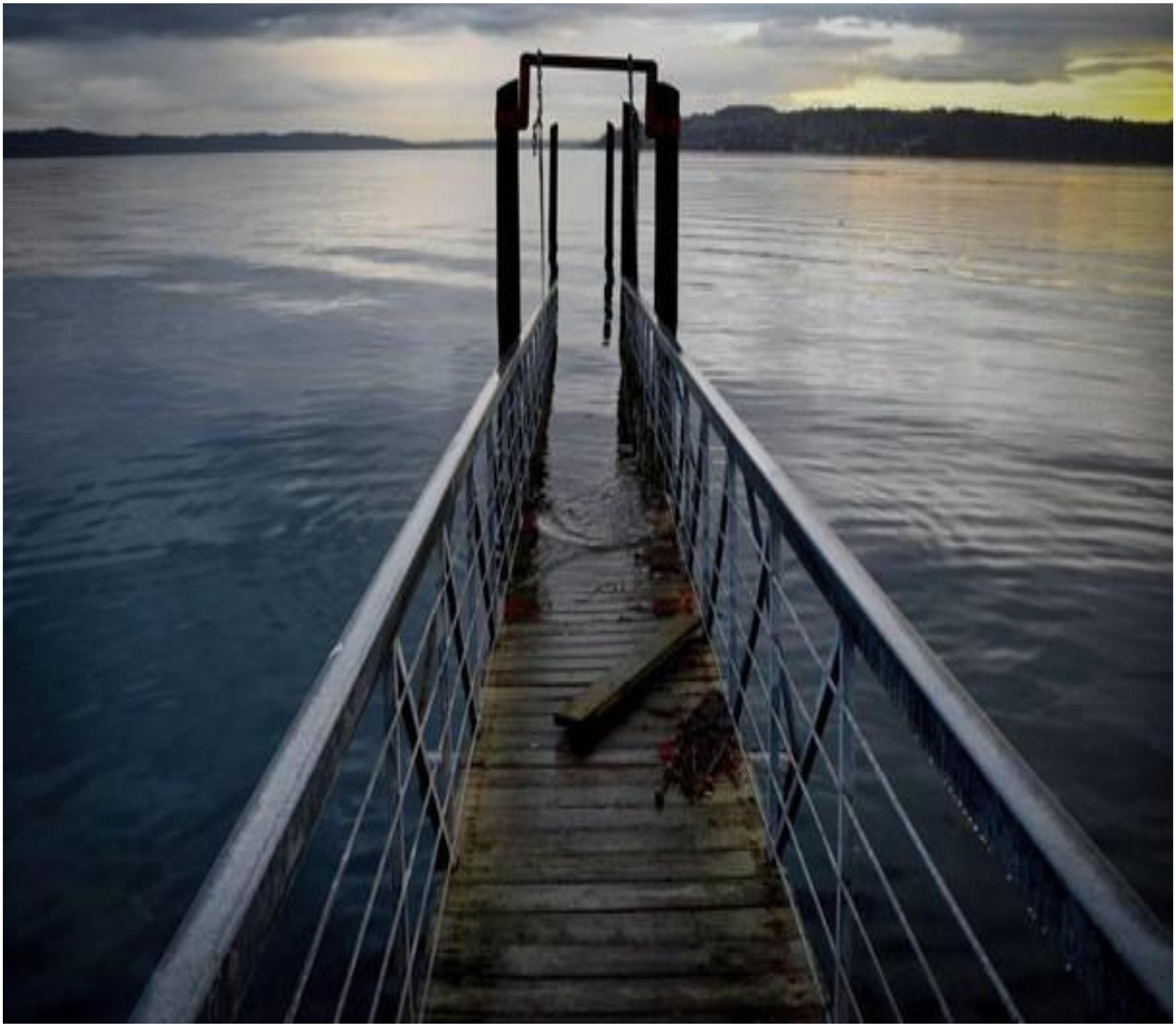

Sea Level Rise and Management Options for Washington's Shorelines

The Washington Coastal Resilience Project (WCRP) is a three-year effort to rapidly increase the state's capacity to prepare for coastal hazards that are related to sea level rise, such as flooding and erosion. The project will improve risk projections, provide better guidance for land use planners and strengthen capital investment programs for coastal restoration and infrastructure. Partners include:

Washington Sea Grant
Washington Department of Ecology
Island County
King County
NOAA Office of Coastal Management
Padilla Bay National Estuary Research Reserve
The City of Tacoma
The Nature Conservancy
United States Geological Survey
University of Oregon
University of Washington Climate Impacts Group
University of Washington Department of Earth and Space Sciences
University of Washington School of Marine and Environmental Affairs
Washington Department of Fish and Wildlife
Pacific Northwest National Laboratory

The project is primarily funded by a grant from the NOAA Regional Coastal Resilience Grants Program (grant #NA16NOS4730015). Additional funds were provided by the State of Washington.

Cover images credits: *Photo by Ryan Dicks on November 28, 2018 near the Tacoma waterfront, and submitted to the King Tides photo archive (see https://mycoast.org/reports/45465)*

Prepared for the Washington Coastal Resilience Project

May 2022 | University of Washington
Ian Miller, Washington Sea Grant
Nicole Faghin, Washington Sea Grant
Sydney Fishman, Washington Department of Ecology

Acknowledgements

Jennifer Griffiths (Washington Department of Fish and Wildlife), Tish Conway-Cranos (Washington Department of Fish and Wildlife), Kollin Higgins (King County), Lara Whitely Binder (King County), Bob Freitag (University of Washington Department of Urban Design and Planning), Jessica Côté (Blue Coast Engineering), Bobbak Talebi (Washington Department of Ecology), and Hugh Shipman (Washington Department of Ecology, retired) provided thoughtful reviews and feedback that improved this report. Jackson Blalock (Washington Sea Grant) provided us with access to photos and case studies.

Recommended Citation

Miller, I., Faghin, N., and Fishman, S. 2022. Sea Level Rise and Management Options for Washington's shorelines. A collaboration of Washington Sea Grant and the Washington Department of Ecology. Prepared for the Washington Coastal Resilience Project.

Table of Contents

Summary

Sea level rise will exacerbate coastal hazards like flooding and erosion on Washington State's shorelines. In this paper we examine trade-offs associated with various coastal management options that are likely to be considered for Washington's shorelines as sea level rises. Specifically, we qualitatively assess the *costs, effectiveness, and social and ecological implications* of four different types of coastal management approaches:

- **Hard defensive structures:** Protecting infrastructure, homes or land from flooding or erosion by building hard shoreline structures. These can include bulkheads, seawalls, revetments, or dikes depending on their design or primary purpose (i.e., controlling flooding versus erosion).
- **Soft shore stabilization:** Protecting infrastructure, homes or land from coastal flooding or erosion with soft shore stabilization techniques. Soft shore stabilization techniques include designs built with natural materials that are intended to replicate features of natural shorelines. Soft shore stabilization techniques can, in some circumstances, reduce risk from erosion and coastal flooding as sea level rises, without some of the social and ecological costs of hard defensive structures.
- **Accommodation:** Accommodation approaches encompass a range of techniques designed to decrease the impacts of flooding when it occurs. Accommodation techniques include elevating homes, floodproofing to keep living areas dry, or raising critical systems (heating and electrical, for example) above flood heights.
- **Retreat and avoidance:** Retreat and avoidance strategies manage erosion and flooding by removing or avoiding the development of homes or infrastructure from present or future hazardous zones along the shoreline. Retreat and avoidance strategies are sometimes associated with steep political hurdles and costs but are effective at reducing risk from coastal hazards and may also be the most cost-effective of the options over long timeframes.

Based on our analysis, we conclude that all four types of approaches can be effective at reducing risk from coastal flooding, though the duration of that effectiveness varies. Only the retreat and avoidance strategies reduce risk in perpetuity as sea level rises. All approaches except accommodation can reduce risks associated with erosion. Each approach provides effectiveness at varying costs, and for varying durations, as sea level rises. Additionally, the social and ecological implications of each category of approach varies. Notably, we find evidence that suggests hard defensive structures are associated with rising costs and reduced risk reduction as sea level rises. Additionally, we find that the first three types of approaches, which are all designed to keep infrastructure in potentially hazardous zones, carry with them a variety of long-term and potentially hidden costs that we frame as "maladaptation." This maladaptation risk should be carefully weighed when considering any of the first three types of approaches.

The initial analysis of trade-offs associated with coastal management options provided in this paper is the first of its sort written specifically for audiences in coastal Washington and with sea level rise as its focus. There are economic, social, and ecological costs and implications for any the four approaches considered in this report, including for hard defensive structures, which our experience suggests is often perceived as a 'go to' solution to increasing erosion or flooding. We conclude, though, that defaulting to defensive approaches to protect homes and infrastructure in place does not always provide the most effective risk reduction and may not be cost-effective over the life of the structure. This paper, however, is not comprehensive, and we also identify and summarize gaps in our knowledge that can help direct future research on this important subject. Our hope in publishing this report is that it will contribute to maintaining ecologically productive, aesthetically pleasing, culturally meaningful and economically rich shorelines for generations to come in Washington State.

Table 1. Summary results table. Effectiveness, financial, ecological and social implications, and maladaptation risk of four different types of coastal risk reduction approaches.

