US HIGHWAY 101 COASTAL HAZARD VULNERABILITY AND RISK ASSESSMENT FOR MITIGATION PRIORITIZATION

Final Report

PROJECT SPR 843

RESEARCH

Oregon Department of Transportation

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by

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16. Abstract: US 101 is a vital economic and emergency lifeline that connects coastal communities and provides access to numerous coastal destinations for Oregonians and tourists. Many sections of this highway are highly susceptible to coastal hazards such as erosion, landsliding, wave action, storm surge, flooding, and rising sea levels. In general, US 101 on the open coast is more impacted by wave-driven erosion hazards and landslides while US 101 in the estuaries is more vulnerable to impacts from storm surge, flooding, and rising sea levels. Structural mitigation of these susceptible areas is challenging due to the extensive Goal 16 and 18 regulatory exceptions processes, which are currently being revisited in the context of maintaining and protecting public infrastructure. To proactively position ODOT to effectively manage risk and support Goal 18 updates, this report describes the development of a coastal highway hazard prioritization matrix that includes vulnerability, risk assessment, mitigation options, and management strategies for planning and project development.

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	Inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	Feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	Yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	Miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	Acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	Gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
~NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	Ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	Pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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Cleaning up rockfall is a chore,
Especially on the road by the shore,
An earthquake came about,
The entire slope slid out,
Now the road is no more.
---Ben Leshchinsky, 2021

DISCLAIMER

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LIST OF ACRONYMS

AAA – American Automobile Association
AADT – Average Annual Daily Traffic
ABRA – Arizona Beach Recreational Area
API – Application Programming Interface
ATRI – American Transportation Research Institute
BBSP – Beverly Beach State Park
CBA – Cost-Benefit Analysis
CDIP – Coastal Data Information Program
CO_2 – Carbon Dioxide
CVI – Coastal Vulnerability Index
DEM – Digital Elevation Model
DLCD – Department of Land Conservation and Development
DM – Detour Mileage
DOGAMI – Department of Geology and Mineral Industries
DSAS – Digital Shoreline Analysis System
DT – Delay Times
DVL – Digital Video Log
ECVI – Enhanced Coastal Vulnerability Index
EIA – Energy Information Administration
EPA – Environmental Protection Agency
FHWA – Federal Highway Administration
FEMA – Federal Emergency Management Agency
GDP – Gross Domestic Product
GHG – Greenhouse Gasses
GIS – Geographic Information System
GPS – Global Positioning System
GROW-FINE NEPAC – Global Reanalysis of Ocean Wave Fine Northeast Pacific Hindcast
HHLSV – Heceta Head Lighthouse Scenic Viewpoint
HMSP – Humbug Mountain State Park
HWY – Highway
IAM – Integrated Assessment Model
IWG – Interagency Working Group
Lidar- Light detection and ranging
LPS – Leica Photography Suite
LS – Landslide
MHHW – Mean Higher High Water
MHW – Mean High Water
MLLW – Mean Sea Level
MP – Mileposts
MPG – Miles per Gallon
n.d. – No date
NASA – National Aeronautics and Space Administration
NAVD – North American Vertical Datum

NDBC – National Data Buoy Center
NED – National Elevation Dataset
NGDC – NOAA National Geophysical Data Center
NOAA – National Oceanic and Atmospheric Administration
NOS – National Ocean Service
NPV – Net Present Value
NRC - National Research Council
OAIP – Oblique Aerial Imagery Program
OAR – Oregon Administrative Rules
OC – Operations Costs
OCM – Oregon Coastal Management Program
ODOT – Oregon Department of Transportation
OLC – Oregon Lidar Consortium
OMB – Office of Management and Budget
OPRD – Oregon Parks and Recreation Department
ORS – Oregon Revised Statutes
OSU – Oregon State University
OWSP – Oswald West State Park
PADD - Petroleum Administration for Defense Districts
PNW – Pacific Northwest
PV – Present Values
RAMBO - Rockfall Analysis Morphological Big data Optimizer
RMS – Root Mean Square
RTK-DGPS – Real-Time Kinematic Differential Global Positioning System
RV – Recreational Vehicle
SC – Seacliff erosion
SCC – Social Cost of Carbon
SLIDO – Statewide Landslide Database of Oregon
SLR – Sea Level Rising
SPR – State Planning and Research
SPS – Shoreline Protection Structures
STIP – Statewide Transportation Improvement Program
SWAN – Simulating Waves Nearshore
TLS – Terrestrial Laser Scanning
TPAU – Transportation Planning Analysis Unit
UAS – Unmanned Aircraft Systems
USACE – United States Army Corps of Engineers
USGS – United States Geological Survey
VT – Value of Time

1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

US 101 is a vital economic and emergency lifeline that connects coastal communities and provides access to numerous coastal destinations for Oregonians and tourists (Figure 1.1). Many sections of this highway are highly susceptible to coastal hazards such as erosion, landsliding, wave action, storm surge, flooding, and rising sea levels. Generally speaking, US 101 on the open coast is more impacted by wave-driven erosion hazards and landslides while US 101 in the estuaries is more vulnerable to impacts from storm surge, flooding, and rising sea levels. Structural mitigation of these susceptible areas is challenging due to the extensive regulatory exceptions process required by the Department of Land Conservation and Development (DLCD) through Statewide Planning Goal 18, which prohibits shoreline armoring of highway infrastructure on the open coast (e.g., beaches, seacliffs, and dunes), and Goal 16, which applies in the estuaries. The need to revisit Goal 18 for maintaining and protecting public infrastructure has been recognized, with ODOT recently participating in a DLCD led Shoreline Armoring Focus Group. This focus group identified that research providing a comprehensive and prioritized coastal highway vulnerability and risk assessment is key to informing upcoming DLCD Goal 18 policy updates. To proactively position ODOT to effectively manage risk and support Goal 18 updates, development of a coastal highway hazard prioritization matrix that includes vulnerability, risk assessment, mitigation options, and management strategies for planning and project development is critical.

Figure 1.1: View of the Beverly Beach State Park highlighting the proximity of Highway 101 to the rapidly eroding seacliffs.

1.2 BACKGROUND

1.2.1 Erosion on Oregon Coast

Rising seas and extreme coastal weather events pose significant risks for the safety, reliability, and effectiveness of ODOT infrastructure and operations along the coast. Coastal erosion is particularly sensitive to the effects and variability of climate drivers, including storm frequency and intensity, wave runup and scour, current and future projections of precipitation, as well as sea level rise. Thus, coastal erosion is an integrated indicator of climate change effects and in many locations along the Oregon coast, directly threatens disruption of ODOT's coastal highway infrastructure. US 101 has been particularly challenging for ODOT, and maintenance has become increasingly costly in the last several decades. As an example, for the section of highway from Port Orford to the California border, ODOT spends over $2 million annually in basic maintenance of pavement and guardrails damaged by seacliff collapse, landslide movements and other erosion-related activities (Figure 1.2). Sudden emergency repairs, such as the February 2019 failure at Hooskanaden, costing several hundred thousand to well over a million dollars are becoming common (Figure 1.3). The resulting closures of the highway generate economic costs to ODOT but also the general public. Allan et al. (2009) provides a detailed overview of coastal geomorphology, hazards and management issues in the Pacific Northwest.

Figure 1.2: Localized slumping on Highway 101 looking north in the southbound lane at a site south of Port Orford, June 2022.

Figure 1.3: Damage to Highway 101 at the Hooskanaden landslide as a result of a major surge event in February 2019 (UAS orthophotograph obtained by Andrew Senogles and Richie Slocum).

Considering that ODOT is designated as a lead implementation agency for the Governor's Executive Order 20-04 on climate change, together with the observation that at least 26 sites totaling nearly 20 miles along Hwy 101 have already been identified by ODOT as erosion areas of concern, the need to assess existing and future coastal erosion impacts will become increasingly critical. The rate and magnitude of retreat, potential for ocean flooding during storms at high tides, sea level rise, and increased potential for landslides are all essential measures to be used in prioritizing highway segments near the coastline (open coast and estuary areas). These parameters would allow the agency to both prioritize sites for repair and financially plan for mitigation projects that are timed to maximize the utility of the existing facility. Research to directly address this concern is needed in order to optimize ODOT infrastructure planning, secure lifeline routes, and address the climate change adaptation focus of the Oregon Transportation Commission work plan.

Numerous studies have previously been undertaken in an effort to quantify short to long-term changes taking place on the Oregon coast. For example, Allan et al. (2003) analyzed early National Ocean Service topographic "T" sheets (measured in the 1920s (entire coast) and 1950s (around certain key estuary mouths)), orthorectified imagery (orthorectified 1967 and modern era imagery), GPS measurements, and lidar. The authors concluded that because Oregon's shoreline is sensitive to large seasonal and interannual (e.g., El Niños) variations in ocean water levels and impacts from storms that are episodic in nature, the use of simple linear regressions or end point rate calculations to determine erosion rates can be problematic. Recognizing the same limitations, Ruggiero et al. (2013) nevertheless completed an assessment of short to long-term changes for the Pacific Northwest Coast of Oregon and Washington as part of the USGS national assessment of coastal change. Key to this work was recognizing the need to differentiate between long- (1800s to 2020) and short- (1960s to 2002) term rates and patterns of change as well as the inclusion of uncertainty bands defined for different littoral cells. Because much of the Oregon coast had little historical data that could be used to document coastal change, while significant areas of the coast are backed by coastal seacliffs and cliffs, Ruggiero et al. (2013) focused their analyses on those beaches backed by dunes. Thus, parts of southern Oregon (e.g., Curry County) were not evaluated because of the dearth of data on which to define any changes that may be taking place.

Analyses by Allan and Hart (2007, 2008) describe efforts to establish GPS monitoring of discrete beach study sites established throughout Tillamook and Clatsop County in order to better define the seasonal to interannual changes taking place on Oregon beaches. The goal of this latter effort was to establish a systematic process for documenting seasonal changes taking place at key "sentinel" transect locations using real-time kinematic GPS (RTK-GPS). The monitoring also included measurements of the mean higher high water (MHHW) tidal datum-based shoreline in order to better account for larger spatial changes in the position of the beach. Results from these studies and others demonstrate that the seasonal variability of Oregon's dissipative beaches are typically around 30 m between summer/winter, increasing to ~60 m on intermediate to reflective beaches (e.g., Gleneden Beach, Gold Beach, Port Orford) and in the most extreme events associated with El Niños could double to ~120 m (Allan et al., 2003). Such monitoring has been expanded to many other locations along the Oregon coast (http://nvs.nanoos.org/BeachMapping), as funding and time has allowed (e.g., Allan et al., 2018). Updated assessments in coastal change have also been undertaken by DOGAMI as part of a FEMA-funded effort to produce new coastal hydraulic flood modeling and storm-induced erosion assessments (e.g., Allan et al., 2012, Allan et al., 2015a,b,c,d, Allan et al., 2017). These latter efforts included estimates of the 1% storm-induced flooding associated with an extreme storm occurring around high tides, as well as updated assessments of coastal change determined from airborne lidar collected in 1997, 1998, 2002, 2010, and most recently in 2016. Additionally, the Oregon Lidar Consortium (OLC) flew coastwide lidar in 2008-2009. Major challenges are discussed concerning these data as the early lidar were not bare-earth and, therefore, include vegetation effects, while in some areas the lidar point density was found to be quite poor.

Given the high levels of storm activity on the coast, sea level rise is of particular concern on the PNW coast. In 2012, the National Research Council (NRC) published an interagency report (NRC, 2012) on the past, present, and future of sea level rise in Oregon and Washington. The report discusses difficulty in assessing sea level rise at the state or regional level given sparse data as well as the expertise required to perform the assessment. A committee of experts was convened to analyze available data and develop statistical predictions (with uncertainty) of sea level rise. The report also documents observations in increased wave heights and storm activities. As part of the Oregon Coastal Management Program, the Department of Land Conservation and Development (DLCD, 2017) evaluated the impact of sea level rise on assets within Oregon's estuaries, including Highway 101. In total, six scenarios were considered based on combinations of time: 2030 (short-term), 2050 (mid-term), and 2100 long-term and exceedance probability (1% and 50% annual probability of exceeding an elevation). Several sites (e.g., Tillamook, Nestcucca, Siletz, Umpqua, and Coos Bay) are anticipated to have more than 1 mile of Highway

101 flooded based on a scenario with projected sea level rise in 2100 from the NRC (2012) projections and a flood event with a 1% annual probability of exceedance. More recent studies (e.g. Sweet et al., 2017; Sweet et al., 2022) have updated future projections of sea level rise to better account for recent advances in knowledge of global ice melt rates and water temperature changes (eustatic effects) as well as updated tectonic effects.

