Climate Resiliency in the Columbia Estuary Ecosystem Restoration Program

FINAL

Prepared by the Expert Regional Technical Group
of the Columbia Estuary Ecosystem Restoration Program

Prepared for the Bonneville Power Administration, National Marine Fisheries Service, and U.S. Army Corps of Engineers

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Abstract

We address approaches and processes for incorporating climate resilience into habitat restoration actions of the Columbia Estuary Ecosystem Restoration Program (CEERP). This includes optimizing project locations, designing long-term self-maintaining projects, and other aspects for reducing uncertainties and above all enhancing project viability, functionality, and longevity to climate change. Undertaking three main avenues of inquiry, we (1) examine predicted changes and forecasts for future Pacific Northwest climate conditions (e.g., runoff, water temperature, etc.) that are relevant to CEERP restoration strategies and project design criteria; (2) define climate change vulnerabilities within the context of the CEERP and outline considerations for ecosystem restoration and long-term resiliency; and, (3) recommend modifications to the Project Template and Scoring Criteria to facilitate Sponsor consideration of potential climate-change impacts throughout the project planning process in pursuit of long-term ecological resiliency in restoration projects. Specific recommendations to CEERP managers, project sponsors, and other program participants are to:

- Develop a framework to assess tidal marsh resiliency to help prioritize restoration actions.
- Implement experimentation into restoration project design to inform design and evaluation of projects relative to climate mitigation strategies and uncertainties, and to enhance resilience.
- Compile science-based, reasonable, and effective examples of resilience in restoration actions.
- Conduct estuary-wide predictive modeling and other analyses to evaluate effects of future climate scenarios on estuarine ecosystems, including restoration projects.
- Expand GIS tools to include climate change and resiliency elements in evaluation of projects.
- Integrate climate resilience into the Project Template and ERTG Scoring Criteria, considering the options presented in this report.

In conclusion, the material herein should assist CEERP in locating, designing, monitoring, and improving sustainability of habitat restoration projects in light of ongoing climate change.

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Preface

In 2009, the Action Agencies (Bonneville Power Administration [BPA] and U.S. Army Corps of Engineers [USACE]) formed the Expert Regional Technical Group (ERTG) in response to the National Marine Fisheries Service's (NMFS's) 2008 Biological Opinion on federal Columbia River hydrosystem operations. NMFS reiterated support for the ERTG in the subsequent 2020 Biological Opinion. The ERTG's overall purpose is to review proposed and completed ecosystem restoration[1] projects in the floodplain of the 234-km lower Columbia River and estuary and provide expert input on subjects relevant to the ERTG process, which is part of the Columbia Estuary Ecosystem Restoration Program (CEERP). The ERTG's work is directed by a Steering Committee composed of representatives from BPA, NMFS, and USACE.

This ERTG work product's objective is to develop a process that incorporates resilience-based actions to climate change into CEERP. The ultimate purpose is to further enhance the long-term functioning of completed and future restoration projects. Climate change is predicted to affect conditions such as water temperature and processes such as sea level rise that affect salmon. This report covers the background science on climate change, specific actions that can enhance resilience, and the process to incorporate climate resilience considerations within the ERTG's responsibilities and CEERP as a whole. The process is also intended to assist and inform project proponents regarding site location and design.

ERTG members Amy Borde and Ron Thom (retired) and Steering Committee member Allan Whiting prepared this document. It was reviewed by the other ERTG members (Dan Bottom, Janine Castro, Kim Jones, and Kirk Krueger) and Steering Committee members (Mark Bierman, Anne Creason, Jason Karnezis, Lynne Krasnow, Chanda Littles, Chris Magel, and Alex McManus). Laura Brown (WDFW) provided peer-review comments. Gary Johnson formatted the document.

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[1] As used here, the term "restoration" refers to conservation, protection, enhancement, restoration, or creation.

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1.0 Introduction

This report addresses the topic of climate change resiliency for restoration projects within the Columbia Estuary Ecosystem Restoration Program (CEERP). We recommend approaches and processes for incorporating resilience actions into CEERP, including optimizing project locations, designing self-maintaining projects, reducing uncertainties in project outcomes, and enhancing project viability, functionality, and longevity to climate change. The intent is to assist program managers, project sponsors, scientists and system managers in locating, designing, monitoring, and improving sustainability of projects in light of climate change. As part of the process, the Expert Regional Technical Group (ERTG) will use the findings from this report to inform their reviews of proposed projects and to learn from completed projects. Project outcomes should be assessed periodically to evaluate the effectiveness of actions and features in project design taken to deal with climate change.

1.1. Motivation

Climate change is one of many stressors facing salmonid populations in the Pacific Northwest (PNW). Crozier et al. (2021) conducted a comprehensive study on climate change effects to Chinook Salmon and concluded:

> "*The urgency is greater than ever to identify successful solutions at a large scale and implement known methods for improving survival. Management actions that open new habitats, improve productivity within existing habitat, or reduce mortality through direct or indirect effects in the ocean are desperately needed. We can find new ways to improve salmon habitats while maintaining other benefits for people, like reconnecting floodplains with rivers and natural marshes to recharge aquifers and mitigate flooding, storm surge, and channel erosion.*"

CEERP focuses on restoring (or enhancing) ecological conditions in the lower Columbia River and estuary (LCRE) to benefit salmonid populations in the Columbia River basin. Activities occur at the site and landscape scales. The program's adaptive management acknowledges the need to account for an actively changing climate. Changes driven by a fluctuating climate directly affect the system across multiple scales through the alteration of habitat forming and maintaining processes, ultimately making the outcome of salmon habitat improvement efforts less certain. Further, ongoing human-caused disturbances in this system compound restoration uncertainty and require thoughtful, science-based actions to meet program goals. Given this reality, climate considerations are critical for implementing structural and management actions that can maximize habitat restoration benefits in a complex system.

Littles et al. (2022) stated that "*CEERP managers are working with the ERTG, scientists, and restoration practitioners to develop strategies for risk assessment and optimizing long-term resiliency*." Restoration projects rely on resiliency initially and for ensuring their longevity. Hence, an overarching goal is to initiate restoration actions that will enhance natural ecosystem processes, and that are resilient to local and system scale disturbances.

Managers implement CEERP using a rigorous, dedicated process of adaptive management (Ebberts et al. 2017; Littles et al. 2022). In this context, the following from Lynch et al. (2022) is pertinent:

> *"Intensifying global change is propelling many ecosystems toward irreversible transformations. Natural resource managers face the complex task of conserving these important resources under unprecedented conditions and expanding uncertainty. As once*

familiar ecological conditions disappear, traditional management approaches that assume the future will reflect the past are becoming increasingly untenable."

One way to address the threats and uncertainties of ecosystem transformations is to employ the Resist-Accept-Direct (RAD) framework (e.g., Schuurman et al. 2020), which can be summarized as follows (from Lynch et al. 2021):

(1) **Resisting** change means attempting to keep an ecosystem in the current state regardless of changing conditions. For example, placement of a thin layer of sediment to increase wetland elevations in the face of sea level rise. Under increasing rates of change, transformations may become more challenging to resist.

(2) **Accepting** change can be difficult as it can result in loss of valued ecosystems; however, this can sometimes be the most cost-effective action. This strategy can be balanced by other actions to resist or direct change.

(3) **Directing** includes methods to promote change toward a desired future condition. An example of directing change would be facilitating marsh migration as sea level rises.

Considering these three actions in an adaptive management framework involves a clear goal statement, a conceptual model, and a decision framework (Thom 2000). The goal ‘drives’ the design and actions (e.g., RAD) of the project and helps guide the development of performance criteria. The goal statement and performance criteria provide how the system can be evaluated. The conceptual model incorporates the knowledge base from the field of ecological science and plays an active and critical role in designing the project to meet the goal. A decision framework allows for determining whether an existing RAD pathway is still viable or an alternative pathway is needed. Monitoring to refine trajectories, experimentation to identify thresholds, and pilot studies to test alternative actions are critical tools that can inform the adaptive management process (Lynch et al. 2022).

In CEERP, we focus on ecosystem resiliency by prioritizing restoration actions that allow natural processes to maintain habitats to be resilient to short and long-term climate disturbances. Ecological resilience is the capacity of an ecosystem to absorb and adapt to disturbances, while maintaining its essential structure and function and assumes the existence of multiple stable states (Holling 1973). In the RAD framework, resisting change to an alternative state means that adaptations, such as increasing elevation, may be needed to maintain ecosystem resilience to hydrologic changes, while in other areas directing change can be facilitated protecting a gently sloping buffer area for wetland expansion.

The primary expected system changes relevant to the function of the LCRE for juvenile salmon are the following: temperature increases, hydrological changes, including lower river flows and timing of the freshet, sea level rise, and salinity dynamics in the lower reaches of the system. These system changes pose threats to the viability of juvenile salmon. Strategies to avoid and minimize these threats through strategic planning of projects are needed. These changes are clearly expected to affect the LCRE (Isaak et al. 2017; Miller et al. 2018; RMJOC 2020). Thus, actions are required to address the long-term viability and functionality of the system for salmonids. The ERTG Uncertainties work product (ERTG 2022a) identified climate change as a key uncertainty and outlined key assumptions and programmatic questions that need to be answered (Table 1). These questions formed the basis for this work product.

Table 1. Primary assumptions and associated programmatic questions concerning the ecological effects of climate change in the LCRE (modified from ERTG 2022a; Table 1). Linkage to pertinent material in this report is also indicated.