	Hard Defensive Structures	Soft Shore Techniques	Accommodation	Retreat or Avoidance
Effectiveness	Can be effective at reducing erosion and may reduce flood risk on certain properties if designed appropriately for changing conditions. Effectiveness, though, may be limited and short-lived as sea level rises.	Can reduce erosion and/or flooding, but effectiveness requires further study. Soft shore techniques are not appropriate in all circumstances. As sea level rises, may be capable of some "self-adaptation" to changing conditions.	Recognized as an effective way to reduce risk from episodic flooding. The effectiveness of accommodation in the future will depend on how and when sea level rise impacts occur.	Effective at reducing risks from erosion and flooding now and as sea level rises. Evidence suggests that it can be the most cost-effective option in some cases, especially over long timeframes.
Financial Implications	Installing new armor may incur a significant upfront cost. Sea level rise may require more expensive designs or increase maintenance costs.	Generally, less expensive than hard armor alternatives, but these projects may incur additional permitting costs or longer timelines. Also generally require specialized consulting for proper project design.	Costs vary considerably depending on technique, and additional costs for permitting and other work may also arise. Some accommodation strategies may help reduce flood insurance premiums.	Often associated with large upfront costs, but studies suggest that retreat and avoidance can result in long-term cost savings. Retreat options such as home relocation may incur additional costs (e.g., permitting costs, utilities).
Social Implications	Can be associated with loss of beach access and impacts to aesthetics. Future demand for expanded armor may require significant coordination among neighbors or communities to install effective structures.	Soft shore stabilization techniques can maintain or even enhance shoreline accessibility and aesthetics. Additional permitting costs or longer timelines can be frustrating for landowners.	Accommodation techniques are already in use today, and may be more familiar to property owners, permitting agencies and contractors. Accommodation may allow property owners to remain on the coast for longer as sea level rises, thereby supporting community cohesion and well-being.	Patchwork retreat and avoidance efforts can result in reduced community cohesion. Publicly funded buyouts may raise equity concerns amongst communities. There are potential legal challenges to implementing regulatory retreat strategies in Washington.
Ecological Implications	Armor has demonstrated impacts to shoreline habitats and sediment transport processes. Sea level rise is expected to cause increased loss of coastal habitat on armored shorelines.	Soft shore stabilization is less ecologically impactful than hard armor but may be more impactful than other approaches.	Usually done within a building's footprint, so it may avoid direct impacts to the shoreline environment. However, accommodation strategies may result in impacts associated with retaining sewage treatment or other services in areas exposed to flooding.	Generally, maximize natural shoreline processes that allow coastal habitat to migrate landward as sea level rises. Retreat can also allow for restoration of previously impacted shorelines, such as by removing hard armor that is no longer needed.
Mal-adaptation Risk?	Yes	Yes	Yes	No

Introduction and Background

Sea level is rising in coastal Washington State, and the rate of rise is almost certain to accelerate in the coming decades. By 2050, most of the coastal areas of Washington State are likely to experience average sea levels that are almost a foot higher than at present. By 2100, sea level in Washington State is likely to be two to three feet higher than it is at present, and the possibility of much larger magnitudes of change, perhaps as much as eight feet or more by 2100, cannot be discarded (Miller et al., 2018).

Figure 1. Road inundation on Vashon Island during and extreme coastal water level event on 17 December 2012. Photo by Greg Rabourn, King county.

Sea level rise will exacerbate coastal flooding and erosion. For example, the magnitude (Miller et al., 2019) and frequency (Vitousek et al., 2018) of coastal flooding events (Figure 1) will increase as sea level rises. This effect is already observed in Seattle on Puget Sound, where minor coastal flooding has increased since 1950 as sea level has risen (Sweet et al., 2018). Erosion of coastal beaches and bluffs is also very likely to accelerate as sea level rises (Glick et al., 2007; Limber et al., 2018), an impact that may already be observed on some shorelines (Romine et al., 2013). Intertidal habitats that are not eroded will be submerged if they are unable to migrate landward (Thorne et al., 2018).

Washington State is vulnerable to flooding and shoreline erosion exacerbated by sea level rise. A recent assessment estimated that over 14,000 homes and structures in Washington State, with a current value of over 8 billion dollars, may be exposed to coastal flooding by 2050 (Climate Central and Zillow, 2018). An analysis conducted for San Juan County (MacLennan et al., 2013) found that sea level rise by 2050 could more than double the number of structures and road miles at risk from flooding or erosion. Changes to natural habitats as sea level rises (Glick et al., 2007), are likely to impact ecosystem services that human communities rely on. Adapting communities for sea level rise-related hazards will come at a cost (LeRoy and Wiles, 2019), but is more cost-effective than doing nothing (Diaz, 2016).

Coastal decision-makers (a term that we use in this report to refer to shoreline property owners, shoreline community groups, local government officials and others) in Washington already deal with flooding and erosion (Figure 2), and shoreline armor is widespread on some of Washington's coasts

(Figure 3). Armoring is present, for example, along approximately 27 percent of Puget Sound's shoreline (Habitat Strategic Initiative, 2018). As sea level rises and the risks to shoreline properties increase, it is likely there will be an increase in the pressure to build new shoreline defenses or expand or raise existing armoring. King County residents are already using sea level rise as justification for permit requests to build bigger bulkheads (Kollin Higgins, King County, personal communication). At the same time, other approaches for responding to flooding and erosion have been employed in coastal Washington State and elsewhere, including using soft shore stabilization techniques, accommodating flooding, and moving homes back from erosive shorelines (Washington Coastal Hazards Resilience Network, 2020).

Figure 2. an eroded road ends abruptly on the beach in North Cove, Washington. July 2019 photo by Ian Miller, Washington Sea Grant

This paper reviews available literature to explore trade-offs associated with various shoreline response approaches, with a primary focus on how those trade-offs may change as sea level rises. We examined the effectiveness and costs of hard defensive approaches (i.e., bulkheads, revetments, dikes and seawalls) as compared to other sea level rise response strategies including "soft" shoreline stabilization, adapting infrastructure to reduce the impacts of flooding, or retreating or avoiding development along the shoreline. We focus not only on the financial costs of each response option, but also examine the impacts to ecosystem services and social values, like aesthetics. We also identify and summarize gaps in our knowledge that should be filled with future analysis. Our intention is to provide insights regarding how to manage Washington's shorelines as sea level rises, and to assist those who will be making difficult decisions in the years ahead. Our hope is that Washington State residents continue to enjoy an ecologically productive, aesthetically pleasing, culturally meaningful and economically rich shoreline for generations to come.

Figure 3. Extensive armoring along the shoreline near Sequim, Washington. August 2013 photo by Ian Miller, Washington Sea Grant.

Response Approaches for Washington’s Shorelines

A variety of response approaches have been used on Washington State’s shorelines to reduce the risks associated with flooding and erosion (Washington Coastal Hazards Resilience Network, 2020). We will consider four of those: (1) hard defensive structures for reducing risks associated with erosion or flooding, (2) reducing the risk of erosion or flooding using soft shore stabilization techniques, (3) accommodation techniques that are designed to reduce the impacts of flooding, and (4) moving infrastructure and structures away from coastal hazard zones (Figure 4) or, for new development, planning to avoid those zones. We most frequently think of these approaches as being relevant only for developed shorelines, but this is not the case. As sea level rises these various response options may also be considered to manage flooding and erosion risks to natural habitats, recreational assets, or cultural resources.

Figure 4. A home being removed from the shoreline in King County, as part of an ecosystem restoration project. Photo by Greg Rabourn, King County.

In the sections that follow, we utilize a literature review to examine benefits of each approach and the trade-offs associated with financial costs, social implications, and impacts to ecosystem functions and services. In each section, the approach is defined, and then followed by an examination of three different factors: the effectiveness and financial implications of the approach, the social implications, and the ecological implications. Effectiveness and financial considerations of each approach are assessed together simply to acknowledge that they are tightly coupled: a less expensive seawall, for example, is unlikely to be as effective as a more expensive one at a given location. Through examining the social implications for each approach, we explore issues such as accessibility and aesthetics. Finally, each approach will have differing levels of impact to the environment.

There is an important overlay associated with our analysis. Some risk is inevitably associated with living or building near shorelines, and a suite of existing management tools (e.g., floodplain building regulations and flood insurance) are designed to reduce or manage that risk. It is important to recognize that our current suite of tools, strategies, and approaches for dealing with flooding and erosion may not work as intended as the effects of climate change materialize. They may even have unintended negative consequences. The term maladaptation is applied to actions that may lead to increased risk of adverse outcomes, now or in the future (IPCC, 2018). These negative impacts may be the unintentional consequence of well-meaning but poorly planned actions taken to adapt to climate change but can also stem from decisions that deliberately prioritize short-term benefits over the long-term needs of climate preparedness (IPCC, 2018; Noble et al., 2014).

Consequences of maladaptation can take many forms. Maladaptive decisions may foreclose or complicate other adaptation strategies in the future, potentially making adaptation more costly in the long run. At the extreme, maladaptation can include actions that put more people in harm's way (Noble et al., 2014). Consider this hypothetical example: A community invests in improving a seawall to reduce flooding. Restrictions on coastal development behind the seawall are relaxed, which encourages additional construction in the hazard zone. The seawall leads to a variety of negative consequences — habitat is impacted, maintenance is required, and access to the shoreline is reduced. When the seawall eventually is overtopped due to sea level rise, the development built because of the seawall is exposed to greater damage. Relying on the false security created by the seawall, the community made considerable associated development investments and has been less likely to consider other strategies, such as retreat or buyouts, because they are trying to protect the investments they have already made.

The potential for maladaptation (and the consequences it can bring to people and property) should be considered in sea level rise planning. We raise the concept of maladaptation not to discourage people from taking adaptive actions, but to encourage thorough consideration of the available options, and their associated costs, as sea level rises.