Notably, sea level rise does not tell the full story. Total Water Level is computed relative to a datum (e.g., Mean Sea Level, MLLW) as the sum of the astronomical tide, nontidal residuals, and wave runup for any given point in time. Mean sea level is provided based on the datum of the measurements (e.g., NAVD88) and astronomical tide and nontidal residuals are estimated from NOAA tide gauge data (https://tidesandcurrents.noaa.gov/). While these stations have high temporal resolution, unfortunately they are relatively sparse across the coast. There are only 6 operating stations along the Pacific Coast within or close to the border of Oregon. Wave run-up is usually computed from Stockdon et al. (2006). These computations consider the beach slope, deep water significant wave height, deep water wavelength, and peak wave period. The beach slope can be reasonably estimated via airborne lidar or from site specific surveys of the beach; however, the beach slope will fluctuate and vary throughout the year. The other parameters can be estimated from wave buoys (e.g., Coastal Data Information Program, CDIP). Serafin et al. (2014) build upon this approach to develop a more robust method to simulate extreme total water levels using a time-dependent, extreme value approach, which also provides confidence bounds.

1.2.2 Oregon Statewide Planning Goals and Guidelines

1.2.2.1 Goal 18 Beaches and Dunes

Goal 18 (DLCD 1988a) is legislation that governs the development and management of beaches, dunes, and seacliff coastal areas with the intent of conserving and protecting the coast and reducing hazard to human life and properties resulting from the dynamic coastal environment. The Goal was originally adopted in 1976 and implemented in June 1977 under Oregon Administrative Rules OAR 660-034 and OAR 660-035. Amendments have been made in 1984 and 1988. An additional amendment to protect public infrastructure is currently being discussed. This planning goal includes several requirements, including:

- Prohibition areas- development is prohibited in the most sensitive and hazardous areas of the coast (e.g., on the beaches themselves, active foredunes, and other hazardous locations).

- Shoreline armoring- placement of protective structures (e.g., seawalls and riprap) is limited in areas with development prior to 1977. There is a cap to the amount of shoreline that can be hardened to limit cumulative impacts.

- Dune grading- contains detailed requirements for foredune grading (i.e., lower dunes to provide a view) for limited situations with existing development. Detailed plans are needed for maintaining flood protection, sand-supply, and stabilization (e.g., planting beach grass).

- Ocean Shore Regulation- Oregon Parks and Recreation Department (OPRD) manages Oregon's ocean beaches and has an extensive permitting system for shoreline protection, stairways, walkways, or other structures that encroach on the beach. Based on the Oregon Beach Bill (ORS 390.605 – 390.770), this has been defined as the ocean shorelands west of the statutory vegetation line or the line of established vegetation, whichever is most landward.

1.2.2.2 Goal 16 Estuarine Resources

Goal 16 (DLCD 1988b) was developed at the same time as, and with a similar intent to, Goal 18 but governs estuaries (i.e., tidal mouth of a river where the freshwater meets the saltwater tide). Estuaries have particular importance to numerous plant and animal species and are highly productive ecosystems. The requirements for preparations of plans and coordination are typically implemented through local estuary plans, but some state agencies are involved in the permitting processes. These plans minimize adverse impacts by designating the appropriate usages allowable within different sections of the estuary based on the ecosystem and geomorphology. Key usage priorities (in decreasing order of importance) include:

1. Uses that maintain the integrity of the estuarine ecosystem,

2. Water-dependent uses requiring estuarine location,

3. Water-dependent uses that avoid degradation of the estuarine resources and values, and

4. Nondependent, nonrelated uses that avoid degradation of the estuarine resources and values.

1.3 OBJECTIVES

While these prior efforts have been substantial, additional research is needed for ODOT to prioritize sites for potential mitigation. First, previous coastal erosion assessments looked comprehensively at the MHW shoreline and previous economic analyses of Goal 18 concentrated on residential parcels (Dundas and Lewis 2020; Beasley and Dundas 2021). Thus, they were not focused on Highway 101 as is necessary for this study. Second, aside from Ruggiero et al. (2013), prior studies were completed for a select group of counties at a time between the 1990s and present. Methods and data quality vary between studies especially given the rapid advance of lidar and photogrammetry technology in recent years; hence research is needed to verify the datasets and analyses to apply them in the context of consistently evaluating sites located throughout Highway 101. Notably, Ruggiero et al. (2013) was part of a broader study evaluating the entire Pacific Northwest shoreline response; however, this work is based on relatively old and sparse airborne lidar derived shorelines (2002) – the best available at that time. Relating shoreline responses, characterized by large spatial and temporal variability, with coastal erosion taking place at the back of the beach or along coastal seacliffs is also problematic. Next, coastal landslides and erosion of coastal seacliffs were only quantified to a limited extent in these prior studies. A more detailed evaluation of seacliff erosion is therefore necessary for understanding the impacts on Highway 101. A common basis is also needed to compare prioritization of sites under Goal 16 (estuaries) with those under the purview of Goal 18 (beaches, seacliffs, dunes). Lastly, prior studies generally quantify erosion rates or flooding extents but do not evaluate economic impacts.

The intent of this research is to leverage the high caliber work completed in these previous studies to develop erosion modeling and an accompanying economic framework that can be applied in a systematic fashion such to aid in the prioritization of adaptation options along Highway 101. This methodology can then be utilized by ODOT in future years for model update as needed, considering that erosional patterns can change dramatically over time.

The primary objective of this research is to systematically identify and prioritize sites along Highway 101 for possible mitigation. Specific objectives include:

- Develop erosion rate model(s) with uncertainty estimates,
- Develop a rigorous methodology for hazard vulnerability assessment considering multiple factors as well as the uncertainty of those factors,
- Develop a framework for evaluating economic costs and benefits of different adaptation options,
- Deliver planning level GIS maps for distribution to ODOT stakeholders, and
- Deliver Final Report and Research Rollout sessions to ODOT stakeholders.

Note that the intent of this work is to develop and illustrate the framework to evaluate potential mitigation options. While realistic mitigation options are presented, these should not be interpreted to be options that are planned at this time. They are merely examples showing how the methodology could be used. For full evaluation of these adaptation options more detailed planning, community input, and design work is necessary.

1.4 IMPLEMENTATION

This research enables ODOT to be proactive in managing coastal risks to infrastructure, directly informing potential Goal 16 and 18 revisions. Conducting this research early in the process also ensures that ODOT is the lead agency assessing risks and priorities for US 101. Without this research, ODOT will remain in a passive and reactive position regarding the mitigation restrictions of Goal 18, while erosion and sea level rise will continue to threaten the safety and reliability of our iconic coastal highway. This research provides valuable “pre-work” for future regulatory approvals for infrastructure protection, and strategic planning for short and longer-term adaptation options. This research also helps build a common understanding of risks and needs pertaining to the management of coastal hazards across ODOT and helps build partnerships amongst federal, state, and local stakeholders. Additionally, this research addresses infrastructure resilience and reliability under changing climate conditions with an adaptation framework that helps ensure a safe and reliable transportation system for the traveling public.

Implementation will require coordinated effort between ODOT’s Adaptation Program Manager, the ODOT Climate Office Director, coastal Region Managers, the Engineering Geology Program, and the Research Coordinator. The coastal hazard prioritization maps will both inform STIP project development and provide direct support for DLCD Goal 18 Policy needs. Importantly, the vulnerability matrix and site options identified will also allow the agency to strategically assess and plan proactive maintenance and protection of US 101, including future Goal 18 exceptions, Region project development, maintenance priorities, and budget assessment for maintenance needs related to coastal hazards. To initiate use and implementation, tailored research showcase/Q&A sessions with the final map products and associated GIS data layers will be provided to ODOT professionals from: Region 2, Region 3, coastal Maintenance Districts, the Maintenance and Operation Branch, the Statewide Project Delivery Branch, the Policy/Data/Analysis Division, and key stakeholders outside of the agency.

The results of this research will also be appropriately distributed to the public through conference proceedings and peer-reviewed publications.

1.5 ORGANIZATION OF REPORT

This report is organized as follows:

- Chapter 2 describes the sites identified on the coast as problematic locations and the virtual initial assessment of each site.
- Chapter 3 presents the development of a hazard vulnerability matrix and coastal vulnerability index in order to rank the sites based on their hazard levels. This chapter describes the analysis of sea level rise impacts as well as landslide hazards. Erosional hazards are only briefly described in this chapter as they are described in detail in Chapters 4 and 5.
- Chapter 4 provides results of erosion analyses performed for relevant sites for both short-term (airborne lidar) and long-term (aerial imagery) rates. It also presents an analysis of projected beach loss due to erosion for Beverly Beach.
- Chapter 5 presents the results of erosion forecasting based on those rates and a physics-based model to determine when highway loss is likely to occur.
- Chapter 6 provides the overall ratings computed for each site for the hazard assessment and selection of sites for detailed economic analysis of adaptation options.
- Chapter 7 provides the proposed site adaptation strategies for each of the selected sites and costs associated with each strategy.
- Chapter 8 presents an economic framework to synthesize the hazard vulnerability work and evaluate different potential future scenarios in terms of measurable economic benefits and costs at the most at-risk sites.
- Chapter 9 describes stakeholder/community outreach products and activities, and

- Chapter 10 presents the conclusions, limitations, and recommendations from this research.

The report also contains several appendices.

- Appendix A contains additional information from the virtual site visits described in Chapter 2.
- Appendix B consists of tables containing the values for each parameter from the flooding\inundation, erosion and landslide and other supporting information for each site (Site Vulnerability Analysis).
- Appendix C describes the digital data files provided with the final report containing scripts, data, spreadsheet tools, and other useful information.
- Appendix D contains the memos and supporting data from TPAU used in the economic analysis.

2.0 DELINEATION OF HAZARD SITES

2.1 PREVIOUS HAZARD SITE EVALUATIONS

Recognizing the susceptibility of U.S. Highway 101 to the effects of extreme storms and future climate variability, district managers and geologists at ODOT and coastal experts from DOGAMI initiated an evaluation of the coastal highway system in 2003. The impetus for this effort was in response to several mass failures along U.S. Highway 101 in the late 1990s (e.g., Arizona Inn, Hoosknaden, Cape Cove, and Cape Foulweather) that illustrated the fragility of sections of the highway. For example, landsliding at Cape Cove caused Highway 101 to be shut down for about 3 months (The World, 2001). Thus, the objective of this effort was to develop an initial assessment of the highway system, and specifically its susceptibility to the effects of future coastal erosion and flooding, as well as to landslide susceptibility and failure processes. However, the assessment was entirely qualitative, having consisted of an initial evaluation by ODOT district managers who identified known maintenance trouble spots (Table 2.1), and then evaluated and discussed by the full team in a workshop. No time or resources were available for a rigorous scientific study of each of these sites. Nevertheless, this initial scoping exercise did provide the mechanism needed for later, more comprehensive evaluations of select problem sites (e.g., Johnson Creek near Beverly Beach (Priest et al, 2008); Johnson Creek (Olsen et al, 2012); Johnson Creek, Carmel Knoll and Arizona Inn (Leshchinsky et al, 2019)).

2.2 DELINEATION OF HAZARD SITES

For the purposes of this study, we used the information in Table 2.1 as a starting point to assess vulnerabilities along U.S. Highway 101. The data were integrated into a GIS and beginning in the north, we systematically worked our way southward evaluating every section of the coastal highway. Problem sites were identified and mapped based on a combination of factors, including:

- Known failures/closures that have impacted the highway over the past several decades.
- Susceptibility to flooding from storm waves and/or extreme tides and river levels.
- Proximity to coastal wave runup effects and hence seacliff/dune erosion potential.
- Knowledge of the local geology (erosion potential/landslide susceptibility).
- Coastal geologic observation and experience; and,
- Review of reports compiled by DOGAMI, ODOT, OSU, and others.

Using this approach, we identified 71 potential hazard sites along U.S. Highway 101 (Figure 2.1), greatly expanding on the original 26 identified in 2003. Within the GIS, each site was classified according to a variety of parameters (Figure 2.2, Table 2.2), most important of which is the hazard type (coastal erosion, landslide, flooding), as well as a qualitative assessment of the relative risk to the highway system. Note that the risk rating is solely to distinguish the relative risk between these sites. Hence, a site labeled as low risk or very low risk indicates that relative to the other sites its risk is much lower; however, the site still has been identified as a vulnerable site with risk. Appendix A provides the Site Analysis Table and associated values.