Ecosystem Effects Assumption	Programmatic Question	Pertinent Material
There will be effects on habitat functions, maintenance, and processes associated with changes in air temperature, water temperature, hydrology and hydrodynamics, sea level, sediment dynamics, pulsed events, salinity, turbidity, nutrients, etc. These effects will be manifested at four primary scales: system, estuary, landscape, and habitat.	What are the best and most relevant scientific predictions of the effects of climate change on these functions and processes? What location, design, or other considerations will strengthen project resilience to these expected changes?	Sections 2.1, 2.2, and 2.3
The primary ecological structures that will be affected include vegetation species and habitat assemblages, geometry, number and distribution of channels, inundation, and water properties.	What is the best site-specific, and reach-specific information that will provide guidance for altering project structural features?	Sections 2.4 and 3.3
The primary ecosystem processes affected will include primary and secondary production, sedimentation, erosion, pulsed flooding events, exchange of organic matter and prey, fish access and residence time, and prey production.	What is the best, site-specific, and reach-specific information that will provide guidance for altering project expectations regarding maintenance of these processes? What are the types of actions to maintain or enhance the resilience of the restoration project knowing the changes in processes?	Sections 2.4 and 3.3
Changes in temporal and spatial habitat distribution will alter certainty of success, juvenile salmon accessibility to rearing habitats, and capacity of those habitats thereby affecting salmon performance in the estuary in terms of growth, survival, condition, etc.	What information is needed to evaluate climate change effects on juvenile salmon use of estuarine habitats and the survival and contributions of juveniles with estuary-associated life histories to adult returns?	Sections 3.1 and 3.2
The best available predictions of climate-driven changes, in conjunction with relevant conceptual and numerical models regarding structure and process changes, can help guide planning of actions to ensure long term maintenance and resilience of projects to climate change.	What are the best examples of ecosystem programs that have integrated climate change in their planning to assure resilience to climate change, and long-term maintenance of ecosystem functions for key aquatic species? How can these results be applied to CEERP?	Sections 3.1, 3.2, 3.3, and 3.4

1.2. Objectives

The objectives of this ERTG work product are the following:

1) Examine predicted changes and forecasts for future PNW climate conditions (e.g., runoff, water temperature, etc.) that are relevant to CEERP restoration strategies and project design.
2) Define climate change vulnerabilities within the context of the CEERP and outline considerations for ecosystem restoration and long-term resiliency.
3) Recommend modifications to the Project Template (ERTG 2020a) and Scoring Criteria (ERTG 2020b) to facilitate Sponsor consideration of potential climate-change impacts throughout the project planning process in pursuit of ecological resiliency in restoration project outcomes.

1.3. Contents

After the Introduction (Section 1), this report contains two main parts, an assessment of Ecosystem Vulnerability and Resilience (Section 2) and development of processes for Integration of Climate Resiliency into CEERP (Section 3). The report closes with a Summary and Recommendations (Section 4). The Literature Cited is in Section 5. The lone appendix (Appendix A) presents Relevant Information from Other Documents.

2.0 Ecosystem Vulnerability and Resilience

To be successful in the long-term, habitat restoration needs to consider potential vulnerability to climate change and options to increase resiliency. This section provides an overview of conceptual frameworks that can be used to evaluate climate change effects from global to local scales. This is followed by a review of the most recent projections and uncertainties for climate-related changes. We then describe current modeling efforts aimed at estimating potential changes within the LCRE, within the bounds of uncertainty. After this, we explain potential vulnerabilities of LCRE ecosystems, processes, and functions. Finally, we outline concepts for ecosystem resiliency to set the stage for Section 3 where we address assessment frameworks and planning, methods for increasing ecosystem resiliency through restoration project design, and considerations for project scoring.

2.1. Conceptual Frameworks to Assess Climate Change Effects

There is a rapidly growing international emphasis on how climate change affects species and natural ecosystems (e.g., Kennish 2021). Effects have been addressed on global to local scales and understanding these effects are imperative for evaluating the viability and functional performance of restored systems (Figure 1). Conceptual frameworks have been developed for a range of ecosystems and at varying scales with the explicit purpose of integrating climate resilience into ecological restoration. Studies relevant to CEERP include Pelletier et al. (2020), Moore and Schindler (2022), Munsch et al. (2022), Simonson et al. (2021) and Thorne et al. (2018). Papers of high topical and geographic relevance are programs in the PNW by Davis et al. (2021) and Thom et al. (2012). Reports developed within the LCRE that provide 'system-specific' practical guidance on application of local resilience actions include USACE (2014) and Bottom et al. (2011). Moreover, management actions relevant to climate effects and estuarine restoration (Figure 2) are important to identify early in the planning process and can provide a framework for project evaluation, as discussed below.

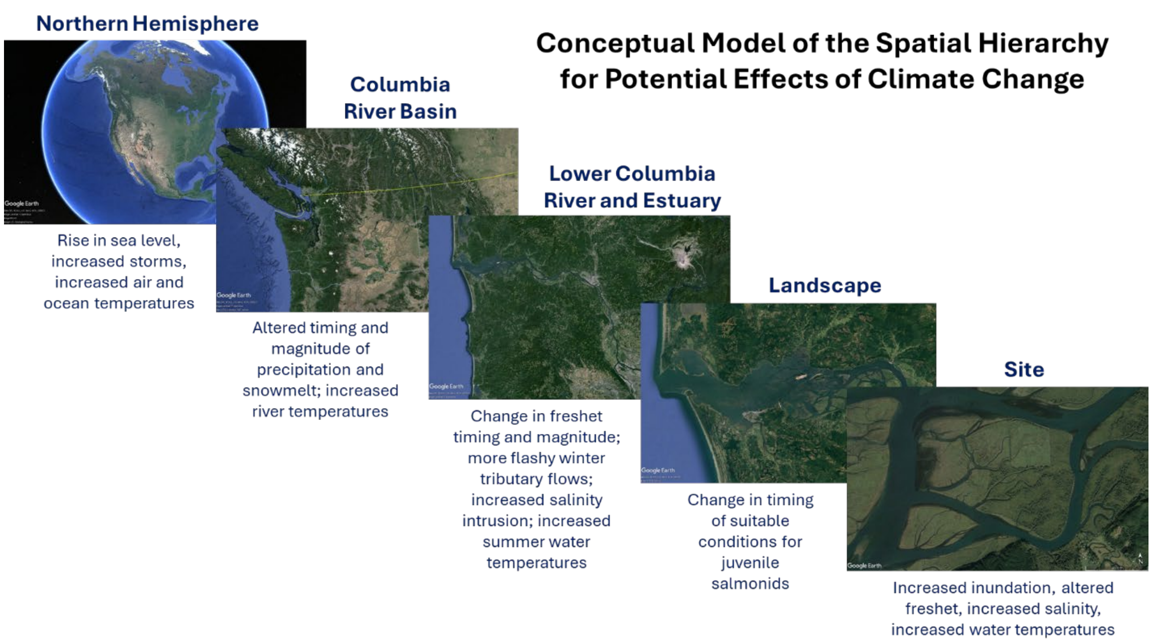

Figure 1. Potential effects of climate change from global to local scales.

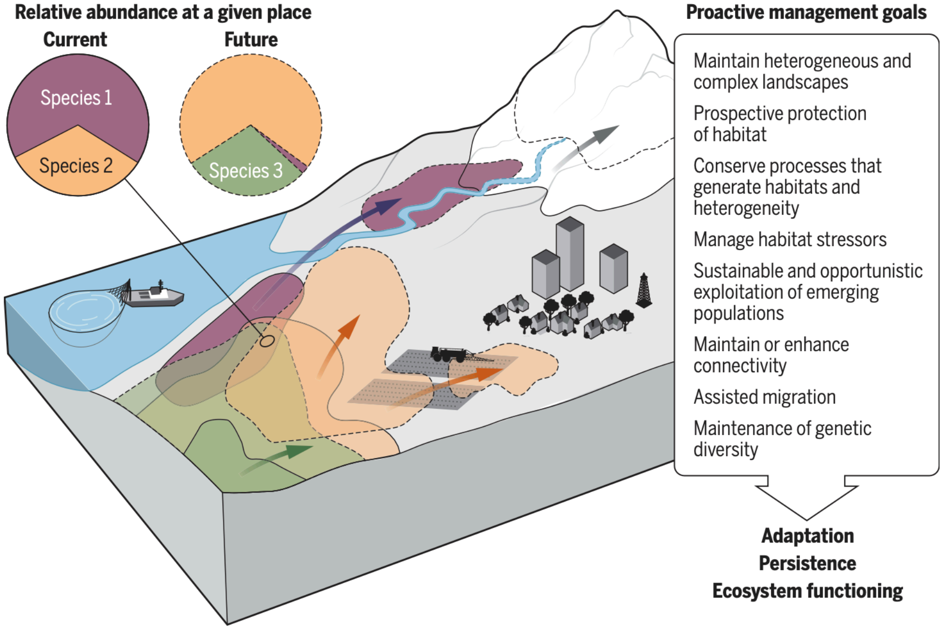

Figure 2. Potential proactive management goals with relevance to climate change and its potential effects on species assemblages (Moore & Schindler 2022).

In this report, we consider conceptual and numerical models that could aid the evaluation of restoration project proposals submitted for CEERP consideration. We also identify conceptual models most relevant to building climate resilience within CEERP. The models are operational and directly applicable for project design and scoring CEERP projects. Furthermore, throughout this report we incorporate the foundational principles defined by Bottom et al. (2009; in review):

A. Salmon habitats (e.g., streams, rivers, floodplains, estuaries, coastal ocean) are subject to changes across multiple scales, including the effects of large-scale shifts in climatic, economic, and geopolitical regimes. Salmon ecosystems include these habitats along with the abiotic and biotic conditions necessary for salmonid persistence. Salmon ecosystem **resilience** directly affects the availability of ecosystem services that salmon populations convey and the diversity of habitat and socioeconomic opportunities that allow both salmon and people to respond to variable conditions.

B. Salmon ecosystem **resilience** then is a measure of whether this integrated and adaptive system can reorganize, renew, and persist in the face of stressors, including climate change.

C. **Resilience** is the amount of disturbance that an ecosystem can accommodate without shifting to a different regime or stability domain as characterized by a fundamentally different structure, function, and feedback mechanisms.

Figure 3 provides an overview of the potential effects of climate change on ecosystems of the LCRE and juvenile salmon. Controlling factors, many of which would be affected directly or indirectly by climate change, affecting structures, processes, and functions (Thom et al. 2004). Specific interactions of controlling factors and the detrimental effect on juvenile salmon growth were modeled by Davies et al. (2021).

