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Multiscale impacts of armoring on Salish Sea shorelines: Evidence for cumulative and threshold effects

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ABSTRACT

Shoreline armoring is widespread in many parts of the protected inland waters of the Pacific Northwest, U.S.A, but impacts on physical and biological features of local nearshore ecosystems have only recently begun to be documented. Armoring marine shorelines can alter natural processes at multiple spatial and temporal scales; some, such as starving the beach of sediments by blocking input from upland bluffs may take decades to become visible, while others such as placement loss of armoring construction are immediate. We quantified a range of geomorphic and biological parameters at paired, nearby armored and unarmored beaches throughout the inland waters of Washington State to test what conditions and parameters are associated with armoring. We gathered identical datasets at a total of 65 pairs of beaches: 6 in South Puget Sound, 23 in Central Puget Sound, and 36 pairs North of Puget Sound proper. At this broad scale, demonstrating differences attributable to armoring is challenging given the high natural variability in measured parameters among beaches and regions. However, we found that armoring was consistently associated with reductions in beach width, riparian vegetation, numbers of accumulated logs, and amounts and types of beach wrack and associated invertebrates. Armoring-related patterns at lower beach elevations (further vertically from armoring) were progressively harder to detect. For some parameters, such as accumulated logs, there was a distinct threshold in armoring elevation that was associated with increased impacts. This large dataset for the first time allowed us to identify cumulative impacts that appear when increasing proportions of shorelines are armored. At large spatial and temporal scales, armoring much of a sediment drift cell may result in reduction of the finer grain-size fractions on beaches, including those used by spawning forage fish. Overall we have shown that local impacts of shoreline armoring can scale-up to have cumulative and threshold effects – these should be considered when managing impacts to public resources along the coast.

1. Introduction

Anthropogenic alteration of shorelines is a worldwide phenomenon as a significant proportion of population growth is in coastal communities. Types of shoreline development are diverse, ranging from simply building houses overlooking the water to completely altering the shore by covering it with fill or structures. The Salish Sea, which includes all the inland marine waters of British Columbia (Canada) and of Washington State (USA), has shorelines that range from virtually pristine beaches to concrete-covered commercial ports. In the face of increasing coastal urban growth and sea level rise, effective management of our shorelines requires understanding both functions of natural beaches and the scales at which we are impacting them (Arkema et al., 2013; Harris et al., 2015).

One of the most prevalent forms of coastal development in the Salish Sea and worldwide is shoreline armoring, comprising various artificial means of stabilizing banks and bluffs that might otherwise erode and endanger infrastructure. A recent conservative

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estimate of armored shoreline in the continental US is 14% (Gittman et al., 2015). Local, mostly biological, effects of shoreline armoring are well known for some types of embayments and marshes (e.g., Bozek and Burdick, 2005; Chapman and Underwood, 2011) and open-coast sandy beaches (e.g., Dugan et al., 2008; review by Nordstrom, 2014), and recently for the gravel-sand beaches of Puget Sound (Sobocinski et al., 2010; Heerhartz et al., 2014). Armoring locally reduces retention of logs and wrack (algae, seagrass, leaf litter, and other organic and inorganic debris left by ebbing tides) and the invertebrate communities that inhabit this detritus. It can also have indirect effects on seabird and shorebird use (Dugan et al., 2008) as well as abundance and diversity of large mobile invertebrates (Chapman, 2003). Potential spawning locations for beach-spawning forage fish, such as surf smelt (*Hypomesus pretiosus*), are reduced when armoring covers the high shore, and egg mortality increases when beach temperatures are raised by shoreline modifications (Rice, 2006). These trophically important fish may also be negatively impacted in cases where armoring coarsens the sediment due to local winnowing of finer grain sizes (Penttila, 2007; Quinn et al., 2012; Fox et al., 2015; Greene et al., 2015). By changing the nearshore habitats encountered by juvenile migrating salmon, armoring affects their diets (Munsch et al., 2015) and possibly residence time (Heerhartz and Toft, 2015).

Considerable study of physical impacts of armoring on beaches has been conducted, although the results are contradictory. In some circumstances, interactions of sediment impoundment, wave reflection, and alterations to nearshore water currents may alter beach scour, mobilization of sediment, and recovery from storms. In theory, these processes may result in narrower, steeper, and coarser-grained beaches (Pilkey and Wright, 1988; Bozek and Burdick, 2005; Nordstrom, 2014). One clear effect is that passive erosion (e.g., caused by relative sea level rise) causes narrowing of armored shorelines because the upper beach is prevented from migrating inland. In contrast, whether active erosion is induced by seawalls is still argued (reviews by Kraus and McDougal, 1996; Ruggiero, 2010); few long-term studies have been attempted but generally do not show a definitive armoring effect (e.g., Griggs et al., 1994; Griggs, 2010). Modeling work (e.g., Ruggiero, 2010) suggests that contradictions seen in the literature may stem from variation among study systems in key physical parameters, in particular the relative elevation of the seawall and the morphology of the beach and nearshore, including their slopes.