Table 2.1: Sites Identified as Susceptible to either Coastal Erosion, Flooding, and/or Landslide Susceptibility along U.S. Highway 101 (ODOT, 2003)

Mile Post	Location
Clatsop County	
31.6 – 32.3	Silver Point Slides
35.9 – 35.92	Arch Cape tunnel (south portal)
Lincoln County	
125.15 – 125.3	Fogarty Creek
126.0 – 126.3	Boiler Bay
133.2 –135.8	Beverly Beach
145.9 – 147.55	Thiel Creek
148.15 –149.2	Ona Beach
151.0 – 151.4	Seal Rock
157.2 – 158.05	Patterson Creek
159.05 – 159.2	Wakonda Beach
159.7 – 159.8	Big Creek
Lane County	
169.85 – 170.6	Bob Creek
171.35 – 171.6	Tenmile Creek
172.5 – 172.7	Squaw Creek
174.1 – 174.45	Rock Creek
174.8 – 175.1	Big Creek
180.8 – 181.2	Baker Beach Slide
Curry County	
301.8 – 302.1	Hubbard Creek Slide
303.2 – 303.6	Rocky Creek Slide
304.5 – 306.1	Retz Creek Slide
318.0 – 320.5	Ophir/Duchre Creek/Nesika Beach
330.0 – 331.0	Kissing Rock/Hunter Creek
336.5 – 337.5	Myers Creek
338.5 – 339.5	Pistol River
344.1 – 344.4	Hoosknaden Slide
353.9 – 354.2	Taylor Creek Slide

Additional attributes included in the GIS describe many other parameters including mile post start/end, distance to the eroding seacliff, presence/absence of coastal engineering, presence/absence of FEMA flood zones, SLR effects, various erosion rate calculations, and many others (Figure 2.2). These data sources are discussed in more detail in Sections 2.0 through 6.0.

This list was reviewed and deliberated in several research team meetings in addition to consultation with the Technical Advisory Committee (TAC) to ensure the list was as complete as possible. Note that the list primarily considers sites in close proximity to the open coast and estuaries as relevant to Goal 18 and Goal 16. There may be additional sites with flooding hazards from rivers, landsliding from unstable slopes, or other hazards further from the coast that were not included in this list given the scope of this research.

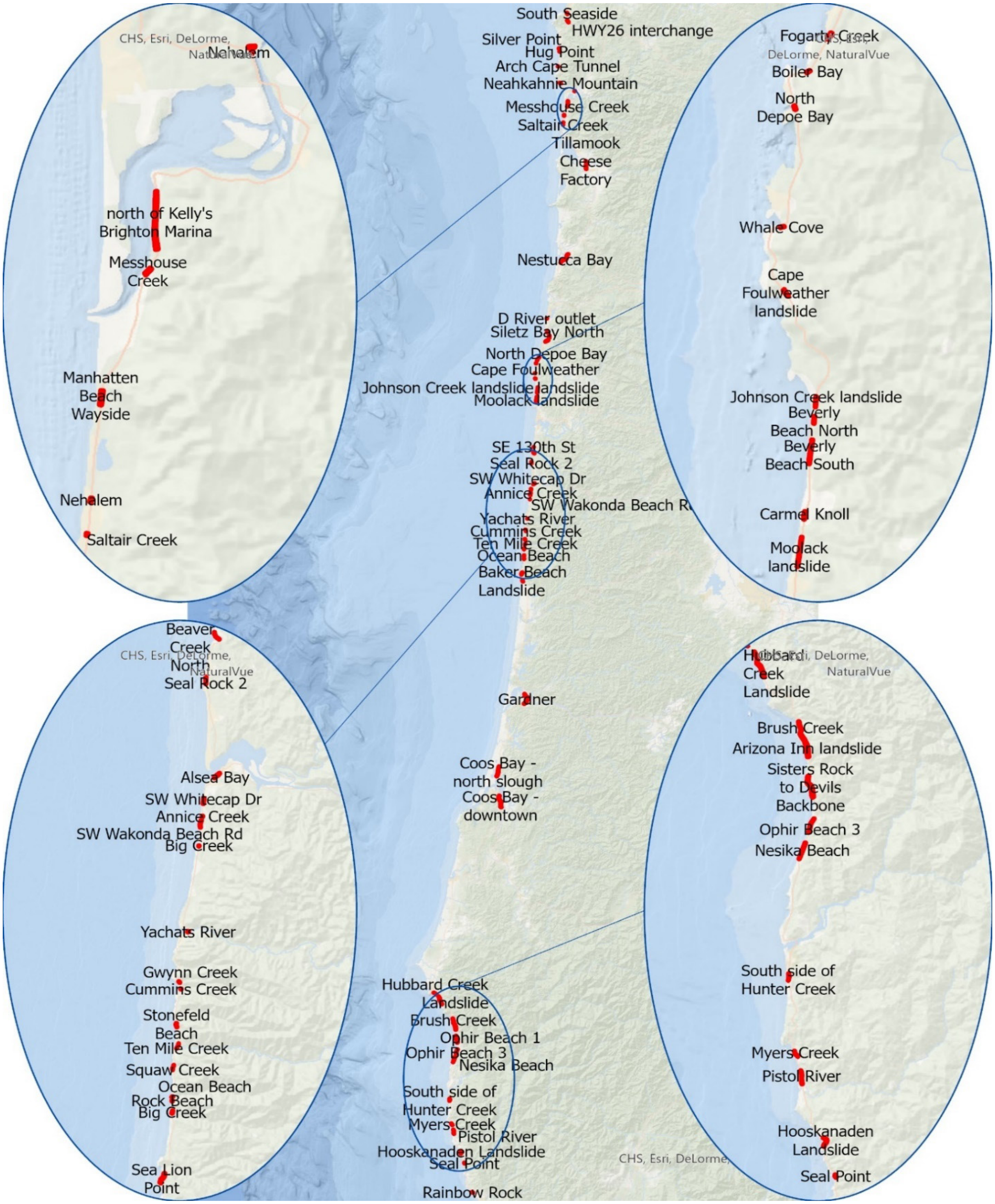


Figure 2.1: Map of the 71 identified vulnerably sites with coastal hazards on Highway 101.

Table 2.2: Details for the 71 identified vulnerably sites with coastal hazards on Highway 101, organized by Region and County. Table includes information on primary site hazard type classification (E= erosion, F = Flooding), corridor segment (Table 2.3), hazards at site, and geomorphological conditions

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
ODOT REGION 2											
Clatsop County											
2	South Seaside	F	1	Floods today under high tides (compounded when river runs high during winter storms)	high	river terrace	22.6	N	13300	18000	554
1	HWY26 interchange	F	1	Floods today under high tides (compounded when river runs high during winter storms)	high	river terrace	24.6	N	12000	14000	889
4	Silver Point	E	2	Landslide	Mitigated-low risk	landslide terrain	31.8	Y	5500	7100	368
3	Hug Point	E	2	Area experienced significant landslide in ~2015. increasing exposure to wave attack	low to moderate	landslide terrain	32.5	N	5500	7100	199
26	Arch Cape Tunnel	E	2	Bluff erosion/landslide	high	cliff subject to toe erosion by waves	35.9	Y	4900	8300	110
Tillamook County											
25	Neahkahnie Mountain	E	2	Bluff erosion/landslide	Mitigated – low risk.	cliffs	40.7	N	4900	7900	579
24	North Nehalem	F	2	Floods today under high tides (compounded	v. high	river terrace, low lying	45.0	N	8300	9100	259

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
				when river runs high during winter storms)							
22	North of Kelly's Brighton Marina	F	3	Landslide	moderate	landslide terrain	45.9	N	4300	4400	1504
23	Messhouse Creek	E	3	Landslide	moderate	landslide terrain, compounded by low elevation	46.9	N	4300	4400	219
21	Manhatten Beach Wayside	F	3	Site is presently eroding rapidly. part of railway protected by riprap	moderate	creek outlet onto beach (dunes)	49.1	N	4900	5000	382
20	South Nehalem	E	3	May be subject to ocean storm wave overtopping. Will likely flood in the near future	moderate	creek outlet onto beach (dunes)	50.8	N	6400	6500	115
19	Saltair Creek	E	3	Floods today under high tides. Storm waves carry material over 101	high	creek outlet onto beach (dunes)	51.3	N	6400	6500	73
18	Tillamook Cheese Factory	F	3	Floods today under high tides (compounded when river runs high during winter storms)	high	Tillamook river valley, low lying area	63.8	N	11800	13000	417
17	Blue Heron Cheese	F	3	Floods today under high tides plus high river flows high during winter storms	high	Tillamook river valley, low lying area	65.0	N	17900	18000	1602

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
71	Nestucca Bay	F	4	Flooding	low to moderate	low lying area, mouth of Nestucca river	91.7	N	5000	5100	4491
Lincoln County											
16	D River outlet	E	5	Flood potential under extreme storm and high tide	moderate	marine/river terrace	114.9	N	25400	25500	177
44	Siletz Bay North	F	5	subject to future sea level rise. v. slow erosion on bluff	low	low lying area within the Siletz valley	118.3	N	14800	14900	601
43	Siletz Bay Central	F	5	subject to future sea level rise	low	low lying area within the Siletz valley	119.7	N	14000	16600	963
42	Siletz Bay South	F	6	subject to future sea level rise	low	low lying area within the Siletz valley	120.9	N	12300	12400	1155
62	Fogarty Creek	F	6	erosion undermines riprap structure during extreme storms	mitigated. Risk prob low?	low creek valley	125.2	Y	11000	11100	230
15	Boiler Bay	E	6	Potential for bluff erosion	moderate to low	marine terrace on basalt	126.0	Y	13200	13500	121
41	North Depoe Bay	E	6	Bluff erosion	moderate to low	marine terrace on basalt	126.9	N	13200	13500	130
13	Whale Cove	E	6	Landslide/bluff erosion (subject to recent failures)	high	moderately high bluff/cliff	129.3	N	8900	9000	127
14	Cape Foulweather landslide	E	6	Landslide - failed ~1997. shut down 101 for some time	mitigated. Risk prob low?	cliffs	130.8	N	8900	9000	230

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
10	Johnson Creek landslide	E	6	Landslide - major movement in late 2002. Bluff erosion high leading to destabilization of block.	moderate	moderately high bluff (Tertiary mudstones)	133.2	Y	8900	9000	334
11	Beverly Beach North	E	6	Landslide/bluff erosion (subject to recent failures)	moderate	moderately high bluff (Tertiary mudstones)	133.5	Y	8900	9000	233
12	Beverly Beach South	E	6	Landslide/bluff erosion (subject to recent failures)	v. high	moderately high bluff (Tertiary mudstones)	134.1	Y	8900	9000	747
9	Carmel Knoll	E	6	Landslide/bluff erosion (subject to recent failures)	high	Moderately high bluff - Carmel Knoll landslide	135.3	Y	8900	9000	255
8	Moolack landslide	E	6	Active landslide block. Seaward edge experiencing rapid erosion into Pleistocene dune sand	moderate	Moderately high bluff - Moolack landslide	136.0	Y	10500	10600	922
7	SE 130th St	E	7	Subject to ocean storm wave overtopping today. Flotsam on 101	high	low creek valley	147.4	Y	10900	11000	130
6	Beaver Creek North	F	7	Foredune likely to be subject to future erosion	moderate to low	fronted by a narrow dune	148.6	Y	10900	11000	451
5	Beaver Creek	F	7	Likely to experience future ocean storm wave overtopping	high	low lying creek valley, fronted by small dunes	148.8	Y	10900	11000	311

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
27	Seal Rock 1	E	7	Potential for bluff erosion	moderate to low	moderately high bluff eroding into marine terrace	151.1	Y	8900	9100	385
28	Seal Rock 2	E	7	Potential for bluff erosion	moderate to low	moderately high bluff eroding into marine terrace	151.4	Y	8900	9100	177
63	Alsea Bay	F	8	Seawall has been built. Subject to wave action and strong currents	low to moderate	low bluff eroding into marine terrace	156.3	N	8700	9300	594
29	SW Whitecap Dr	E	8	Potential for bluff erosion	moderate to low	low bluff eroding into marine terrace	157.8	Y	6500	6600	480
32	Annice Creek	E	8	Existing riprap @ bridge abutments. May be subject to increase in TWLs in the future +SLR	low	low bluff eroding into marine terrace	158.6	N	6100	6500	111
31	SW Wakonda Beach Rd	F	8	low bluffs, existing erosion issues, some riprap. close proximity to 101	moderate to low	low bluff eroding into marine terrace	159.0	Y	6100	6500	637
30	Big Creek	F	8	Existing riprap @ bridge abutments. May be subject to increase in TWLs in the future +SLR	low	marine/river terrace	160.2	Y	6100	6500	94
36	Yachats River	F	8	Potential for erosion to abutments. May be subject to increase in	low	marine/river terrace	164.7	N	4000	4100	113