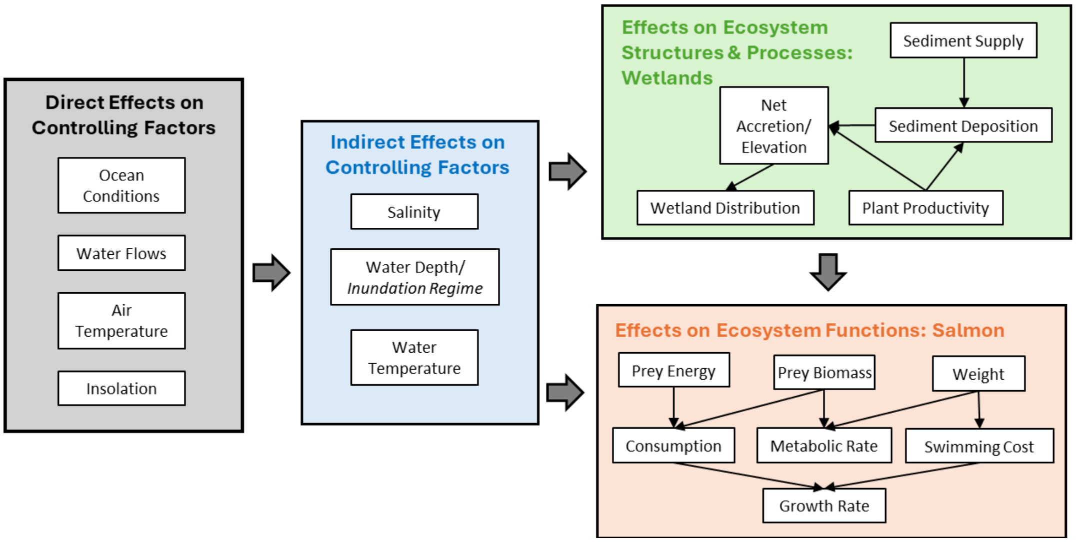

Figure 3. Conceptual model showing how extreme climatic events and longer-term system changes potentially stress all ecosystem controlling factors either directly or indirectly and ultimately affect wetland ecosystems and juvenile salmon (based on Davies et al. 2021, Reed 2002, Thom et al. 2004).

2.2. Climate Change Projections

Climate change models have been developed by various agencies and organizations globally, nationally, and regionally (e.g., RMJOC 2020) to better understand changes in air and water temperature, precipitation, riverine flows, and sea level rise. In the PNW, these models project increased water temperatures, increases in winter, spring, and fall precipitation, lower snowpack, and decreased summer precipitation. Since 2010, intense marine heat waves have occurred in the Northwest Pacific (Wang et al. 2024). These events have impacted marine coastal and estuarine shallow water habitats (Thompson et al. 2022). Additionally, heavy rainfall events (2-year storm) are expected to be of greater magnitude, affecting the timing and magnitude of the spring freshet and winter flood events. Coincident with these hydrologic changes, sea level is also projected to increase. Projected changes for the LCRE are summarized in Table 2.

Table 2. Summary of climate vulnerabilities in the LCRE. Table continues on next page.

Indicator	Projected Change	Source of Vulnerability Assessment
Water Temperature	Projected change in average August water temperature at Vancouver relative to the average for 1993–2011 for the Moderate scenario A1B. 2040s: +1.65°C 2080s: +2.83°C Bottom-line: Water temperature is expected to increase.	The US Forest Service NorWeST summer stream temperature model, based on a crowd-sourced database of US western rivers and streams (Isaak et al. 2017). Interactive map: https://www.fs.usda.gov/rm/boise/AWAE/projects/NorWeST.html

Indicator	Projected Change	Source of Vulnerability Assessment
Precipitation Annual Seasonal	Projected changes for Clark County* relative to the average for 1980-2009 for the High emissions scenario RCP 8.5. Values are model median and 10-90th percentile. Total annual precipitation: 2040s: +6.7% (-2.6 to +12.0%) 2080s: +11.6% (+5.7 to +14.7%) Late summer precipitation: 2040s: -11.5% (-33.3 to -3.7%) 2080s: -22.5% (-31.0 to -1.7%) 2-yr storm magnitude: 2040s: +5% (+1 to +16%) 2080s: +17% (+7 to +28%) Bottom-lines: Total annual precipitation is expected to increase; late summer precipitation is expected to decrease; 2-year storm magnitude is expected to increase.	Climate Mapping for a Resilient Washington. Based on University of Washington Climate Impacts Group downscaled regional climate model projection methods (Salathé et al. 2010): https://data.cig.uw.edu/climatemapping/
River Hydrology	Columbia River mainstem (RCP 8.5 @ Dalles Dam) - Increased winter flows (Dec-March). Largest changes are projected for Jan and Feb - Increased flows spring and early summer (April-July) - Freshet timing is projected to shift two weeks earlier (2030s) and one month earlier (2070s) - Late summer flows (Aug-Oct) are projected to decrease Columbia River tributaries - Increased winter flows (Dec-March), more noticeable in tributaries in transitional snow/rain-dominated watersheds (Cascade Range) than those currently in rain-dominated watersheds (Coast Range). - Greater Willamette influences on water levels downstream of Vancouver, particularly in winter. Bottom-lines: Increased winter, spring, and early summer flows; earlier spring freshet; reduced late summer flows.	Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies (2nd edition). Part II: Columbia River Reservoir Regulation and Operations—Modeling and Analyses (RMJOC 2020) RMJOC = River Management Joint Operating Committee
Sea Level Rise	Sea level rise projections estimate the following water level increases approximately 30 river kilometers from the mouth of the estuary. High emission scenario RCP 8.5 with 50% Meet or Exceed by Year (includes vertical land movement estimate): Site — 2050 — 2100 Astoria, OR (Rkm 29) — +0.8 ft (0.25 m) — 5.5 ft (1.7 m) Grays Bay, WA (Rkm ~30) — +1.1 ft (0.33 m) — 1.6 ft (0.49 m) Bottom-line: SLR will result in higher water levels in the lower estuary.	Grays Bay, WA estimate: University of Washington Climate Impacts Group and Washington SeaGrant Analysis Tools | Climate Impacts Group (uw.edu) (Miller et al. 2018) Astoria, OR estimate: (Sweet et al., 2022; Interagency Sea Level Rise Scenario Tool)

* Clark County, Washington includes the city of Vancouver on the north side of the Columbia River across from Portland, Oregon.

2.3. Climate Change Vulnerabilities in the LCRE

Climate change is causing persistent gradual changes, such as sea level rise and increases in rainfall, which present challenges to ecosystems, including tidal wetland habitats. In addition, episodic extreme events (historic flooding events, unprecedented heat waves) are also becoming more frequent and can potentially tip the state of an ecosystem. The impact of these gradual and episodic extreme events can fundamentally alter tidal wetland ecosystems. Habitat forming process, structure, morphology, and functions can be significantly affected. Resilience of coastal wetlands, especially related to extreme heat events, must be addressed at broad system scales (He et al. 2025; Smith et al. 2024).

To determine potential effects on LCRE tidal wetland ecosystems and juvenile salmon using those habitats, vulnerability thresholds can be determined by analyzing existing data. While this has been done for some metrics, such as water temperature, further work is needed to determine vulnerability thresholds related to inundation and salinity changes for tidal wetlands and juvenile salmonids. Additionally, existing data on relationships between habitat forming processes and tidal wetlands should be used to develop predictive models (see ERTG 2022b) that can be used with future climate scenarios to better predict wetland changes. In turn, these models can help guide planning of actions to ensure long term maintenance and resilience of these ecosystems to climate change. The focus here is to describe potential changes in habitat forming processes, structures, and functions and to outline modeling efforts underway to predict tidal wetland vulnerability in the LCRE.

2.3.1. Habitat Forming Processes

Habitat forming processes include hydrology and sedimentation. We also include salinity and temperature here since they are important to habitat conditions for juvenile salmonids.

Hydrology

Sea level rise (SLR) has not been observed to date in the LCRE, in part due to strong tectonic uplift near the mouth of the estuary (Talke et al 2020; Newton et al. 2021). However, SLR is already occurring in some areas of coastal United States and is predicted to occur throughout the PNW in the coming decades (Sweet et al. 2022). Increased storm intensity and frequency are also predicted to increase storm surge and will be exacerbated by SLR (Bromirski et al. 2017). Additionally, changes in tidal ranges and amplitude are also predicted and need to be considered when evaluating the effects of SLR and storm surge on flooding (Hague and Talke 2024).

Many tools are available to assess potential water level changes and flood risk. NOAA has developed a SLR online viewer[2] available at a national scale. USGS has developed a Coastal Storm Modeling System (CoSMoS)[3] that provides detailed predictions of coastal flooding due to future sea-level rise, storms, tides, and river flooding. This tool is currently available for regions of California and Whatcom County (Bellingham) in Puget Sound. At a more regional level, the University of Washington Climate Impacts Group created a locally specific, relative SLR data visualization tool[4] based on Miller et al. (2018) which considers the geographic variability of vertical land movement (Table 2). A follow-on study developed a parcel-based vulnerability assessment for Puget Sound to rank the likelihood and severity of SLR impacts on infrastructure and habitats, including an assessment of marsh migration potential

[2] https://coast.noaa.gov/slr/
[3] CoSMoS website link
[4] https://cig.uw.edu/projects/interactive-sea-level-rise-data-visualizations/

(Coastal Geologic Services et al. 2022). Future efforts could expand those results to the Washington coast and the Columbia River estuary (Ian Miller, personal communication May 2024). The USACE developed an AdH model for the LCRE and has modeled three SLR scenarios (0.5 m, 1.0 m, and 1.5 m increases) to evaluate the effects on water levels throughout the estuary (Pevey et al. 2020; Appendix A1). The Lower Columbia Estuary Partnership conducted an assessment evaluating the potential impact of the three USACE SLR model projections on tidal wetlands of the LCRE. The assessment found that a loss of 6 to 16 percent of the current extent of wetlands were likely to occur. A summary of the results and an online viewer are available on their website.[5]

Watershed hydrology is expected to change at varying spatial and temporal scales. At the scale of the Columbia Basin, climate change scenarios have been modeled with potential reservoir regulation and operations (RMJOC 2020) to gain an understanding of changes to the timing and magnitude of winter and spring flood events and summer low flow levels (Table 2). Several efforts are currently underway to model the effects of flow changes on LCRE water levels. In some cases, these models will also include projected SLR changes and will evaluate the subsequent effects on wetland ecosystems (personal communications Maggie McKeon, PNNL, September 2023; Hans R. Moritz, USACE, March 2024; Charles Seaton, CRITFC, June 2024). Ultimately the goal is to bring together the results of all three models to develop an ensemble of possible model outputs.

