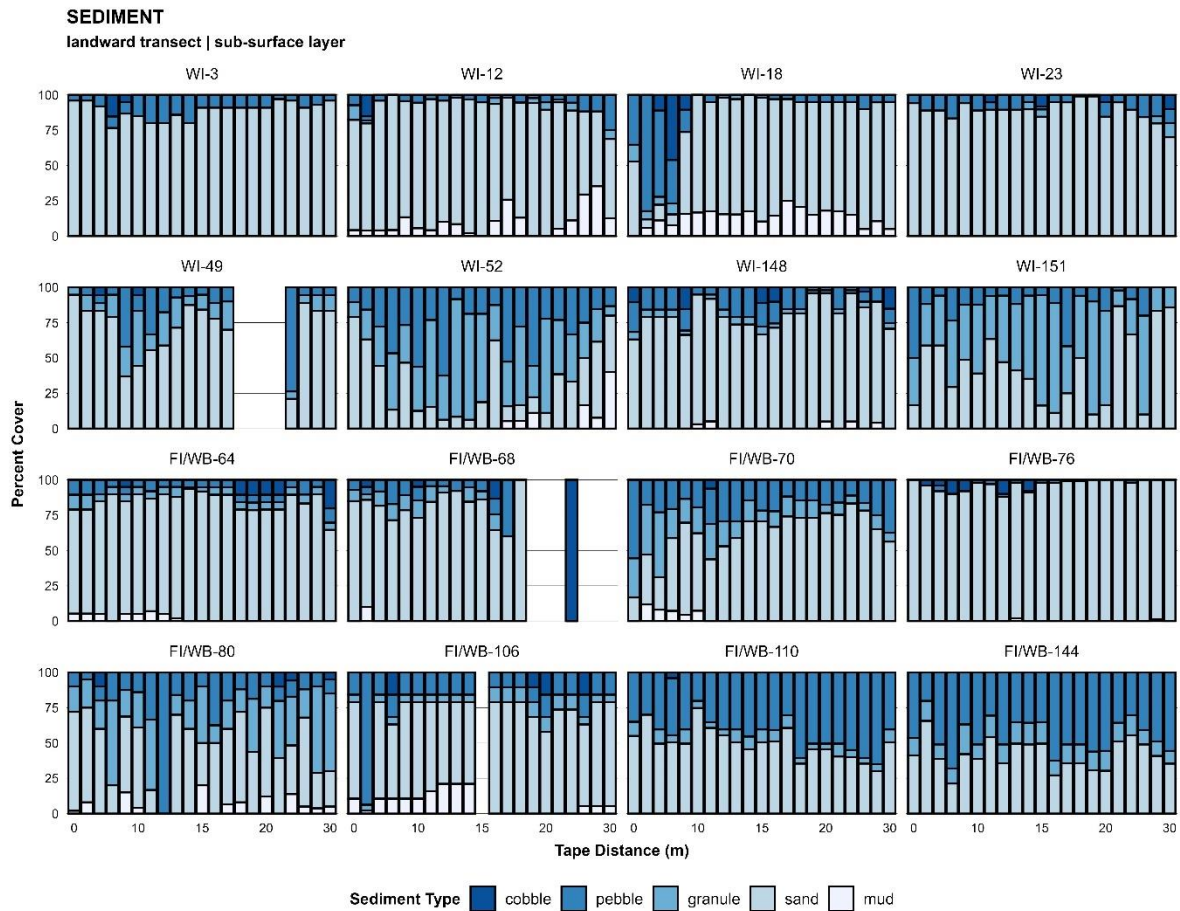
Supplementary Figure S3: Granule (2-4mm) proportion across (A) landward surface, (B) landward sub-surface, (C) waterward surface, and (D) waterward sub-surface transects. In each panel, dashed teal lines represent individual sites, and the solid black line indicates the mean granule proportion across all sites. The two red dashed vertical lines delineate the separation of transect bins (0-10m, 10-20m, and 20-30m). Tape distance (m) on the x-axis is oriented from upstream to downstream along the prevailing drift cell flow direction, when known (left to right).



Supplementary Figure S4: Mud (smooth between fingers) proportion across (A) landward surface, (B) landward sub-surface, (C) waterward surface, and (D) waterward sub-surface transects. In each panel, dashed teal lines represent individual sites, and the solid black line indicates the mean mud proportion across all sites. The two red dashed vertical lines delineate the separation of transect bins (0-10m, 10-20m, and 20-30m). Tape distance (m) on the x-axis is oriented from upstream to downstream along the prevailing drift cell flow direction, when known (left to right).

