SEA LEVEL RISE CONSIDERATIONS for NEARSHORE RESTORATION PROJECTS in PUGET SOUND

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

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INTRODUCTION

Sea level is rising along much of Washington's coast and is projected to rise at an accelerating rate as the climate continues to warm. Local variation in vertical land movement causes different rates of relative sea level change along the coast and in Puget Sound. For example, the Seattle tide gauge shows relative sea level rise (SLR) of 8.6 inches since 1900 due to a combination of land subsidence and SLR. In contrast, relative sea level has dropped in Neah Bay by 5.2 inches since 1934 due to a localized area of rapid uplift of the land. Rising seas and associated changes in coastal hazards such as flooding, erosion, and saltwater intrusion will impact nearshore restoration projects. Given these observed and projected future changes in sea level and coastal hazards, we developed this document to assist restoration professionals with considering SLR impacts in the planning and design of nearshore restoration projects in Puget Sound.

Scope and Intended Audience

This document was developed in partnership with the University of Washington Climate Impacts Group, Washington Sea Grant, and Washington Department of Fish and Wildlife's Estuary and Salmon Restoration Program (ESRP). The ESRP funds nearshore restoration in the Puget Sound region -- defined here as the inland waters east of Cape Flattery (Neah Bay) to the US/Canada border (Figure 1). Therefore, the geographic scope of this document is consistent with the geographic scope of the ESRP program.

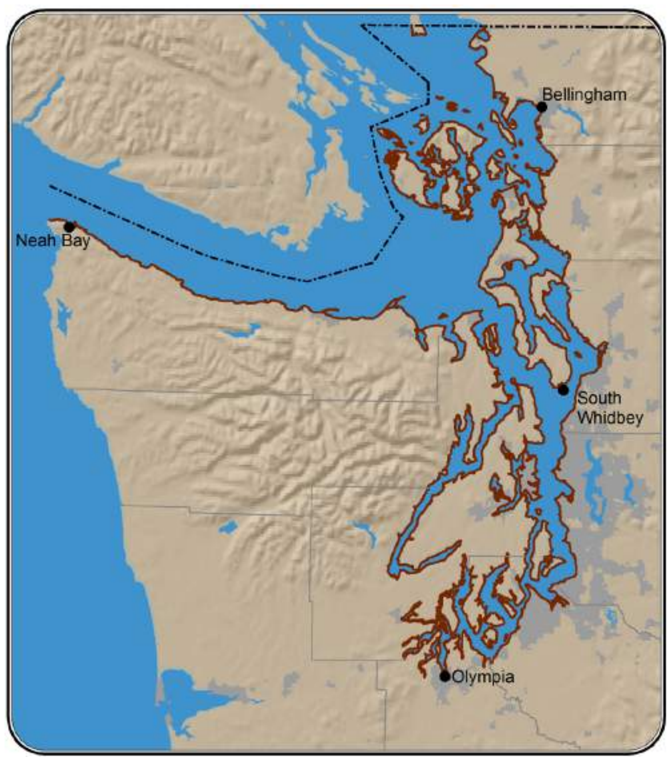

Figure 1. The red lines show the extent of the Washington coastline covered by the Estuary and Salmon Restoration Program (ESRP). A summary of sea level rise projections (Miller et al., 2018) for the points indicated are provided in Table 1.

The content and structure of this document were informed by two workshops led by Washington Sea Grant. These workshops convened restoration professionals and scientists in Puget Sound to identify key questions faced by the restoration community regarding SLR and restoration, as well as resources that could help address these questions.

This document provides information to evaluate the extent to which nearshore restoration projects are likely to be resilient to the impacts of SLR. The intended purpose is to assist restoration practitioners with identifying SLR impacts relevant for specific restoration actions. Restoration projects can also improve resilience for surrounding coastal communities if conditions adjacent to a site are incorporated into restoration planning and design.

The intended audiences are sponsors, designers, proponents, and reviewers of nearshore restoration projects and proposals. In addition, scientists leading our evolving understanding of nearshore ecosystems may find this information useful for informing future research priorities. Capital funding programs for restoration (e.g., ESRP) may find this information useful as they consider emerging policies to address climate resilience, but we do not anticipate this document to be used directly in the review of restoration projects. This document is not intended to be prescriptive, require modifications of a project, nor provide project-specific direction on how to modify a project to increase resilience to SLR. Instead, this document is designed to provide a structured process to help guide such decisions.

This document is organized into six sections:

1. **Process-Based Restoration and Resilience:** an overview of process-based restoration for nearshore habitats and a definition of resilience to SLR in this context.
2. **Sea Level Rise Impacts**: a brief summary of key impacts related to SLR that can affect nearshore restoration sites and projects.
3. **Sea Level Rise Projections**: an overview of the most recent SLR projections for Washington's coastlines presented in the report *Projected Sea Level Rise for Washington State – A 2018 Assessment* (Miller et al., 2018).
4. **Timeframe and Risk Considerations**: factors to consider when selecting the appropriate SLR projections to use in evaluating potential impacts on restoration sites and projects, including the timeframe and acceptable level of risk.
5. **Management Measure Considerations:** factors to consider in evaluating the effects of SLR on restoration actions (referred to as management measures by Clancy et al., 2009) commonly used to restore ecosystem processes in nearshore restoration projects. Considerations include impacts on the biophysical environment and infrastructure.
6. **Additional Information and Resources:** a list of products and reports developed as part of the Washington Coastal Resilience Project and a list of resources that were identified in the workshops with restoration professionals and scientists.

I. Process-Based Restoration and Resilience

A core mission of the ESRP program is to fund projects that restore physical ecological processes, recognizing the fundamental role that physical processes play in shaping habitat structure and associated ecological functions. The primary objective of restoring ecosystem processes is to facilitate the development of dynamic, self-sustaining habitats. Consistent with this mission we focus on SLR impacts for restoration actions that are designed to restore ecosystems to the greatest extent possible. We expect that the most resilient projects will be those that most fully restore ecosystem processes or exist within a landscape of functioning processes (Box 1). Nonetheless, we recognize that these projects may also include infrastructure to protect the site or adjacent properties from coastal hazards. Some projects also exist within constrained landscapes that prevent the full restoration of processes (Simenstad et al., 2006; Cereghino et al., 2012). The conceptual relationships between SLR impacts, ecosystem process, structure and function, and restoration actions (i.e., management measures) are depicted in Figure 2.

Box 1. Defining Resilience in the Context of Process-Based Restoration

In the context of sea level rise and process-based restoration, we define resilience as the capacity of the project to continue to sustain the processes and functions it was designed to restore, despite a gradual change in the sea level and associated impacts of flooding, waves, and salt-water intrusion. Resilience is defined by the Intergovernmental Panel on Climate Change (IPCC) as the ability of systems to absorb change and disturbance while maintaining ecological functions (IPCC, 2007). Thus, resilience is not intended to imply that the project will be *resistant* to any change, but that it can absorb changes without negative consequences. Recognizing the links between ecosystem processes, structure and function (Simenstad et al., 2006), resilient restoration projects are those with qualities that will lead to continued habitat function in the face of change.

A key aspect of process-based restoration is the understanding that once physical processes have been restored (e.g., tidal influence), habitat structure and ecological functions take time to develop (Simenstad and Thom, 1996). Some aspects of this temporal trajectory of habitat formation and associated function are well understood, yet uncertainty remains in both the rate and ecological trajectory that restoring habitats experience over time (e.g., Simenstad and Cordell, 2000). Because of this uncertainty, restoration objectives may be best expressed in terms of habitat development over time, rather than static habitat types (Goetz et al., 2004).

Resilience to SLR can be enhanced by considering SLR impacts in all stages of a restoration project (e.g., feasibility, planning, design, implementation, and monitoring). However, because restoration actions may be implemented differently to accommodate rising seas it may be more efficient to include SLR early in the planning and design process rather than altering projects after they are implemented. Given the uncertainties in how nearshore ecosystems will respond to rising sea levels, it may also be useful to consider SLR impacts in other phases of the project, such as when designing and implementing adaptive management approaches and monitoring programs.

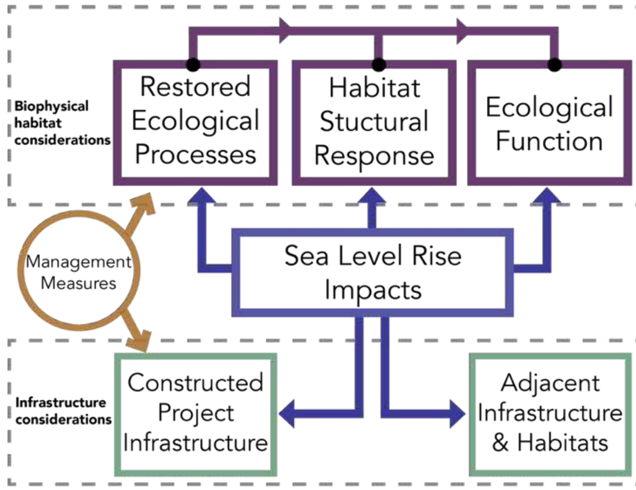

Figure 2. Diagram showing the conceptual relationship between sea level rise impacts, restoration management measures, ecosystem process, structure and function.