Changes in extreme precipitation events are also likely to increase in frequency and increase stormwater runoff at the smaller watershed scale. The University of Washington (UW) Climate Impacts Group conducted regional climate model simulations from 1970 through 2099 at hourly intervals to evaluate precipitation totals and extremes (Morgan et al. 2021). The group also developed a tool, designed for stormwater managers, to assess localized extreme precipitation projections.[6] While an increase in these events may not directly affect juvenile salmonid habitat, it is worth noting that they could increase landslide events, flooding, and flushing of pollutants into the water, all of which could be detrimental to salmonids.

Sedimentation

Riverine sediments contribute to tidal wetland accretion rates and can help alleviate the effects of SLR, particularly in the PNW where large-river sediment loads have been estimated to be adequate to keep up with SLR (Ensign et al. 2023). Additionally, estuarine restoration sites in the PNW have higher sedimentation rates than reference wetlands, particularly where sediment inputs are high (Davis et al., 2024). Sediment dynamics are variable throughout the LCRE because they are shaped by factors including the sediments' physical characteristics (e.g., grain size), location within the LCRE, location within the floodplain, distance from tributaries, elevation, proximity to dredge material placement, and landscape scale disturbances to sediment transport (e.g., jetties, pile structures, linear barriers such as roadways, railways, and dikes) (Diefenderfer et al. 2021; Diefenderfer et al. 2024). In the context of climate change, sedimentation will be most affected by 1) changes in mainstem hydrology timing and magnitude and 2) changes in the frequency of pulsed flood events in the tributaries. Researchers at PNNL are currently studying accretion rates with sediment elevation tables (SETs) at nine sites and evaluating the mechanisms for sedimentation using a velocimeter, acoustic doppler profiler (ADP), and a turbidity sensor at four of the nine locations (personal communication Maggie McKeon, PNNL, March 2024). This research will add to the existing database of sediment accretion data, collected using sediment stakes or pins, from previous and ongoing studies in the estuary (Reference Site Study, Ecosystem Monitoring

[5] https://www.estuarypartnership.org/sea-level-rise-impacts-lower-columbia-river-and-estuary
[6] https://data.cig.uw.edu/picea/stormwater/pub/viz/

Program, and Action Effectiveness Monitoring and Research) to ultimately allow sediment transport modeling and estimation of sedimentation rates at proposed restoration sites.

Temperature

Research on water temperature in the estuary has indicated that temperatures have warmed 1.2 °C on average since 1938 (Scott et al. 2023; Talke et al. 2023). Water temperatures are projected to continue to increase at a higher rate, corresponding to increases in air temperature (Table 2). Water temperature tends to be consistent spatially within the mainstem LCRE (Needoba 2023), however forested wetlands can have a cooling effect especially in the warmer months of the year (Buenau et al. 2025), while emergent wetlands can exhibit warmer temperatures compared to the mainstem (Needoba et al. 2023). Extreme heat waves will need to be included in considerations of actions. Additional analysis of emergent wetland temperatures is currently underway (Buenau et al. in prep).

Salinity

Spatial and temporal changes in salinity are expected from SLR and riverine hydrology changes. Salinity intrusion is expected to increase with SLR, while salinity concentrations are likely to increase in the summer/fall low-flow period. Modeling efforts described above will also include predictions of salinity changes. Most prominent changes are expected in the deeper salt wedge, although surface salinity may also change affecting vegetation communities and juvenile salmonids.

2.3.2. Habitat Structures

Habitat structures relevant to the CEERP include the plant communities and shallow water associated with tidal wetland habitats. Sea-level rise is likely to alter the extent of PNW wetland habitats (Thorne et al. 2018), with vegetation communities primarily affected by changes in inundation and salinity. Inundation is a primary driver of wetland plant distribution in the LCRE (Borde et al. 2020). Changes in inundation are complex in a system like the LCRE where changes will come from SLR and hydrologic changes in Columbia basin watersheds. Predictive modeling of vegetation community response to future hydrologic conditions can inform changes in area and distribution of wetlands, such as was conducted in the LCRE to evaluate the effects of a subduction zone earthquake (Brand et al. 2023).

Inundation timing due to riverine hydrologic change, such as more inundation earlier in the growing season or lower water later in the season, could result in plant species shifts. Plants that express lower moisture tolerance during germination, such as reed canarygrass (*Phalaris arundinacea*), could have reduced ability to colonize effectively. In turn, this could provide an opportunity for native species to establish, although long periods of inundation may be needed to change established plant communities. For example, studies evaluating the effect of managed inundation levels on the invasive species reed canarygrass found that >1.4 m depth for 7.5 months in the spring and summer reduced *P. arundinacea* and increased native *Polygonum* species, while at a higher elevation 0.6 m depth for 6 months increased native *Carex* species (Jenkins et al., 2008; Farrelly 2012).

The effect of salinity on vegetation communities often depends on the duration of exposure. Li et al. (2022) found the effects of chronic increased salinity reduced cover or depleted cover of all common species over four years (two disappeared within first growing season, two declined over four years). A short, pulsed treatment of salinity resulted in decline of one species, but there was no effect at the community level. Then again, there can be a feedback loop, where the decline in species cover associated with salinity change leads to a reduction in marsh accretion; a condition that would further exacerbate the effects of sea level rise.

Primary production in marshes will likely be affected by changes in hydrology and temperature. If the spring freshet's timing is shifted earlier in the growing season, this may delay plant growth, but the detrimental effects of this may be compensated by more favorable summer conditions such as earlier low water and warmer sunnier conditions (Borde et al. 2017; Kidd et al. 2023).

Shallow-water habitat is on average less than 2 m deep and found in sloughs, wetland tidal channels, and sand flats of off channel and mainstem areas in the LCRE. This habitat feature provides juvenile salmon with slow-moving water (30 cm/s) with feeding opportunities (Bottom et al. 2005). Shallow-water habitat area in the LCRE has decreased approximately 55 % over the past century, primarily due to diking (Templeton et al. 2023). Hydrologic changes due to climate effects could further reduce shallow-water habitat area because of the already reduced area of low-gradient floodplain.

2.3.3. Habitat Functions for Juvenile Salmon

Coincident with changes to the extent of intertidal habitats, sea-level rise could also affect the amount of wetland area accessible to juvenile salmonids (Flitcroft et al. 2013). Prey export from wetlands to the mainstem and elsewhere may become even more important as a means of providing indirect wetland benefits (Thom et al. 2018; Roegner and Johnson 2023). However, reduced intertidal habitats would also result in reduced prey production overall (e.g., Rullens et al. 2022). Additionally, since some prey biomass can decrease with increasing temperature (e.g., Cordell et al. 2023), earlier temperature increases could reduce salmonid prey biomass in the spring.

Temporal shifts in hydrology may change when habitats are accessible to juvenile salmon. For example, some sites may be beneficial for Coho Salmon in the winter but may not be functional rearing habitat in summer. The timing of organic material and prey flux could also change due to changes in the timing of flood events, both pulses from tributary floods and freshet events from the Columbia River.

Vast literature exists on the potential effects of climate change on salmon, with the juvenile life stage studied most extensively (Crozier and Siegel 2023). The effects on salmon behavior within the estuary are less certain (Crozier et al. 2021); however, studies in the LCRE have indicated that patterns and timing of migration and rearing are much less diverse than they were a hundred years ago (Burke 2004; Bottom et al. 2005). This reduced life history diversity may limit resilience to climate-related changes (Bottom et al. 2009). For example, increased temperature could shift migration timing earlier (Roegner and Teel 2014) and stocks that have limited life history strategies may not adapt to this change.

Increasing estuarine habitat diversity can help maintain life-history diversity, thereby contributing to population resilience of salmonids into the future (Bottom et al. 2009). The imperiled state of juvenile salmon exacerbates the need to reduce habitat losses and increase restoration success and resilience. Concurrently, we need to develop indicators of climate stress useful at sites and landscape scales, implement research to better predict climate effects on prey resources, and test methods to increase cool water habitats.

2.4. Resiliency

Climate change can cause a cascade of changes that impact habitats, ecological landscapes, and natural processes (reviewed in Pelletier et al. 2022). Ecosystem resiliency to climate change is dependent on the maintenance or enhancement of ecosystem processes and the capacity for ecosystems to adapt to change. Actions may be needed to enhance or improve existing processes and to facilitate adaptation.

There is strong support in literature for protecting, enhancing or preserving natural features, processes and functions (Pelletier et al. 2020) (Table 3).

Table 3. Factors affecting climate resilience from Pelletier et al. (2020), with examples added. Additional information may be found in Appendix A3.

Decreasing Resilience	Increasing Resilience	Direction Depends on Context
Increasing stressors loads (contaminant loading) **Urbanization** (land use changes) **Overharvesting** (overharvest of fish) **Climate changes** (pushing systems well beyond ecological thresholds) **Multiple stressors** (overfishing and warming water) **Lack of equity** (development in one place may negatively affect others) **Biological Homogeneity** Simplification of life history characteristics and reduction of populations/stocks	**Connectivity** (access to multiple habitats and refugia) **Habitat heterogeneity** (use of different habitat for different purposes) **Functional redundancy** (multiple salmonid population with different life histories) **Diversity** (with more species and populations, some species may be able to functionally compensate for extirpated species) **Strong links between social & ecological systems** (resilience from connected social, economic, institutional, and ecological subsystems)	**Disturbance** (storms can maintain diversity and allow reorganization of the system, or destroy the potential for recovery) **Life history characteristics** (slow growing species may not recover from disturbances, where faster growing species may recover) (generational overlap [Chinook Salmon] may fare better than no overlap [chum and coho salmon] **Scalar issues** (ecosystem components may be impacted by local and/or larger scale conditions, as well as temporal conditions. The size or location of an ecosystem may affect recovery)

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3.0 Integration of Climate Resiliency into CEERP

Project sponsors, program managers, and resource agencies involved in CEERP are actively working to identify actions to mitigate adverse effects to habitat as part of the program's adaptive management framework (Figure 4). This approach serves as an ideal platform for managing uncertainties inherent to restoration and for validating assumptions of climate change effects on the LCRE ecosystem. In this section we provide an overview of assessment tools to quantify potential vulnerabilities and outline an approach for an assessment framework in the LCRE. Next, using conceptual and predictive modeling from previous sections as context, we outline emerging research questions to address key uncertainties related to climate change. This section will also provide planning and design guidance useful at the outset of restoration project development, goal setting, and ERTG Project Template development.