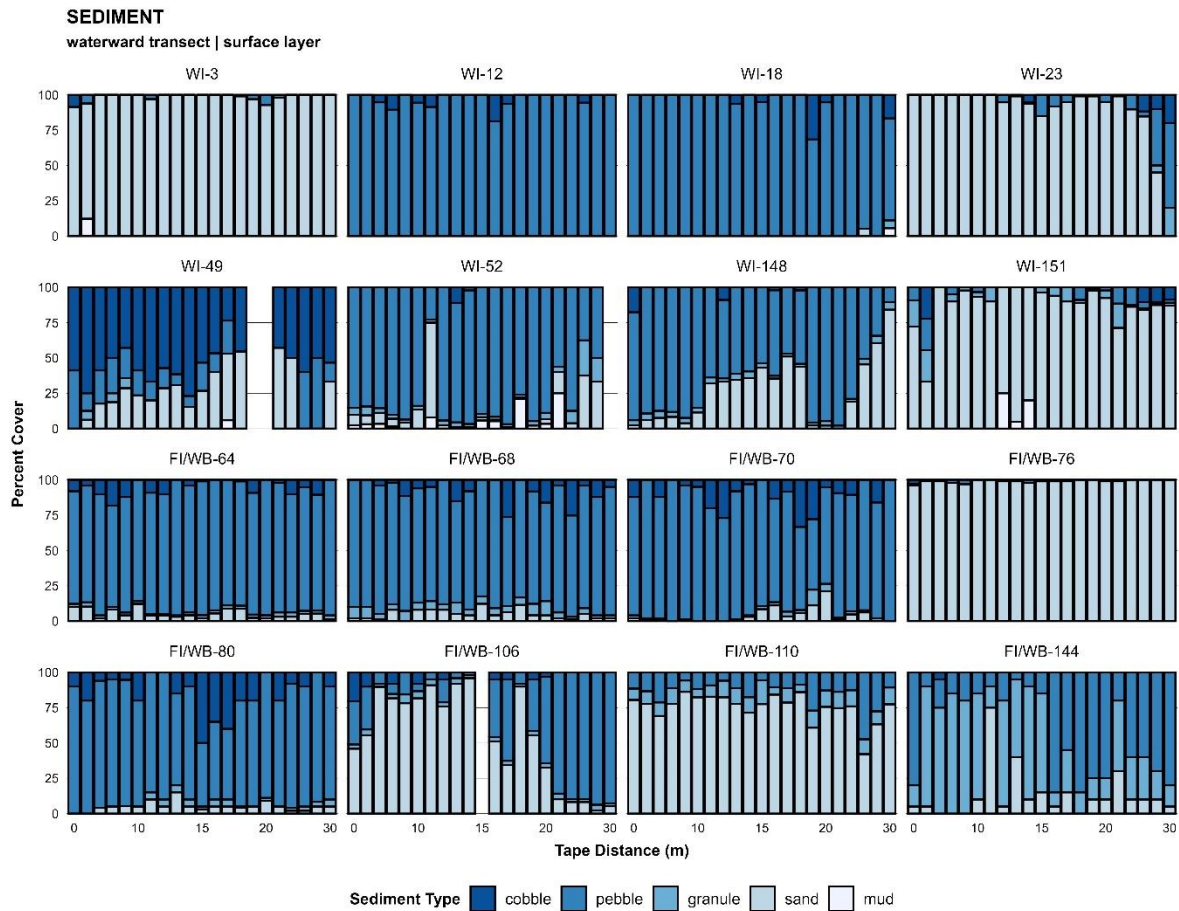


Supplementary Figure S5: Percent cover of sediment type (denoted by color) along the landward surface transect. The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined. Sediment grain sizes are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), and mud (smooth between fingers).