Approach 1: Hard Defensive Structures

Hard defensive structures include a suite of constructed shoreline modifications typically made of metal, concrete, wood, rock, treated wood, packed earth or other hard materials that are designed to be fixed in place. Hard defensive approaches have been used extensively in coastal Washington for over a century to limit coastal flooding and erosion, or to protect filled areas (Carman et al., 2010). For example, over 27 percent of the shoreline of Puget Sound is currently treated with some form of shoreline "armor," a term used colloquially in Puget Sound, and in the section below, to refer primarily to erosion-control structures like bulkheads and revetments (Johannessen et al., 2014).

Hard defensive structures currently require approval and permitting at multiple levels of government (Carman et al., 2010), and new shoreline armor is actively discouraged in some jurisdictions in

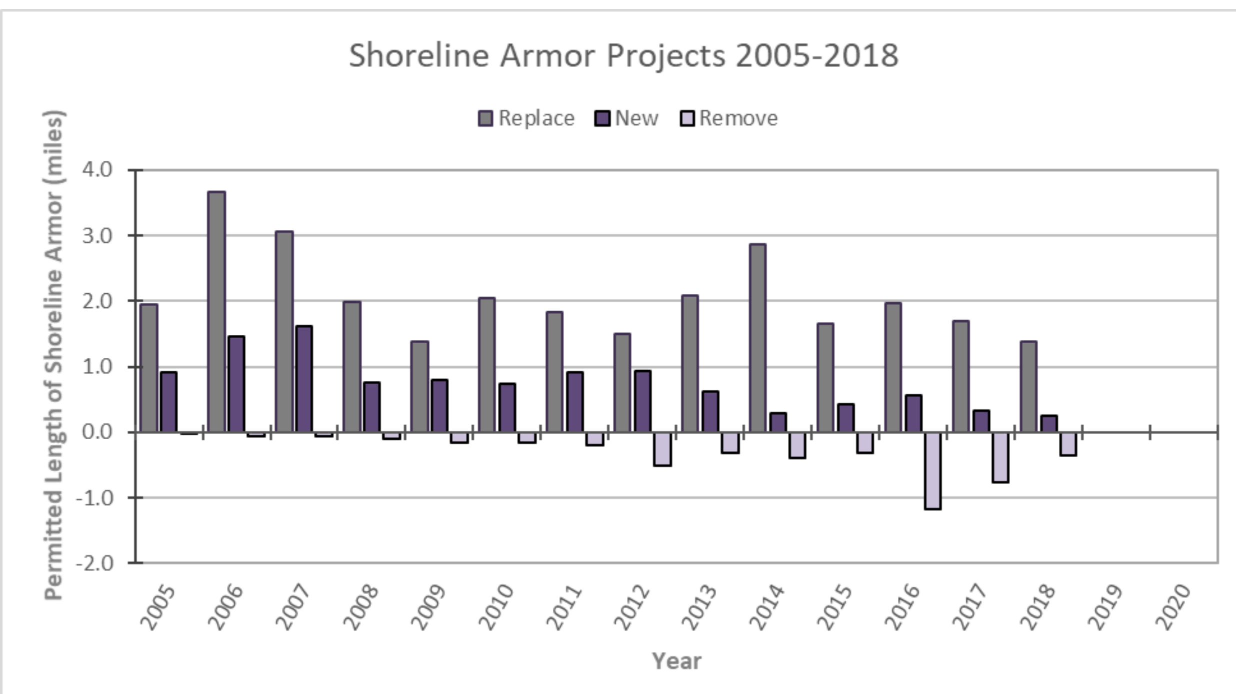

Figure 5. Length of shoreline armor replacements, installations and removals in Puget Sound, by year, between 2005 and 2018. Modified using data provided by the Puget Sound Partnership, 2019.

Washington. Perhaps consequently, the construction rate of new shoreline armoring has slowed in Washington's Puget Sound (Figure 5).

Effectiveness and Financial Considerations

On most shorelines, hard defensive structures can be designed to effectively reduce erosion over some period and are likely to be a viable option for reducing erosion under a future of rising sea level (Mills et al., 2018). Hard defensive structures can also reduce or eliminate backshore flooding on low-lying shorelands if built to an adequate elevation (National Research Council, 2014). Absent sea level rise, hard defensive structures can work effectively for longer periods of time, though maintenance, like nourishment or periodic repairs, may be required to keep shoreline armor structures functioning adequately (Galster and Schwartz, 1990; Figure 6).

Figure 6. Cobble nourishment on Ediz Hook, Washington is placed approximately every 5 years to protect larger rip-rap material from undercutting. February 2017 photo by Ian Miller, Washington Sea Grant.

Hard defensive structures do not, though, eliminate the risk of erosion or backshore flooding. Shoreline armor, for example, may lead to erosion along the toe of the structure that can contribute to structural failure (Ruggiero, 2010). structures can also fail if exposed to conditions outside of their design specifications, for example during extreme storms (Thieler and Young, 1991), or with changing environmental conditions. There are limits, even absent of sea level rise, to the risk reduction services that hard defensive structures can provide (Figure 7). Additionally, the effectiveness of hard defensive structures comes at a price. An analysis of project costs for a variety of types of shoreline treatments in Island County, Washington found that hard shoreline armor designs were generally more expensive than other alternatives (Côté and Domanski, 2019).

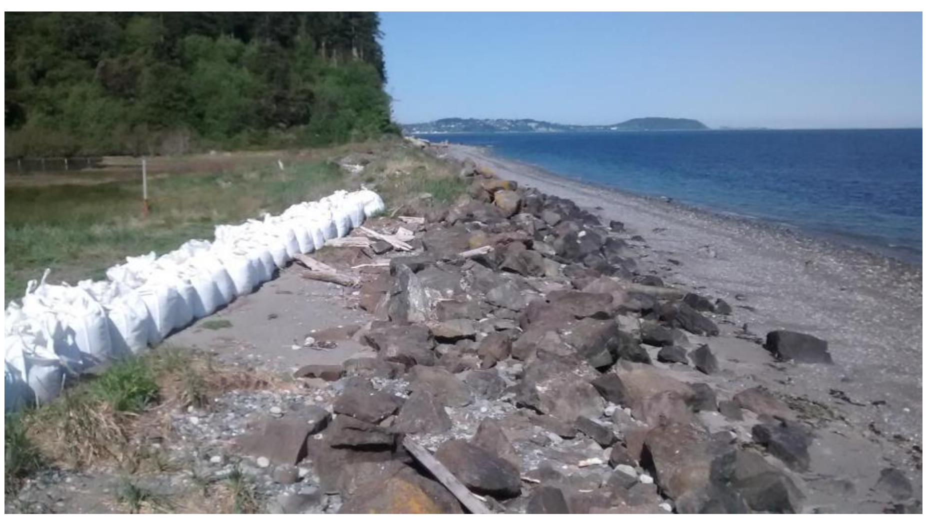

Figure 7. A failing rip-rap structure near Fort Flagler is supplemented with an additional placement of quasi-temporary sandbags to reduce backshore flooding. May 2015 photo by Ian Miller, Washington Sea Grant.

Sea level rise may compromise the risk reduction services provided by hard defensive structures and increase construction and/or maintenance costs. Hard defensive structures are typically not built to be easily adapted or modified after construction, so their effectiveness may decrease as sea levels continue to rise (Sutton-Grier et al., 2015). Approaches that could make hard defensive structures on the shoreline more adaptable to sea level rise—such as modular designs that can be altered as conditions change—have been proposed (Headland, 2013). Such approaches, though, may require additional space to implement, and add cost to the design and construction of the structures. Sea level rise is therefore likely to increase the costs of construction and maintenance associated with hard defensive structures (Grays Harbor Coastal Futures Project, 2018), even as their effectiveness and lifespans decrease.

Social Implications

Hard defensive structures along shorelines can lead to a loss of access to the beach, either because the beach fronting the structure is eliminated by coastal squeeze—a process by which intertidal habitats are lost when they are prevented from migrating landward as sea level rises—(Pontee, 2013), or because the structure needs to be built at a height that would preclude easy physical and visual access to the shoreline. This, in turn, may affect the value of coastal properties. Côté and Domanski (2019), for example, found that shoreline armor on individual parcels in Island County, Washington reduced property values in some cases, as compared to adjacent parcels without armor, due to reduced access to the shoreline and compromised aesthetics. Shoreline armoring also may increase the risk of shoreline erosion on neighboring properties (National Research Council, 2014). Such an effect could be exacerbated if rates of armoring increase as sea level rises, placing cost burdens on neighbors.

Increasing coastal flood frequency and magnitude associated with sea level rise may also require larger hard defensive structures that cover multiple parcels. Flooding of an entire neighborhood may still occur, for example, if just one homeowner cannot or will not build their defensive structure high enough to account for sea level rise. In other words, a degree of cooperation, decision-making and coordination may be necessary, which could require an additional investment of time, social capital and perhaps money from homeowners (Figure 8).

Figure 8. A soft shore engineered berm protects 15 parcels along a stretch of shoreline near Sequim, Washington. This project requires collaboration and coordination between neighbors to fund, build and maintain the berm, providing a template for coordinated approaches that may be required as sea level rises. August 2013 photo by Ian Miller, Washington Sea Grant.