Even for the more consistent biological impacts of armoring, translating local effects to a landscape scale is challenging because of the myriad other natural and anthropogenic factors that affect shoreline processes. The signal to noise problem is particularly large in inland waters such as the Salish Sea because of the complexities of underlying geology, shoreline shape, freshwater input, wave fetch, orientation to prevailing winds, nearshore bathymetry, and sources of sediments, vegetation, and organisms. In most of the world, beach sediments derive predominantly from rivers. On sandy shorelines, these sediments are jealously retained with groins, and millions of dollars are spent annually to replenish beaches where natural sources have been locked up by dams (Berry et al., 2013). Although numerous rivers empty into the Salish Sea and a few of them create large deltas, much of the riverine sediment is deposited in deep fjord-like basins rather than building beaches. Instead, most beach-building sediment comes from erosion of bluffs (Keuler, 1988). It follows that “locking up” these sediments by armoring shorelines should have large-scale and long-term impacts, including cumulative effects if few sediment sources are left unaltered (reviewed by Berry et al., 2013; Nordstrom, 2014). However, demonstrating cumulative effects, e.g. changes that continue to worsen with additional armoring, is notoriously difficult – especially if changes appear gradually, as is likely with many geomorphic processes. In Europe, extensive coastal armoring is thought to have contributed to broad-scale steepening of the shoreline (Taylor et al., 2004), but many other processes could be important.

In the southern part of the Salish Sea (in Washington State), which includes Puget Sound, extensive shoreline armoring has accompanied the last 100 years of development along the greater Everett-Seattle-Tacoma urban corridor, and is thought to significantly impair nearshore ecosystem processes (Simenstad et al., 2011). While local effects have recently been documented (e.g., Sobocinski et al., 2010; Heerhartz et al., 2014), broader or cumulative impacts have not. This uncertainty stymies managers and regulators who lack compelling data that would provide the “best available science” to inform guidelines. Pressures to relax armoring regulations stem from the need to protect valuable infrastructure from erosion, especially with risk exacerbated by sea level rise. Sociological studies show that decisions by a few homeowners to armor their shoreline often triggers neighbors to do the same, leading to cascading local impacts (Scyphers et al., 2015). In addition to such possible cumulative effects, regulators are particularly interested in which types or locations of armoring have greater impacts than others, and whether there are thresholds that trigger these impacts. Samhouri et al. (2010) define an ecological threshold as a point at which small changes in environmental conditions produce large (non-linear) responses in ecosystem state. For example, ecological thresholds have been associated with habitat fragmentation (e.g., Andrén, 1994) and edge effects (Toms and Lesperance, 2003). One possible threshold that may apply to shoreline armoring is the extent that structures encroach on the beach. In addition, slow and delayed “latent impacts” (Coverdale et al., 2013) may exist but are very difficult to detect, especially given signal-to-noise problems.

Previous studies by our research team have focused on local impacts of shoreline armoring in central and southern Puget Sound (Heerhartz et al., 2014, 2015). We dealt with among-site ‘noise’ by use of a paired sampling design, focusing our surveys on nearby, physically-paired, armored and unarmored beaches. Here we broaden our geographic scale to test whether the documented biological effects of armoring exist on beaches in the Salish Sea north of Puget Sound. We also test whether any physical impacts are detectable, because our previous work in central and southern Puget Sound found few differences in quantified physical parameters that were correlated with armoring. The northern region has more bedrock shorelines and different oceanographic characteristics, so we anticipated that there would be some regional differences in beach parameters. Based on our own localized studies and on literature from other systems (e.g., open-coast beaches), we hypothesized that: 1) Armoring-associated reduction of logs, wrack, and invertebrates would be consistent across regions in paired-beach analyses; 2) These associations would be increasingly clear when armoring is lower on the beach face; 3) By examining a large range of sites, the predicted pattern of armoring altering beach slope and sediment coarseness might be detectable; and 4) Such geomorphic signals would be most distinct where extensive stretches of armoring have “locked up” more sediment sources in an area. To address these questions, we discuss regional patterns but ignore the huge beach-to-beach variation in geomorphic conditions, to be discussed elsewhere (A.N. McBride, pers. comm.).

2. Methods

2.1. Sites

Our analyses include data from 65 pairs of armored and unarmored beaches in the inside marine waters of Washington State,