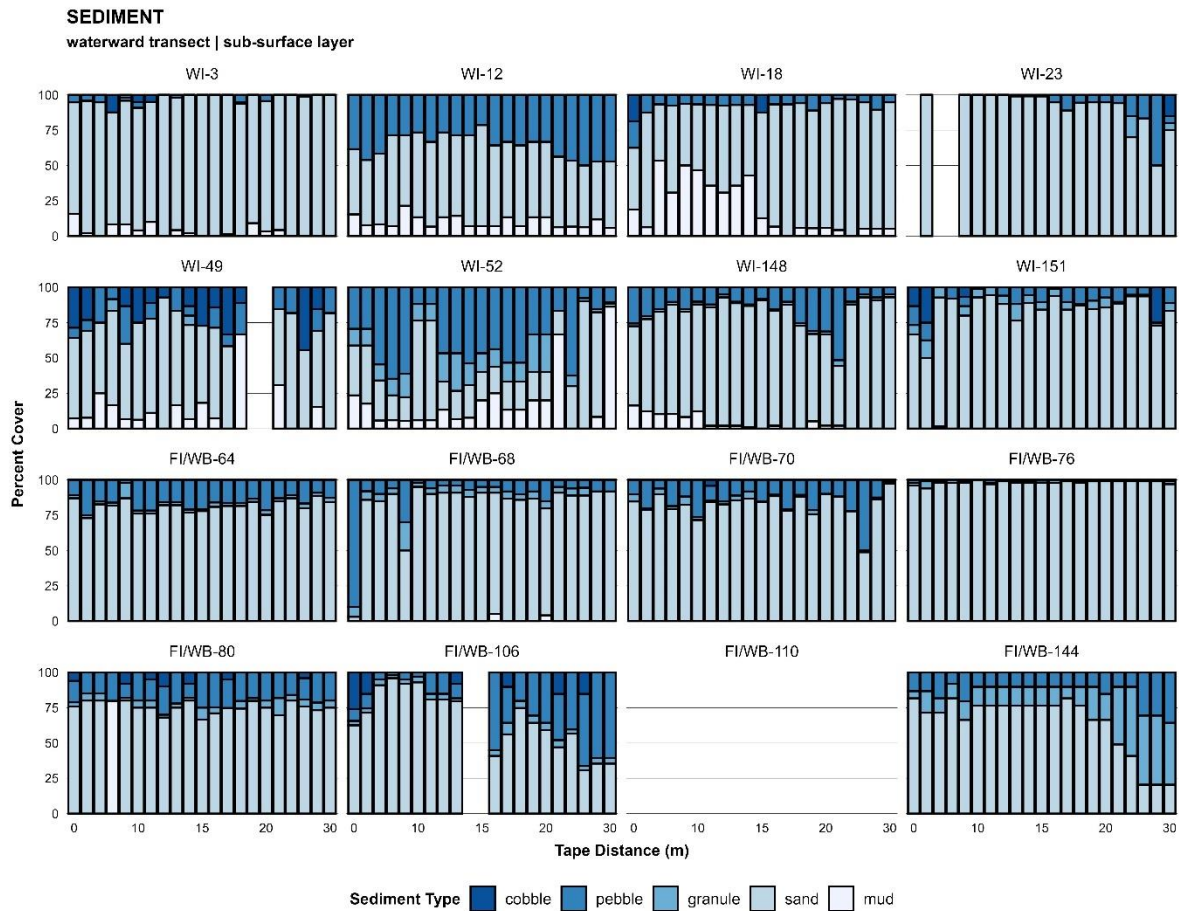


Supplementary Figure S6: Percent cover of sediment type (denoted by color) along the landward sub-surface transect.

The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined. Sediment grain sizes are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), and mud (smooth between fingers).

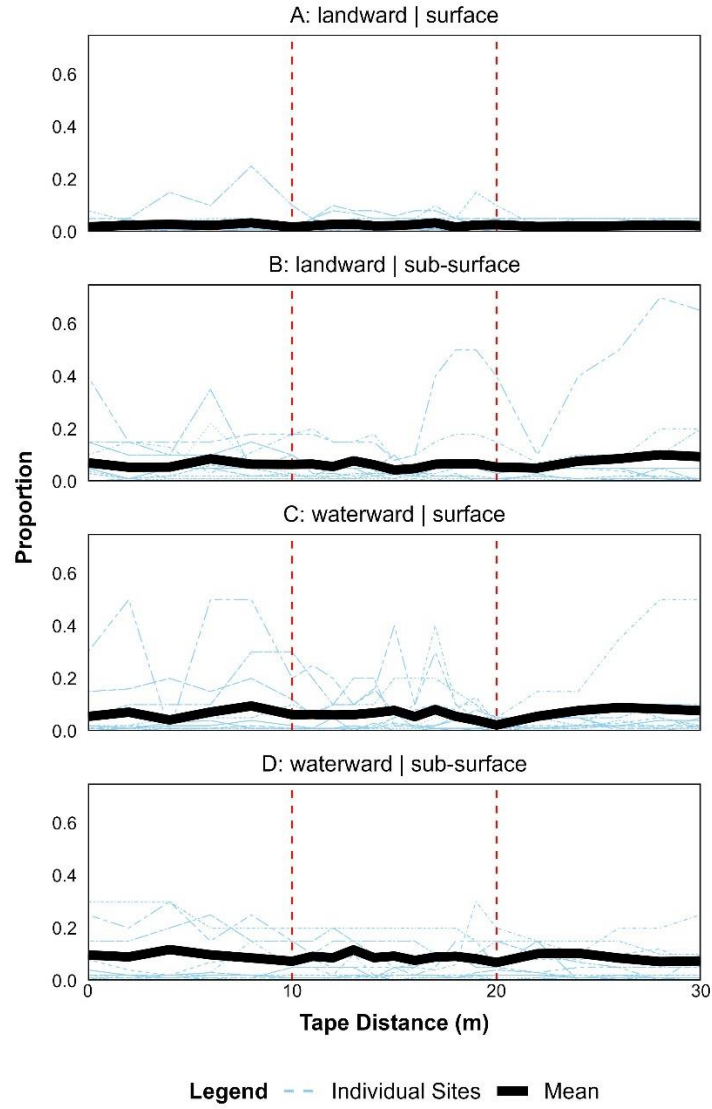


Supplementary Figure S7: Percent cover of sediment type (denoted by color) along the waterward surface transect. The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined. Sediment grain sizes are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), and mud (smooth between fingers).