Ecological Implications

Shoreline armor is associated with the loss of large wood and wrack (drift seaweed that accumulates on beaches) from beaches, and a reduction in the abundance of intertidal invertebrates (Dethier et al., 2016). If sea level rise leads to an increase in the number and extent of hard defensive structures along Washington's coasts, these impacts to ecosystem structure and function would be expected to increase. Additionally, coastal squeeze will have the effect of further reducing the area of intertidal habitat available to support organisms that depend on those habitats. A modeling study focused on the beaches of Grays Harbor, Washington, for example, found that scenarios in which homeowners relied on hard defensive structures to protect their properties as sea level rose led to a large decline in the beach habitat utilized by razor clams (Grays Harbor Coastal Futures Project, 2018).

Hard defensive structures can also interact with hydrodynamic processes along shorelines (i.e., waves and currents) in ways that can lead to adverse physical impacts to intertidal habitats, including scouring and erosion. Ruggiero (2010) notes that these physical impacts do not occur in all cases, and are not well understood, but seem to be related to the orientation and elevation of structures on the shoreline. In areas where these impacts do occur, they can lead to beach coarsening and narrowing, which would impact the habitat quality of the intertidal shoreline. Already there is some evidence that beaches in Puget Sound adjacent to shoreline armoring are narrower than nearby unarmored shorelines segments (Hacking et al., 2014). The expansion of hard defensive structures as sea level rises would presumably make those impacts more likely (Lamont et al., 2014).

Approach 2: Protection with Soft Shore Techniques

Soft shore techniques include a broad set of designs that are built with materials that replicate natural beaches, but still reduce risks from erosion and flooding (Sutton-Grier et al., 2015). In Washington State, soft shore techniques often refer to small beach nourishments, gravel berms, vegetation enhancement, and the structural use of large wood on the shoreline (Figure 9; Johannessen et al., 2014). Soft shore techniques are generally viewed as being less ecologically damaging compared to hard defensive structures (Figure 10), and their use is encouraged in Washington State where some form of engineered risk reduction action is needed (Johannessen et al., 2014, Carman et al., 2010).

Figure 9. A cobble "dynamic revetment", with placed large wood, built along the shoreline near North Cove, Washington and designed to reduce erosion. Photo by Jackson Blalock, Washington Sea Grant.

Effectiveness and Financial Considerations

Soft shore techniques generally cost one-third to one-half as much as shoreline armor alternatives (Lamont et al., 2014, Côté and Domanski, 2019; Table 2) per linear foot of shoreline. Additionally, homeowners in some locations in Washington State may be eligible for financial incentives to help implement soft shore techniques (e.g., Shore Friendly programs; Kinney, 2018). However, the effectiveness of soft shore techniques at reducing erosion or flood risk remains relatively poorly understood (Shipman, 2017), and soft shore techniques are not effective or appropriate in all circumstances (Johannessen et al., 2014).

Figure 10. Before (left panel) and after (right panel) the removal of shoreline armor and implementation of soft shore techniques at Cornet Bay near Deception Pass on Whidbey Island. The presence of large wood, beach wrack and vegetation on the upper beach suggests removing the shoreline amor improved ecological function along this stretch of shoreline. August 24, 2009 (left) and February 23, 2016 (right) photos by Hugh Shipman, Washington Department of Ecology.

There are some encouraging signs, though, that suggest soft shore techniques can provide effective protection from erosion and flooding. Many soft shore projects constructed in Washington State have persisted for many years (Figure 11), and evidence is accumulating that they can provide cost-effective risk reduction services (Johannessen et al., 2014; Weiner et al., 2019).

Soft shore techniques such as beach nourishment and log placement may also provide some advantages over hard armor as sea level rises. Some engineers report that sea level rise is considered in the design of soft shore projects, mostly by designing projects to be taller and wider (Johannessen et al., 2014; Lamont et al., 2014). Additionally, in a review of a variety of shoreline treatments, Lamont et al. (2014) found cost savings associated with soft shore projects relative to shoreline armor, even in instances in which sea level rise was considered in the design of the project. Given some soft shore techniques allow the project to deform and reform in response to natural processes, they may have a distinct advantage over hard defensive structures in an era of sea level rise, in that they can naturally move up and down the shoreline rather than be overtopped (Blenkinsopp et al., 2019). The projects, therefore, may be capable of some degree of self-adaptation to changing conditions (Sutton-Grier et al., 2015).

Table 2. Comparison of characteristics of three residential shoreline treatments conducted in Puget Sound, Washington State. Modified From Côté and Domanski, 2019.

	Property 1	*Property 2*	*Property 3*
***New** Shore Treatment*	*Hard armor*	*Hard armor*	*Soft shore structure*
***Previous** Shore Treatment*	*Hard armor*	*Natural beach*	*Mix of riprap and natural beach*
Aesthetic Condition and Shore Access	*No change: 3-4 foot vertical bulkhead between yard and beach. No change in access.*	*Decreased:3-4 foot vertical bulkhead between yard and beach. Decreased shore access.*	*Increased: Natural slope from yard to beach. Possibly increased shore access.*
Cost of Project	*$69,400*	*$57,447*	*$32,729*

Like all defensive approaches, soft shore techniques come with a maladaptation risk (Woodruff et al., 2018). This risk was highlighted in a model-based study conducted for Grays Harbor County (Grays Harbor Coastal Futures Project, 2018), in which the policy options that emphasized in-place protection of structures, regardless of whether the protection was afforded by hard defensive structures or soft shore techniques, led to the biggest flooding risk to structures by the end of the century, especially for the worst sea level rise scenarios (i.e., highest future sea level).

Social Implications

Côté and Domanski (2019) found that soft shore techniques can reduce erosion risk while also maintaining or enhancing shoreline accessibility and aesthetics. Homeowners that have chosen soft shore techniques report that aesthetics and access are key elements in their satisfaction with the designs they have selected and built (Côté and Domanski, 2019). The accessibility benefit may persist as sea level rises. A study conducted for Grays Harbor County in Washington State found that beach accessibility was highest as sea level rises under policy scenarios that emphasize dune restoration and nourishment. Interestingly, in the model those same policy scenarios were implemented at a relatively low cost, providing a significant cost-benefit ratio for accessibility—much higher than other policy scenarios examined in the study (Grays Harbor Coastal Future Project, 2018). However, the relative novelty of soft shore techniques, coupled with the diversity of existing design concepts (Johannessen et al., 2014) may be obstacles to their permitting and construction in Washington State (Shipman, 2017). Some homeowners report frustration with the permitting process for projects incorporating soft shore techniques (Flynn and Flynn, 2019).

Ecological Implications

Figure 11. A cobble berm installed in 1992 at a site on the north side of Orcas Island, Washington replaced shoreline armor. This soft shore project has performed well since installation, providing erosion control and flood risk reduction at this site (Johannessen et al., 2014). 2006 photo by Hugh Shipman, Washington Department of Ecology.

Soft shore techniques are often promoted because they are viewed as being less ecologically impactful than hard defensive structures. There is some evidence to support the assumption that soft shore projects are less impactful ecologically relative to shoreline armor; and shoreline armor has been shown to have a variety of negative impacts on beach fauna (Dethier et al., 2016) and physical beach processes (Ruggiero, 2010). Soft shore techniques likely lessen many of those impacts (Johannessen et al., 2014). Lamont et al. (2014), Sutton-Grier et al. (2015), and Côté and Domanski (2019) classified the relative ecological impacts of various hard and soft shore stabilization approaches by comparing attributes of their designs. In all cases their results suggest that soft shore techniques are less ecologically impactful than hard defensive structures. In each case, though, the actual impacts of benefits on fauna or other ecosystem services were not directly measured.

Approach 3: Adapting in Place - Accommodation

Accommodation encompasses a suite of techniques that reduce flooding impacts to infrastructure through building or site modifications that can be utilized in industrial, commercial, and residential structures. Options include elevating structures on piles or fill; extending the height of walls; floodproofing to keep water out of living areas; or elevating building systems such as electrical equipment or HVAC above flood heights (Figure 12; Federal Emergency Management Agency, 2014; New York City Department of City Planning, 2013).