In this document we build on the scientific principles and strategies of the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP)[1]. The PSNERP general investigation identified a suite of ecosystem processes and management measures that shape and sustain the physical structure of nearshore habitats in Puget Sound (Simenstad et al., 2006; Schlenger et al., 2011; Clancy et al., 2009; Cereghino et al., 2012). The PSNERP effort also included a workshop on climate change and restoration (Logan et al., 2010). In this workshop, one of the key information needs identified by restoration practitioners was the magnitude and spatial variation in SLR in Puget Sound. While this information need was addressed by the SLR projections in Miller et al., (2018), there remains uncertainty in how nearshore ecosystems will respond to projected changes in SLR, as well as the ecosystem response to the combined effects of SLR and restoration actions. Here we suggest some considerations for how SLR may interact with restoration actions in Puget Sound and provide an organized way to use these considerations for planning, designing and implementation restoration in nearshore ecosystems.

A description of the ecosystem processes addressed in this document and how climate change may affect them can be found in Tables A1 and A2 in Appendix A of this document. The management measures evaluated in the context of SLR are part of a suite of management measures described by Clancy et al. (2009). PSNERP applies these management measures to restore ecosystem process for three primary shoreforms: beaches, river deltas, and embayments (Shipman, 2008; see descriptions in Appendix B). Similarly, this document provides information to help evaluate whether nearshore restoration actions for these three shoreforms will be resilient to the impacts of SLR.

[1] The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) is a comprehensive assessment of Puget Sound's 2,500 miles of shoreline to understand how humans have impacted the nearshore and what opportunities exist to improve it http://www.pugetsoundnearshore.org/

II. SEA LEVEL RISE IMPACTS

Sea level rise can affect nearshore restoration sites and projects in multiple ways. In this document we have organized SLR impacts into four primary categories, summarized below. These SLR impacts will affect the particular project or restoration design differently depending on the management measure, shoreform, and site-specific conditions. The potential impacts of SLR and other effects of global climate change on nearshore processes are described in Clancy et al., 2009; see also Appendix A, Table A2).

Inundation and coastal flooding: Higher sea levels are expected to inundate farther inland and increase the frequency and severity of coastal flooding associated with high tides, storm surge, and episodic flooding associated with waves (Hamman, 2012; Hamman et al., 2016). Although the magnitude of storm surges are not expected to increase, higher sea level means that the same storm events would result in higher water levels and potentially more damage.

Wave impacts: Higher water level is expected to increase the reach and energy of waves. Similar to storm surge, climate change is not expected to significantly change wave generation, but higher water levels are projected to increase the energy, frequency, and duration of wave impacts alongshore and more so in fetch and depth-limited settings (e.g., embayments and river-deltas). Greater wave energy will lead to more wave-driven flooding, erosion, and changes in sediment mobility that is expected to lead to greater potential for bluff, beach, and barrier erosion (Ruggiero et al., 2010; MacLennan et al., 2013). Wave-related impacts are likely to be most important in areas that already experience wave-driven flooding and erosion.

Saltwater intrusion: Higher water levels and more frequent flooding are expected to increase the salinity of groundwater and porewater as the denser saltwater pushes up and into a fresh-water estuary or tidal river (e.g., KCWTD, 2011). Higher salinity can affect plants and habitat types that are adapted to a specific balance of salt and freshwater. Higher salinity could also have implications for corrosion of infrastructure, nutrient and contaminant cycling, land use (particularly agriculture), and septic systems.

Changes in Groundwater: Higher water levels are expected to raise the groundwater surface elevation and cause flooding from below. Higher water levels below ground are expected to increasingly fill the unsaturated zone and limit infiltration causing water to pond above the land surface. Changes in groundwater are expected to increasingly modify substrate stability, vegetation assemblages, porewater chemistry, and nutrient mobility in complex ways before the effects of saltwater intrusion are realized or even in the absence of saltwater intrusion.

It is important to recognize that these impacts will interact to create a combined effect of SLR at a location. Also, SLR will interact with other impacts of climate change, including changes in ocean chemistry, freshwater flow, and sediment dynamics. The primary focus here is on SLR, but it may be important to consider the interaction of SLR with other climate change impacts.

III. SEA LEVEL PROJECTIONS FOR WASHINGTON'S COAST

Probabilistic Projections of Relative Sea Level Rise

In *Projected Sea Level Rise for Washington State – A 2018 Assessment*, Miller et al. (2018) present probabilistic projections of relative SLR for Washington's coastal areas. As the global climate warms, sea level is projected to rise due to three main factors: thermal expansion of warmer ocean waters, melting of land-based glaciers and ice caps, and melting of the Antarctic and Greenland ice sheets. Added together, projections give a central estimate of 1.6 and 2.0 feet of absolute SLR by 2100 (relative to 1991 - 2009), for a high and a low greenhouse gas scenario, respectively. However, these projections do not include vertical movements of the land.

Washington state is a tectonically and geologically dynamic region, with vertical land movement causing both subsidence and uplift along the coasts. This land movement influences the relative amount of sea level in a specific location. Local rates of vertical land movement vary along the Washington coast from subsidence of about 0.5 ft per century in central and southern Puget Sound to uplift of up to 1.1 ft per century on the northwest Olympic Peninsula near Neah Bay. Projections of relative SLR combine the global factors that drive increases in sea level with the local factors that drive vertical land movement.

In contrast to previous assessments for Washington state (Mote et al., 2008; NRC 2012), the projections in Miller et al. (2018) are presented as probabilities, the likelihood that sea level will meet or exceed a specific elevation by a certain time. Previous assessments focused on either a narrow range around a best estimate for future sea level, or presented wide ranges without an assessment of likelihood within that range. In the 2018 report, projections are expressed in terms of the "probability of exceedance" for two different greenhouse gas scenarios (Representative Concentration Pathway [RCP] 4.5 ["Low"] and RCP 8.5 ["High"]; (van Vuuren et al., 2011)[2]. For example, a 1% probability of 4 ft of SLR by 2100 means that there is a 1% chance that the change in sea level will meet or exceed 4 ft by that time. The likelihoods conveyed by these probabilities provide information that can be used to assess the risk to a restoration site or project and associated infrastructure, habitat, and surrounding lands.

Relative SLR projections are provided for 171 locations along Washington's coastal areas at approximately 5 to 7 mile intervals. Table 1 shows an example of these projections in four locations within the ESRP program geography. These relative SLR projections are useful for assessing and planning for the impacts of SLR on nearshore restoration projects because they provide localized information on future water levels for the area where the project is located. Projections are available for download from the Washington Coastal Hazards Resilience website (http://www.wacoastalnetwork.com/wcrp-documents.html). For each location, tables show

[2] For more information about greenhouse gas scenarios, see Section 1 of Mauger et al., 2015. Note that the projections include a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario, while omitting two others: RCP 2.6 and RCP 6.0. Recent research suggests that it is no longer feasible to achieve the dramatic reductions required under RCP 2.6 (e.g., Davis and Socolow, 2014; Pfeiffer et al., 2016). RCP 6.0 is not included because of a limited amount of projections that continue past 2100.

projected SLR for two greenhouse gas scenarios, a range of probabilities and 19-year time periods between 2010 and 2150.

Table 1. Relative sea level projections, in feet, for four of the 171 locations along Washington's coastline. Example locations include Olympia, Neah Bay, South Whidbey Island and Bellingham. Projections are expressed in terms of the "probability of exceedance" for 2100 (2091-2109) for two different greenhouse gas scenarios (RCP 4.5 and RCP 8.5; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which defined here as the average sea level between 1991-2009. Data for all 171 locations are available at www.wacoastalnetwork.com/wcrp-documents.html. Modified from Miller et al. (2018).

PROJECTED RELATIVE SEA LEVEL CHANGE FOR 2100
(feet, averaged over a 19-year time period)

Location	Vertical Land Movement Estimate	Greenhouse Gas Scenario	Central Estimate (50%)	Likely Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
					10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
Bellingham (48.8N, 122.5W)	0.1 ± 0.2	Low	1.5	0.9-2.1	2.4	4.0	7.4
		High	1.9	1.3-2.7	3.0	4.7	8.3
Neah Bay (48.4N, 124.6W)	1.1 ± 0.3	Low	0.5	-0.1 - 1.2	1.5	3.1	6.3
		High	1	0.3 - 1.7	2	3.8	7.4
South Whidbey (47.9N, 122.4W)	-0.4± 0.2	Low	2.0	1.4-2.6	2.9	4.5	7.8
		High	2.4	1.8-3.2	3.5	5.2	8.7
Olympia (47.0N, 122.9W)	-0.6± 0.3	Low	2.2	1.6-2.9	3.2	4.8	8.0
		High	2.7	2.0-3.4	3.7	5.5	8.9

The rate of sea level rise increases further into the future and is faster for the low-probability, high-magnitude projections (e.g., 0.1%, 1%, 10%; Figure 3). The data available in the spreadsheets is not in the form of rates of sea level rise but rates can be calculated from these data for a given SLR probability and timeframe. The rate may be critical for understanding the effect of SLR on ecological processes such as sediment erosion and accretion and the habitat response to these processes.

Projections provided in Miller et al. (2018) reflect the best available science on changing sea levels (e.g., Kopp et al., 2014) and expand on the information provided in previous assessments for Washington State. Therefore, we describe these new projections as a resource for restoration practitioners. It is important to note that these are only one of several projections available. They may differ from the suite of sea level scenarios incorporated by the U.S. Army Corps of Engineers (USACE, 2014) in their sea level planning tool, which are also used in assessments of SLR impacts on nearshore restoration projects. Furthermore, the projections in

Miller et al. (2018; and any other SLR projections) will certainly change as the science evolves (Box 2). However, the principles for selecting SLR scenarios and considering impacts on nearshore restoration described here can be applied using any projections and will remain relevant regardless of the projections considered.