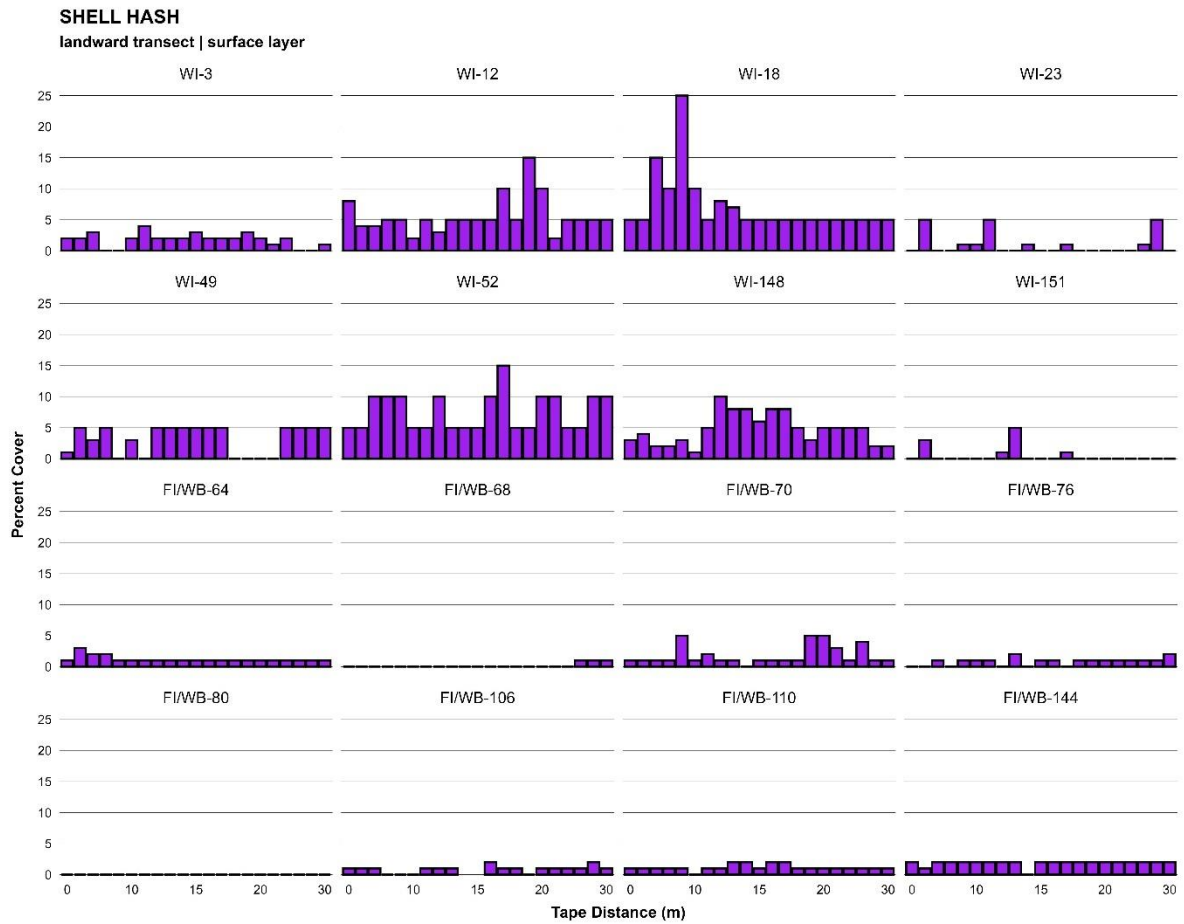


Supplementary Figure S8: Percent cover of sediment type (denoted by color) along the waterward sub-surface transect.

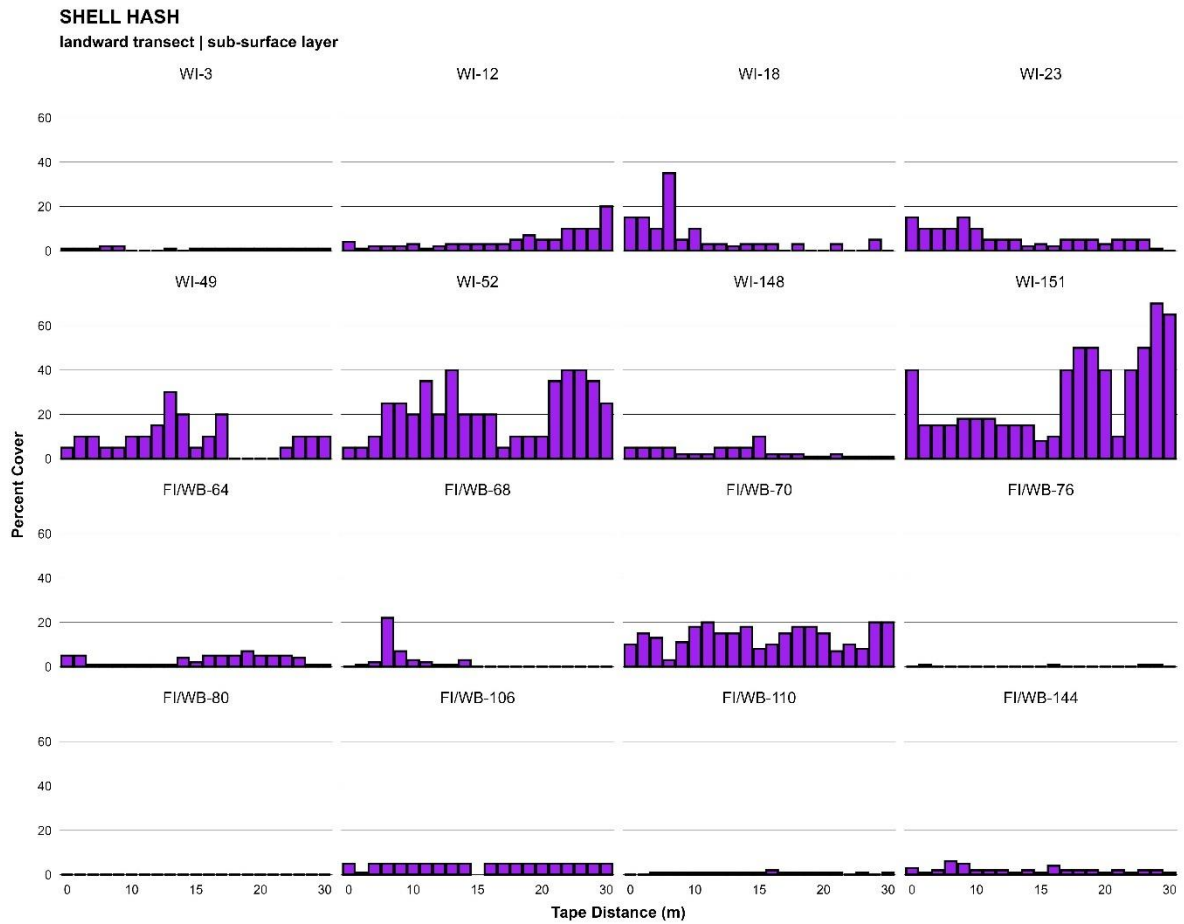
The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined. Sediment grain sizes are described using the following categories: cobble (>6 cm), pebble (4 mm to 6 cm), granule (2–4 mm), sand (<2 mm), and mud (smooth between fingers).