Figure 4. Adaptive management framework to improve restoration and incorporate understanding of climate-related effects (from Littles et al., 2022).

3.1. Assessment Framework

Tidal wetland ecosystems are at risk from climate stressors and, therefore, methods to assess their current condition, previous impacts, and vulnerability are needed. Additionally, methods to increase tidal wetland resiliency are essential to ensure sustainability of natural and restored ecosystems in the face of an uncertain future climate. Here we evaluate guidance documents, assessment frameworks, and other tools from other areas to inform future approaches within CEERP.

Other ecosystem restoration programs have begun to integrate climate change resilience planning to ensure the long-term maintenance of ecosystem functions for key aquatic species. A few examples are summarized below:

- The Puget Sound Partnership (PSP) with the UW Climate Impacts Group developed guidance documents to provide guiding principles about climate change and to also provide practical guidance for addressing climate change in the PSP recovery program and for specific projects (Vogel and Mauger 2020). The 11 principles outlined for adaptation and the 7 steps for project level decision making are provided in Appendix A4.

- Stein et al. (2020) developed a framework to assess and prioritize restoration projects using historical conditions and future benefit analysis. The premise is that potential future losses could be offset by facilitated wetland migration and sediment augmentation. Although the future distribution of wetlands would be different from current conditions, increased habitat would be provided region wide.
- Raposa et al. (2016) developed a tool for assessing tidal marsh resiliency (MARS) and prioritizing restoration actions. The method was tested at the National Estuarine Research Reserves (NERRs) in the US and has been implemented in Canada by the Nature Trust in collaboration with local tribal nations (Reid 2024).
- Ganju et al. (2022) developed a method to evaluate marsh vulnerability at the estuary-scale by estimating the unvegetated-vegetated marsh ratio utilizing remotely sensed datasets. The data can be collected repeatedly to track changes over time and also to compare amongst estuaries or reaches to prioritize management actions.
- Graves (2021) conducted a GIS analysis to evaluate climate change and fish habitat restoration on Columbia River tribal lands.[7] The study analyzed location and conditions of existing restoration projects (of many categories including habitat improvements, passage improvements, conservation, and change in water practices) and found that over 50% of projects exist where conditions are likely to limit success unless management intervention occurs.

Many tools exist to evaluate potential effects of SLR. Davis et al. (2019) developed an ecological model to forecast habitat change in response to SLR. The model incorporates feedback between tidal inundation, vegetation, and sediment accretion and can evaluate scenarios with increased sediment inputs. Additionally, tools are being developed to estimate wetland migration potential in response to future water levels (e.g. Enwright et al. 2024).

In 2012 and 2014, the LCRE community convened workshops that used conceptual models as a tool to identify relevant climate change variables to consider during restoration project planning and design. As a part of that process, case studies were used with conceptual models as a guide to selecting climate change adaptation strategies. Recent workshops with CEERP researchers and restoration sponsors have documented key scientific uncertainties in the estuary. The outcome of these regional conversations has identified climate change as a high priority for researchers and managers to address. To that end, there is a need to develop a more robust assessment framework that includes but is not limited to the following:

- Develop metrics for marsh vulnerability and resiliency across tidal-fluvial continuum to evaluate priority areas for restoration, similar to the MARS tool.
- Select candidate sites to measure metrics across system and identify “sentinel sites” to measure climate change indicators.
- Update project design considerations as more data and information become available.
- Develop restoration strategy that is unique to each site.
- OUTCOME: Marsh resiliency profile that provides a rank for each climate indicator and an overall score for reaches/sites of the LCRE.
- OUTCOME: Identification of data gaps and/or modeling needed to complete assessment.

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[7] https://critfc-gis.maps.arcgis.com/apps/webappviewer/index.html?id=f34b0606e1794b358f975cbbf7e99d22

3.2. Targeted Research Questions

Expanding on the CEERP's uncertainties exposition (ERTG 2022a), synthesis memos (Thom et al. 2013; Johnson et al. 2018), and the annual CEERP Restoration and Monitoring plans (e.g., BPA and USACE 2024), research questions are being generated to improve the region's collective understanding of climate change impacts on the LCRE. These questions can test assumptions related to climate change vulnerabilities. Research efforts can be adjusted for landscape scales, linked to ecological responses from restoration projects, and inform broader indicators of climate resiliency. Expounding on uncertainties inherent to restoration science and the LCRE ecosystem, additional questions are listed here to bolster understanding related to climate change:

- What are the most informative indicators and locations to monitor to assist in addressing climate uncertainties?
- What insights/reflections are borne out of existing datasets from CEERP (i.e. action effectiveness, status and trends)?
- What are the processes driving spatial variability of sediment accretion in LCRE wetland ecosystems and are accretion rates adequate to keep up with SLR?
- How much will water temperature change in critical habitats of the system, including side channels and wetlands, during peak migration through the estuary?
- How does temperature affect the distribution and extent of cold water refugia in the LCRE? What are effective project design elements for minimizing cold water mixing in summer?
- How will salinity intrusion affect wetland plant communities, particularly remnant Sitka spruce swamps?
- How does a shift in hydrology patterns affect vegetation structure and related food-web pathways supportive of juvenile rearing needs?
- How do habitat restoration actions affect overall carbon balance of ecosystems and capacity to buffer climate change impacts in the future?

3.3. Planning and Design Considerations

We suggest CEERP consider the best site-specific, and reach-specific information on existing conditions to provide guidance for project designs to be resilient to climate effects. Figure 5 identifies potential resilience actions in the context of landscape factors that affect salmonid habitats. These actions will need to be adapted as new information becomes available from downscale modeling and novel restoration technologies evolve (e.g., channel and levee design, plant species selection).

Previously completed climate change studies in the estuary emphasize conceptual models to frame resilient site planning and design (e.g., USACE 2012 and 2014). These models can be applied during project goal development to frame a range of restoration measures and design considerations for developing resilient restoration projects and its translation into Scoring Criteria (ERTG 2020) for *certainty of success, opportunity*, *and capacity.* Appendix A2 provides examples from the earlier study (USACE 2014) linking the effects of climate change on estuarine habitat structure and function while providing a list of measures used to address it. Below we describe information from additional, more recent studies for consideration in developing climate resilient restoration projects. Table 3 provides examples of the types of measures that could be considered for a given climate change vulnerability.

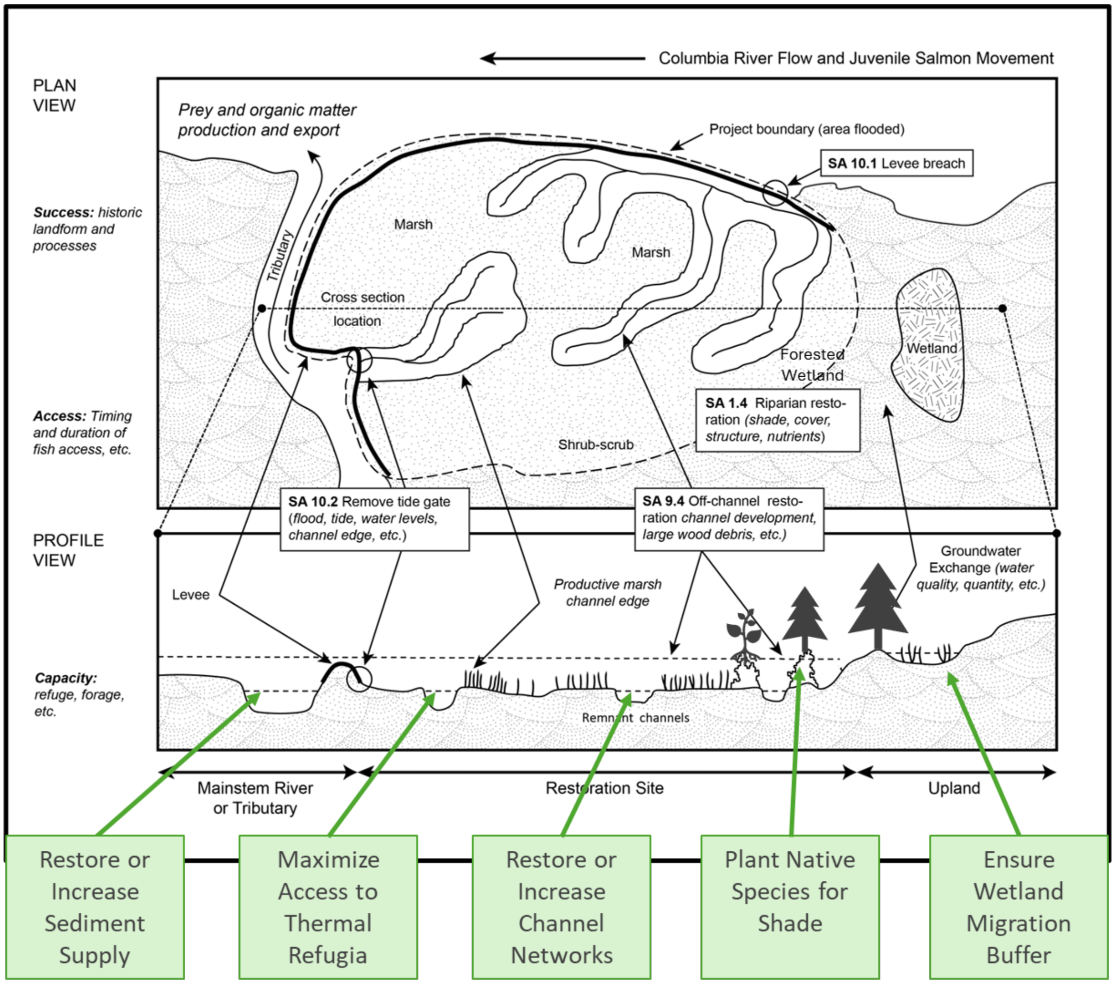

Figure 5. Incorporating climate resiliency in the context of the ERTG's conceptual model for reviewing projects (based on Kruger et al., 2017). Boxes indicate actions that could be implemented within specific habitat zones or landscapes to mitigate for climate stressors.