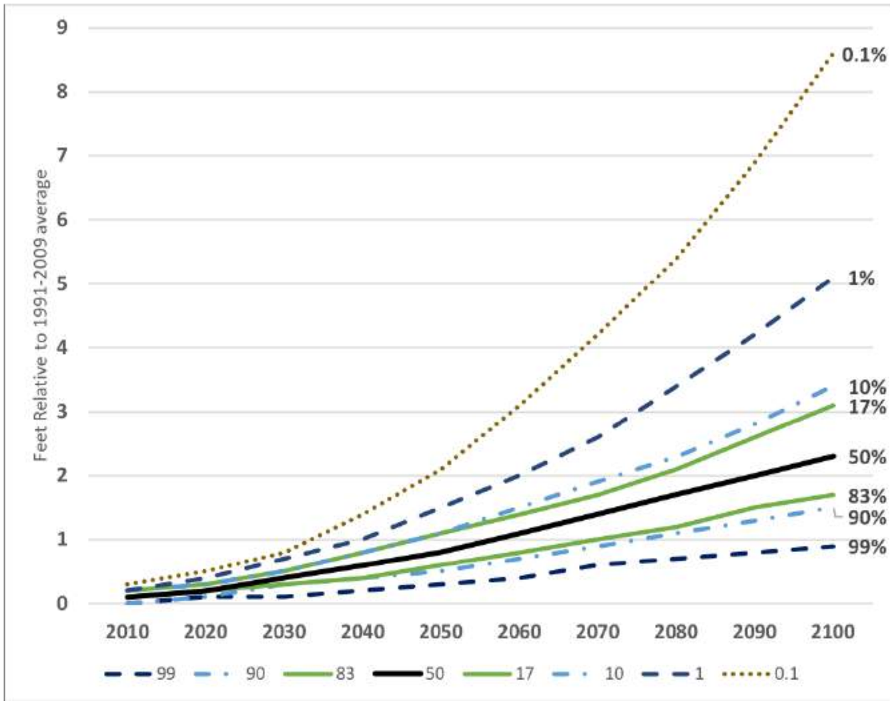

Figure 3. Relative sea level rise projections, through 2100, for a high greenhouse gas scenario (RCP 8.5), for Seattle. Projections are from Miller et al. (2018). The probability values for each curve are "probabilities of exceedance", (i.e., the likelihood that relative sea level will meet or exceed a particular elevation). Note that the rate of sea level rise increases later in the century and is faster for the low-probability, high-magnitude projections (e.g., 0.1%, 1%, 10%).

Box 2. Adaptive Management and Uncertainty

The projections of sea level rise presented in *Projected Sea Level Rise for Washington State – A 2018 Assessment* (Miller et al., 2018) are the most recently available for Washington's coastline. The use of these, or any other SLR projections, in restoration design requires an explicit approach to account for uncertainty. The current projections give a wide range of future water levels and this range increases further into the future. Projections of SLR are certain to be updated again as the science evolves. Furthermore, the response of ecosystems to these higher water levels and associated impacts is not fully understood. One approach to account for these uncertainties is through the adaptive management cycle of learn, implement, and reassess. If a restoration project is unlikely to be resilient to SLR, then the project design can be adjusted, implemented and the adaptive management cycle can be used to evaluate effectiveness over time. Through monitoring and reassessment, restoration projects have the potential to be modified again to account for observed water levels that differ from projections or unanticipated ecosystem responses to higher water levels.

Projections of Changes in Extreme Water Levels

The SLR projections in Miller et al. (2018) denote the change in sea level over time and can be applied to any water level, such as mean higher high water (MHHW) or ordinary high water. For example, when these values are applied to the local MHHW tidal datum they indicate areas exposed to the daily average highest tide. However, daily inundation is only one way that SLR can affect coastal infrastructure, habitat, and ecosystem processes. The considerations described below for management measures include the potential impacts of more extreme water levels and episodic flooding associated with storm surge and waves, as well as the physical impacts of waves on infrastructure and shoreline stability. The importance of considering these impact pathways, in addition to daily inundation, will vary by project and location. In locations where these coastal disturbance mechanisms have been important processes historically, they are likely to be even more important mechanisms to consider as average water levels rise.

Forthcoming products from the Washington Coastal Resilience Program (expected in January 2019) will provide additional analysis and estimates of the return frequency of extreme still water levels (water levels associated with tides and storm surge), as well as total water levels (water levels associated with tides, storm surge, and wave run-up) for Puget Sound and the coast of Washington. When available, these resources will be posted on the website: www.wacoastalnetwork.com/washington-coastal-resilience-project.html.

When coupled with SLR projections, this information can be used to assess impacts associated with less frequent (i.e., occurring annually or once a decade) but potentially damaging future events. To accomplish the same objective (i.e., assessing the hazard exposure associated with extreme coastal water level events when combined with SLR), users can also consider coupling sea level projections with extreme water level datums available at their nearest tide gauge (i.e., Highest Observed Water Level, or HOWL), or Base Flood Elevations derived from the Federal Emergency Management Agency (FEMA) administered coastal flood modelling studies.

IV. CONSIDERATIONS FOR TIMEFRAME AND RISK

A challenge with incorporating SLR projections into restoration planning and design is making sense of a range of projections, rather than a single number. The user must select from a range of timeframes, probabilities, and greenhouse gas scenarios. A forthcoming report will provide a general approach for selecting projections to use in planning (expected winter 2018). We provide some considerations for selecting projections specifically for use in nearshore restoration planning. The two primary factors for selecting a projection are the timeframe and the level of risk that is acceptable for the project. If scenarios are selected for the far future (after 2050), a third factor to consider is which of the two greenhouse gas concentrations to use (RCP 4.5 or RCP 8.5; Table 1). SLR projections for these two greenhouse gas scenarios begin to diverge in about 2050 with the RCP 8.5 greenhouse gas scenario having higher sea levels than RCP 4.5.

Timeframe

A critical first step is to select one or multiple timeframes between now and 2150 to use when evaluating the impacts of SLR. In the case of infrastructure design, this can often be determined by the design lifetime of the infrastructure, but the decision is more complicated for the restoration of ecosystems because this is a process that evolves over time. On the one hand, restored ecosystem processes are often intended to maintain habitat and ecological function in perpetuity, suggesting the importance of a long-term (2100) or very long-term (2150) timeframe. On the other hand, the initial stages of restoring ecological processes and establishing habitat structure may be more sensitive to the impacts of SLR, suggesting the need for a more near-term (e.g., 2040) time-frame. Furthermore, different timeframes may be relevant and worth considering for different components of the same restoration project. For example, one timeframe may be appropriate for infrastructure design and a different timeframe may be appropriate for assessing impacts on vegetation or habitat. Box 3 provides suggestions for what to consider in selecting one or more timeframes that are relevant for the project objectives and restoration actions used to achieve these objectives.

Box 3. Timeframe: Factors to Consider

- Design lifetime of infrastructure to be built, modified, or retained in the project
- Potential for infrastructure modification in the future
- Near- and long-term objectives for vegetation establishment and survival
- Near- and long-term objectives for habitat establishment, and persistence
- Expectations for the trajectory of habitat establishment over time
- Potential for adaptive management
- Consistency with other regulatory process or requirements to address SLR

Risk Tolerance

The risk that SLR poses to a restoration project depends upon the likelihood of various magnitudes of SLR and the associated consequences of those changes in sea level. The SLR projections by Miller et al. (2018) are probabilistic, meaning they describe the likelihood that water levels will meet or exceed a particular elevation by a specified time period.

Some SLR elevations are virtually certain (e.g., 99% probability of exceedance), but less likely, high magnitude scenarios (e.g., 1% or 0.1% probability of exceedance) may have greater consequences for a restoration site.

These likelihoods are well suited for considering the risk to a restoration project. For example, using low likelihood (high magnitude) values for SLR indicates that the chance of exceeding those values is low and therefore the project will be less at risk of being under designed if high magnitudes of SLR are realized. When planning and designing restoration projects to reduce the potential consequences of SLR impacts, we recommend considering projections that are consistent with the level of risk that project proponents, sponsors, or funders are willing to accept. This is a policy decision, not a scientific question, and therefore will vary from project to project.

For restoration projects for which a high level of risk is unacceptable (Box 4), project designs will be more resilient if they are based on high magnitude, low probability projections (probabilities between 17% and 0.1%). For restoration projects for which a high level of risk can be tolerated (Box 5), designing to low or middle magnitude, high probability (between 50% and 99%) projections may be sufficient to ensure a resilient design.

For restoration projects for which the consequences of SLR impacts are not well understood or the emphasis is on robust decision making, project designers may be interested in considering a

Box 4. Factors that may contribute to low risk tolerance (i.e., risk averse)

In risk averse situations, consider planning for high magnitude, low likelihood projections with probabilities between 17% and 0.1%.

- Protection of neighboring property and land uses from flooding and other coastal hazards
- Establishment or protection of critical species or habitats
- Limited potential to adapt infrastructure in the future
- Limited potential for adaptive management of ecosystem process and habitats in the future
- Low tolerance of habitat development to rapid rates of SLR (i.e., low sediment input and slow accretion rates)

Box 5. Factors that may contribute to high risk tolerance (i.e., risk tolerant)

In risk tolerant situations, consider planning for low magnitude, higher likelihood projections with probabilities between 83% and 17%.

- Ecosystem processes are relatively intact or will be restored with restoration action
- Sufficient upland space for landward migration of habitats
- High potential to adapt infrastructure in the future
- High potential for adaptive management of vegetation, habitats, and ecosystem process in the future

wide range of SLR projections. This range can be used to better understand the ecosystem response to potential future sea levels and inform the acceptable level of risk for a restoration project. The goal of robust decision making is to ensure that the restoration site is resilient across this range of possible future sea levels.