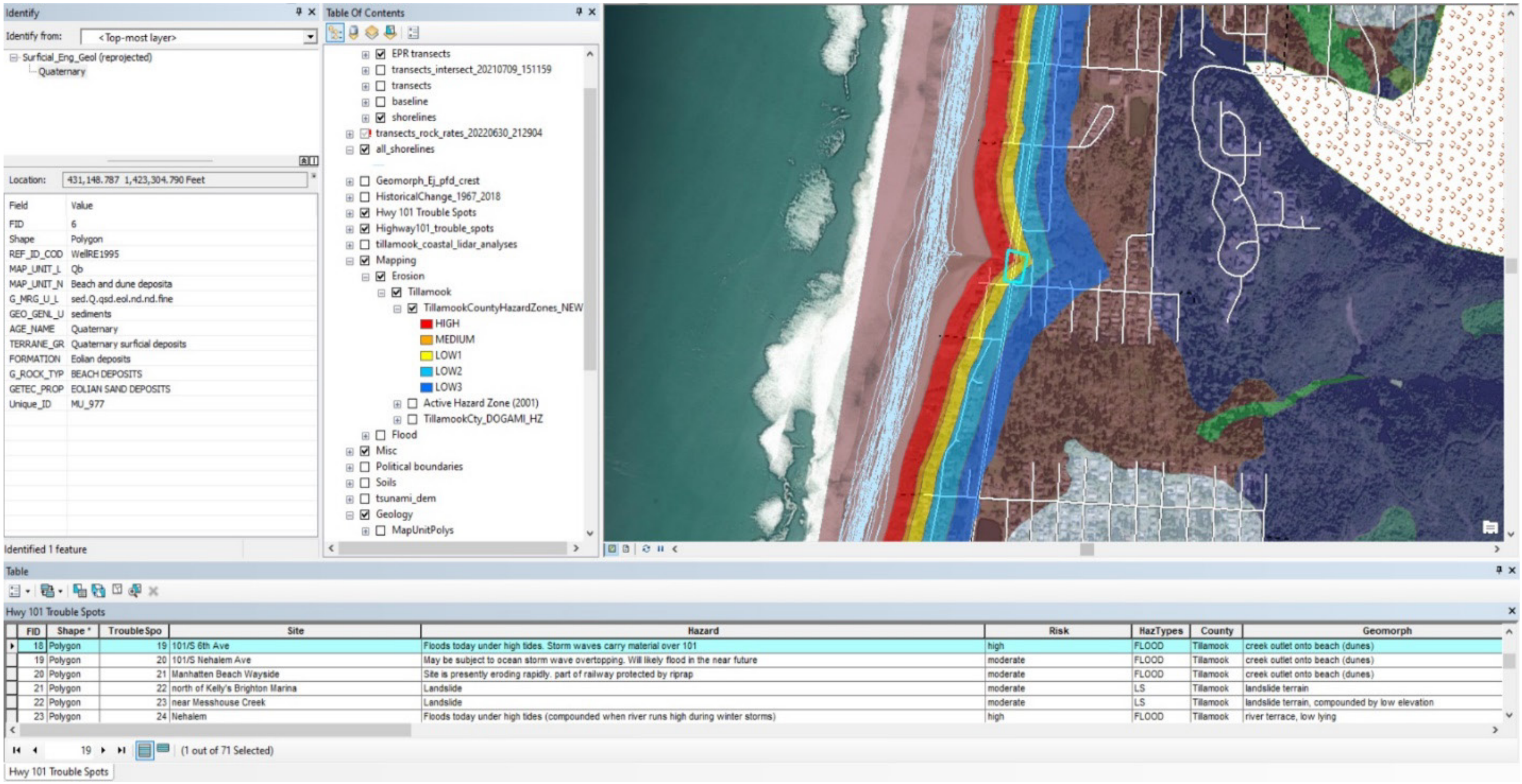
Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
				TWLs in the future +SLR							
				Lane County							
37	Gwynn Creek	E	8	surficial material on top of basalt slowly eroding landward	low	low to moderately high bluff	168.1	N	3100	3200	157
38	Cummins Creek	F	8	May be subject to increase in TWLs in the future +SLR impacting bridge abutments	low	marine terrace	168.4	N	3100	3200	77
33	Stonefeld Beach	E	8	high bluffs, slowly eroding landward. May be subject to localized landslide failures	low	moderately high bluff	170.4	Y	3100	3200	357
67	Ten Mile Creek	F	8	Low erosion	v. low	marine/river terrace	171.5	Y	3100	3200	482
68	Squaw Creek	E	8	Low erosion. Protective Reef. Localized slumping	low	moderately high bluff	172.6	Y	3000	3100	443
35	Ocean Beach	E	8	high bluffs, slowly eroding landward. May be subject to localized landslide failures	v. low	moderately high bluff	174.2	Y	3100	3200	121
34	Rock Beach	F	8	May be subject to increase in TWLs in the future +SLR impacting bridge abutments	v. low	marine terrace	174.4	Y	3100	3200	107

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
39	Big Creek	F	8	Bluffs slowly eroding... problems to bridge abutments	low	marine terrace	175.0	Y	3100	3200	265
40	Sea Lion Point	E	8	Landsliding (~1997, landslide by tunnel closed 101 for months)	moderate	cliffs - landslide terrain	178.9	N	3200	4000	909
69	Baker Beach Landslide	E	8	low erosion. Protective dune. Slide probably slow moving	v. low	cliffs-landslide terrain	181.0	Y	3200	4000	742
				ODOT REGION 3							
				Douglas County							
64	Gardner	F	9	Potential for increased future flooding due to accelerated SLR	v. low	river terrace	209.9	N	12200	12300	4498
				Coos County							
65	Coos Bay - north slough	F	10	Potential for increased future flooding due to accelerated SLR	low	low lying (interdune?) area adjacent to slough	230.6	N	11000	11100	3783
66	Coos Bay - downtown	F	10	Potential for increased future flooding due to accelerated SLR	low	River floodplain - Port/urban waterfront	237.5	N	27300	32200	4636
				Curry County							
70	Hubbard Creek Landslide	E	11	Bluff erosion	high	cliffs- landslide terrain	301.8	Y	3000	3100	1272

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
45	Port Orford (Gregory Point)	E	11	Landsliding (entire stretch subject to significant movement - Gregory Pt slide ~Mar 2006)	moderate	moderately high bluffs - landslide terrain	303.2	Y	2500	2600	1424
46	Rocky Point to Coal Point	E	11	Landsliding entire section subject to landsliding	moderate	moderately high bluffs - landslide terrain	304.3	Y	2500	2600	1861
47	Brush Creek	E	11	Eroding bluffs/Landsliding entire section subject to landsliding	moderate	high bluffs/cliffs	310.2	N	2500	2600	1339
48	Arizona Inn landslide	E	11	Landsliding entire section subject to landsliding, including Arizona Inn slide	high	landslide terrain - v. high bluffs/cliffs	311.6	N	2500	2600	2996
49	Sisters Rock to Devils Backbone	E	11	Landsliding entire section subject to landsliding	moderate to high	landslide terrain - high bluffs	315.0	N	2500	2600	2733
50	Ophir Beach 1	E	11	Coastal erosion occurring at Gregg Creek could cause problems for the highway	moderate	low bluff fronted by dune sand	317.8	N	2500	2600	1011
51	Ophir Beach 2	E	11	Coastal erosion occurring at Gregg Creek could cause problems for the highway	moderate	low bluff	318.2	Y	2500	2600	371

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
52	Ophir Beach 3	E	11	Coastal erosion occurring at Gregg Creek could cause problems for the highway	moderate to high	low bluff	318.4	Y	2600	2700	138
53	Ophir Beach 4	E	11	Coastal erosion occurring at Gregg Creek could cause problems for the highway	moderate	low bluff fronted by dune sand	318.5	Y	2600	2700	246
54	Nesika Beach	E	11	Existing riprap in place. Future problems reflect undermining and collapse of structure	moderate	moderately high bluff protected by riprap	320.0	Y	2600	2700	2035
55	North side of Hunter Creek	F	11	Existing groynes in place to control river movement against highway. Erosion prob	moderate	fill probably	330.3	Y	5900	6000	614
56	South side of Hunter Creek	F	11	May be subject to coastal erosion	low	low bluff. fronted by sand dunes at times	330.6	Y	4800	4900	204
57	Myers Creek	F	11	Potential for bluff erosion	moderate	low bluff. fronted by sand dunes at times	336.8	Y	3800	3900	826
58	Pistol River	F	11	Future erosion potential	moderate to low	low bluff. fronted by sand dunes at times	338.6	Y	3600	3700	1638
59	Hooskanaden Landslide	E	11	Active landslide	high	landslide terrain, low bluff at toe	343.8	Y	3600	3700	1353

Trouble Spot ID	Site Name	Primary Site Hazard Type	Corridor Seg.	Hazards	Initial Relative Risk Rating	Geomorph -ologic Desc.	Appr. MilePost	ODOT 2003 List	AADT (Curr.)	AADT (20 years)	Approx. Site Length (m)
61	Seal Point	E	11	bluff erosion potential	low	high bluff	346.6	N	3800	3900	363
60	Rainbow Rock	E	11	bluff erosion potential	low	moderately high bluff...colluvium?	354.0	Y	5400	8400	490



Identify from: <Top-most layer>

Surficial_Eng_Geol (reprojected)
- Quaternary

Location: 431,148.787 1,423,304.790 Feet

Field	Value
FID	6
Shape	Polygon
REF_ID_COD	WellRE1995
MAP_UNIT_L	Qb
MAP_UNIT_N	Beach and dune deposita
G_MRG_U_L	sed.Q.qsd.eol.nd.nd.fine
GEO_GENL_U	sediments
AGE_NAME	Quaternary
TERRANE_GR	Quaternary surficial deposits
FORMATION	Eolian deposits
G_ROCK_TYP	BEACH DEPOSITS
GETEC_PROP	EOLIAN SAND DEPOSITS
Unique_ID	MU_977

Identified 1 feature

- ☑ EPR transects
- ☐ transects_intersect_20210709_151159
- ☐ transects
- ☐ baseline
- ☑ shorelines
- ☑ transects_rock_rates_20220630_212904
- ☑ all_shorelines
- ☐ Geomorph_Ej_pfd_crest
- ☐ HistoricalChange_1967_2018
- ☑ Hwy 101 Trouble Spots
- ☑ Highway101_trouble_spots
- ☐ tillamook_coastal_lidar_analyses
- ☑ Mapping
  - ☑ Erosion
    - ☑ Tillamook
      - ☑ TillamookCountyHazardZones_NEW
        - 🟥 HIGH
        - 🟧 MEDIUM
        - 🟨 LOW1
        - 🟦 LOW2
        - 🟦 LOW3
      - ☐ Active Hazard Zone (2001)
      - ☐ TillamookCty_DOGAMI_HZ
  - ☐ Flood
- ☑ Misc
- ☐ Political boundaries
- ☐ Soils
- ☐ tsunami_dem
- ☑ Geology
  - ☐ MapUnitPolys

Hwy 101 Trouble Spots

FID	Shape *	TroubleSpo	Site	Hazard	Risk	HazTypes	County	Geomorph
18	Polygon	19	101/S 6th Ave	Floods today under high tides. Storm waves carry material over 101	high	FLOOD	Tillamook	creek outlet onto beach (dunes)
19	Polygon	20	101/S Nehalem Ave	May be subject to ocean storm wave overtopping. Will likely flood in the near future	moderate	FLOOD	Tillamook	creek outlet onto beach (dunes)
20	Polygon	21	Manhatten Beach Wayside	Site is presently eroding rapidly. part of railway protected by riprap	moderate	FLOOD	Tillamook	creek outlet onto beach (dunes)
21	Polygon	22	north of Kelly's Brighton Marina	Landslide	moderate	LS	Tillamook	landslide terrain
22	Polygon	23	near Messhouse Creek	Landslide	moderate	LS	Tillamook	landslide terrain, compounded by low elevation
23	Polygon	24	Nehalem	Floods today under high tides (compounded when river runs high during winter storms)	high	FLOOD	Tillamook	river terrace, low lying

19 (1 out of 71 Selected)

Figure 2.2: Examples of geospatial data used to evaluate coastal hazard sites along U.S. Highway 101. This example is of the Saltair Creek site located at the intersection of Highway 101 6th St at Rockaway Beach that floods periodically during major storms coupled with high tides. Existing erosion hazard zones, shoreline variability, coastal monitoring, FEMA flood zones and local geology were used to assess each site.

Table 2.3: Definitions of Corridor Segments Defined by Intersecting Highways

Corridor Segment ID	Northern Highway	Southern Highway
1	HWY30	HWY 26
2	HWY 26	HWY53
3	HWY53	HWY 6
4	HWY 6	HWY 18
5	HWY 18	HWY 229
6	HWY 229	HWY 20
7	HWY 20	HWY 34
8	HWY 34	HWY 126
9	HWY 126	HWY 38
10	HWY 38	HWY 42
11	HWY 42	HWY 199 (CA)

Figure 2.3 provides a breakdown of risk according to each site from very low to high risk. For the purposes of this classification, low risk was assigned to those sites where long-term coastal erosion is expected to be extremely slow/negligible, and/or the potential for ground movement is low. Moderate risk was assigned to those sites located close to an eroding seacliff and based on the local geology we assume that the site could experience slightly higher erosion rates in the future due to sea level rise. High risk was assigned to those sites with known susceptibility to coastal flooding (i.e., it currently floods under certain conditions today), higher rates of erosion, proximity of the highway to the eroding seacliff, and/or subject to known, substantial rates of landslide movement. The goal here was to provide an initial qualitative measure of risk, which could be used to perform more detailed erosion analyses due to future sea level rise and wave runup. As can be seen in Figure 2-3, 18 sites are classified as having a moderate level of risk, 2 sites have moderate to high risk, and 14 sites were classified as high risk. The remaining sites fall into the very low and low to moderate classes.