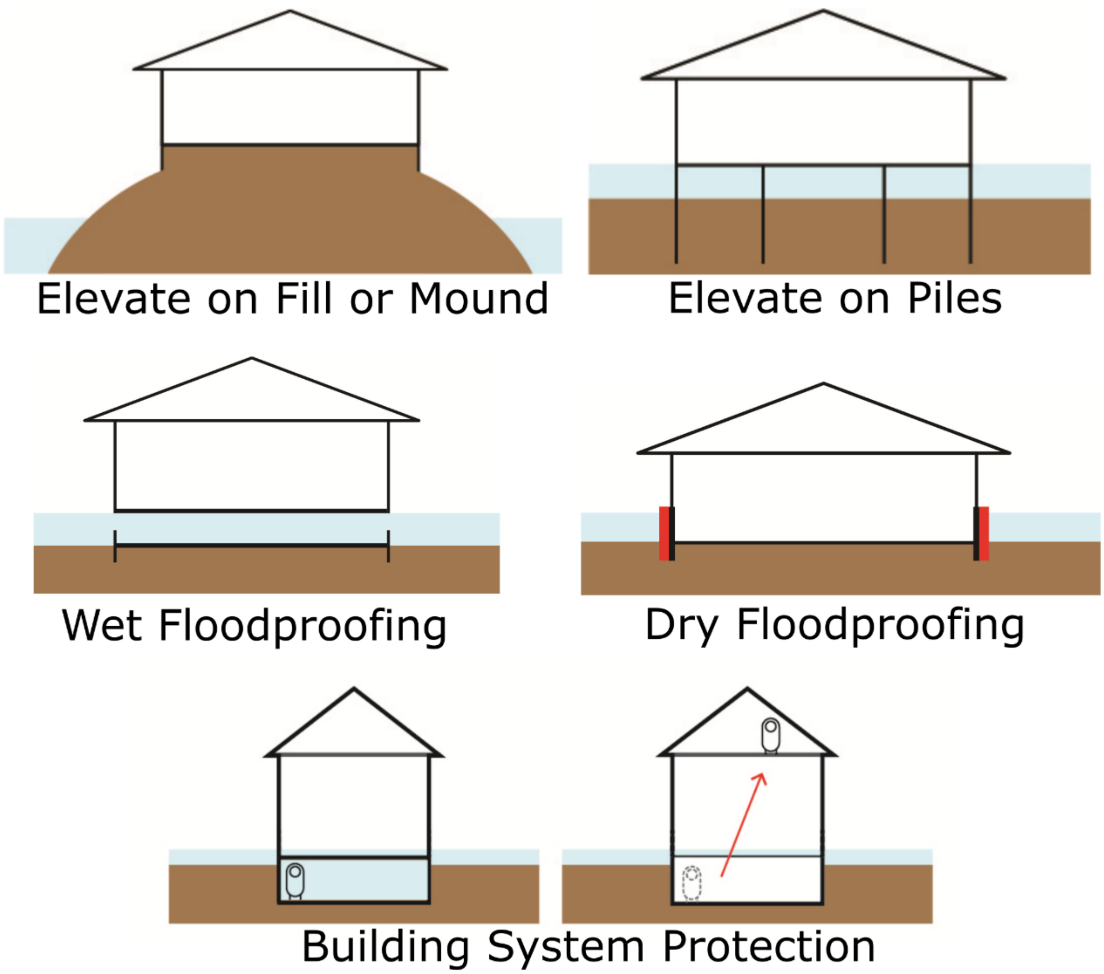

Figure 12. Illustration of accommodation techniques for new and retrofitted structures. Source: Inventory of Adaptive Strategies. Used with permission of the New York City Department of City Planning. All rights reserved.

The applicability of these techniques varies depending on the type of structure and whether it is a new or a retrofit building. For example, it is much more feasible to elevate structures at the time of construction than it is to raise them later, especially for large commercial and industrial facilities (New York City Department of City Planning, 2013). The feasibility of elevating an existing structure may depend on several factors, including the size and footprint of the building, its position on a parcel and impacts to adjacent properties, the type and condition of the foundation, the structural integrity of the building, any historic designation of the structure, and the aesthetic context of the neighborhood or community (Louisiana Office of Cultural Development, 2014). By contrast, modifying or moving flood-sensitive building systems (e.g., electrical panels, heating compressors) is a strategy that may be more feasible for many homeowners or building managers. These actions can be part of a retrofit or can be incorporated in the design of new structures from the outset (New York City Department of City Planning, 2013; Urban Green Council, 2013).

Effectiveness and Financial Considerations

Accommodation techniques are used to reduce damage from episodic flooding and are recognized as an effective way to reduce flood risk to properties (Federal Emergency Management Agency, 2014). However, costs range widely across different accommodation techniques. Wet floodproofing (allowing water to pass under or through a structure) is generally the least expensive option for new construction or retrofits, while dry floodproofing (keeping water from entering a structure) is typically more costly. Elevating an existing structure is typically more expensive than either of the two floodproofing options and property owners may incur additional costs for permitting, foundation work, and utilities (Côté and Domanski, 2019). Elevating a new structure may increase construction costs due to the need for pile driving or importing fill material, but may also lead to cost savings by eliminating the need for a foundation.

Figure 13. Examples of a home on Guemes Island undergoing elevation retrofits due to flooding. Source: DB Davis Structural Moving and Raising, Island County, Washington. Reproduced with permission.

Elevating building systems may or may not be cost-effective relative to other protection or accommodation options, depending on the size of the building and the complexity of its systems. In some cases, it can be less costly to protect the systems in place through floodproofing than to move them (New York City Department of City Planning, 2013).

Accommodation techniques may offer some insurance benefits. The Federal Emergency Management Agency (FEMA) defines areas at risk of coastal flooding and certifies Flood Insurance Rate Maps delineating those areas (Federal Emergency Management Agency, 2005). Under the National Flood Insurance Program (NFIP), properties in some mapped flood zones are required to have flood insurance and to follow FEMA construction and development standards. Where flood insurance is a significant cost to property owners, accommodation techniques may offer a way to reduce risk and lower insurance premiums.

Like defensive approaches (i.e., armoring), investments in accommodation may give people a sense that they are not at risk from coastal hazards and may encourage residents to remain in potentially vulnerable locations (Grannis, 2011). As sea level rises and the severity or frequency of flooding increases, this may lead to a long-term financial burden, where property owners must continue to invest additional resources to accommodate flooding to maintain the use of their properties. The benefits of accommodation techniques, therefore, must be carefully weighed to assess whether accommodation will provide adequate protection over the desired life of the structure, and whether future investments might be required to maintain that level of protection.

Social Implications

Accommodation techniques like vertical elevation and floodproofing are not new concepts to shoreline homeowners, regulators, or construction professionals, and in many instances are regulated by local building codes. Furthermore, accommodation techniques can be employed to protect a wide range of structures, including critical infrastructure, existing homes and businesses, and planned developments (Grannis, 2011; New York City Department of City Planning, 2013). These attributes may make accommodation approaches easier for homeowners or building managers to implement.

Communities can also require or encourage accommodation techniques through building codes or rebuilding requirements to promote implementation in new construction and building retrofits (Grannis, 2011). Following Hurricane Sandy, New York City undertook an analysis of potential building and zoning code changes that would be needed to improve resiliency in the built environment. Their Building Resiliency Task Force identified a suite of strategies for implementing accommodation techniques, including developing or altering code language, and providing incentives to property owners and developers (Urban Green Council, 2013).

Accommodation techniques may allow coastal residents and businesses to remain in flood hazard zones, avoiding disruption to economies and communities, thereby supporting community vitality and well-being. However, this may also put communities at long-term risk and require additional investments in infrastructure (e.g., roads, water and waste-water utilities) to support the homes or businesses remaining near the shoreline. Additionally, if the use of accommodation techniques encourages additional development in coastal flood zones, more people and property become exposed to flood hazards.

Ecological Implications

Accommodation techniques are usually employed within the building footprint, and therefore have fewer direct ecological implications than hard defensive structures. Net ecological benefits may be achieved, for example, if accommodation techniques are paired with restrictions on shoreline armor or requirements for its removal (Grannis, 2011). By designing or retrofitting buildings with potential flooding in mind, structures may be less sensitive to periodic flooding and may not require other approaches to reduce flood risks. This may allow for some limited preservation or restoration of shoreline processes and habitat in developed areas.

However, accommodation strategies may result in environmental consequences if harmful materials remain exposed to flooding. Septic systems, for example, are relatively difficult to elevate out of a flood zone and are therefore likely to fail if exposed to floodwaters, potentially releasing sewage, bacteria and excess nutrients into the marine environment (Mihaly, 2017).

Approach 4: Making Space Along the Coast – Retreat or Avoidance

Retreat is the act of moving existing assets away from at-risk areas along the coast, while avoidance refers to approaches that prevent placing new assets in at-risk areas. These two concepts are addressed together in this section. The concept of retreat is not a new one. Approximately 1.3 million people have relocated in response to natural hazard risks within 22 countries across the globe (Mach et al., 2019). However, retreat from coastal hazards zones is often challenging for homeowners and municipalities to accept (Mulkern, 2019). Below, we examine voluntary and regulatory approaches for implementing retreat in coastal communities.

Voluntary buyout programs typically involve making public funds available to purchase at-risk properties from willing property owners at market rates. FEMA, for example, has a long record of funding the purchase of properties in areas prone to river flooding (Mach et al., 2019). Washington State has implemented state-funded buyouts of at-risk riverside properties through programs like Floodplains by Design, which over the past few years has funded the relocation of approximately 700 homes. In King County, 63 residences were bought out and removed along the Cedar River (Brown, 2019). Relatively few public funds have been used for coastal home buyouts in Washington State (Tim Cook, Washington State EMD, personal communication, 11 February 2020), but coastal buyout programs do exist in other states. After Hurricane Sandy, the Blue Acres Buyout program was established in New Jersey, and more than 700 properties in coastal flood hazard zones have been purchased and removed (Schwartz, 2018).