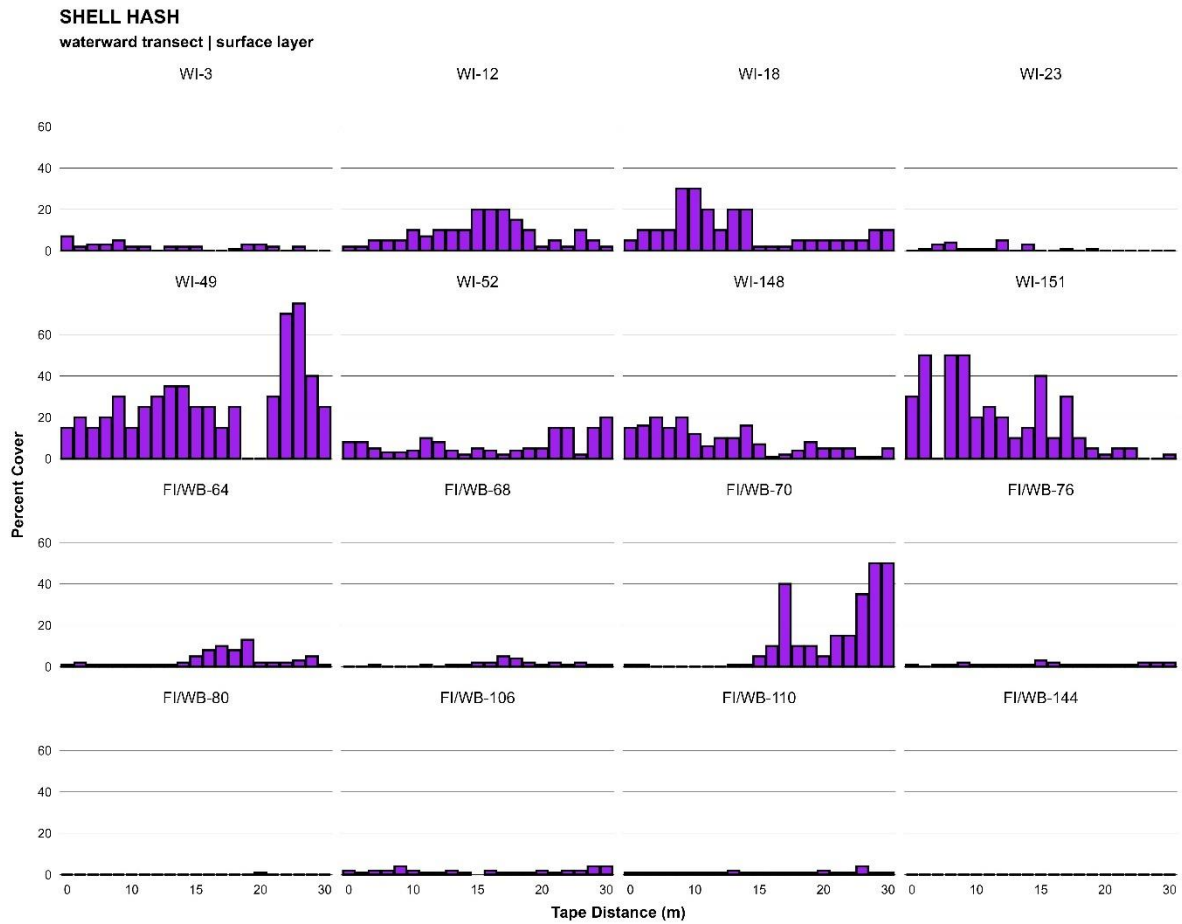
Supplementary Figure S9: Shell hash (pieces of shell) proportion across (A) landward surface, (B) landward sub-surface, (C) waterward surface, and (D) waterward sub-surface transects. In each panel, dashed teal lines represent individual sites, and the solid black line indicates the mean shell hash proportion across all sites. The two red dashed vertical lines delineate the separation of transect bins (0-10m, 10-20m, and 20-30m). Tape distance (m) on the x-axis is oriented from upstream to downstream along the prevailing drift cell flow direction, when known (left to right).