V. SEA LEVEL RISE CONSIDERATIONS FOR NEARSHORE RESTORATION MANAGEMENT MEASURES

The projections described in *Projected Sea Level Rise for Washington State – A 2018 Assessment* (Miller et al., 2018) can be used to assess the SLR exposure of a restoration project location. Forthcoming products can be used to evaluate associated coastal hazards including flooding and wave run up. Identifying project objectives, anticipated management measures, and risk tolerance are important first steps to help project proponents increase project resilience to SLR. Then SLR projections can be used to assess the extent to which a project is likely to be resilient to SLR, or to inform design alternatives and considerations for individual management measures to reduce SLR impacts. This risk tolerance and the associated sensitivity of habitat responses to management measures can be based on either a qualitative assessment or more quantitative models of how the system might respond. The considerations for management measures described below can be used to develop a conceptual model or to identify information needed for quantitative models of system resilience to SLR.

We group considerations of SLR impacts into two primary categories: (1) biophysical/habitat considerations, and (2) infrastructure considerations. When appropriate, we also describe social/political considerations that address some of the human dimensions of SLR impacts.

1. Biophysical/habitat considerations address potential impacts on the biophysical environment, including impacts on vegetation, habitats and ecosystem processes and function.

2. Infrastructure considerations address potential impacts on restoration project infrastructure (e.g., setback dikes, bridges), as well as potential impacts on adjacent properties and land uses.

3. Social/Political considerations address potential impacts associated with human perception and responses to both restoration and risks associated with sea level rise.

In this section, we first describe considerations that are relevant for all restoration projects regardless of management measures, followed by considerations for specific management measures. We focus on a suite of management measures that are commonly employed in Puget Sound nearshore habitats (adapted from Clancy et al., 2009):

- Acquisition for Protection or Restoration
- Revegetation
- Armor, Groin, and Structure Removal
- Dike/Berm Removal and Channel Rehabilitation
- Hydraulic Modification

- Topography Restoration

These management measures were selected for two reasons: (1) they are commonly used in projects focused on restoring ecosystem processes consistent with ESRP objectives, and (2) they are expected to be affected by SLR. We consider groin removal jointly with armor removal, as these actions are often associated with each other and have similar considerations for SLR. Similarly, we consider channel rehabilitation jointly with dike/berm removal because removal of these protections exposes inland areas where tidal channels have been removed or lost. These considerations are intended to assist the user in identifying aspects of a project and its objectives that may increase resilience to SLR, as well as evaluating how a management measure could be affected by SLR.

If appropriate, we indicate how these considerations may differ when the management measures are applied in the three different types of nearshore habitats: beaches, estuaries, and embayments (described in Appendix B). We recommend that the user review common considerations for all management measures, as well as the considerations that apply to the management measures used in a specific project.

Considerations Common to All Management Measures

Biophysical/habitat considerations

1. *Consider the extent to which there is upland space to accommodate landward migration of nearshore habitat.*

Sea level rise may shift nearshore habitats inland as they experience impacts associated with inundation, coastal flooding, wave stress, salinity, and erosion. Restoration projects are more likely to be resilient to SLR in locations where upland infrastructure, land use, and topography do not restrict the inland migration necessary for nearshore habitats to adapt to rising water levels. Furthermore, restoration projects will be more adaptable and able to take advantage of this space if projects are not designed with specific objectives for static habitat types in certain locations, but rather if the landward migration of habitats and processes is explicitly considered in project design.

2. *Consider the extent to which increasing coastal flooding and wave energy will increase erosion rates of nearshore habitats.*

Increases in erosion can directly reduce the land available for habitat or indirectly affect habitat by altering the processes of sediment supply and transport on the site and within the larger drift cell or river delta. In locations that are susceptible to waves and associated erosion, projects are more likely to be resilient to SLR if projected changes in wave dynamics and higher rates of shoreline erosion are considered in the project objectives and design.

3. *Consider the extent to which stormwater runoff could increase due to increasing proximity of nearshore habitats to impervious surfaces.*

As sea level rises and habitats migrate landward, habitats may come in closer proximity with developed areas and land uses that alter hydrology, including impervious surfaces, drained lands, and point/non-point source inputs. When restoration projects are located near drained lands or impervious services (e.g., roads), pollutants in stormwater runoff can be counterproductive for restoration efforts by increasing exposure to toxic contaminants found in water or sediment. For projects that consider stormwater runoff in the design, it may also be beneficial to assess future changes in stormwater runoff (Mauger et al., 2015), and how they may affect project resilience.

Social/Political considerations

4. *Consider the extent to which changing coastal hazards (inundation, flooding, and erosion) may affect landowner willingness and political will to conduct restoration*.

SLR is expected to increase coastal flooding from inundation, storm surge, and waves. Greater wave run up could also increase beach and bluff erosion, and thus risk to shoreline properties. In addition to an increase in actual risk, there could be a perceived increase in risk among landowners without accessible and clear information. Landowner and community engagement processes that directly address changing coastal hazards can facilitate the incorporation of SLR considerations into restoration projects. For example, landowner engagement may empower project proponents to select full-restoration design alternatives (as opposed to partial-restoration designs). This consideration is most relevant for projects that are either in the feasibility phase or in the earliest stages of design because projects that are further along in the design process have already engaged landowners and stakeholders to inform the selected design alternative. Stakeholder engagement is also an important consideration for coordinating restoration at the regional scale. The ability to sustain landowner and political support for ongoing restoration efforts could be affected by how well projects account for existing and future coastal hazards and communicate this with target audiences.

Considerations Specific to Management Measures

Specific management measures may require additional considerations of SLR impacts beyond the common considerations described in the previous section. For each management measure, we briefly describe the action, how it contributes to the restoration of ecosystem processes, and how restoration of these processes could improve resilience to SLR impacts. Similar to the section above, we describe biophysical/habitat and infrastructure considerations for the potential impacts of SLR. We also list information needs that can help restoration practitioners explore these considerations in more detail.

Acquisition for Protection or Restoration

Relevant shoreforms: all

Acquisition of property may either be intended to protect intact processes and habitat features, or else can be a precursor to enable or enhance other measures to restore ecosystem processes (Clancy et al., 2009). Property acquisition may increase resilience to SLR by increasing the area to support landward migration of habitat and to facilitate further restoration actions.

Biophysical/habitat considerations

1. *Consider the extent to which additional land may be necessary to support landward migration of habitats or increased shoreline erosion.*

With SLR, more land may be necessary to support the same habitat area and habitat types as would be expected in the absence of SLR. Acquisitions intended to protect intact processes are more likely to be resilient to SLR if the extent of the project area is sized to accommodate gradual changes in inundation, flooding, and shoreline erosion. Likewise, acquisitions intended to facilitate restoration are more likely to support resilient restoration if the extent of the project area accommodates gradual changes in inundation, flooding, and shoreline erosion.

2. *Consider the extent to which sediment sources in the drift cell are unarmored and sediment supply is intact (Beach and barrier embayment shoreforms).*

Acquisition projects are more likely to be resilient to SLR if they are within a drift cell with more intact processes of sediment supply and transport. Sites in these areas may have greater potential to maintain existing habitat features if processes are intact because rates of sediment supply, transport, and accretion may be able to keep pace with SLR. Quantitatively defining the level of sediment supply necessary to maintain beach accretion in response to inundation or erosion associated with SLR is an area of future research.

Infrastructure considerations

3. *Consider the extent to which associated project infrastructure may be affected by SLR.*

Many acquisition projects, particularly those for the purposes of protecting intact processes, do not include project-related infrastructure, but some acquisition projects may include infrastructure components that are not directly related to restoration goals. Understanding and adjusting for the potential interaction between SLR, the location of future habitats, and proposed location of infrastructure will increase the likelihood that habitat objectives are met under future conditions.

Information needs

- Inland and upland topography, infrastructure, and land use
- The degree to which current sediment supply and transport processes are intact at the process unit scale

Revegetation

Relevant shoreforms: all

Revegetation includes restoration actions to support the development of natural vegetation. Existing and newly established vegetation may be sensitive to the impacts of SLR through inundation, salinity, and greater wave energy (Callaway et al., 2007). Sensitivity will vary by plant species and habitat type. River delta, embayments and beach shoreforms support vegetation communities that are dominated by different species with varying tolerances to stressors (e.g., turbidity, salinity, wave stress, desiccation, and sediment characteristics).

The relative importance of these stressors will differ across shoreforms. In general, revegetation measures are more likely to be resilient to SLR if the sensitivity of the species and habitats to SLR impacts are accounted for in project design (Box 6).

Box 6. Revegetation: specific considerations for timeframe and risk

Short-term objectives of survival and growth of plant species are likely to be less sensitive to the impacts of SLR. For these projects, it may be sufficient to ensure that planted vegetation establishes and survives under near-term projections of SLR.

Long-term objectives for creating conditions that facilitate the establishment of specific vegetation types will be more sensitive to the rate of SLR due to the longer time frame. Considering a long-term SLR projection (e.g., 2100 or 2150), as well as potential sources of sediment supply and capacity for upland migration, may be necessary to ensure that the objectives for vegetation establishment can still be achieved with greater inundation and coastal flooding associated with long-term SLR projections.

If the revegetation measure is intended to establish or protect a critical species of concern, risk tolerance is likely to be lower and the resilience of the project will be greater if a higher SLR projection is used in project planning and design.