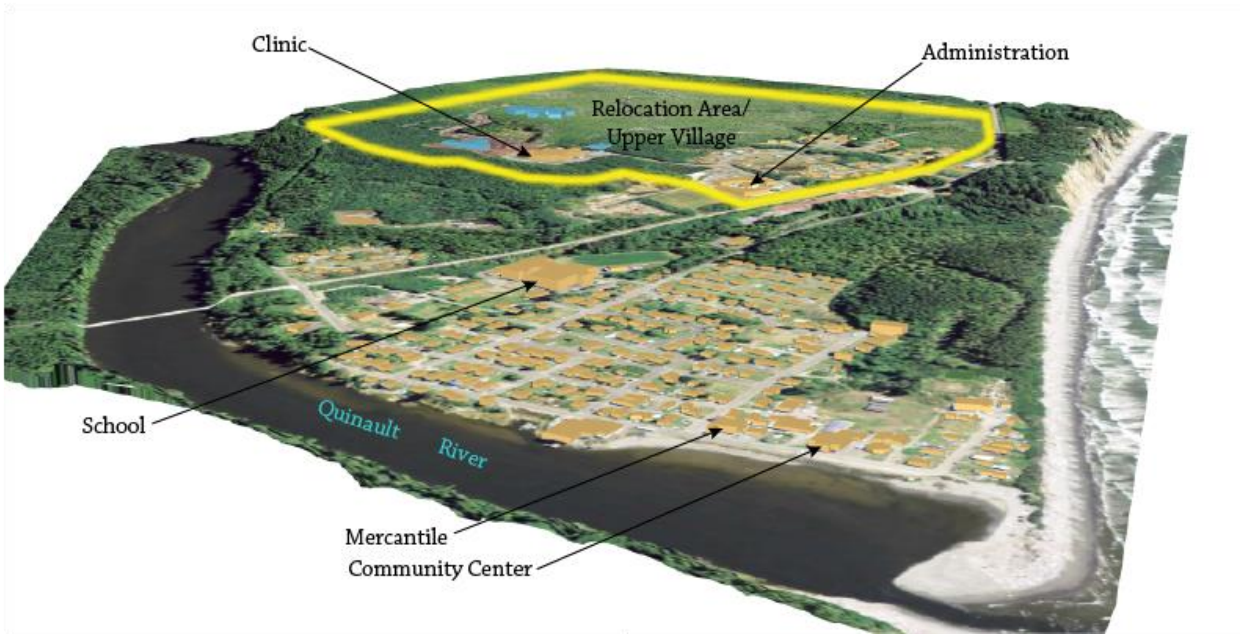

Figure 14. Quinault Indian Nation relocation plan overview for the village of Taholah. Taholah Community Relocation Plan, Quinault Tribe.

Some coastal communities are actively implementing community-scale coastal retreat as a preferred alternative to reducing risk from coastal hazards. The Quinault Indian Nation, for example, spent many years developing a relocation plan to address future anticipated flooding of tribal governmental infrastructure (Figure 14). The plan also designates locations for individuals to voluntarily relocate their homes to higher ground.

Property owners may also choose to fund the relocation of structures away from the shoreline in response to flooding and erosion (Figure 15; Washington Coastal Hazards Resilience Network, 2020). Conservation easements can be placed on a property by a landowner to restrict future uses or development near the shoreline. A number of these sorts of conservation easements have been implemented in coastal Washington State. For example, in San Juan County, the San Juan Preservation Trust holds conservation easements that restrict shoreline armor or coastal vegetation removal (Loring, 2014).

Regulatory approaches for making space along the coast generally fall into one of three categories (Neal et al., 2017):

Avoidance approaches disallow, through regulation, development or redevelopment in hazard zones using techniques such as no-build areas, building setbacks, fixed or rolling easements, and zoning. Many of these tools—like no-build zones in hazardous areas, vegetation buffers and shoreline setbacks—are currently implemented in Washington State. For example, critical area buffers are intended to locate structures away from erosion, landslide, or flood hazards on the coast or elsewhere (Washington State Department of Ecology, 2017). Rolling easements refer to a large range of techniques, either regulatory or voluntary, that facilitate landward migration as property is impacted by rising sea levels or erosion. Examples of regulatory rolling easements include prohibitions on hard defensive structures or requirements for the removal of those structures, and can be embedded in law, or written into property titles or community covenants. A voluntary approach might include conservation easements, or the transfer of development rights as seas rise (Titus, 2011). In each case, the property owner maintains full rights to use the land until the property is threatened in a specific and predetermined way. Implementation of rolling easements depends upon state law, and examples can be found in California, Hawaii, Maryland, Maine, North Carolina, Rhode Island, South Carolina and Texas (Titus, 2011).

Abandonment approaches disallow reconstruction after damage or a disaster (Neal et al., 2017), and are specified in zoning or permitting regulations or are part of post-disaster response policies. For example, South Carolina limited reconstruction of heavily damaged structures after Hurricane Hugo, though the policy was challenged for going too far in restricting property rights and was softened (Neal, et al., 2017). Local governments could also use condemnation to achieve abandonment in cases where a damaged building no longer has a septic system, sewer lines or safe access (Neal, et al., 2017).

Figure 15. Multifamily housing moved back from a bluff due to erosion on Whidbey Island in 2018. Source: DB Davis Structural Moving and Raising, Island County, Washington. Reproduced with permission.

Relocation approaches use building codes to require that infrastructure be moved in response to a hazard, either after impact or when there is a clear and present danger of imminent impact.

Effectiveness and Financial Considerations

From a risk reduction standpoint, avoiding, removing, or relocating development from the shoreline is effective. By reducing new at-risk development and moving structures and services out of erosion and flood hazard zones, coastal decision-makers reduce potential damages and reduce or eliminate the need to construct protective structures. Diaz (2016) modelled adaptation pathways for 12,000 segments of the world’s coastlines, finding that retreating from hazardous shoreline areas is cost-effective in most cases, if it is done proactively (i.e., a coordinated effort managed through a planning process). Retreat is a viable approach in Washington State. A 2019 study evaluated two instances in which bluff-top property owners in Washington State moved their homes inland in response to coastal erosion. These homeowners incurred costs for the move, as well as additional costs for permitting, new foundations, utilities, and other construction expenses (Côté and Domanski, 2019). The study evaluated the effect of the approach and found, aside from the reduction in risk that the move provided, that relocating the homes increased property values and provided other benefits.

By contrast, reactive retreat—moving away from the shoreline in response to incurred damages—is not as cost-effective, as it assumes that individuals suffer losses to land and property prior to relocating and that local jurisdictions do not limit development until hazardous conditions manifest (Diaz, 2016). This is a critical point: a well-planned strategy with community buy-in is necessary for the success of retreat or avoidance approaches (Abel et al., 2011).

As sea level rises, the cost-effectiveness of relocating or removing development is likely to remain high. A study in Grays Harbor County found that the continual maintenance or construction of new hard defensive structures like bulkheads far exceeded the cost of relocating structures, and that the cost discrepancy between the two only grew over time and as sea level rose (Grays Harbor Coastal Futures Project, 2018).

It is important to note that there are limited examples to draw from, and that feasibility, costs and benefits are site-specific. Yet these examples suggest that retreat can provide risk reduction over the long term at comparable costs, while also providing more open space for geological and ecological functions. Of all the options for managing shorelines in the face of sea level rise, managed retreat creates the greatest opportunity to avoid the problem of maladaptation. Structures removed from harm's way will be more resilient than those that are protected with either hard or soft solutions, or those that have been designed to accommodate increases in flooding.

Social Implications

The major impediments to managed retreat are political or socioeconomic in nature (Neal et al., 2017). In a recent example in Del Mar, California, the concept of managed retreat—recommended by the California Coastal Commission as an adaptation measure for the city's coastal plan—was rejected. Property owners balked at the concept that a local government could use regulations to force relocation of expensive waterfront homes (Mulkern, 2019). Retreat strategies often are not viewed as feasible by coastal planners in urban settings with dense development, due to cost, permitting, land-use constraints and legal considerations (New York City Department of City Planning, 2013). Political will is often limited when proposals are made to allocate local funds for costly buyout of coastal properties, or their maintenance (Doberstein et al., 2020). Regulatory relocation or avoidance approaches may also be associated with legal challenges. While Washington's regulatory structure allows for the implementation of building setbacks and creation of buffers to address impacts to habitat, the legal implications for imposing these types of development restrictions to address unrealized sea level rise risk require further examination.

Ecological Implications

Retreat from the shoreline, via either avoidance or relocation, is generally viewed as optimal from an ecological perspective, since it maximizes space for natural shoreline processes (Koslov, 2016). Unlike either protection or accommodation strategies, retreat allows for the shoreline to migrate while maintaining natural habitat in most cases (Neal et al., 2019), thereby avoiding the phenomenon of coastal squeeze (Pontee, 2013). For example, in a modeling study of future shoreline conditions in Grays Harbor County, Washington, intertidal habitat for razor clams was maintained only under policy scenarios that emphasized retreat of infrastructure from the coast (Grays Harbor Coastal Futures Project, 2018). Retreat can also allow for the restoration of degraded shorelines, such as by removing hard armor that is no longer needed. On Puget Sound beaches, for example, shoreline armor removal (enabled in some cases by relocation of infrastructure; Figure 16) is associated with an increase in shoreline biota and other ecological metrics (e.g., beach wrack) that support ecosystem function (Lee et al., 2018).

Figure 16. Before and after (inset photo) of a shoreline property on Vashon Island purchased by King County for a shoreline restoration project. Both the home, and the shoreline armor were removed in this project. Photos by Kollin Higgins and Greg Rabourn, King County.

Conclusion and Recommendations

The purpose of this paper was to assess trade-offs associated with coastal management approaches and strategies that can be applied in Washington State as sea level rises. The choice of whether and how to attempt to protect shorelines—or to implement accommodation or retreat strategies—is an example of the complex and difficult decisions that sea level rise will force individuals and communities to make. For example, the 2018 Shoreline Armoring Implementation Strategy included four strategies for reducing shoreline armoring in Puget Sound: developing homeowner incentives, effectiveness of regulations, technical and design improvements, and planning. Sea level rise will complicate the implementation of all four of these strategies and should be part of the planning and implementation conversations coastal scientists and managers are having with each other and with property owners (Habitat Strategic Initiative, 2018).