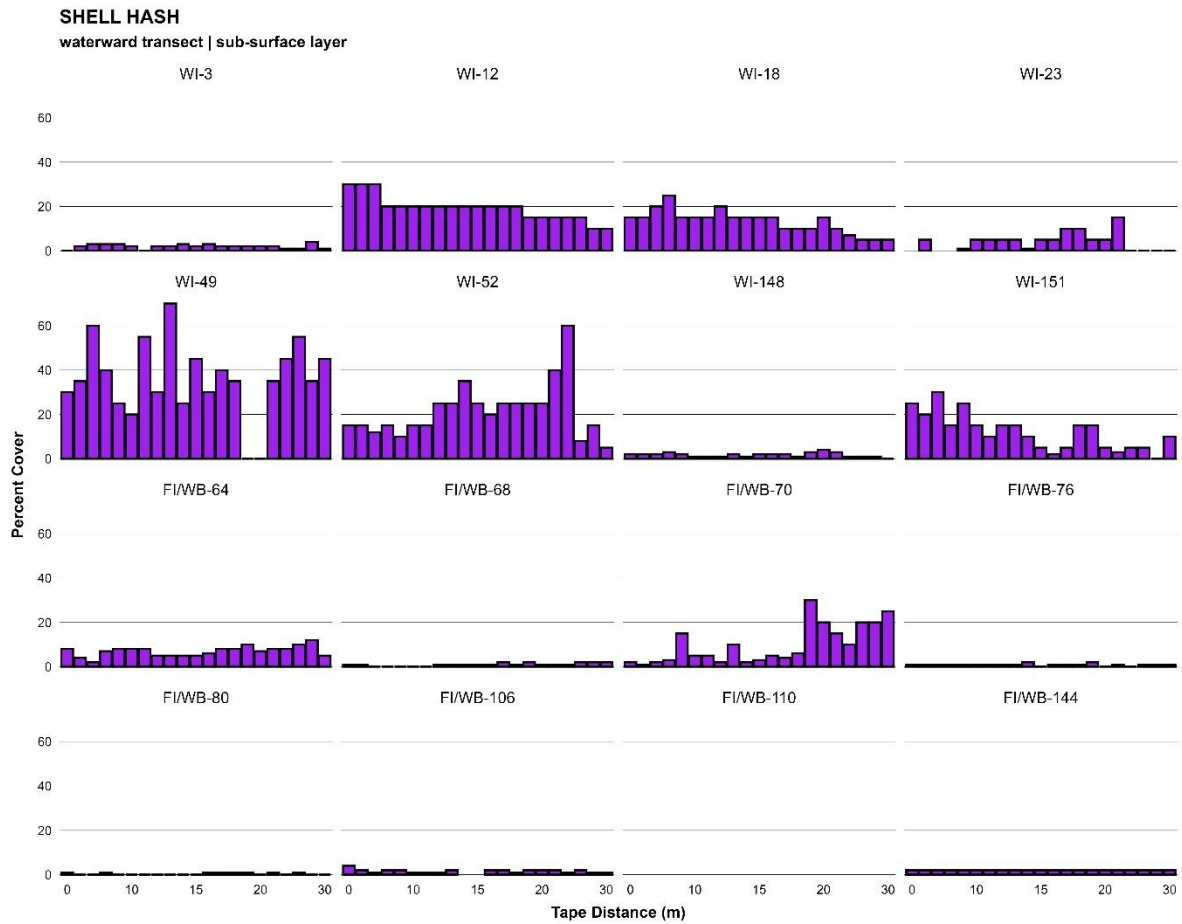
Supplementary Figure S10: Percent cover of shell hash (pieces of shell) along the landward surface transect. The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined.



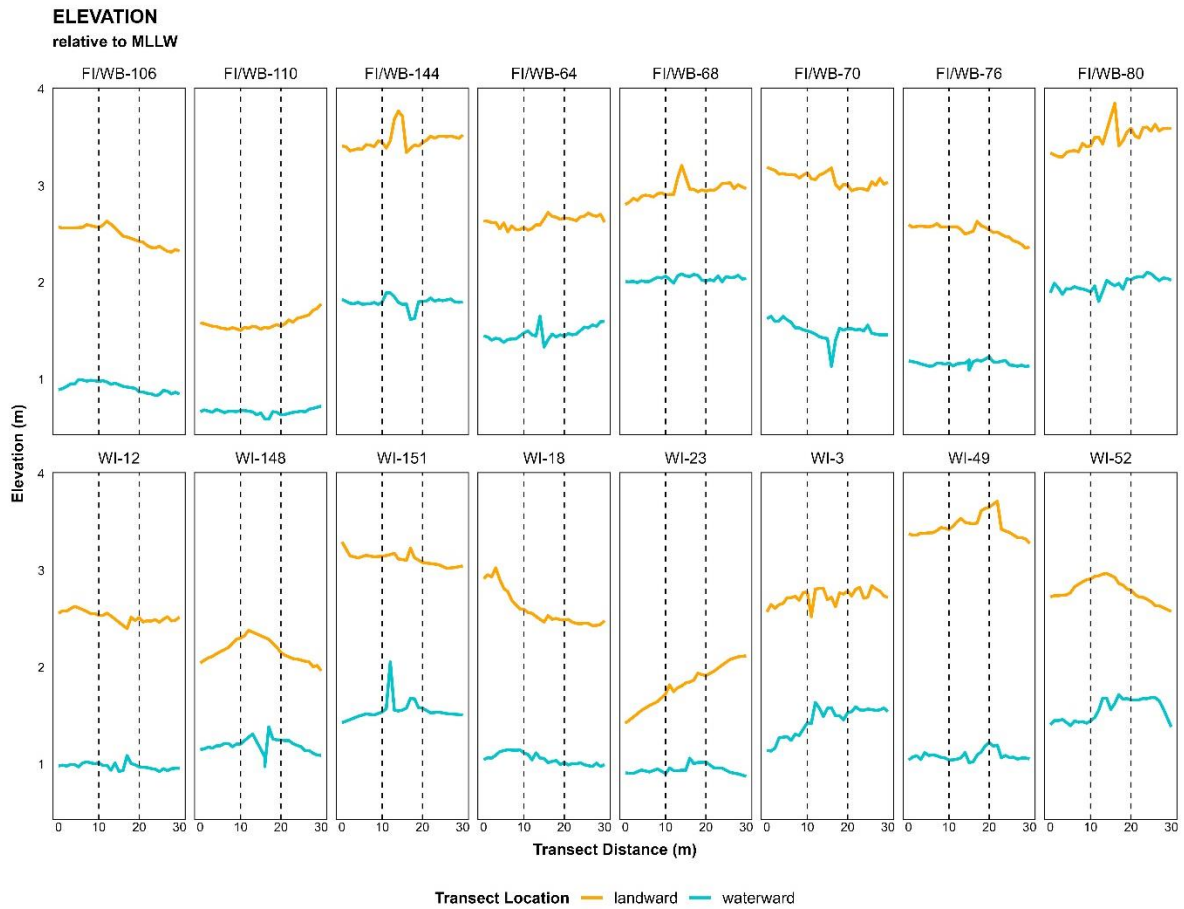
Supplementary Figure S11: Percent cover of shell hash (pieces of shell) along the landward sub-surface transect. The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined.