Figure 2.4 characterizes the complete suite of sites by predominant hazard type (flooding, landslide (LS), seacliff erosion (SC), and seacliff erosion + landsliding (SC + LS), and the proportion of those types according to their level of estimated risk. For the latter we only consider those sites having a risk rating greater than moderate. The largest hazard is flooding (25), followed by coastal erosion (22). Sites classified as having a landslide hazard and subject to coastal erosion cover 17 sites; combining this group with sites characterized as purely landslide indicates 23 vulnerable sites along the coast. Note that this breakdown only considers predominant hazard type, and some sites may experience some level of the other hazards.

Table 2.4: Subset of key GIS attributes defined in the coastal highway 101 vulnerability layer. Descriptions of other fields are captured in Tables 3.4, 3.5, and 3.6.

Attribute	Description
TroubleSpotID	**Site ID**
Site	**Site name**
Hazard	A description of the existing hazard and/or potential for future hazard development Hazard to ODOT infrastructure identified at site location. Field provides notes and description of the existing hazard and/or potential for future hazard development. Descriptions are site-specific.
Relative Risk	A qualitative description of the relative site risk that ranges from low to moderate to high. Additional qualifiers are included where applicable Risk to ODOT infrastructure identified at site location. Field includes qualitative description of the site risk that ranges from very low (v. low) to moderate to high. Additional qualifiers are included where applicable.
HazTypes	Where the hazard description is reduced to: Flood (F), Landslide (LS), and seacliff experience erosion (SC) or other climate change effects. Type of hazard with descriptions: Flood (FLOOD), Landslide (LS), and seacliff experience erosion (SC), or other climate change effects.
County	Self-explanatory
Geomorph	A brief description of the local geomorphology
CorridorSegment	Corridor Segment
MPstart	Mile post start for site analysis
MPEnd	Mile post end for site analysis
MPlength	Mile post length for site analysis
Site Type	Short code for the geomporpholgical site type (LLA= low lying area, LST= Landslide Terrain, HSC= high sea cliff, MSC= medium sea cliff, LSC = low sea cliff, DUNE= dune)
ODOTname	Name of the site from the 2003 ODOT study
ODOT Region	Site location by ODOT Region Number
Comments	Comments
AADT_Count_Max	Maximum Average Annual Daily Traffic (AADT) count on highway 101 within the trouble spot area.
AADT_20yearVol_MAX	Maximum Average Annual Daily Traffic (AADT) count on highway 101 within the trouble spot area, projected for 20 years in the future
RoadLenZone_M	Road Length Within Zone In meters. The length of Highway 101 within trouble spot area in meters.

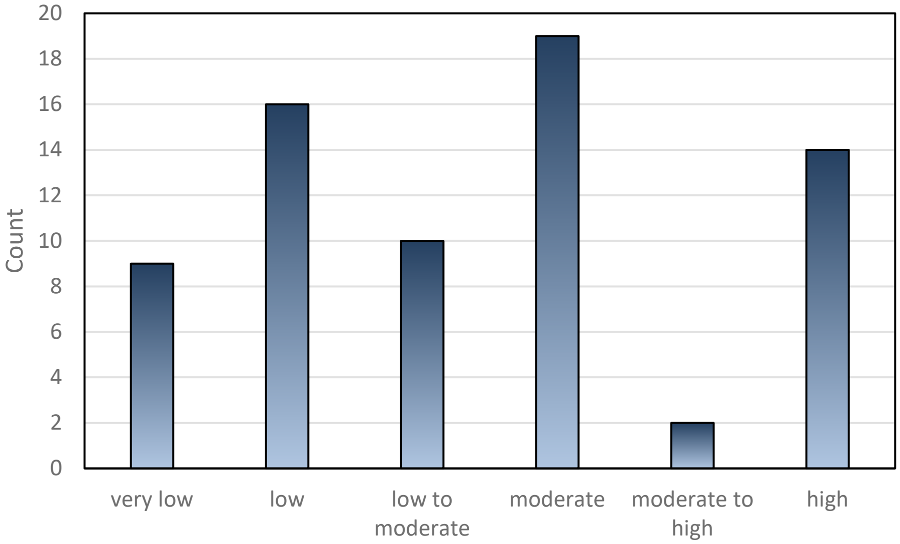


Figure 2.3: Number of vulnerable sites along U.S. Highway 101 classified by risk.

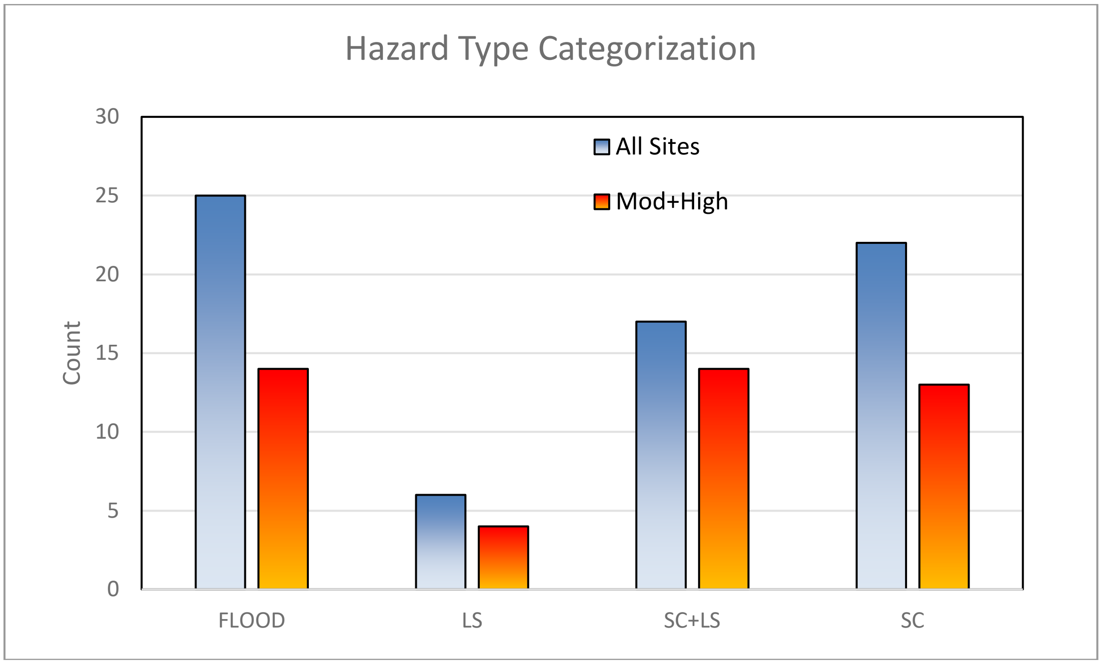


Figure 2.4: Distributions of sites based on predominant hazard type and rating.

2.3 SHORELINE MITIGATION VIRTUAL ASSESSMENT

As part of the preliminary analysis of potential hazard sites, virtual site visits were conducted by the research team using GIS, Google Earth, and a range of publicly-accessible datasets and data portals. The objectives of these virtual site visits included assessing the presence, condition, and quality of shoreline protection structures, the presence of other structures (e.g., bridges, culverts, and piers), and the general geomorphic setting and characteristics of each site. The primary datasets, portals, and map servers used in the virtual site visits included:

1. The “Potential Trouble Spots” GIS data layer generated by the project team, overlaid on ESRI World Imagery and World Street Map base layers

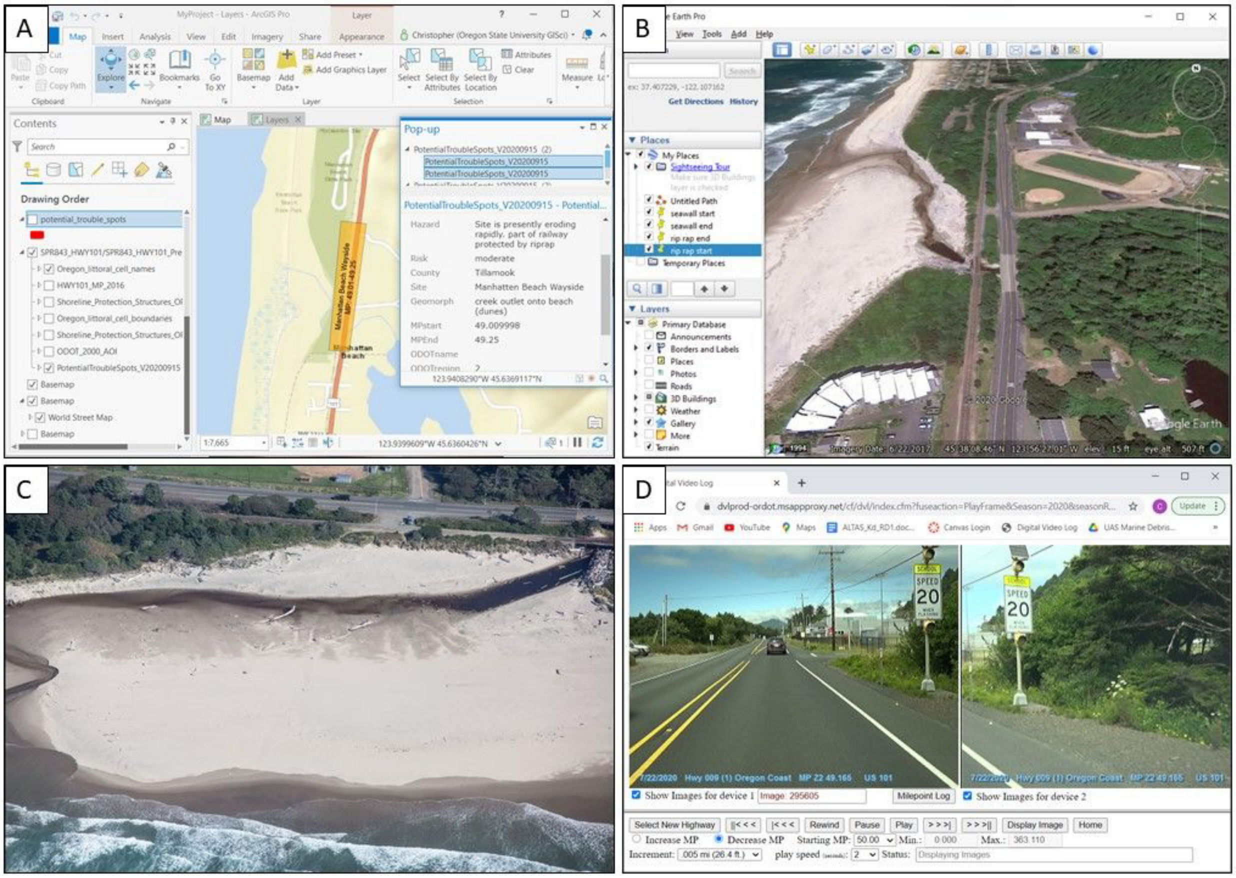
2. Oregon Parks and Recreation Department (OPRD) shoreline protection structures (SPS) data layers (OPRD, n.d.; Dundas and Lewis, 2020)

3. Google Earth and StreetView imagery (Anguelov et al., 2010; Andriolo et al., 2019)

4. Oregon Parks and Recreation Department (OPRD) Oblique Aerial Imagery Program (OAIP) imagery (OPRD, n.d.)

5. The ODOT Digital Video Log (ODOT, n.d.)

6. Bridge information along Highway 101, compiled from the ODOT Public RoaOf these many sources of data, those that enabled viewing changes through time, including the ODOT Digital Video Log (DVL, (ODOT, 2022)) and Google Earth, were found to be especially beneficial in this analysis. An example of this evaluation for the Manhattan Beach Wayside potential hazard site is shown in Figure 2-5. Appendix B contains the full list of all sites included in this assessment, ordered from south (border with California) to north (i.e., in order of descending milepost number), including attributes indicating the presence/absence of shoreline protection structures, type, condition, and general notes.



Hazard	Site is presently eroding rapidly, part of railway protected by riprap
Risk	moderate
County	Tillamook
Site	Manhatten Beach Wayside
Geomorph	creek outlet onto beach (dunes)
MPstart	49.009998
MPEnd	49.25
ODOTname	
ODOTregion	2

Figure 2.5: Manhattan Beach Wayside virtual site analysis: A) GIS data layers, B) Google Earth imagery, C) OPRD oblique aerial imagery, and D) ODOT Digital Video Log.