A method being implemented in several estuaries to alleviate the effects of SLR is the use of dredge material to raise elevations where subsidence or lack of sediment inputs have resulted in the risk of marsh loss. A study of thin layer sediment placement in California found that the placed material was coarser than the native sediment and that the depth (25 cm) resulted in slow vegetation colonization (Fard et al. 2024). In contrast, Raposa et al., (2023) evaluated eight sites where sediment was placed experimentally at depths of 7 cm and 14 cm and found that vegetation colonized both depths. The 14 cm depth was slower initially but equalized by year 3. Thin layer placement could be a method to increase elevation in lower reaches of the LCRE where subsidence has reduced elevations and SLR could be a threat to marsh resilience.

One challenge that comes with the placement of sediment is concern regarding the loss of existing habitat. The Southern California Coastal Water Research Project (SCWRP) has developed a framework to evaluate the conversion of aquatic habitat from one type to another, which can be used to evaluate potential climate resiliency strategies (Stein et al., 2022). The framework considers feasibility, site-specific functions, and regional context to determine the overall environmental outcome based on a change from the existing habitat type. Potential changes include restoration which changes habitat from one type to another, for example from marsh to swamp to improve long-term resilience or to increase limited habitat type. Sediment placement from dredge material is another method that could be employed to improve long-term resilience in subsided marshes or to create more area for wetland migration as SLR occurs. Placement in open water areas to create new wetlands habitats could also be evaluated with this framework. The ability to conduct the evaluation is based on availability of data sources.

Lower water in late summer could provide additional opportunity for species at both low and high elevation areas of the floodplain. Areas of elevation lower than the existing marsh could provide a place for species to colonize in low water years. Conversely, high elevation areas withing the wetland could potentially support woody vegetation under climate change conditions. Changes in hydrology should inform planting plan development in restoration design to include plants that have a high range of moisture tolerance to adapt to more varying hydrology in the upper reaches of LCRE system. Increased salinity intrusion from climate change should also inform planting strategy in the lower estuary where restored areas are subject to SLR effects.

Temperature mediation measures include increased hyporheic connectivity and plantings along channels (Beechie et al. 2023). In stream systems, restoring connectivity to the floodplain can increase access to thermal refugia and reduce summer temperatures by increasing hyporheic flow paths beneath the floodplain, (Poole et al. 2008; Hester and Gooseff 2010; Beechie et al. 2013; Singh et al. 2018). Studies have also shown the occurrence of groundwater discharge in tidal marshes (Peterson et al. 2019; Zhan et al. 2023) and Moffett et al. (2008) documented cool groundwater inputs throughout tidal marsh channels, however the overall effect on temperature amelioration warrants further study. Buenau et al. (2025) found that temperatures were lower in forested swamp locations in the summer months compared to emergent marsh and mainstem Columbia River. Though the mechanisms for the reduced temperatures were not part of the study, presumably the increased shade was a factor and potentially beaver activity and groundwater connectivity.

Research questions specific to project design considerations include the following:

- What is the best way to estimate necessary wetland migration buffers?
- Are watershed processes also affected by climate change (i.e. increased storminess, legacy logging practices effect on sediment sources) and linked to estuary habitat forming processes?
- How can groundwater be accessed to reduce wetland channel temperatures?
- Can beavers play a role in reducing wetland channel temperatures?
- Does channel morphology affect water temperature?
- Can plantings and shade decrease water temperature?

Table 3. Examples of potential restoration measures linked to vulnerability assessments in the LCRE. This table links vulnerabilities to design features and restoration measures and serves as the basis for ERTG template development and evaluation.

Vulnerability Category	Example Vulnerability Assessment Findings	Design Element	Restoration Measures
Sea Level Rise	SLR = 0.3 m	**Floodplain Wetland/Upland Transition areas,** including veg communities above current king tide elevation	• Incorporate higher elevation from historic floodplain template to broader buffer areas • Grade gradual slopes to upland transition areas • Channel invert elevations adjustment to new tidal range
Temperature	Increase >0.5 °C	**Plantings**, with a diversity shrub/scrub /woody species **Channel Design**	• Expand plant species to include successional processes and canopy shading • Maximize connectivity including design of deeper channels • Explore groundwater/hyporheic flow contributions and methods to activate in restoration design • Less LWD in emergent marshes and more channel riparian plantings to decrease W:D ratio to increase bank cover and shading • Develop matrix habitat
Hydrology patterns	Timing of winter flows and spring freshet maxima 3 weeks earlier than baseline	**Expansion of Wetland Buffers** **Upland:** plant with species that have a high range of inundation tolerance and are competitive with RCG (e.g., spirea, willows) **Low Elevation:** provide area for low marsh expansion in low water years.	• Expand plant selection to accommodate early water level peaks and low summer flows • Size levee openings and channel inverts to accommodate new volumes and shift in tidal prism • Reduce levee heights to natural berms
Sediment availability	Sediment accretion not adequate to keep up with SLR	Increase marsh surface elevation	• Import material and grade to marsh colonization elevation
Salinity	Salinity intrusion from SLR causing vegetation die-off	**Plantings**	• Develop list of appropriate salinity tolerant species and pilot installation in Reaches A and B.

3.4. Project Scoring

Resilience methods must be evaluated to determine effectiveness for reducing vulnerability of different project types and to incorporate location-specific constraints. The Puget Sound Partnership (2017) developed a set of questions to help project sponsors develop climate resilient projects and to help project reviewers to assess whether a proposed project will be effective in supporting salmon and implementing climate resilient projects. Questions include the following:

- Has the project proposal sufficiently identified and considered how climate change will affect the project?
- Does the project design adequately address the primary climate change concerns that have the potential to decrease the effectiveness of the project (or have a plan to evaluate them during the design process)?
- Is the project designed to be flexible, and can it be modified over time as conditions change?

Scoring criteria should also include an evaluation of resilience associated with the proposed project. The LCRE habitats are in many ways unique. The broader elements of water flow dynamics and sediment sources, water temperature, and anomalous flooding events complicate the assessment of resilience and volumes complicate the formulation of actions to address the resilience question. Hence, developing and scoring projects should consider the general list of factors affecting resilience (e.g., Table 3).

We recommend incorporating factors addressing climate change resilience into the ERTG scoring process. Two options are presented here for consideration: 1) amend the current process (ERTG 2020b), which evaluates scoring criteria at the landscape and site scales, to include explicit elaboration on factors addressing climate resilience; or 2) scoring a project's potential relevance to improving climate resiliency as a separate analysis, similar to landscape scoring (ERTG 2020b). For either scoring option, integration of GIS mapping would be critical. This tool has been essential for site evaluation and scoring at the site and landscape scales. Evaluating climate resiliency elements using GIS could include sources of cool water, presence of natural shade, proximity of sources of sediment for accretion and for natural plant propagules, flood attenuation capacity, and adjacent buffer areas immediately landward of the sites where plant communities can retreat to with higher sea level. The analysis of these alternatives could be supported by numerical modelling efforts. For example, expected changes in water temperature, inundation, or salinity could be assessed under future scenarios and incorporated into the existing implementation forecasting tool. The two options are explored next.

Option 1: *Incorporate climate considerations into existing scoring criteria. This scoring option would expand and define existing elements, including connectivity, location, size, self-maintenance, access, site size, etc., to include climate resilience elements (Table 4). Climate projections and effects will vary by hydrogeomorphic reach. Examples of extreme climate events include rain on snow, storm surge, extreme and extended drought.*

Table 4. Existing scoring criteria and examples of resilience actions following extreme climate events (Option 1).

Existing Scoring Criteria	Examples of Resilience Actions
Landscape Scale	
High connectivity and access for most species and populations	Continued habitat connectivity and access following extreme climate events.

Existing Scoring Criteria	Examples of Resilience Actions
Located in a mainstem area or a priority reach (see Section 4.5.2 in *Landscape Principles Applications and Operations*; based on habitat loss relative to historical conditions)	High priority habitats and location of sites continue to support stepping stone function following extreme climate events.
Located in a habitat gap >5 km long; proximity (<0.5 km) to large tributary confluence (e.g., > 1000 cfs mean annual flow) or a significant reach transition (e.g., from fresh to saltwater; from above to below dam)	High priority habitats in reach transitions continue to support stepping stone function following extreme climate events
Stepping stone patch is large (>30 acres)	Optimal stepping stone patches recover following extreme climatic events.
High synergy with adjacent or nearby habitat or restoration project, i.e., strongly interacting such that there is greater geomorphological expression/dynamics, residence time for juvenile salmon, nutrient export, or similar non-linear (i.e., disproportional, or multiplicative) benefit from the interacting sites.	Optimal synergy level is maintained with adjacent or nearby habitat or restoration project following extreme climate events.
Site Scale	
Success - Restoring a natural process or landforms; proven restoration method; highly likely to be self-maintaining; minimal to no risk of detrimental effects; highly manageable project complexity; minimal to no uncertainties regarding benefit to fish, minimal to no exotic/invasive species expected	Juvenile salmon are entering sites and utilizing sites during and/or following extreme events (e.g., floods, droughts, heat waves). Sediment accretion is keeping up with SLR.
Opportunity - High site-scale connectivity and access to site at most water level stages; simple access to project within site; converts a site's condition from one of no or limited access to one of fully restored access. Levees are removed entirely, and the number of dike breaches/channel outlets matches or exceeds allometric predictions for the site.	Juvenile salmon are entering sites following extreme events (e.g., floods, droughts, heat waves).
Capacity - Maximum habitat ecological diversity; well-developed natural disturbance regime and ecosystem functions; extensive channel and edge network and large wood (where appropriate); much prey resource production and export; no invasive species or nuisance predators; water quality/temperature excellent; increases site C/Q from near zero to near maximum site potential, site relatively large (> 100 ac); there is coincident restoration of associated/adjacent shoreline matrix habitat; length of restored matrix is at least 50% of the restored patch habitat's river border; matrix quality is similar to that described for matrix-only projects that also merit a 5 score	Channel geometry is maintained and recovered from extreme events. Water temperature is maintained below levels harmful to salmon through shade and other actions. Vegetation assemblages return after anomalous events (e.g., flood, droughts). Juvenile salmonid prey resources are maintained and recovered from anomalous climate events. Vegetation detritus and salmon prey are exported from wetland sites to the mainstem.