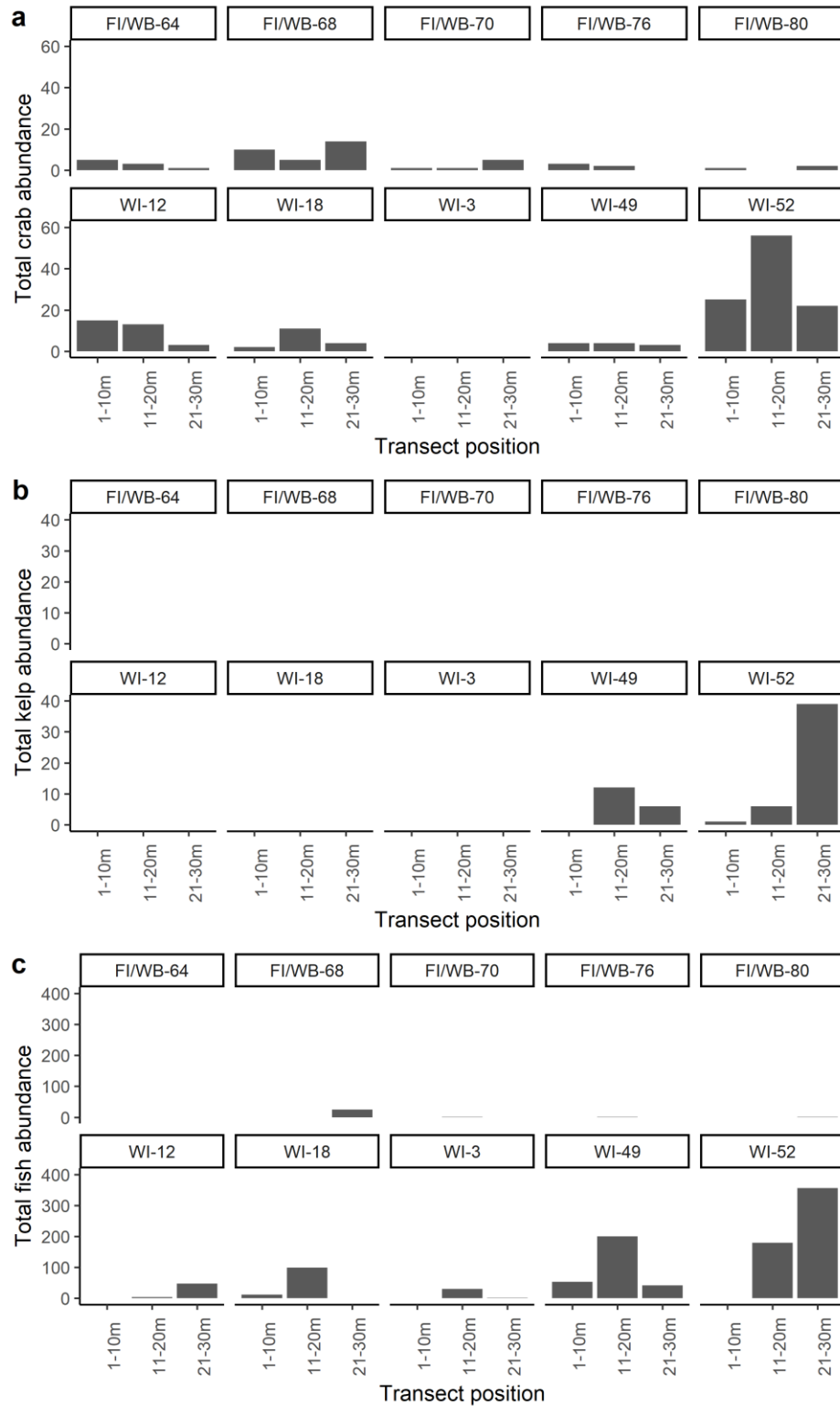
Supplementary Figure S12: Percent cover of shell hash (pieces of shell) along the waterward surface transect. The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined.