A general finding from this assessment was that very few of the identified hazard sites include shoreline protection structures that provide direct protection to Highway 101. In most cases in which shoreline protection structures were noted as present within a site, they primarily consisted of riprap protecting individual properties (e.g., residences or hotels), extending over only a small portion of the site and not at the locations of greatest potential threat to the highway (e.g., Figure 2.6). In many of the sites containing bridges over rivers near the river mouths, riprap was noted along both banks, including at the bridge abutments (e.g., Figure 2.7). Some sites contained some evidence of riprap placed decades ago, likely from dropping the rocks from the cliff top onto the beach or rocky platform below. These rocks in the riprap are now scattered and offer minimal, if any, shoreline protection.

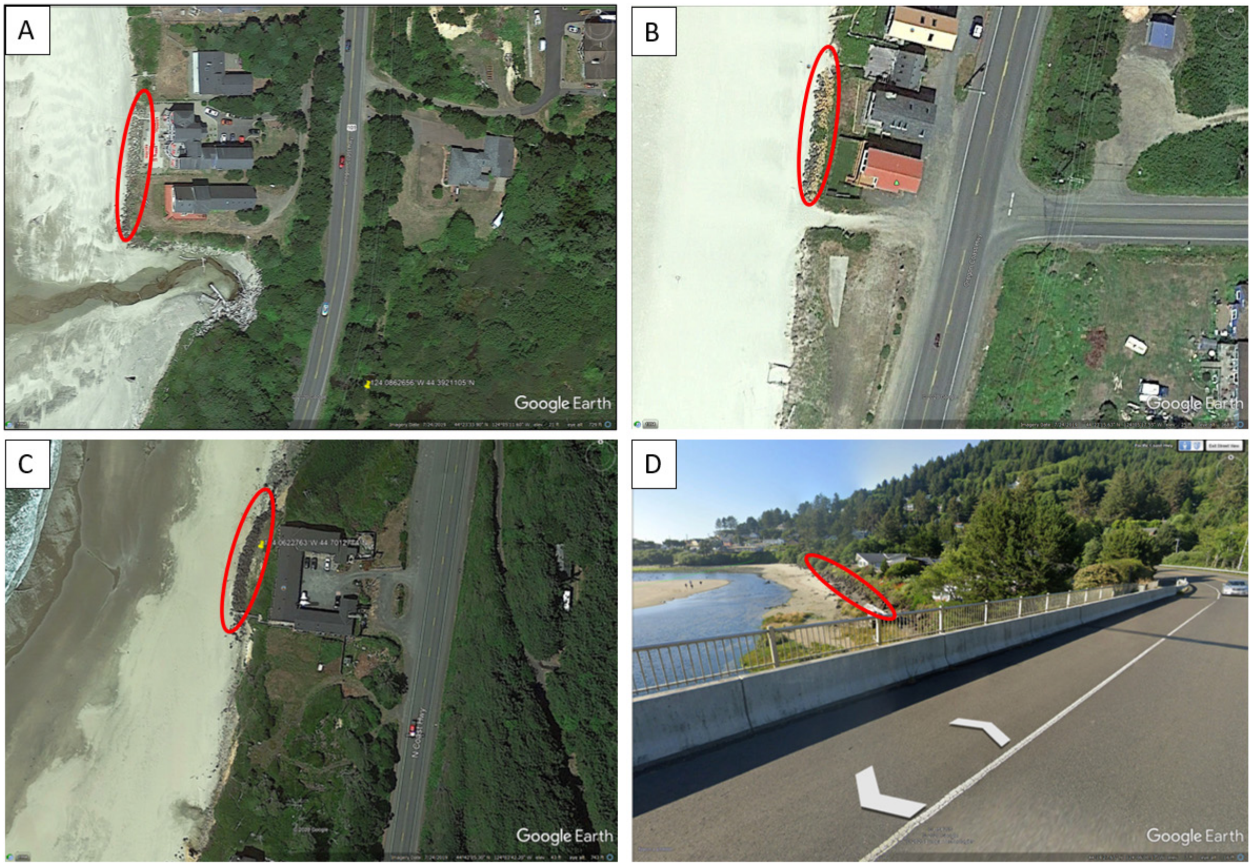


Figure 2.6: Examples of riprap revetments affording protection to individual properties, but not necessarily to the highway at the points of highest vulnerability. The sites shown are: A) Annice Creek; B) Wakonda Beach; C) Beverly Beach/Moolack landslide; and D) just north of bridge over Yachats River, MP 164.73. Note that Wakonda Beach provides road access to the beach for emergency vehicles.

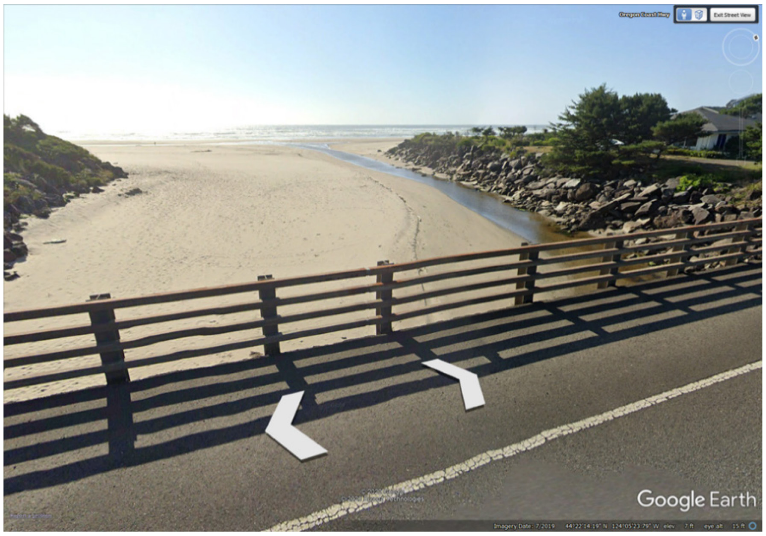


Figure 2.7: Riprap placed along the north and south stream banks and abutments at the bridge over Big Creek, MP: 160.15.

At the few potential hazard sites for which shoreline protection structures were identified as currently providing some level of protection to Highway 101 or directly adjacent cliffs, analysis was performed to identify the type and condition of the structures, to the extent possible in the available data layers. The first of these sites, Nesika Beach, contains riprap adjacent to a 1.7-km section of the highway, roughly between mileposts 319.34 and 320.45 (Figure 2-8A). The second site, Alsea Bay, contains a 0.3-km seawall, roughly extending from milepost 156.22 to 156.42 (Figure 2.8B). A third site of interest is Boiler Bay (Figure 2.8C). The Google Earth imagery indicates the presence of riprap, and this observation is supported by the discussion in Byrne and North (1973). However, this riprap appears to have been constructed decades ago and to currently be in poor condition. Field visits in 2022 confirmed that this riprap was providing minimal protection to the cliffs given that it was functioning more like a boulder beach rather than intact riprap. Another site containing riprap that may afford some protection to the highway is Fogarty Creek, just north of the bridge (Figure 2.8D). However, based on field visits by DOGAMI, erosion undermines the riprap structure during extreme storms.

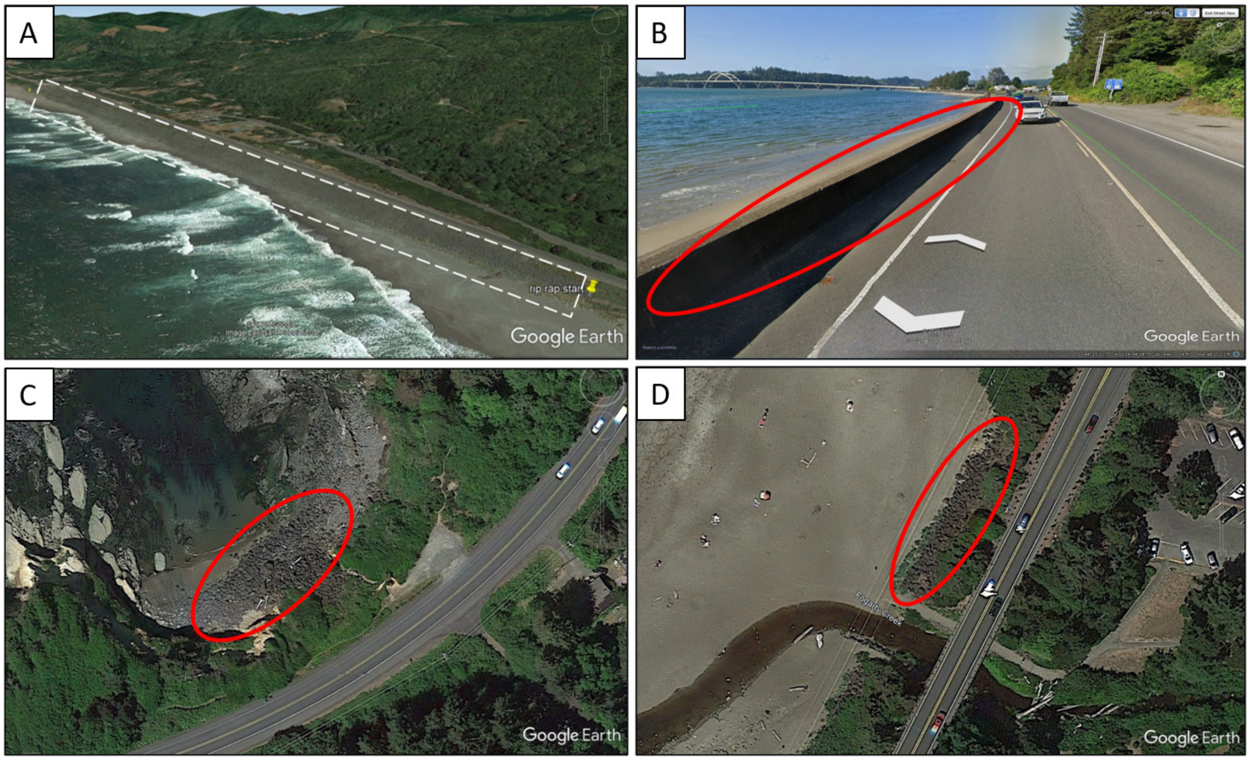


Figure 2.8: Shoreline protection structures affording varying levels of protection to highway: A) riprap along Highway 101 in the Nesika Beach site; B) Alsea Bay seawall; C) riprap at Boiler Bay site, currently in poor condition; and D) riprap at Fogarty Creek site, just north of bridge.

Another finding from this analysis is that very few of the shoreline protection structures that afford protection to Highway 101 are contained in the OPRD shoreline protection structure database. There are many reasons why an individual structure may not be included in the database, ranging from having been constructed prior to Goal 18 to being outside the "Ocean Shore Recreation Area," defined by ORS 390.770 as the area between extreme low tide and the statutory vegetation line. Additionally, for those structures that are included in the database, condition information is generally not available. Although outside the scope of this project, a recommendation for future work is to compile a comprehensive Highway 101 shoreline protection structures geospatial database, including structure type, construction date, periodic condition assessment, permit number (if applicable), protection to or impacts to Highway 101, and other applicable information.

3.0 HAZARD VULNERABILITY MATRIX

This section describes the development of a GIS-based methodology to prioritize sites through a coastal hazard vulnerability assessment for the hazard sites. This methodology considers (1) erosion rate observations, analyses, and predictive modeling for seacliffs and dunes; (2) evidences and impacts of landslide hazards; and (3) evaluations of the vulnerability to flooding or inundation from extreme tides, storm events, and sea level rise. The analyses for the inundation and landslide hazards will be described in this chapter. However, the erosion analysis and forecasting will be presented and discussed in Sections 4.0 and 5.0, respectively, given their complexity. The erosion hazards were given more attention given their relevance to Goal 18. The resulting hazard vulnerability scores and rankings are presented in Section 6.0.

3.1 COASTAL VULNERABILITY INDEX

The coastal vulnerability index (CVI) is a relative rating system originally developed by Gornitz et al. (1990) to identify sites that are most vulnerable to sea level rise considering several variables. CVI is typically computed as either the geometric mean (Equation 3-1), where x_i is the rating for variable i and n is the total number of variables considered, or as the square root of the product of the ranking factors divided by the number of variables present (Equation 3-2), which allows factors to “amplify” one another:

$$\boldsymbol{CVI = {(\textstyle\sum_{i=1}^{n} X_i)}/{n}} \tag{3-1}$$

$$\boldsymbol{CVI = \sqrt{{(x_1 \cdot x_2 \cdot \cdots \cdot x_n)}/{n}}} \tag{3-2}$$

Many other forms and uses of CVI have been proposed. The US Army Corps of Engineers (VanZomeren et al., 2019) provides a comprehensive review of approaches to calculate CVI for a variety of applications. Note that the functional form of the equation and factors considered depend on the purpose of the study, primary hazards of concerns, and sites themselves (Table 3-1).