Biophysical/habitat considerations

1. *Consider how vegetation species will be impacted by inundation, greater wave stress, and exposure to saltwater.*

If SLR is expected to increase inundation, wave stress, saltwater intrusion, and the salinity of porewater in restoration sites slated for revegetation, the survival and establishment of the vegetation will depend on the tolerance of the planted species to changes in these stressors. Empirical evidence is limited on the tolerance of plant species to the combined effects of these stressors (Clancy et al., 2009), so studies of site-specific conditions may be necessary to determine plant survival given a particular SLR projection. Furthermore, an individual plant species may be able to tolerate an increase in inundation alone, but the indirect effects of changes on surrounding soils and sediments, as well as interactions with other plant species, may ultimately determine the vegetation community response to SLR. Future research can help to address the uncertainty in these indirect and combined effects for marsh and beach vegetation in Puget Sound.

2. *Consider the extent to which revegetation will be exposed to an increase in wave-driven erosion*.

If revegetation is being proposed for areas that are susceptible to wave-driven erosion, increases in wave energy and reach with SLR could accelerate erosion and expose new areas not previously considered susceptible. This could reduce the effectiveness of vegetation establishment and the land area available for habitat development.

3. *Consider the extent to which the distribution of vegetation types within a project area may be affected by SLR.*

Some restoration projects may target the establishment of particular vegetation types (e.g., high marsh) that are distributed according to environmental factors across the landscape, such as elevation and salinity. Projects that include design elements to facilitate the development of these target vegetation types, despite changes in the environmental factors will be more resilient to SLR. A design element could include altering the project footprint to accommodate changes in the distribution of vegetation types through upland migration.

Information needs

- Tolerances of vegetation plantings to salinity, wave stress, and inundation
- Saltwater intrusion risk maps
- Sediment accretion rates

Armor, Groin and Structure Removal

Relevant shoreforms: beaches, barrier embayments

Removing armor, groins or other structures that were built to protect property from wave-driven erosion can restore shoreline sediment input and transport processes, typically in beach or barrier embayment shoreforms. Armor and groin removal can increase resilience of the site and down-drift shores to the impacts of SLR by restoring the natural supply and transport of sediment. A natural supply of sediment may facilitate natural adaptation to the landward migration of the shoreline if beach accretion rates can keep pace with SLR (Clancy et al., 2009).

Biophysical/habitat Considerations

1. *Consider the extent to which objectives for habitat creation can be achieved with additional inundation, erosion, and landward migration of habitat types.*

Removal of armor or other structures creates additional land for habitat, but portions of this land may transition to subtidal, rather than intertidal habitat, as a result of future inundation. Projects that involve armor/structure removal are more likely to be resilient to SLR if the goals for habitat creation are flexible rather than static (i.e., a certain type of habitat in a specific location). Restoring similar types of habitat over time may require additional upland space for landward migration as water levels rise.

2. *Consider the extent to which current sediment input and transport processes in the drift cell are intact.*

A key benefit of armor and groin removal is the restoration of sediment supply and transport processes in the drift cell. The increased reach and energy of waves may accelerate erosion rates, altering the sediment supply. Structure removal projects are more likely to be resilient to the effects of wave-driven erosion if the sediment sources are intact and can naturally adapt to changing rates of erosion and sedimentation. Information on the current sediment budget and erosion rates in the drift cell can be combined with information on changes in inundation and waves to better understand the potential of the project to restore habitat-forming sediment processes.

3. *Consider the extent to which there is upland space for increased shoreline erosion.*

With armor and groin removal, erosion of the shoreline may increase without any increases in wave energy. Higher storm surge and wave reach may cause the rate of erosion to increase even further, depending on how erosion processes are currently affected by these factors. Armor and groin removal projects are more likely to be resilient to SLR if they are designed with upland space to accommodate higher rates of erosion or if potential erosion patterns are considered in the design of the project.

4. Consider the extent to which greater coastal flooding will contribute to erosion of habitats.
Higher water levels and increased wave energy during storm events have the potential to increase erosion beyond what would be expected in the absence of SLR. Removal of protective structures, combined with higher rates of erosion, could affect the accretion and sediment transport processes at the project site and in the drift cell. This can affect the rate of habitat development and potentially reduce the land area available for restoring habitat. Fetch[3] and associated wind direction are primary factors in understanding wave energy in Puget Sound.

Infrastructure Considerations

5. Consider the extent to which the expected level of adjacent property protection from erosion for existing or planned infrastructure will be achievable with increasing coastal flooding and wave run-up.

SLR could increase the rate of wave-driven erosion, depending on the influence of waves on local erosion processes. For example, SLR could increase wave-driven erosion that the armor or groin was designed to protect against, assuming the structure is providing protection. Thus, removal of these structures may increase the risk of erosion on the restoration site and adjacent properties. If the project design includes modifying existing structures or building new structures, the level of protection provided by these structures could be less than expected with SLR. If the site is on an accretion shoreform, an understanding of the ability of sediment supply and transport to keep pace with future erosion rates will inform the degree to which the site will be resilient to SLR.

6. Consider the extent to which increased exposure to saltwater affects adjacent land uses.
Removal of protection structures, such as armor, will increase exposure to saltwater of the formerly impounded shoreline. SLR may increase the landward extent of saltwater intrusion and elevate groundwater levels, which could affect adjacent land uses such as wells and septic systems. Projects are more likely to be resilient to SLR if sufficient buffers exist between the projected tidal influence of surface or groundwater and neighboring land uses that might be adversely affected.

Information needs

- Type of shoreline (e.g., feeder bluff, transport zone, accretion shoreform) and local shoreline topography
- Sediment budget (e.g., current erosion rates based on local shoreline geology and wave influences)
- Potential effects of SLR on future sediment budgets
- Inland/upland topography, infrastructure and land use
- Degree to which sediment supply and transport processes are intact in the drift cell
- Level of protection that existing structures provide to site and adjacent infrastructure

[3] Wave energy increases the longer an unimpeded line of wind can travel over the surface of the water. This unit of measurement is called fetch.

Dike/Berm Removal and Channel Rehabilitation

Relevant shoreforms: river deltas, inlet-type and barrier-type embayments

The removal of dikes and berms restores the flow of tidal waters, typically in deltas and embayment shoreforms. These structures have been built to eliminate tidal flooding, disconnecting former estuarine habitat from tidal waters. Removal of dikes can restore physical processes associated with sediment supply and transport, freshwater hydrology, and tidal hydrology. Generally projects in delta and embayment shoreforms will be more resilient to SLR with more complete restoration of these processes. These restoration actions increase resilience to SLR by providing space for sediment accretion and associated vegetation development. Removal of dikes increases tidal inundation at the restoration location, but can also have offsite impacts or benefits by changing the balance of freshwater and tidal hydrology. Climate-driven changes in riverine hydrology (Mauger et al., 2015) are also important to consider in conjunction with SLR in estuarine systems.

Channel rehabilitation is typically a secondary management measure in conjunction with dike and berm removal. Channel rehabilitation may involve removing flow blockages, reestablishing flows to channels, or creating new channels. Restoration of historic channels improves connectivity of the marsh with the nearshore environment and channel functions, including the transport of water, sediment, nutrients, and aquatic organisms.

Biophysical/habitat considerations

1. *Consider the extent to which the project changes the position of the tidal exchange.*

Removal of dikes or berms can affect the position of the tidal exchange, causing habitats to shift in response to the new mixing of salt and freshwater. Tidal exchange is where typical tides and riverine flows meet, creating a dynamic zone of brackish water. The landscape position of this zone is driven by the relative strength of tidal and riverine forcing. Landscape topography (e.g., elevation, slope, and shape of the land), combined with future sea level and river flows, will determine the future location of tidal exchange. SLR may push the position of tidal exchange further inland relative to what would be expected by removal of the infrastructure alone. Resilience of the restoration project and expectations of habitat development may be enhanced by understanding how tidal and riverine forcing will combine to affect the position of tidal exchange over time. Understanding immediate impacts and benefits is important, while also planning for expected long-term changes in landscape-level habitat response to the changing position of the tidal exchange.

2. *Consider the extent to which sediment deposition and current rates of marsh accretion are expected to keep pace with SLR.*

Marsh habitat recruitment and survival is highly sensitive to elevation above sea level. Even small changes in sea level can directly affect the tidal processes that establish and maintain marsh habitat, including the feedback between sediment accretion, marsh elevation, and vegetation establishment. Increases in sea level and associated changes in the inland extent of tidal exchange could disrupt the equilibrium that forms between sediment deposition and redistribution of sediment through tidal processes. Projects are more likely to be resilient to SLR if the design considers the extent to which restoration is expected to restore this balance under current conditions, as well as how this balance may be affected by higher sea levels. For barrier embayment systems, an assessment of the sediment budget in the drift cell will help determine the future potential for self-sustaining habitats.

3. *Consider the extent to which future rates of riverine sediment transport and deposition could alter rates of marsh accretion*

Increases in riverine sediment transport due to climate change (e.g., Lee et al., 2015) are likely to interact with SLR. Riverine sediment inputs may increase marsh elevation sufficiently to maintain current estuarine habitat types as sea levels rise. Projects are more likely to be resilient to SLR if they are designed with an understanding of potential marsh accretion rates, as well as the tidal exchange levels and sediment supply necessary to support self-sustaining marsh habitats.

4. *Consider the extent to which future conditions of freshwater input will support development of marsh vegetation.*

Restoration projects are more likely to be resilient to SLR if they are designed to maintain sufficient freshwater input to sustain a balance between fresh and salt water that supports marsh vegetation development. If projects are not designed to provide sufficient connectivity with freshwater, the lack of freshwater could be exacerbated by higher levels of saltwater, as well as lower freshwater input in summer due to climate change (Mauger et al., 2015). This could lead to drought and salinity stress that prevents successful recruitment and survival of marsh vegetation. Salinity stress could also increase due to a combination of more frequent tidal flooding and higher salinity in groundwater.