Option 2: *Develop separate climate-specific scoring criteria*.

This option would evaluate stand-alone scoring criteria that would be included in the overall scoring along with the results of the site-scale and landscape-scale scoring. These criteria would consider the likelihood of a restoration project being resilient to climate stressors based on the planning and design features described in Section 3.3. Projects would be scored 1 to 5 similar to existing site and landscape scale scoring criteria. Table 5 provides potential scoring criteria and ranking. Some stressors will not be applicable to some reaches of the estuary (i.e. salinity change in upper reaches). See Section 3.3 for a description of the various design considerations.

Table 5. Example scoring criteria matrix for stand-alone climate resilience scoring (Option 2).

		Climate Metric				
		Sea level rise	Change in hydrologic patterns and timing	Sediment availability	Increased temperature	Salinity increase
		Resilient Design Considerations:				
Rank		Gradual slope upland buffer (% of project area)	Gradual slope buffer lower than project elevation (% of project area)	• Located in area of high sedimentation rates (e.g, near tributary) • Supplemental sediment added	• Shade channels • Deeper channels • Tributary proximity • Groundwater	Plant species tolerant of salinity
High	5	Buffer included	Buffer included	High availability	Factors affecting most of the channels	Tolerant species planted
	4				Some channel area affected	
	3					
	2				Small area	
Low	1	none	none	Low availability	none	No plantings
N/A	0					

To determine project score, apply the rank to each consideration and average the ranks for an overall score. For example, a project that ranks 3, 2, 4, 5, 3 would get a score of 3.4. If salinity increase is not a concern, then the rank would be the mean of 4 metrics.

4.0 Summary and Recommendations

The science supporting climate change is well developed. Ecosystems, such as the LCRE, will be affected by these changes, which have a high chance of negatively affecting the maintenance and functionality of habitats, especially those utilized by juvenile salmonids. That said, there is considerable uncertainty regarding how, when, where and the magnitude of changes will affect the estuary, salmon and CEERP (see Table 1). The available studies provide science-based approaches to predict and address climate change in aquatic systems. Because of the mature, well-developed, and science based-CEERP adaptive management framework, incorporating climate resilience into CEERP should be clear and plausible; there is no reason to wait. We offer the following recommendations to CEERP managers and program participants.

1) Further consider, prioritize, and research programmatic questions in Table 1. Include modeling and other analyses to evaluate the effect of future climate scenarios on restoration projects in the Columbia River basin.
2) Develop tidal marsh resiliency assessment framework to prioritize restoration (e.g., Raposa et al. 2016) (see Appendix A5) and include the unvegetated to vegetated ratio (Ganju et al. 2022).
3) Implement experimentation into restoration project design to reduce climate-related uncertainties, enhance resilience related to climate mitigation strategies, and inform design and evaluation of projects.
4) Compile science-based, reasonable, and effective examples of resilience in restoration actions.
5) Monitor indicators that can identify vulnerabilities and inform adaptation measures, such as temperature, sediment accretion, inundation frequency, vegetated area, prey
6) Consider dredge material placement options to gain wetland area or increase elevation in vulnerable wetlands. Implement a framework to evaluate costs and benefits from converting one type of aquatic habitat to another, similar to Stein et al. (2022).
7) Conduct predictive modeling to evaluate the effects of future climate scenarios on restoration projects.
8) Develop a bioenergetics model to understand how climate change may affect prey production and utility for juvenile salmon similar to (Davis et al. 2021)
9) Expand GIS tools to include climate change and resiliency elements in evaluation of projects.
10) Integrate climate resilience into the Project Template (ERTG 2020a) and Scoring Criteria (ERTG 2020b), considering the options presented in this report.

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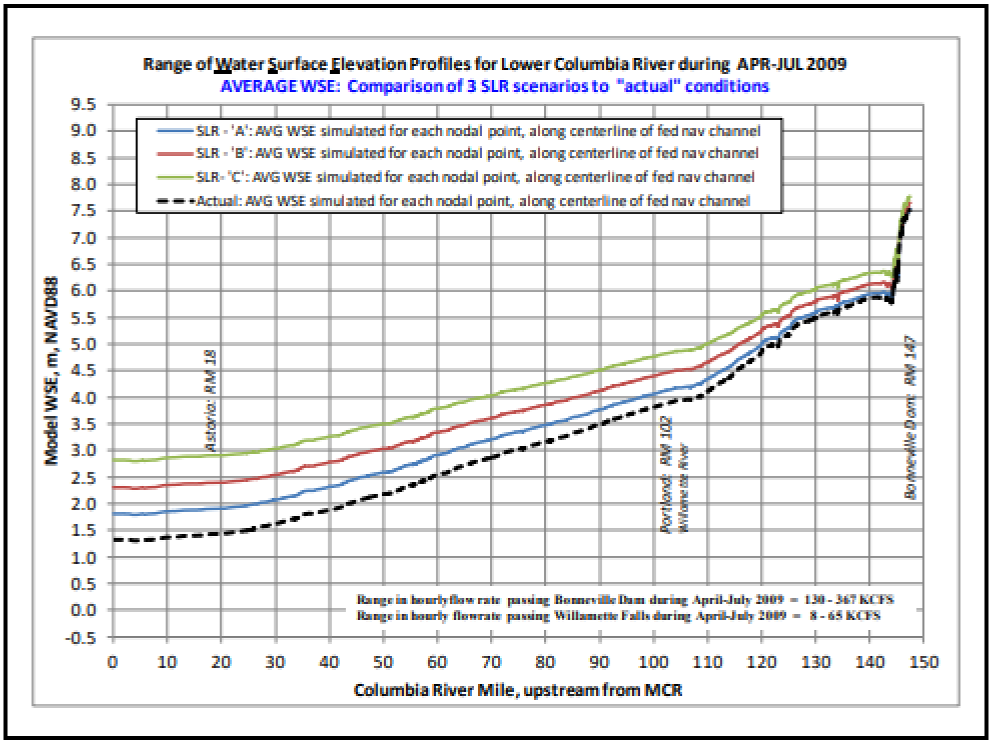
Appendix A. Relevant Information from Other Documents

A1. LCRE USACE AdH Model SLR results (Pevey et al. 2020)

Figure 6-6. Average water surface elevation for actual and three SLR scenarios along LCR channel.



A2. *Climate change and resiliency Lower Columbia (Tables and figures; USACE, 2014)*

Table 2: Summary of Projected Changes in the Climate of the Pacific Northwest

Variable	*Projected Long-term Change*
Temperature *Annual*	▪ Warming projected for all GHG scenarios ▪ More frequent extreme heat events and less frequent extreme cold events ▪ Projected change in Pacific Northwest average annual temperature for the 2050s (2041–2070), relative to the average for 1950–1999: Low emissions (RCP 4.5): +4.3°F (range: 2.0 to 6.7°F) High emissions (RCP 8.5): +5.8°F (range: 3.1 to 8.5°F)
Seasonal	Warming in all seasons for 2041–2070, relative to 1950–1999: *Winter* Low emissions (RCP 4.5): +4.5°F (range: 1.6 to 7.2°F) High emissions (RCP 8.5): +5.8°F (range: 2.3 to 9.2°F) *Summer* Low emissions (RCP 4.5): +4.7°F (range: 2.3 to 7.4°F) High emissions (RCP 8.5): +6.5°F (range: 3.4 to 9.4°F)
Precipitation *Annual*	▪ Annual changes for all models are small relative to year-to-year variability. Some models project wetter conditions while others project drier conditions. ▪ Heavy rainfall events are expected to occur more frequently. ▪ Projected change in annual Pacific Northwest precipitation for the 2050s (2041–2070, relative to 1950–1999): Low emissions (RCP 4.5): −4.3 to +10.1% High emissions (RCP 8.5): −4.7 to +13.5%
Seasonal	▪ A majority of models project increases in winter, spring, and fall precipitation for the Pacific Northwest for mid-century, as well as decreasing summer precipitation. ▪ Average projected change for summer for the 2050s (2041–2070, relative to 1950–1999) is: −6% to −8% for a low (RCP 4.5) and high (RCP 8.5) scenario, respectively. However, some models project more than a 30% decrease in summer precipitation.
River Hydrology	▪ Columbia River freshet peak to occur 3 to 4 weeks sooner (based on unregulated flows). ▪ Similar shift in flow timing for Columbia River tributaries, although more noticeable in tributaries in transitional snow-/rain-dominated watersheds than those currently in rain-dominated watersheds (i.e., Cascade Range versus Coast Range watersheds).
Sea Level Rise	▪ Sea level rise is projected to occur within the estuary, but will vary along the length of the river. ▪ Sea level rise estimates based on: **2064** / **2100** Astoria, OR (RM 0.0): +1.83 ft / +4.18 ft Vancouver, WA (RM 105.1): +0.95 ft / +2.5 ft Bonneville Dam (RM 145.2): +0.15 ft / +0.68 ft ▪ Sea level rise will push salinity wedge further upriver, but no projections are currently available.
Sources: Temperature and precipitation information from Snover et al. 2013. River Hydrology information from USACE 2014a and UW-CIG data highlighted in Section 2.2). Sea level rise information based on the Corps sea level rise analysis Curve 3 (high Sea level rise), and Adaptive Hydraulics modeling system (ADH)model of the 2009 April-July event of 130-367 kcfs on the Columbia and 8-65 kcfs on the Willamette Rivers; change is relative to 2014.	