The USGS (Thieler et al., 1999) performed a detailed shoreline vulnerability assessment due to sea level rise utilizing CVI for the entire coastline of the conterminous US (Table 3.2). This assessment was mapped at a 3’ grid cell resolution. Each variable was categorized based on five coastal risk classes: *Very Low (1), Low (2), Moderate (3), High (4), and Very High* (5). Six variables were considered in this model (Table 3-2) following the form of Equation 3-2. Different CVI variable thresholds were used for the Atlantic Ocean and Gulf Coast sections compared with the Pacific Coast (Table 3.1). For the Pacific Coast, the CVI used is similar to the CVI of Gornitz et al. (1994) and the sensitivity index used by Shaw et al. (1998).

Table 3.1: Examples of CVI used for different applications and factors considered (information summarized from USACE, 2019).

Purpose	Parameters	References
Cyclones	mean tidal range, relative sea level rise, mean wave height, significant wave height, rainfalls, storm surge, winds	Sahoo and Bhaskaran (2018), Bahinipati (2014), Hedge and Reju (2007), Sahoo and Bhaskaran (2018), Arkema et al. (2013), Balica et al. (2012)
Floods	Bathymetry, coastline length and width, river discharge, tides and currents	Bahinipati (2014), Balica et al. (2012)
Erosion	shoreline change, geomorphology, coastal slope, elevation, geology	Addo (2013), Boruff et al. (2005), Doukakis (2005b), Hedge and Reju (2007), Kumar et al. (2010), McLaughlin & Cooper (2010), McLaughlin et al. (2002), Szlafztein and Sterr (2007), Kumar and Kunte (2012)
Sea Level Rise	Tides and currents, flooding areas, flood frequency, depth to ground water, ice cover, surface waves, rising water table	Arkema et al. (2013), Diez et al. (2007), Gaki-Papanastassiou et al. (2010), Gornitz (1990, 1991), Gornitz and White (1992), Gornitz et al. (1991, 1997), Ozyurt and Ergin (2010), Pendleton et al. (2010), Rani et al. (2015), Rao et al. (2008), Thatcher et al. (2013), Theiler and Hammar-Klose (1999), Theiler and Hammar-Klose (2000a,b), Yin et al. (2012), Klein and Nicholls (1999)
Human Activity	Population, urbanization, agricultural sediment, dam and levee construction, deforestation, road/railway network	Klein et al. (1998, 1999), Kirwan et al. (2010), Day et al. (2007), Hedge and Reju (2007), McLaughlin and Cooper (2010), McLaughlin et al. (2002), Sahoo and Bhaskaran (2018)

Table 3.2: CVI parameters used by the USGS vulnerability assessment of the Pacific Coast (modified from Thieler et al. 1999, 2000).

#	Variable	Description/Rationale
1	Tidal Range	Hazards associated with inundation resulting from fluctuations in tides.
2	Wave Height	Hazards associated with inundation resulting from storm events.
3	Coastal Slope	Hazards associated with inundation and the speed of shoreline retreat.
4	Shoreline erosion rates	Hazards associated with erosion (based on field data).
5	Geomorphology	Hazards associated with deposition and other geomorphic processes.
6	Historical rates of relative sea-level rise	Hazards associated with inundation and local tectonic processes (land motion such as uplift or subsidence).

Table 3.3: CVI variable thresholds used by the USGS (Thielier et al. 2000) for the Pacific Coast.

VARIABLE	Very Low	Low	Moderate	High	Very High
	1	**2**	**3**	**4**	**5**
Geomorphology	Rocky cliffed coasts, Fiords, Fiards	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
Coastal Slope (%)	> 1.9	1.3 - 1.9	0.9 - 1.3	0.6 - 0.9	< 0.6
Relative sea-level change (mm/yr)	< -1.21	-1.21 - 0.1	0.1 - 1.24	1.24 - 1.36	> 1.36
Shoreline erosion/ accretion (m/yr)	> 2.0	1.0 - 2.0	-1.0 - +1.0	-1.1 - -2.0	< -2.0
Mean tide range (m)	> 6.0	4.1 - 6.0	2.0 - 4.0	1.0 - 1.9	< 1.0
Mean wave height (m)	< 1.1	1.1 - 2.0	2.0 - 2.25	2.25 - 2.6	> 2.6

3.2 EXPANDED COASTAL VULNERABILITY ASSESSMENT (ECVI)

While the CVI has proven useful for general shoreline assessment, it is typically applied coarsely over large geographic scales. It also generally focuses more on sea level/flooding hazards rather than erosion and landslide hazards, which are prevalent on the Oregon Coast (e.g., Leshchinsky et al. 2019). Hence, many of the models and associated factors considered were either not relevant to or specific enough to evaluate the trouble sites located along Oregon Coast spanning hundreds of miles. Most models did not include a sufficient number of factors to capturing different geomorphic, climatic zones, and landscapes which are present along the Oregon Coast. Lastly, many implementations of CVI treat all factors equally and do not apply weighting. As a result, they do not rigorously incorporate uncertainty.

While the basic form of the model used in this research is similar to those proposed in prior work, in addition to adapting to consider factors more pertinent to the Oregon Coast, the model also includes weighting strategies:

$$\boldsymbol{ECVI = \left(\sum_{i=1}^{n} w_i X_i\right)}$$

(Equation 3-3a)

$$\boldsymbol{ECVI\ Score = 0.25 \times ECVI \times 100\%}$$

(Equation 3-3b)

where w_i is the normalized weight for parameter i and the other variables are defined previously. Weighting was applied to account for (1) the uncertainty associated with the data, (2) the importance of the parameter based on expert judgment from the interdisciplinary research team, consultation with the TAC, and the overall objectives. Similar weighting strategies have been implemented in many studies (Diez et al., 2007, Doukakis et al., 2005, Gaki-Papanastassiou et al., 2010, Gornitz et al., 1989, 1997 and others).

In Equation 3-3b, the coefficient of 0.25 normalizes the Expanded Coastal Vulnerability Index (ECVI) score to be the range of 0-100% for ease of interpretation compared with a range of 0-4 from Equation 3-3a. Note that ECVI is a relative index for these sites- not an absolute score. All sites have been identified as a current or potential trouble area. Hence, one should not interpret the low scores to mean that a problem is not or will not be present at the site; rather it simply ranks lower than the other sites in terms of hazard and priority.

Coastal hazards were divided into three primary groups: Flooding/Inundation, Coastal Erosion, and Landslides. A variety of data collection resources were used, such as ground and airborne lidar data, imagery as well as both statistical and historical data of the Oregon Coast. These variables are described in this and the following Sections of this report. Many parameters were considered; however, twenty-six were selected and categorized within these groups for the assessment (Tables 3.4-3.6). Python code was developed to compute the aggregated score as well as interpret situations of missing data for some sites without affecting the score (Krivova et al., 2023).

All parameters (Potential hazards) were classified and scored based on five risk classes: Very Low (0), Low (1), Moderate (2), High (3), and Very High (4), with the exception of Overtopping, which was classified in a binary fashion as either 0 or 4. Appendix C.2. contains the full parameter table with associated thresholds and weights.

3.2.1 Flooding\Inundation Parameters

Several parameters related to flooding and sea level rise were considered in the flooding category of the matrix (Table 3.4). These factors consider current (~2020) hazards (e.g., road elevation, current flooding issues) as well as projections of future inundation and flooding from sea level rise. The projections consider levels of sea level rise of 1.57 ft (2050) and 4.66 ft (2100) given that these are the values and dates used in other coastal hazard assessments (DLCD 2017) in the Oregon Coastal Management Plan compared with the more general NRC (2012) study.

Table 3.4: Coastal hazards associated with flooding. The table includes weights, thresholds, rationale, and data source. (Total Weight: 15%).

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
Floods	3.00%	Measure of current flooding status	No Flood Risk	Slight or future flood risk	Flooding likely in near future	Occasional flooding	Regularly flooding	If the site is currently flooding then future sea level rise will only compound the problem.	Current news reports and other information, DOGAMI site investigations, FEMA (2021) data.
Flooded Length	3.00%	Current flooded length (m)	0	0-25	25-50	50-100	>100	Sites that are currently flooded now are only expected to become more problematic as sea level rise occurs.	Based on FEMA (2021) national flood hazard layer considering storm events with 1% prob. of exceedance
Highway Elevation	1.50%	Minimum elevation of highway or seacliff height (m)	>20	15-20	10-15	5-10	0-5	Sites at lower elevations are more likely to flood, especially during major storm events.	Measure of potential for storm/wave overtopping. OLC Lidar (2008/2009)
SLR Inundation Length, 2050	1.88%	Length (m) of highway expected to be inundated	0	0-50	50-150	150-250	>250	Sites that will have a large exposure length will require more protection/adaptation	NOAA Sea Level Rise Viewer (2021) at the epoch of interest

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
								or experience frequent closures	
SLR Inundation Length, 2100	1.88%	Length (m) of highway expected to be inundated	0	0-50	50-150	150-250	>250	Sites that will have a large exposure length will require more protection/adaptation or experience frequent closures	NOAA Sea Level Rise Viewer (2021) at the epoch of interest
SLR Inundation Depth, 2050	1.88%	Maximum inundation depth (m)	0	<0.33	0.33-0.66	0.66-1.0	>1	Sites that will have are covered in deeper water levels will require more protection/adaptation or experience frequent closures	NOAA Sea Level Rise Viewer (2021) at the epoch of interest
SLR Inundation Depth,2100	1.88%	Maximum inundation depth (m)	0	<0.33	0.33-0.66	0.66-1.0	>1	Sites that will have are covered in deeper water levels will require more protection/adaptation or experience frequent closures	NOAA Sea Level Rise Viewer (2021) at the epoch of interest

3.2.1.1 Current Flooding

The first three parameters in Table 3.4 represent current the flooding situation. The first two were estimated based on FEMA flood mapping analysis considering storm events with 1% probability of exceedance (FEMA 2021). *Floods* indicates the degree of flooding the site is currently or likely to experience storm or other surge events based on intersection with the FEMA flood mapping/flood high risk zones (labeled as A, AE, V, VE – defined in Table 3.5). *Flooded Length* indicates the length of the highway 101 susceptible to flooding based on the FEMA flood mapping/flood high risk zones (Figure 3.1). These locations would be expected to become more problematic as sea level rise occurs.

Figure 3.1: Example of intersection of FEMA flood zones with sites.

Table 3.5: FEMA flood zone definitions (applicable categories only)

Zone	FEMA Definition
A	Areas with a 1% annual chance of flooding. Detailed analyses are not performed in these areas so depths or base flood elevations are not provided.
AE	The base floodplain with base flood elevations provided. Wave heights < 3ft.
V	Coastal areas with a 1% or greater chance of flooding and an additional hazard associated with storm waves.
VE	Coastal high hazard areas with a 1% or greater chance of flooding and an additional hazard associated with storm waves. Wave action and fast-moving water can cause extensive damage during a base flood event.

Highway Elevation represents the minimum elevation within each delineated hazard section of the highway. The elevations were extracted from the 2008/2009 Oregon Coast lidar DEM available through the Oregon Lidar Consortium (n.d.) which are based on NAVD88 defined by Geoid 03. Note that current local mean sea levels vary from NAVD88 by approximately 1 m along the Oregon Coast. This difference is inconsequential in this study given that this difference was considered in the parameter thresholds and that the CVI is a relative score between the sites.

3.2.1.2 Future Sea Level Rise Analysis

The next four parameters focus on sea level rise impacts, which will amplify current flooding conditions captured by the previously described parameters. This analysis was performed on all relevant sites and consists of two parameters computed for two epochs: *SLR Length* and *SLR Depth.* To compute the parameters, an analysis was completed based on the projected water levels from SLR simulations performed by NOAA (2021). NOAA provides the simulated inundation extent maps based on 1 ft increments of sea level rise (e.g., 1 ft, 2 ft, etc.) rather than for a specific scenario so that users can perform the analysis based on specific SLR projections relevant to their study. NOAA provides two layers. The first shows the horizontal extents of inundation based on each 1ft increment. The second estimates the inundation depth by differencing the DEM from the estimated water levels.

Inundation extents for those sites vulnerable to flooding were determined for SLR heights of 1.57 and 4.66 ft based on estimates by the Oregon Department of Land Conservation and Development (DLCD 2017) for 2050 and 2100, respectively. First, inundation extents were computed based on the intersection of Highway 101 with the bounding 1, 2, 4, and 5 ft NOAA SLR inundation layers (Figure 3.2). The length of the highway intersecting with the flooded zones for each of the bounding inundation layers were then computed. SLR Length was then computed for both epochs by linear interpolation between the lengths estimated for the bounding inundation layers.

SLR Depth was computed in a similar fashion for each site but using the bounding depth layers instead of the horizontal inundation layers. The maximum vertical inundations within the highway section were extracted from the bounding inundation layers and linearly interpolated for the 1.57 and 4.66 ft estimates for 2050 and 2100.