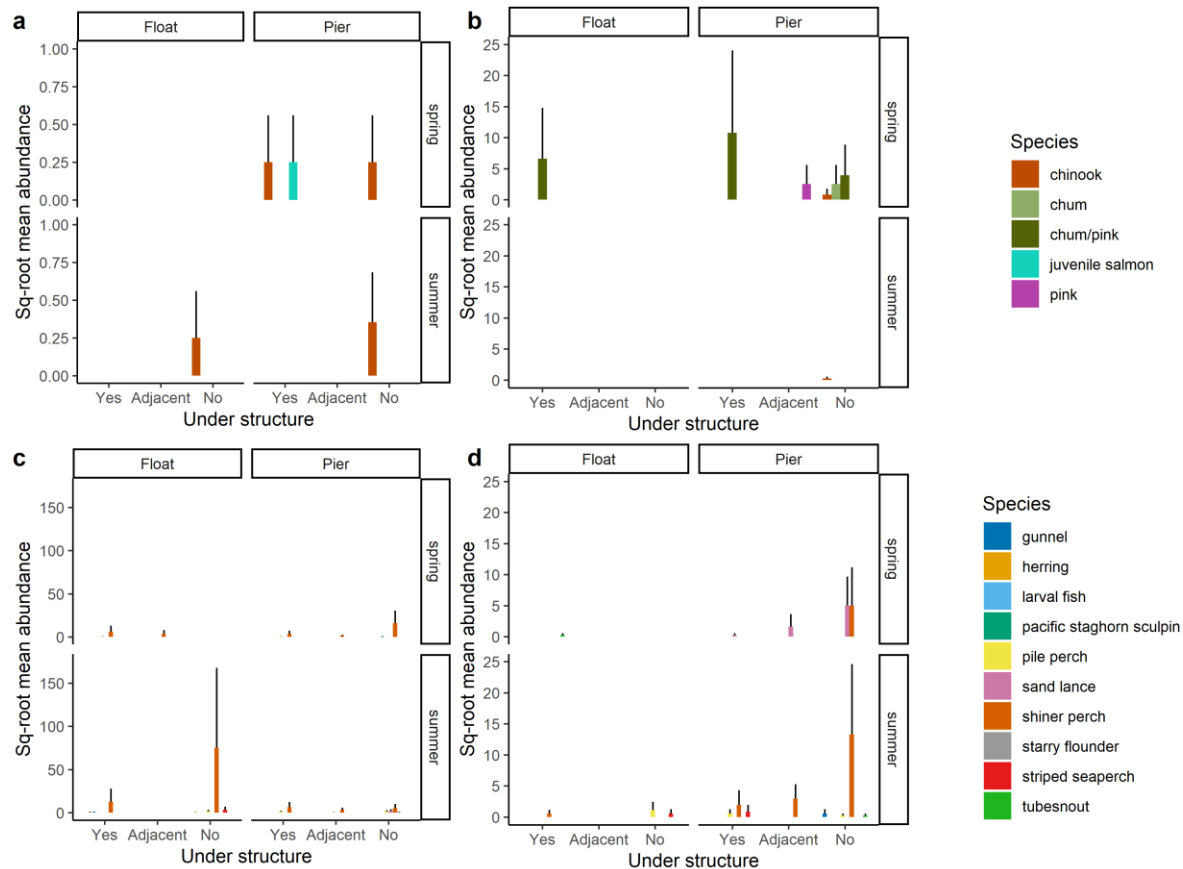
Supplementary Figure S13: Percent cover of shell hash (pieces of shell) along the landward sub-surface transect. The top two rows are sites within the Whidbey Island region, and the bottom two rows are sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined.



Supplementary Figure S14: Elevation (m) profiles along landward (orange) and waterward (teal) transects. Elevations are relative to MLLW. The top row is sites within the Whidbey Island region, and the bottom row is sites within the Fox Island/Wollochet Bay region. Tape distance (m) along the x-axis is oriented from upstream to downstream of the prevailing drift cell flow direction (left to right), except for sites WI-3, FI/WB-106, and FI/WB-110 that are located in zones that are divergent, or the drift cell is undefined. The two dashed vertical lines delineate the separation of transect bins (0-10m, 10-20m, and 20-30m).



Supplementary Figure S15: Total crab (a), kelp (b), and benthic fish (c) abundance by transect bin and site.



Supplemental Figure S16: Square-root of mean salmonid (a) and other fishes (b) abundance observed under (yes), adjacent, or not (no) under the small overwater structure. Abundance is summarized as observations near the float or most waterward portion of the structure or the mean of 4 or 5 transects (depending on site) that bisected the pier of the structure.

Appendix A – Spatial Analysis of Small Overwater Structures in Puget Sound

See separate PDF “Spatial Analysis of Small Overwater Structures in Puget Sound”
[Appendix_A_Spatial_Analysis_of_SOWS.pdf](#)