5. *Consider the extent to which past subsidence on the site will interact with future inundation levels to affect the expected trajectory of habitat development.*

Subsidence of the site due to past diking and land use could exacerbate the effects of SLR. The project is more likely to be resilient to SLR if this historical subsidence on the site is minimal. Where subsidence has been significant, the resilience of the project may be enhanced by considering the combined effects of subsidence and higher inundation on the trajectory of habitat development, and the potential for sediment supply to compensate. The importance of considering this factor depends on the extent of subsidence due to past land use, connectivity with riverine sediment supply, and the expected erosion/accretion rates.

6. *Consider the extent to which increases in storm surge and wave-driven erosion will affect restoring habitat.*

With dike or berm removal, the change in the tidal exchange and inundation area will cause different areas to be exposed to storm surge and wave-driven erosion. SLR is expected to increase erosion rates due to increases in storm surge or wave run up. This may affect the balance of sedimentation and erosion in marsh channels, potentially changing the expected channel configuration for a site, as well as the rate of development of new channels.

7. *Consider the extent to which inundation will change the tidal prism and the elevation of sea water relative to the marsh*.

Restoring natural channels and hydraulic flows will affect the tidal prism. Increases in sea level could have an additional effect on the tidal prism that may be important to consider when designing a channel restoration project to ensure that objectives for restoring hydraulic processes can be achieved even as water levels rise. In locations where SLR is projected to be high, this impact could influence the suitability of the site for channel restoration. Changes in freshwater flows with climate change (Mauger et al., 2015) may also affect the tidal prism and channel network.

Infrastructure considerations

8. *Consider the extent to which the combination of infrastructure removal, inundation, and higher extreme water levels could affect flood hazard to adjacent properties*.

Removing structural protections may increase flood hazards on the site and adjacent properties, which could be exacerbated by SLR. Typically, restoration projects that remove a dike evaluate the potential change in flood hazard, commonly with the use of a hydrodynamic model. Projects are more likely to be resilient to SLR if this modeling also evaluates the impact of SLR on inundation and flood hazard. Projects may also alter tidal influence on the site, which could modify the landscape position of storm surge and waves. Understanding this repositioning of storm surge and waves is important for anticipating potential impacts to adjacent habitats or properties, as well Identifying project design features that could mitigate these impacts. The design of these project features will be more resilient if the additional flood and storm hazard associated with SLR are considered.

9. *Consider the extent to which increased inundation and coastal flooding will affect the intended function of the setback dike or other project infrastructure*.

Increased coastal inundation and altered river flows may change the degree to which setback dikes can effectively protect land adjacent to restoration projects if SLR is not factored into the design of these protection structures. If land use behind a new setback dike is different from the land use behind the removed dike, maintaining similar dike dimensions for the new setback dike might not be appropriate if the new land use has a lower risk tolerance for potential increases in flooding, salt water intrusion, or changes to groundwater hydrology from SLR.

10. Consider the extent to which greater wave energy could contribute to flood hazard on adjacent land.

Higher sea levels can increase wave-driven flooding. In locations that are exposed to large fetch, it may also be important to consider the influence of increased wave run up when evaluating the effect of removing infrastructure. The impact will be locally specific depending the contribution of waves to flood hazard.

11. Consider the extent to which increasing exposure to saltwater and changes in below-ground hydrology will affect neighboring land uses.

Changes in below-ground hydrology with rising sea levels may affect drainage and groundwater salinity adjacent to restoration projects. This may have implications for adjacent land uses and alter the cost of maintaining land uses through actions such as pumping of water. Below-ground hydrology is complex and difficult to observe without monitoring and modeling. Changes to below-ground hydrology with SLR have implications for both land use and habitat objectives and is a current area of research.

12. Consider the extent to which project infrastructure could be physically stressed by greater wave energy.

In addition to wave-driven flooding, waves can physically affect the function of structures on the restoration site, and this may be exacerbated by greater wave energy with SLR. Project resilience to SLR can be improved by considering greater wave stress in the design criteria related to newly created or existing infrastructure that is sensitive to physical effects of waves.

Information needs

- Anticipated marsh accretion rates from riverine deposition on site
- Riverine sediment supply and anticipated changes due to climate-driven changes in flow
- Topography of project and adjacent upland
- Tidal range of project location
- Current trajectory of marsh habitat
- Projected erosion rates with SLR
- Inundation tolerances of marsh vegetation
- Groundwater salinity intrusion risk maps

Hydraulic Modification

Relevant shoreforms: River deltas, inlet-type and barrier-type embayments

Hydraulic modification involves the removal of or changes to structures that control hydraulic flow, such as culverts, tide gates, bridges, and flood gates. Hydraulic modification can also include creating openings on structures (e.g., dikes, road fills and causeways) to influence tidal flow and drainage of the site and associated habitats. This management measure can increase resilience of a site by restoring hydraulic and habitat connectivity and allowing tidal inundation, marsh development, fish passage, sediment transport, and debris movement processes to evolve. The degree to which these processes are restored may contribute to the capacity of a site to adapt to SLR.

Biophysical/habitat considerations

1. *Consider the extent to which increases in storm surge and wave-driven erosion will affect restoring habitat.*

Higher erosion rates associated with increases in storm surge or wave energy may affect the balance of sedimentation and erosion in marsh channels of newly opened habitat from hydraulic modification. This could potentially change the expected channel configuration for a site, as well as the rate of development of new channels.

2. *Consider the extent to which the restoration project changes the position of tidal exchange.*

Removal or expansion of hydraulic structures typically shifts the tidal exchange inland, causing a shift in habitat in response to the new mixing of salt and freshwater. The shoreline profile (e.g., elevation and slope) and site-specific geomorphology, combined with future sea level, will determine the future location of the tidal exchange. SLR will likely push the position of the tidal exchange further inland relative to what would be expected by removal of the structure alone. Understanding of how these factors will combine to affect the position of the tidal exchange over time will help with evaluation of ecosystem impacts.

3. *Consider the extent to which sediment deposition and current rates of marsh accretion are expected to keep pace with SLR.*

Marsh habitat recruitment and survival is highly sensitive to elevation above sea level. Even small changes in sea level can directly affect the tidal processes that establish and maintain marsh habitat, including the feedback between sediment accretion, marsh elevation, and vegetation establishment. Increases in sea level and associated changes in the inland extent of tidal exchange could disrupt the equilibrium that forms between sediment deposition and redistribution of sediment through tidal processes. Projects are more likely to be resilient to SLR if the design considers the extent to which restoration is expected to restore this balance under current conditions, as well as how this balance may be affected by higher sea levels. For barrier embayment systems, an assessment of the sediment budget in the drift cell will help determine the future potential for self-sustaining habitats.

4. *Consider the extent to which future rates of riverine sediment transport and deposition could alter rates of marsh accretion*

Increases in riverine sediment transport due to climate change (e.g., Lee et al., 2015) are likely to interact with rising sea levels. Riverine sediment inputs may increase marsh elevation sufficiently to maintain current estuarine habitat types as sea levels rise. Projects are more likely to be resilient to SLR if they are designed with an understanding of future marsh accretion rates, tidal exchange, and sediment supply necessary to support self-sustaining marsh habitats.

Infrastructure considerations:

5. *Consider the combined effects of structure removal and SLR on the implications of flooding, drainage, and saltwater intrusion on adjacent properties and land uses.*

Removing or modifying hydraulic control structures typically requires an understanding of how inundation and flooding of the site will change once the tidal and fluvial flows are restored. Projects will be more resilient to SLR if this analysis includes and understanding of how higher sea levels will contribute to inundation and flood hazard over time once the structure is removed. Similarly, removing these structures can change the tidal prism and increase saltwater intrusion. SLR could shift the range of saltwater intrusion further inland, which could have consequences for adjacent properties and land uses.

6. *Consider the extent to which project infrastructure will continue to function as expected given greater inundation, coastal flooding, and changes in groundwater hydrology.*

Infrastructure design is typically based on assumptions about historical tidal and riverine flows that control inundation and flooding. Tidal input and its interaction with fluvial flows may change with SLR. For example, infrastructure such as bridges or culverts may need to be sized to accommodate larger tidal and fluvial flows. This is also a consideration when the removal of the hydraulic control structures requires a setback dike for additional flood protection inland. The expected function of this infrastructure for flood protection could be affected by SLR.

Information needs

- Hydraulic modeling of openings
- Predicted sediment deposition
- Detailed topography

Topography Restoration

Relevant Shoreforms: All

Topography restoration consists of dredging, excavating, or filling to remove or add layers of surface material to alter the elevation of project surfaces (Clancy et al., 2009). Objectives for this action can include modifying elevations to support the development of vegetation where it has been altered by diking or creating irregular topography to support microhabitats (Diefenderfer et al., 2018).

Biophysical/habitat considerations

1. *Consider the extent to which inundation will change the elevation of the water relative to expected vegetation development.*

Topographic restoration is likely to be sensitive to SLR because vegetation development is greatly influenced by the elevation of the land relative to water. As sea levels rise, the distribution of habitat types will evolve over time. The rate of SLR will influence the extent to which other process can accommodate the rising water. Projects are more likely to be resilient to inundation if there is space for landward migration for vegetation, flexibility in the objectives for habitat creation, and a consideration of the rate of SLR in the design of topographic modifications.

2. *Consider the extent to which greater coastal flooding will contribute to erosion of restoring habitat.*

Higher water levels and wave run up have the potential to increase erosion beyond what would be expected in the absence of SLR. Higher rates of erosion could affect the designed topography and reduce the land area available for restoring habitat. Projects are more likely to be resilient to SLR if changes in coastal flooding and its effects on erosion are considered in the design of the site topography.