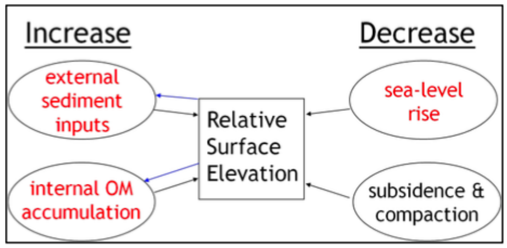


Figure 10: Factors Affecting Elevation within Tidal Marsh

Table 4: Example of Potential Stressors, Sensitivities, and Adaptation Measures for the LCRE

Stressor	Impacts/Sensitivities	Adaptation Management Measure
Sea Level Rise	• Effects to habitat sensitive to water levels, elevation bands. • Impacts to food web/prey resource. • Alterations to marshes from inundation depth changes. • Increased erosion due to higher and more extreme waves/fetch. • Reduced flood protection due to higher water elevations. • Effect on salinity, subsidence issues, infrastructure/land use habitat to be protected	• Re-grading site for anticipated future conditions. • Design for higher elevation targets, provide sloping gradients and some benching to help provide for long-term succession if possible, thereby increasing site resilience. Gradual transitions could provide additional value to the current approach. • Need to identify water elevation thresholds in adaptive management plans, etc. • Adjust design of channels with future climate change sea level rise as it affects the tidal levels etc.
Temperatures (Air/Water)	• Higher air temps will increase evapotranspiration and likely stress drought-sensitive vegetation. • Wetland communities could be adversely affected by the higher temperatures and likely lower water levels. • Increase in invasive species due to shift. • Higher water temperatures will adversely affect fish (juveniles etc.). • Increased temperatures might truncate the amount of use time expected for juveniles using areas. Summer conditions could arrive more quickly than expected. Winter is expected to be more extreme for precipitation but likely still warmer than current conditions and freshet will arrive sooner. The summer season might arrive earlier and might last past late fall, etc. • Adverse effect on food web/prey resources due to increased stresses, primarily on the vegetation.	• Provide increased (riparian) canopy and shading. • Build deeper channels and provide more extensive floodplain reconnection. • Provide more robust long-term vegetation plan.
Local Precipitation Changes	• Less summer and late spring and fall precipitation. • Change in summer precipitation timing and higher evapotranspiration, leading to stress on vegetation. • Potentially high rainfall intensities during winter. • Winter precipitation may cause increased erosion and local sedimentation issues.	• Provide more robust long-term revegetation plan. • Address potential increase in wintertime erosion, incision, and downstream deposition by increasing use of low impact development (LID) Best Management Practices, bio swales and bio stabilization as well as sediment traps to account for more sediment arriving on-site, etc.
Streamflows (seasonal)	• Higher winter flows, lower summer flows, the same annual volume. • Shift in Columbia freshets to earlier occurrence, up to several weeks to approximately a month earlier. • Winter flood volumes and peaks have likelihood of increasing. • Could affect water management. This translates to change in regulated streamflow. • Generally, streamflow change will affect structures that are set by a water elevation (e.g., levees). • Fish timing may change; freshet arrives several weeks earlier. • Erosion may increase from higher events and sediment transport may be altered due to lower flows. • Food web/prey resource will likely be affected by changes in hydrology and inundation duration.	• Adjust the anticipated habitat benefit targets in light of lower summer flows and higher winter flows. Calculations could recognize potential shift in inundation and duration. • Adjust design of channel inverts and geometry, size the levee openings and overtopping elevations to account for future projected stream flows and sea level rise, being mindful of effects on the tidal prism volume etc.
Change in Frequency of Extreme Events	• Increased erosion from anticipated frequency of extreme events.	• Increase level of armor protection at key infrastructure locations. • Relocate sensitive infrastructure farther from potential increased erosion areas.
Salinity	• Potential increase up-estuary as salinity range increases. There is high uncertainty due to lack of specific science and research.	• Monitor salinity. • Update the adaptive management plan (e.g., vegetation management) to reflect new data as it becomes available.
Sediment/Turbidity	• Increased stream flows may increase local sediment loads. • Uncertain how climate change will affect accretion rates. Rise in sea levels would on balance offset accretion. • Concern is that the inundation regime changes, and it could result in adverse habitat shifts, e.g., accretion.	• Management of pile dike system • Management of dredge disposal practices • Use reference sites for existing rates of sediment and sensitivity to sediment patterns being affected by climate change. • Monitor sediment patterns into the future.

Table 6: Potential Climate Change Adaptation Measures at Steamboat Slough Site

#	Management Measure	Objective	Success Criteria
1	Increase setback levee elevation by sea level rise residual (i.e., 1.83 feet at 2064 or 4.18 feet at 2100.)	Match existing flood protection in light of potential increase of sea level rise elevations.	Levee elevation is high enough to provide flood protection to the landward area inhabited by white-tailed deer.
2	Potentially change the channel design so that it self-adjusts. Over-excavate the breach, remove hard point features to allow dynamic change.	Design to current conditions but ensure future capacity for channel to adjust naturally.	Revised design is flexible enough to meet future conditions.
3	Excavate channels deeper.	Greater amount of cold water refugia.	Channels maintain designed depth, which provides cool water during summer.
4	Provide habitat elevation gradients along proposed benches, or a gradual slope instead of benches at single elevation criterion.	Ensure greater vegetative diversity and site flexibility to resist warmer temps and lower precipitation in the summers and changing hydrographs.	Additional areas for plant succession in light of climate change are provided, although this could be constrained by availability of site fill material, etc.
5	Add high spots to marsh surface (i.e., grade) or conduct targeted revegetation to accelerate accretion rates.	Foster marsh accretion processes.	Vegetated wetland habitats keep pace with projected sea level rise.
6	Establish desirable vegetation as conditions change.	Support desired habitat functions over the life of the project.	Plant communities continue to provide desired habitat benefits over the life of the project.

A3. *Defining Resilience (Tables; Pelletier et al. 2020).*

Table 1 Definition of resilience-related concepts

Concept	Definition	References
Alternate stable states	More than one ecosystem condition (state) possible for a particular set of environmental variables. Associated with abrupt shifts in ecosystems, tipping points, and hysteresis	Oliver et al. (2015)
Cross-scale resilience	Diverse and overlapping function within scales and redundancy of function across scales	Petersen et al. (1998)
Early warning (leading) indicators	Statistical characteristics that allow prediction of a regime shift	Dakos et al. (2012)
Ecological threshold ("tipping point")	Point at which there is an abrupt change in ecological state; may be due to a small change or distubance	Groffman et al. (2006)
Ecological resilience	Capacity of an ecosystem to absorb and adapt to disturbances while maintaining its essential structure and function and assumes the existence of multiple stable ecosystem states	Holling (1973)
Ecosystem services	Direct and indirect benefits provided to humans from ecosystems	Costanza et al. (1997)
Engineering resilience	Stability of an ecosystem and the speed it reverts to a steady state condition following disturbance. Only one stable state or regime is assumed	Holling (1996)
Functional diversity	Diversity based on species ecological traits (feeding guild, trophic position, etc.) rather than taxonomy	Petchey and Gaston (2006)
Functional redundancy	Species or aspects of the socioecological system perform similar roles	Biggs et al. (2012)
Hysteresis	Forward trajectory not equivalent to the return trajectory between alternate states	Beisner et al. (2003)
Natural capital	Living and non-living components of ecosystems that contribute to people	Guerry et al. (2015)
Panarchy	Hierarchical structure of socioecological systems at multiple spatial and temporal scales characterized by adaptive cycles of growth, accumulation, restructuring, and renewal	Holling (2001)
Regime shift	Ecosystem threshold is crossed due to due to a sudden change in feedbacks; system trajectory moves towards a different attractor (change to an alternative stable state, e.g., shift from clear to turbid water in shallow lakes)	Folke et al. (2004)
Resistance	Capacity of a populations and communities to remain unchanged in the face of disturbance	Angeler and Allen (2016)
Response diversity	Within a given functional group, individual species respond differently to environmental stress, which acts to stabilize the ecological system. Diversity in the spatial distribution of species within a functional group may also contribute	Elmqvist et al. (2003)
Socioecological resilience	Ability of the coupled social and ecological system to retain similar structure, function and feedback mechanisms; considers the importance of multiple scales (panarchy)	Alberti and Marzluff (2004), Walker et al. (2004)

A4. *Puget Sound Partnership Climate Guidance (Vogel and Mauger 2020)*

11 principles for adaptation:

1) Put recovery objectives first.
2) Ask the "climate question."
3) Take action in the face of uncertainty.
4) Start now (or keep at it).
5) Talk about climate change explicitly.
6) Integrate adaptation into planning and decision making.
7) Prepare for multiple climate futures.
8) Identify near- and long-term actions.
9) Employ commonly used recovery techniques and adjust to changing conditions.
10) Prioritize no- and low-regret actions.
11) Look for climate change opportunities (positive outcomes from climate change).

7 steps for project level climate-change decision making:

1) Project Planning
    a. Goal selection – choose targets that make sense in the context of climate change
    b. Selection of reference site – historic wetlands may not provide the best option; focus on recovery objectives and consider choosing a climate adapted reference site.
    c. Building support – look to interested parties to provide local knowledge, identify key issues, help with problem-solving, and cultivate project support. Careful communication is crucial for community-building around climate change.
2) Project Selection
    a. Explicit consideration of climate impacts can help with project prioritization and even open doors to new climate-focused funding sources.
3) Site Assessment
    a. Site selection – prioritize sites that are within the potential future range for habitats or provide corridors for target species.
    b. Assess conditions at the project site to understand baseline conditions and clarify objectives.
4) Preliminary Design
    a. Hydrologic design – incorporate future hydrologic changes into design.
    b. Species selection – select species for planting that are likely to be adapted to future conditions.
    c. Design projects for multiple potential climate futures to decrease need to future management actions.
5) Final Design and Implementation
    a. Interface early and often with entities reviewing final design plans to ensure they understand the reasoning behind climate related features.
6) Monitoring
    a. Collect baseline data to compare to post-project data.
    b. Long-term data collection will be necessary to evaluate the effectiveness of climate-resilient strategies.
7) Management of Recovery Sites
    a. Adaptive management is particularly important for restoration efforts in the face of climate change.
    b. Continued evaluation of site vulnerability is important as more accurate projections become available to identify management actions necessary to maintain project benefits.

A5. *Assessing tidal marsh resilience to sea-level rise (Raposa et al. 2016; Reid 2024).*

MARS Resilience Category	**Metric**
Marsh Elevation Distribution	Percent of marsh below local Mean High Water
	Percent of marsh in the lowest third of overall plant distribution
	Skewness (proportion of low marsh or high marsh in an estuary)
	Unvegetated to Vegetated Ratio[1]
Marsh Elevation Change	Rate of marsh elevation change over time
Sediment Supply	Short-term sediment accretion
	Long-term sediment accretion
	Turbidity
Tidal Range	Tidal range
Sea-Level Rise (SLR)	Long-term rate of relative SLR
	Short-term inter-annual variability in water levels

[1] Metric added from Ganju et al. (2013) based on recommendations presented in Wasson et al. (2019).