As we conducted our research, we found limited localized information about the costs and benefits associated with various approaches and strategies. However, as we explored the economic, social, and environmental costs and tradeoffs of different coastal management options, we distilled a set of insights and conclusions (Table 1). We conclude, based on the evidence currently available, that adopting defensive strategies to protect homes and infrastructure in place does not always provide the most effective risk reduction, and may not be cost-effective over the life of the structure. These are important considerations for coastal decision-makers as they begin to weigh their options for responding to sea level rise. Fortunately, there are other options available that can reduce the risks associated with erosion and flooding as sea level rises. Where shoreline protection is necessary, soft shore techniques should be carefully evaluated against more traditional hard defensive structures because of their cost-effectiveness, the likelihood that they cause less damage to ecosystem functions, and because they may be more able to adapt to changing conditions as sea level rises.

If flooding is the main concern, accommodation techniques can be implemented to allow new and existing structures to “live with water” during periodic coastal flooding, but this option may not suffice as inundation becomes a more permanent pattern on the landscape. Managed retreat from the shoreline, through relocation and avoidance strategies, can permanently reduce risk to life and property and may present the most cost-effective option in the long run. This suggests that shoreline policies in Washington State should emphasize avoidance strategies for new development, and that the state should begin to develop policies that facilitate the relocation of existing shoreline development. However, more research is needed to understand how to best implement retreat in a socially acceptable and legally defensible manner.

We also identified several gaps in our knowledge that we grouped into five categories:

Design and Technical Considerations: How will climate change and sea level rise alter the environmental conditions on Washington’s shorelines (e.g., wave impacts and flood height, frequency, and duration)? How will these changing conditions impact the design of shoreline protection structures and accommodation techniques?

Areas of future research may include:

- How different shoreline types on Washington’s coasts (e.g., accretion shoreforms, feeder bluffs) will respond to changing conditions. Filling this gap may rely on modeling approaches, as well as long-term field monitoring as sea level rises. Improved knowledge will influence our understanding of which response approaches are most appropriate in different locations.
- The durability of hard defensive structures and soft shore projects over time, both under current conditions and as sea level rises. This will impact the rate of repair or replacement of these

designs, and therefore expected costs. This can be achieved through monitoring and evaluating projects over their lifespan.

Economic Considerations: How do the costs of different approaches compare under today's conditions? How might sea level rise impact those costs, both for initial design and construction, and for maintenance over the lifespan of the chosen approach? Can we quantify the benefits associated with the different approaches?

Areas of future research may include:

- Costs to repair or replace hard defensive structures and soft shore projects over their lifespans, and how sea level rise might impact the cost-effectiveness of repairing or replacing these designs.
- The total costs (including permitting, utilities, etc.) and time commitments to elevate or relocate homes, buildings, roads and other types of infrastructure. When is it cost-effective compared to the other approaches?
- Long-term costs and benefits of property buyouts to the individual property owner. What costs or challenges are faced upfront, and how might they compare to benefits accrued or losses avoided in the future? What is the individual return on investment for participating in a buyout?
- Analysis specific to Washington State of the financial, social and political costs for implementing relocation options.
- Ecosystem services valuation of the nearshore—what is the economic value of a functioning nearshore environment? How will sea level rise and potential loss of this habitat impact those ecosystem services and their value?

Social Considerations: What impacts might sea level rise have on Washington's coastal communities? How does the decision to undertake each response approach impact the surrounding community? How do social implications differ between approaches?

Areas of future research may include:

- Repurposing existing data (e.g., building footprint data, FEMA flood zones, mapped flood heights and extents) to analyze sea level rise vulnerability and identify adaptation options.
- Social benefits and drawbacks of buyouts. What challenges are faced upfront, and how might they compare to benefits accrued or losses avoided in the future? What is the community's or the public's return on investment for funding buyouts?

Ecological Considerations: Can we quantify the full range of ecological functions and benefits (both to environmental systems and to humans) that the nearshore provides today? How will sea level rise and its associated impacts affect nearshore species and functions?

Areas of future research may include:

- What are the ecological trade-offs associated with soft shore projects? Will sea level rise alter the balance of these trade-offs?
- Connections between the nearshore ecosystem and human well-being (ecosystem services). What are the benefits that individuals and society experience today from a functioning nearshore ecosystem, and how might sea level rise impact these benefits?

Governance Considerations: Addressing sea level rise will raise challenging administrative, legal and political questions. Is Washington's current shoreline permitting environment amenable to these response options? How might the state and federal regulatory environment change in response to sea level rise? Are there legal or political risks for local governments associated with acting (or not acting) to address sea level rise?

Areas of future research may include:

- Use of emergency permitting to address flooding and erosion, and how impacts from sea level rise might alter the demand, use and administration of these permits.
- What is the range of land use regulatory options currently available in Washington to restrict new development in vulnerable areas after experiencing damaging storm events?
- What is the nature and extent of local government authority to impose regulatory approaches to managing retreat, such as rolling easements, transfer of development rights, or erosion hazard setbacks?
- How can local governments, advocacy organizations, and others effectively communicate the trade-offs associated with each response option to shoreline property owners and other constituents?

These knowledge gaps point the way towards new research and analysis that will support coastal managers as they decide how to best plan for potential damage to infrastructure, financial and social impacts, and ecological protection.

References

Abel, Nick, R. Gorddard, B. Harman, A. Leitch, J. Langridge, A. Ryan, S. Heyenga. 2011. Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study, Article in Environmental Science & Policy, DOI: 10.1016/j.envsci.2010.12.002

Blenkinsopp, C.E., P.M. Bayle, D. Conley, G. Masselink, E. Gulson, I. Kelly, R. Almar, I.L, Turner, T.E. Baldock, T. Beuzen, R. McCall, H. Rijper, A. Reniers, P. Troch, D. Gallach-Sanchez, A. Hunter, O. Bryan, G. Hennessey, P. Ganderton, S. Schimmels, M. Kudella. 2019. Dynamic coastal protection: Resilience of dynamic revetments (DYNAREV). Proceedings of HYDRALAB. Bucharest, May 2019.

Brown, Alex, 2019. Washington State experiments with buyouts, restoring floodplains to avoid future disasters. Retrieved 15 January 2020 from https://phys.org/news/2019-10-washingtonstate-buyouts-floodplains-future.html

Carman, R., Taylor, K., and Skowlund, P., 2010, Regulating shoreline armoring in Puget Sound, in Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S., eds., 2010, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254, p. 49-54.

Climate Central and Zillow. 2018. Ocean at the door: New homes and the rising sea. Published by Climate Central. Available at https://www.climatecentral.org/news/ocean-at-the-door-new-homes-in-harms-way-zillow-analysis-21953

Côté, J., and A. Domanski, 2019, Benefit Cost Analysis of Shore Friendly Practices in Island County, Prepared for Island County Department of Natural Resources.

Dethier, M.N., W.W. Raymond, A.N. McBride, J.D. Toft, J.R. Cordell, A.S. Ogston, S.M. Heerhartz, H.D. Berry. 2016. Multiscale impacts of armoring on Salish Sea shorelines: evidence for cumulative and threshold effects Estuar. Coast Shelf Sci., 175 (2016), pp. 106-117

Diaz, Delvane B., 2016. Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). Climatic Change 137: 143. https://doi.org/10.1007/s10584-016-1675-4

Doberstein, B, A. Tadgell, A. Rutledge. 2020. Managed retreat for climate change adaptation in coastal megacities: A comparison of policy and practice in Manila and Vancouver, https://doi.org/10.1016/j.jenvman.2019.109753

Federal Emergency Management Agency. 2005. National Flood Insurance Program (NFIP) Floodplain Management Requirements: A Study Guide and Desk Reference for Local Officials. https://www.fema.gov/media-library-data/1481032638839-48ec3cc10cf62a791ab44ecc0d49006e/FEMA_480_Complete_reduced_v7.pdf

Federal Emergency Management Agency. 2014. Homeowner's Guide to Retrofitting: Six Ways to Protect Your Home From Flooding. https://www.fema.gov/media-library-data/1404148604102-f210b5e43aba0fb393443fe7ae9cd953/FEMA_P-312.pdf

Flynn, Sheri and Michael Flynn. 2019. Bulkhead Removal and Shoreline Restoration Project on Miller Bay: A Lesson in Patience, Persistence and Perseverance. Testimonial provided to Shore Friendly Kitsap. http://shorefriendlykitsap.com/wp-content/uploads/2019/12/flynntestimonial.pdf

Galster, R., & Schwartz, M. 1990. Ediz Hook—A Case History of Coastal Erosion and Rehabilitation. *Journal of Coastal Research,* (6), 103-113.

Glick, P., J. Clough & B. Nunley. 2007. Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon. A publication of the National Wildlife Federation. https://www.nwf.org/~/media/PDFs/Water/200707_PacificNWSeaLevelRise_Report.ashx

Grannis, Jessica. 2011. Adaptation Tool Kit: Sea-Level Rise and Coastal Land Use. Georgetown Climate Center, Washington, D.C. https://www.georgetownclimate.org/reports/adaptation-tool-kit-sea-level-rise-and-coastal-land-use.html

Grays Harbor Coastal Futures Project, 2018. Posters presented at workshop, 9 April 2018, at Grays Harbor College, Aberdeen, WA. Available at http://explorer.bee.oregonstate.edu/Topic/GraysHarbor/Presentations.aspx

Habitat Strategic Initiative. 2018. Narrative. Shoreline Armoring Implementation Strategy.Washington Department of Fish and Wildlife and Washington Department of Natural Resources.https://pspwa.box.com/v/PublicIS-ShoreArmoring

Hacking, A., K. Bolles, G.M. Kaminsky, D. McCandless, H.M. Baron. 2014. An initial comparison of armored and unarmored beaches from boast-based LiDAR. Poster presented at Salish Sea Ecosystem Conference, 2014.