3. *Consider the extent to which sediment deposition and current rates of marsh accretion are expected to keep pace with SLR.*

Marsh habitat recruitment and survival is highly sensitive to elevation above sea level. Even small changes in sea level can directly affect the tidal processes that establish and maintain marsh habitat, including the feedback between sediment accretion, marsh elevation, and vegetation establishment. Increases in sea level and associated changes in the inland extent of tidal exchange could disrupt the equilibrium that forms between sediment deposition and redistribution of sediment through tidal processes. Projects are more likely to be resilient to SLR if the design considers the extent to which restoration is expected to restore this balance under current conditions, as well as how this balance may be affected by higher sea levels. For barrier embayment systems, an assessment of the sediment budget in the drift cell will help determine the future potential for self-sustaining habitats.

4. Consider the extent to which future rates of riverine sediment transport and deposition could alter rates of marsh accretion

Increases in riverine sediment transport due to climate change (e.g., Lee et al., 2015) are likely to interact with rising sea levels. Riverine sediment inputs may have the potential to increase marsh elevation sufficiently to maintain current estuarine habitat types as sea levels rise. Projects are more likely to be resilient to SLR if they are designed with an understanding of future marsh accretion rates, tidal exchange levels, and sediment supply necessary to support self-sustaining marsh habitats.

Information needs

- Marsh accretion rates from riverine deposition
- Status of riverine sediment supply
- Topography of project and adjacent upland
- Current trajectory of marsh habitat (eroding or accreting)
- Inundation tolerances of marsh vegetation

VI. ADDITIONAL INFORMATION AND RESOURCES

The products and reports developed as part of the Washington Coastal Resilience Project and referenced in this document are available from the Washington Coastal Hazards Resilience Network website http://www.wacoastalnetwork.com/wcrp-documents.html. These documents include a comprehensive guide on how to use the 2018 SLR projections for Washington's coastal areas.

- *Projected Sea Level Rise for Washington State - A 2018 Assessment* (Miller et al., 2018)
    - *Appendix A: Absolute Sea Level Methods and Projection Tables*
    - *Appendix B: Global and Regional Sea Level Rise - A Review of the Science*
    - *Appendix C: Vertical Land Motion Background and Analysis*

- *Guidelines for Mapping Sea Level Rise in Washington State* (Norheim et al., 2018)

- *How to Choose? A Framework for Using the 2018 Washington State Probabilistic Sea Level Rise Projections*

During the two workshops that supported the development of these restoration considerations, we solicited resources that restoration practitioners use for the information needs listed under each management measure. A summary of these resources is listed below. This is not a comprehensive list, but is intended to be a starting place for additional information and data. With sufficient data, models can be used to assess the effects of SLR on ecological processes and restoration. In this document we did not review the scientific literature on SLR impacts or the listed information needs; however, these would also be useful resources.

Local topography:

- NOAA digital coast (including Lidar data): https://coast.noaa.gov/digitalcoast/
- Google Earth Engine Time lapse: https://earthengine.google.com/timelapse/
- Boat-based LiDAR of beach and bluff topography, WA Department of Ecology Coastal Monitoring and Analysis Program: https://ecology.wa.gov/Research-Data/Monitoring-assessment/Coastal-monitoring-assessment/Data-products
- Puget Sound LiDAR consortium: http://pugetsoundlidar.ess.washington.edu/
- Washington Department of Natural Resources LiDAR portal: http://lidarportal.dnr.wa.gov/
- GIS and survey data from local counties

Information on sediment sources, supply, and transport processes:

- PSNERP Strategies for Nearshore Protection and Restoration in Puget Sound: http://www.pugetsoundnearshore.org/technical_reports.html

- ESRP Beach Strategies Project
- Washington Department of Ecology Oblique Photography: https://fortress.wa.gov/ecy/publications/SummaryPages/1706026.html
- Washington State Coastal Atlas, Washington Department of Ecology: https://fortress.wa.gov/ecy/coastalatlas/
- Marine Shoreline Design Guidelines: https://wdfw.wa.gov/publications/01583/

Erosion and accretion rates:

- Local studies in specific deltas may be available for some deltas (e.g., Hood et al., 2016; Thom, 1992; Thorne et al., 2018)
- Google Earth Engine Time lapse https://earthengine.google.com/timelapse/
- Lidar data (see resources listed for local topography).
- CGS Bluff recession rate study

Salinity and flood tolerance of vegetation:

- Base flood elevation maps: FEMA https://msc.fema.gov/portal/home
- Information resources on vegetation from local conservation districts and WSU Extension

Coastal wave and marsh models

- WARMER (Swanson et al., 2014, Thorne et al., 2018)
- Sea Level Affecting Marshes Model (SLAMM) (https://coast.noaa.gov/digitalcoast/tools/slamm.html)
- Coastal Storm Modeling System (CoSMOS) (https://walrus.wr.usgs.gov/coastal_processes/cosmos/puget/)

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Appendix A. Tables from supporting documents from the Puget Sound Nearshore Ecosystem Restoration Program (PSNERP)

Table A1. Description of nearshore ecosystem processes from Schlenger et al. (2011).

Nearshore Ecosystem Process	Process Description
Sediment Input	• Delivery of sediment from bluff, stream, and marine sources into the nearshore; depending on landscape setting, inputs can vary in scale from acute, low-frequency episodes (hillslope mass wasting from bluffs) to chronic, high-frequency events (some streams and rivers). Sediment input interacts with sediment transport to control the structure of beaches.
Sediment Transport	• Bedload and suspended transport of sediments and other matter by water and wind along (longshore) and across (cross-shore) the shoreline. The continuity of sediment transport strongly influences the longshore structure of beaches.
Erosion and Accretion of Sediments	• Deposition (dune formation, delta building) of non-suspended (e.g., bedload) sediments and mineral particulate material by water, wind, and other forces. • Settling (accretion) of suspended sediments and organic matter on marsh and other intertidal wetland surfaces. These processes are responsible for creation and maintenance of barrier beaches (e.g., spits) and tidal wetlands.
Tidal Flow	• Localized tidal effects on water elevation and currents, differing significantly from regional tidal regime mostly in tidal freshwater and estuarine ecosystems.
Distributary Channel Migration	• Change of distributary channel form and location caused by combined freshwater and tidal flow. Distributary channel migration affects the distribution of alluvial material across a river delta.
Tidal Channel Formation and Maintenance	• Geomorphic processes, primarily tidally driven, that form and maintain tidal channel geometry. • Natural levee formation.
Freshwater Input	• Freshwater inflow from surface (stream flow) or groundwater (seepage) in terms of seasonal and event hydrography. Freshwater input affects the pattern of salinity and sediment and soil moisture content across the nearshore.
Detritus Import and Export	• Import and deposition of particulate (dead) organic matter. • Soil formation. • Recruitment, disturbance, and export of large wood.
Exchange of Aquatic Organisms	• Organism transport and movement driven predominantly by water (tidal, fluvial) movement.
Physical Disturbance	• Change of shoreline shape or character caused by exposure to local wind and wave energy input. • Localized and chronic disturbance of biotic assemblages caused by large wood movement, scour, and overwash.
Solar Incidence	• Exposure, absorption, and reflectance of solar radiation (e.g., radiant light and heat) and resulting effects. Solar incidence controls photosynthesis rates and temperature patterns in the nearshore.

Table A2. Description of effects of climate change on nearshore ecosystem processes from Clancy et al. (2009).

Process	Anticipated Impacts
Sediment Supply and Transport	Increased sediment supply from bluff erosion and streams, increased littoral drift rates, likely loss of sediment sources due to new shore protection.
Beach Erosion and Accretion	Exacerbated erosion along erosional and generally stable shores, and likely shifted areas of accretion. Overall landward shift (transgression) of shore features and associated habitats.
Distributary Channel Migration	Channels may accrete with rising sea levels and have greater tendency for migration in response to altered freshwater input.
Tidal Channel Formation and Maintenance	Tidal channels may accrete and processes may become less predictable in response to altered freshwater input.
Freshwater Input	Freshwater input predicted to become more variable, with more flooding (winter-spring) and drought conditions (summer-fall).
Tidal Hydrology	Greater inundation and tidal flows into semi-enclosed systems, increased saltwater incursion.
Detritus Recruitment and Retention	Likely greater detritus recruitment due to overall greater wave energy reaching marine riparian zone. Likely increased storminess and storm surges (including more frequent and intense *El Nino* storms) and from rivers due to increased peak flows.
Exchange of Aquatic Organisms	Reduced productivity of threatened salmon stocks due to increased winter flooding, decreased summer and fall stream flows, and elevated warm season stream and estuary temperatures. Loss of biological diversity/localized extinctions of marine and freshwater species if habitat shifts outpace ability of species to migrate or adapt to changing conditions.
Solar Radiation	Altered solar patterns due to hotter summers and colder winters.
Wind and Waves	Overall greater wave erosion and potential accretion due to SLR and likely increased storminess and storm surges (including more frequent and intense *El Nino*).

Appendix B: Shoreform Descriptions

Beaches

Beaches in Puget Sound are formed by the erosion of bluffs, transport of sediment alongshore and through the net accretion and retention of sediments (Shipman, 2008; Johannessen and Maclennan, 2007). These processes are both the key elements of habitat formation in beach systems and also the likely drivers of resilience of restoration projects. If these processes are intact within a given drift cell or Shoreline Process Unit, then a restoration action is more likely to be resilient to the impacts of sea level rise.

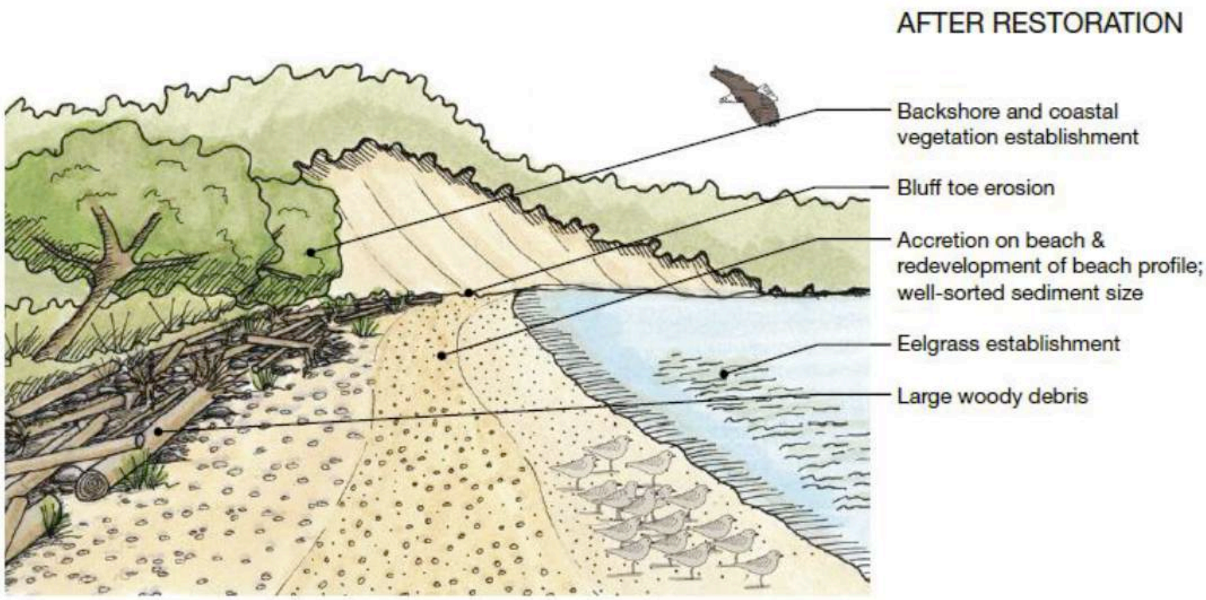

Figure 1. Diagram of a beach with intact ecosystem processes and corresponding structural responses (from Brandon et al., 2013).

Beach Target Ecosystem Processes: Sediment supply, sediment transport, beach erosion and accretion, detritus import and export, primary production

Beach Management Measures: Acquisition for protection, armor/structure removal, groin/fill removal, topography restoration, revegetation

River Deltas
We adopt the terminology of Shipman (2008) and Cereghino et al. (2012) to refer to the estuarine habitat formed by the 16 largest rivers in Puget Sound as River Deltas. These 16 rivers form extensive tidal wetland habitat where they meet Puget Sound and are shaped to varying degrees by fluvial and tidal processes (Shipman, 2008). Key processes that sustain delta habitats are riverine sediment transport and deposition and tidal action. The degree to which these processes are intact is likely contribute to resilience of restoration projects to sea level rise in river deltas. Vegetation development following restoration is a key indicator of habitat function in river deltas.

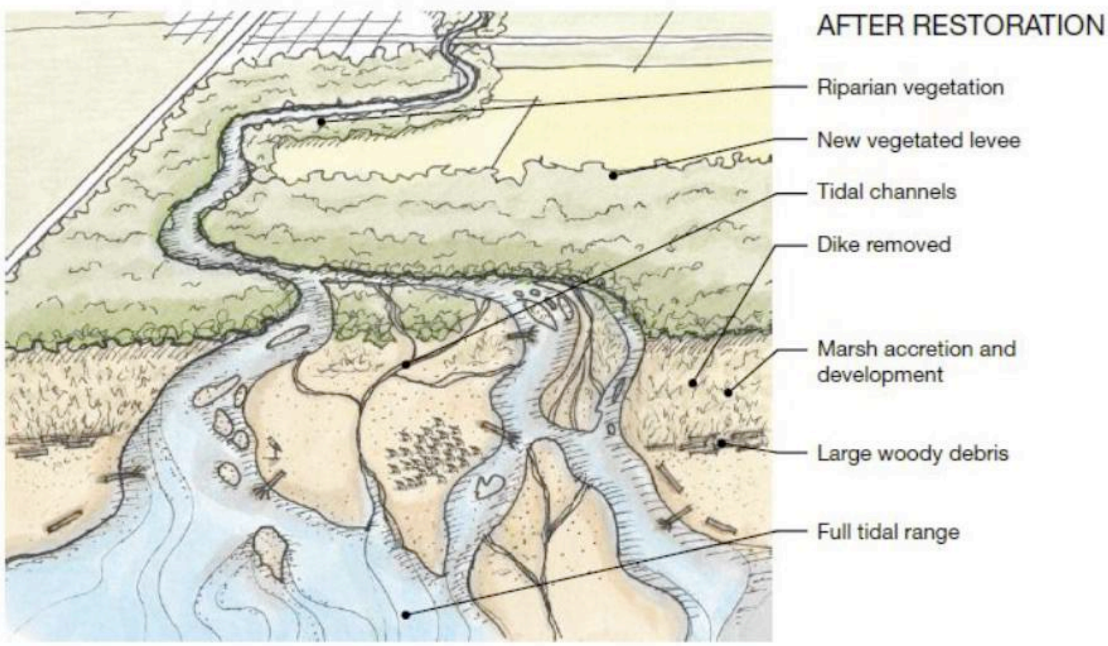

Figure 2. Diagram of river delta with intact ecosystem processes and corresponding structural responses within a matrix of surrounding agricultural land (from Brandon et al., 2013).

River Delta Target Ecosystem Processes: Sediment supply, sediment transport, distributary channel migration, tidal channel formation and maintenance, freshwater input, tidal hydrology, primary production, detritus import and export, erosion and accretion and tidal flow

River Delta Management Measures: Acquisition for protection, channel rehabilitation, dike/berm removal, hydraulic modification, topography restoration, revegetation

Embayments
We follow the terminology of Shipman (2008), to describe embayments as consisting of estuaries and lagoons within Puget Sound. Cereghino et al. (2012) and Brandon et al. (2013) further distinguish between barrier embayments (those embayments that are partially or wholly dependent on along-shore sediment transport and contain a barrier spit) and coastal inlets (which do not have a barrier spit). This shoreform includes pocket estuaries as defined by Beamer et al., 2003. Embayments are dependent on many of the same processes as both beaches and river deltas, so they have many considerations in common with beaches and deltas.

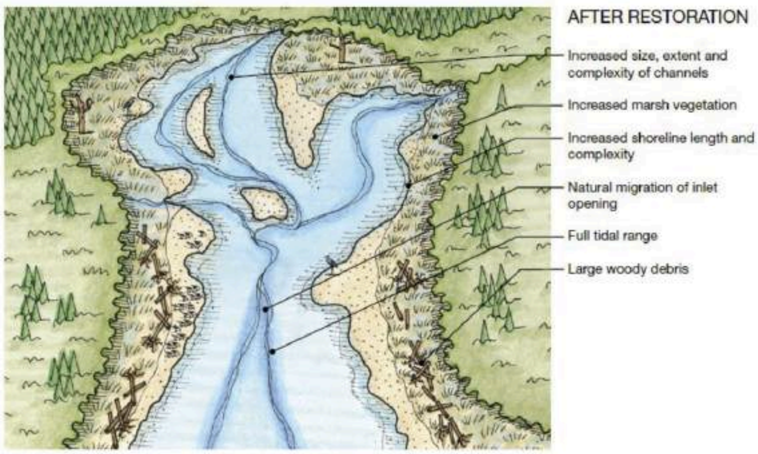

Figure 3. Diagram of an **inlet-type** of embayment following restoration with intact ecosystem processes and corresponding structural responses (from Brandon et al., 2013).

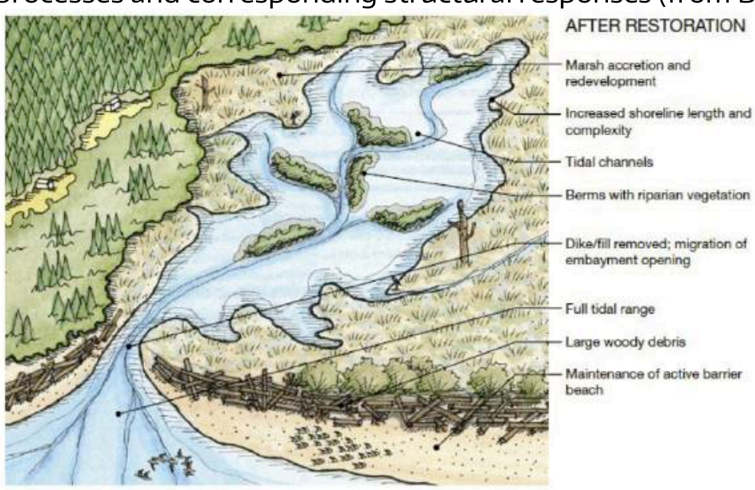

Figure. 4. Diagram of a **barrier-type** embayment following restoration with intact ecosystem processes and corresponding structural responses (from Brandon et al., 2013).

Embayment Target Ecosystem Processes: Sediment supply, sediment transport, erosion and accretion, distributary channel migration, tidal channel formation and maintenance, freshwater input, tidal hydrology, primary production, detritus important and export, and tidal flow

Embayment Management Measures: Acquisition for protection, channel rehabilitation, armor/structure removal, dike/berm removal, hydraulic modification, topography restoration, revegetation