Headland, J. 2013. Coastal Structures & Sea Level Rise: An Optimized Adaptive Management Approach. In: Proceedings of Coastal Structures 2011, pp. 109-119 (2013)

IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_AnnexI_Glossary.pdf

Johannessen, J., A. MacLennan, A. Blue, J. Waggone , S. Williams, W. Gerstel, R. Barnard, R. Carman, and H. Shipman. 2014. Marine Shoreline Design Guidelines. Washington Department of Fish and Wildlife, Olympia, Washington. https://wdfw.wa.gov/sites/default/files/publications/01583/wdfw01583.pdf

Kinney, Aimee. 2018. Shoreline Armoring Vital Sign Base Program Analysis. Puget Sound National Estuary Program.

Koslov, Liz. 2016. The Case for Retreat. Public Culture 28:2 doi 10.1215/08992363-3427487.

Lamont, G., Readshaw, J., Robinson, C., and St-Germain, P. 2014. Greening Shorelines to Enhance Resilience: An Evaluation of Approaches for Adaptation to Sea Level Rise; guide prepared by SNC-Lavalin Inc. for the Stewardship Centre for B.C. and submitted to Climate Change Impacts and Adaptation Division, Natural Resources Canada (AP040), 46p. http://www.stewardshipcentrebc.ca/PDF_docs/greenshores/Resources/Greening_Shorelines_to_Enhance_Resilience.pdf

Lee, T.S., Toft, J.D., Cordell, J.R., Dethier, M.N., Adams, J.W., and Kelly, R.P. 2018. Quantifying the effectiveness of shoreline armoring removal on coastal biota of Puget Sound. *PeerJ* 6:e4275 https://doi.org/10.7717/peerj.4275

LeRoy, S. and Wiles, R. 2019. High Tide Tax: The Price to Protect Coastal Communities from Rising Seas, The Center for Climate Integrity Resilient Analytics. https://climatecosts2040.org/files/ClimateCosts2040_Report.pdf

Limber, P. W., Barnard, P. L., Vitousek, S., & Erikson, L. H. 2018. A model ensemble for projecting multidecadal coastal cliff retreat during the 21st century. *Journal of Geophysical Research: Earth Surface*, 123, 1566– 1589. https://doi.org/10.1029/2017JF004401

Loring, Kyle. 2014. Addressing Sea Level Rise and Cumulative Ecological Impacts in San Juan County, Washington Through Improved Implementation and Effective Amendment of Local, State, and Federal Laws. Friends of the San Juans, Friday Harbor, WA. http://www.sanjuans.org/documents/Loring_2014_sea_level_rise_regulatory_review.pdf

Louisiana Office of Cultural Development. 2014. Elevation Design Guidelines For Historic Buildings in the Louisiana GO Zone. URS Group, Inc., Baton Rouge, LA. https://www.crt.state.la.us/Assets/OCD/hp/uniquely-louisiana-education/Disaster-Recovery/Final%20Elevation%20Design%20Booklet%2012-07-15%20v2.pdf

Mach, K. J., C. M. Kraan, M. Hino, A. R. Siders, E. M. Johnston, C. B. Field. 2019. Managed retreat through voluntary buyouts of flood-prone properties. Sci. Adv. 5, eaax8995.

MacLennan, A.J., J. F. Waggoner, J. W. Johannessen, and S. A. Williams. 2013. Sea Level Rise Vulnerability in San Juan County, Washington. Prepared for: Friends of the San Juans. Available at http://www.sanjuans.org/documents/MacLennanetal_2014_SJC_Sea_Level_Rise_Vulnerability_final.pdf

Mihaly, Elena. 2017. Avoiding Septic Shock: How Climate Change Can Cause Septic System Failure and Whether New England States are Prepared. Conservation Law Foundation, Boston, MA. https://www.clf.org/wp-content/uploads/2017/02/Avoiding-Septic-Shock_CLF-White-Paper_2017.pdf

Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. 2018. Projected Sea Level Rise for Washington State – A 2018 Assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project. Available at http://www.wacoastalnetwork.com/wcrp-documents.html

Miller, I.M., Yang, Z., VanArendonk, N., Grossman, E., Mauger, G. S., Morgan, H. 2019. Extreme Coastal Water Level in Washington State: Guidelines to Support Sea Level Rise Planning. A collaboration of Washington Sea Grant, University of

Washington Climate Impacts Group, Oregon State University, University of Washington, and U.S. Geological Survey. Prepared for the Washington Coastal Resilience Project.

Mills, A.K., J.P. Bolte, P. Ruggiero, K.A. Serafin, E. Lipiec, P. Corcoran, J. Stevenson, C. Zanocco, and D. Lach. 2018. Exploring the impacts of climate and policy changes on coastal community resilience: simulating alternative future scenarios. Environ. Model. Softw, 109, pp. 80-92. https://doi.org/10.1016/j.envsoft.2018.07.022

Mulkern, Anne C., October 7, 2019. Coastal City Refuses to Retreat, Scientific American. https://www.scientificamerican.com/article/coastal-city-refuses-to-retreat/

National Research Council. 2014. Reducing Coastal Risk on the East and Gulf Coasts. Washington, DC: The National Academies Press. https://doi.org/10.17226/18811.

Neal, William & Bush, David & Pilkey, Orrin. 2017. Managed Retreat. https://www.researchgate.net/profile/William_Neal/publication/318184981_Managed_Retreat/links/5ae352950f7e9b9793c2a1bf/Managed-Retreat.pdf

New York City Department of City Planning. 2013. Coastal Climate Resilience: Urban Waterfront Adaptive Strategies. New York City, NY. https://www1.nyc.gov/assets/planning/download/pdf/plans-studies/sustainable-communities/climate-resilience/urban_waterfront.pdf

Noble, I.R., S. Huq, Y.A. Anokhin, J. Carmin, D. Goudou, F.P. Lansigan, F.P. et al. 2014. Adaptation needs options. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.R. et al. (eds.) Cambridge, UK: Cambridge University Press. 833-868. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap14_FINAL.pdf

Pontee, N. 2013. Defining coastal squeeze: A discussion. *Ocean & coastal management*, 84, pp.204-207. https://doi.org/10.1016/j.ocecoaman.2013.07.010

Puget Sound Partnership, 2019. Net Change in Permitted Shoreline Armor. https://www.pugetsoundinfo.wa.gov/ProgressMeasure/Detail/42/VitalSigns

Romine, B.M., C. H. Fletcher, M. M. Barbee, T. R. Anderson, and L. N. Frazer. 2013. Are beach erosion rates and sea-level rise related in Hawaii? Global and Planetary Change,108: 149-157. https://doi.org/10.1016/j.gloplacha.2013.06.009.

Ruggiero, P. 2010. Impacts of shoreline armoring on sediment dynamics, in Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S., eds., 2010, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254, p. 179- 186.

Schwartz, Jen, August 1, 2018, Surrendering to Rising Seas, Scientific American. https://www.scientificamerican.com/article/surrendering-to-rising-seas/

Shipman, Hugh. 2017. The Use of Soft Shoreline Techniques: Implications for the Shoreline Armor Vital Sign, prepared for Puget Sound Partnership.

Sutton-Grier, A.E., K. Wowk, & H. Bamford. 2015. Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environmental Science & Policy. 51: 137-148, https://doi.org/10.1016/j.envsci.2015.04.006.

Sweet, W. V., Dusek, G., Obeysekera, J., and J.J. Marra. 2018. Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold, NOAA Tech. Rep. NOS CO-OPS 86. https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf

Thieler, E., & Young, R. 1991. Quantitative Evaluation of Coastal Geomorphological Changes in South Carolina After Hurricane Hugo. Journal of Coastal Research, 187-200. Retrieved January 30, 2020, from www.jstor.org/stable/25735415

Thorne, K. G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C. Freeman, and J. Takekawa. 2018. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. Science Advances, 4 (2)

Titus, James G. 2011. Rolling Easements, Climate Ready Estuaries, Environmental Protection Agency.
Web site at: water.epa.gov/type/oceb/cre/upload/rollingeasementsprimer.pdf

Urban Green Council. 2013. NYC Building Resiliency Task Force. New York Chapter of the U.S. Green Building Council, New York City, NY. https://www.urbangreencouncil.org/sites/default/files/2013_brtf_summaryreport_0.pdf

Vitousek, S., Barnard, P., Fletcher, C. *et al.* Doubling of coastal flooding frequency within decades due to sea-level rise. *Sci Rep* 7, 1399 (2017). https://doi.org/10.1038/s41598-017-01362-7

Washington Coastal Hazards Resilience Network. 2020. Washington Coastal Hazards Risk Reduction Project Mapper. https://waecy.maps.arcgis.com/apps/Shortlist/index.html?appid=58bac8d897ea48559d624eb06836a0d2

Washington State Department of Ecology. 2017. Shoreline Master Programs Handbook Chapter 11. https://fortress.wa.gov/ecy/publications/parts/1106010part11.pdf

Weiner, H.M., Kaminsky, G.M., Hacking, A., and McCandless, D., 2019. North Cove Dynamic Revetment Monitoring: Winter 2018-2019. Shorelands and Environmental Assistance Program, Washington State Department of Ecology, Olympia, WA. Publication #19-06-008. https://fortress.wa.gov/ecy/publications/summarypages/1906008.html

Woodruff, S., BenDor, T.K. and Strong, A.L. 2018. Fighting the inevitable: infrastructure investment and coastal community adaptation to sea level rise. *System Dynamics Review*, *34*(1-2), pp.48-77. https://onlinelibrary.wiley.com/doi/pdf/10.1002/sdr.1597