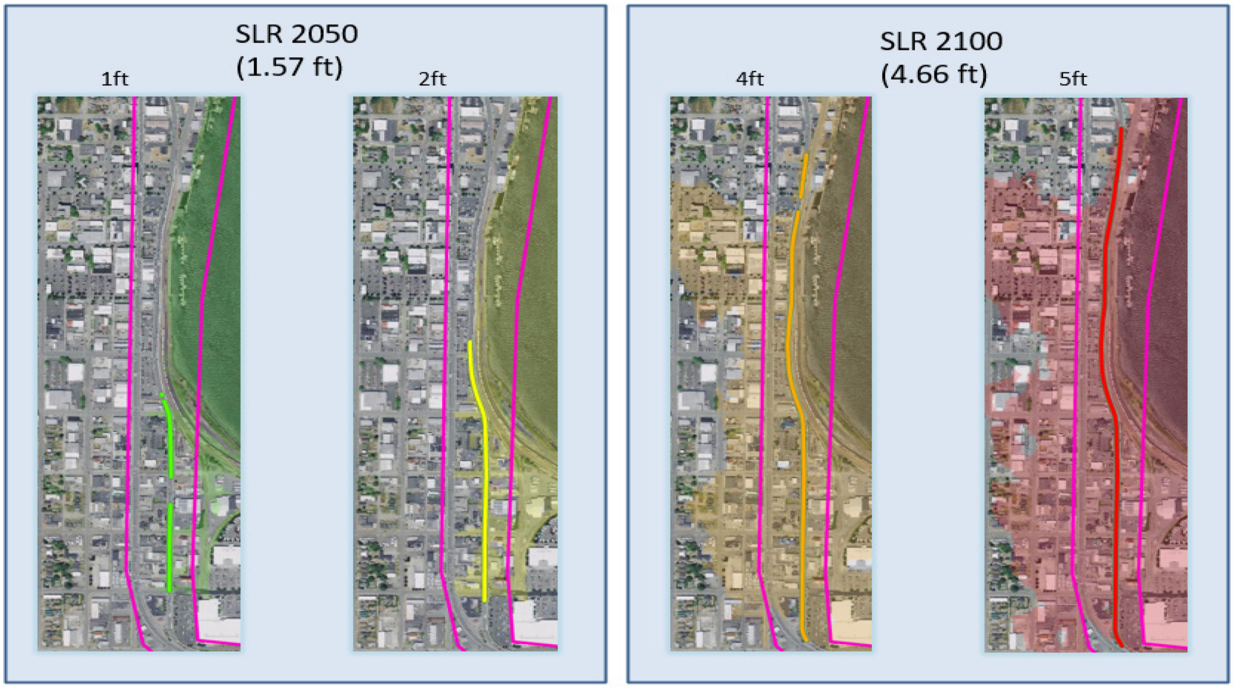


Figure 3.2: Example of sea level rise projection and potential damage to U.S. Highway 101 for 2050 and 2100 at Coos Bay, Oregon (basemap source: Oregon Explorer imagery with 1 ft resolution, 2018).

3.2.2 Erosion Parameters

A wide range of erosional parameters were considered (Table 3.6). These include geomorphologic, topographic, geologic data, as well as information on the level of the shoreline protection. The more simplistic parameters will be described in this section, with further descriptions of the more complex parameters covered in Sections 4.0 and 5.0.

Similar to inundation, these parameters capture existing conditions and future projections; however, they also consider historical erosion information based on data that are available. Given the wide range of uncertainty, several methods were employed and included. As a result, there will likely be some correlation between several parameters (e.g., erosion rates estimated from airborne lidar vs aerial photographs). However, these potential correlations were considered in the weightings assigned to the individual parameters such that when aggregated they would have a similar weight if only one estimate of erosion were considered. This approach allows the ECVI to incorporate the uncertainty associated with the parameters compared with using a single parameter given that parameters can vary based on the time period and the specifics of what is being measured (e.g., seacliff crest, seacliff face).

Table 3.6: Coastal hazards associated with erosion (Total Weight: 70%).

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
Geomorphology Class	10.50%	General description of the geology/ Geomorphology of the site.	Rocky Cliffed Coasts, Engineered structures/ fill	Medium Cliffs, Indented Coasts	Low Cliffs, dunes, Alluvial Plains, river terrace	Cobble Beaches, Estuary, Lagoon	Barrier beaches, sand beaches, salt marsh, mud flats, deltas, coral reefs	The geomorphology metric encompasses the vulnerability of the topography as well as the erodibility of the source material.	Modified from USGS CVI. Based on Co-PI Allan, DOGAMI.
Qualitative Field Change Analysis (Expert Rating)	10.50%	Prioritization of sites by a coastal geomorphologist	0	1	2	3	4	Ratings were provided by a coastal geomorphologist with decades of experience on the Oregon Coast based on their empirical field observations.	DOGAMI. Based on extensive field and observations visits over several decades.
Erosion Rate (2002-2016)	3.50%	Average erosion rate at site (m/year)	>-0.01	-0.025 to -0.01	-0.05 to -0.025	-0.05 to -0.1	<-0.1	Sites with high erosion rates are more vulnerable to episodic change as well as routine erosion. This category was	Airborne lidar surveys (2002-2016). See Section 4.1. Data from NOAA Digital Coast and OLC.

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
								given relatively lower weight though because it was an input to the distance analyses in the other categories.	
Erosion Rate (2008-2016)	7.00%	Average erosion rate at site (m/year)	>-0.01	-0.025 to -0.01	-0.05 to -0.025	-0.05 to -0.1	<-0.1	Sites with high erosion rates are more vulnerable to episodic change as well as routine erosion. This category was given relatively lower weight though because it was an input to the distance analyses in the other categories.	Airborne lidar surveys (2008-2016). See Section 4.1 Data from NOAA Digital Coast and OLC.
Maximum Erosion Rate (1967-2018)	7.00%	Maximum erosion rate computed for a transect	>-0.01	-0.05 to -0.01	-0.15 to -0.05	-0.15 to -0.3	<-0.30	This analysis evaluated a longer time series from the aerial photographs. However, they tend to have	Analyses of aerial imagery (1967-2018).See Section 4.2.

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
								more uncertainty due to difficulty visualizing the cliff's edge from vegetation.	
Percentage of Transects	7.00%	Percentage of transects that showed significant negative change	0	1-20	20-50	50-70	>70	This parameter indicates the relative length that is experiencing erosion.	Analyses of aerial imagery (1967-2018). See Section 4.2
Total Water Level	3.50%	Total Water Levels (m)	<7	7-8	8-9	9-10	>10	Total water levels are a parameter describing the site geometry (e.g., height) and wave energy (e.g., wave height, runup)	Allan et al., 2012, Allan et al., 2015a,b,c,d, Allan et al., 2017
Overtopping	3.50%	Overtopping from Total Water Level Analysis	No Overtopping (-99 or 2)	-	-	-	Overtopping (1)	If the cliffs are regularly overtopped, then they can experience ore significant erosion.	Allan et al., 2012, Allan et al., 2015a,b,c,d, Allan et al., 2017

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
Current Distance to Seacliff Highway	3.50%	Current distance (m) between westward road shoulder and seacliff crest after erosion modeling at closest point	>100	50-100	20-50	3-20	<3	If the highway is currently close to the seacliff edge, there is minimal protection against waves/storms.	ArcGIS Near distances from digitized seacliff crests and highway 101 shoulder.
Projected Distance from Seacliff Edge to Highway (Average, 2050)	3.50%	Mean predicted distance (m) between westward road shoulder and seacliff crest after erosion modeling at closest point. Considers factors such as cliff slope, cliff height, geomorphology, and strength from back analysis	>50	20-50	10-20	3-10	<3	Based on the erosion analysis, how much buffer is there between the road and seacliff's edge in the future?	Herrmann (2022)
Projected Distance from Seacliff Edge to	3.50%	Mean predicted distance (m) between westward road shoulder and	>50	20-50	10-20	3-10	<3	Based on the erosion analysis, how much buffer is there between the	Herrmann (2022)

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
Highway (Average, 2100)		seacliff crest after erosion modeling at closest point. Considers factors such as cliff slope, cliff height, geomorphology, and strength from back analysis						road and seacliff's edge in the future?	
Shoreline Protection Length	3.50%	Percent length of shoreline protected	80-100%	60-80%	40-60%	20-40%	<20%	The longer the length protected, the less erosion that would be anticipated to occur.	Oregon State Parks Department (OPRD)
Shoreline Protection Condition	3.50%	Highway Protection Condition	Excellent condition	Good condition	Fair condition	Poor condition	None present	Sites with good shoreline protection will experience less erosion/retreat	OPRD

3.2.2.1 Geomorphic Factors

Geomorphology dictates the vulnerability of a site to erosion hazards by considering the source materials present in the geology as well as the geometry and evolutionary trends of the site. The ranking of *Geomorphology Class* was adapted from the USGS CVI (Thieler et al., 1999) and modified be more consistent with geomorphological characteristics of Oregon.

The *Qualitative Field Change Analysis* is a site rating determined using qualitative and quantitative field observations carried out by co-PI Allan based on field observations over the last few decades combined with review of reports from DOGAMI, OSU, ODOT and other agencies compiled for various sites/ or regions on the coast.

3.2.2.2 Erosion Rate Factors

Historical erosion trends were derived from multiple data sources considering the difficulty in computing erosional rates given the substantial spatial and temporal variability of erosion and limited remote sensing data capturing these trends. The data sources and methods to compute these erosion rates are described in more detail in Section 4.1. The *Average Erosion Rate* is estimated by differencing serial airborne lidar surveys (2002-2016 and 2008-2016). Although the spatial resolution and accuracy of 2008-2016 surveys are better, those datasets span a shorter period. The 2002-2016 measurements provide a longer time series, but were significantly lower quality. Hence, both estimates were used to make up for their respective limitations. The *Maximum Erosion Rate* was derived by evaluating the locations of the seacliff top/vegetation line using 1967 and 2018 aerial photographs (and in some cases 2016 lidar) of the Oregon coast. Erosion rates were computed using transects spaced 10m apart using the Digital Shoreline Analysis System (DSAS, Himmelstoss et al. 2018) and was based on the *Percentage of Transects* that showed significant negative change nearest to the highway. For sites that had DSAS erosion estimates but not airborne lidar, rates were estimated from the DSAS values and used as a proxy for the airborne lidar erosion rates and vice versa if the site did not have DSAS values. This substitution helped ensure that the site was not penalized in the scoring.

3.2.2.3 Projected Erosion Factors

One of the important parameters is the distance from the cliff to the edge of pavement, which provides an indication of when failure is likely to occur based on the computed erosion rates. The *Current Distance* was estimated with the ArcGIS proximity tool to calculate the minimum distance between two feature classes: points representing the cliff edges and a polyline delineating the edge of the highway pavement. These edges were estimated using imagery with 0.3 m (1ft) spatial resolution (2018) and the 2008/2009 lidar. The *Projected Distances* were calculated for both 2050 and 2100 as the mean of distances between westward road shoulder and the closest point on the seacliff crest from the forecasted erosion modeling. These projections considered factors such as cliff geometry, slope stability, rock shear strength, wave scour and total water levels projected over the 80-year time period (Herrmann, 2022). The modeling process to obtain the forecast estimates for the sites are described in Section 5.0.

3.2.2.4 Erosion contributing/resisting factors

The next set of parameters reflect the wave impact energy contributing to the erosion at the site. Probabilistic Total Water Levels (T_{WLS}) for the Oregon coast were derived from Allan et al. (2012), Allan et al., (2015a,b,c,d), Allan et al. (2017). *Total Water Level* is the calculated 2% wave runup combined with the tidal datum for specific transect sites in each County. The T_{WL} provides a measure of how high storms waves are expected to affect and erode the cliff face. *Overtopping* occurs when the Total Water Level exceeds the seacliff or dune crest (D_{high}) and is expressed as a binary value.

Shoreline Protection is based on the inventory of Oregon Shoreline Protection Structures administered by the Oregon Parks and Recreation Department (OPRD, n.d., based on ORS 390.640, 390.715 and 390.725) and virtual assessment. The validation work performed to verify this information is described in Section 2.3. Two factors are considered. The first is the relative length of shoreline protection at the site (*Shoreline Protection Length*), and the second is the condition of that shoreline protection (*Shoreline Protection Condition*).

3.2.3 Landslide Factors

Unstable slopes are prevalent along U.S. Highway 101. Some of these are directly triggered or accelerated by coastal erosion processes, while others are primarily triggered by other sources (e.g., Priest et al, 2008; Leshchinsky et al, 2019, Alberti et al. 2022a). Many parameters associated with landsliding were considered, including proximity to right-of-way, susceptibility and impact, among others (Table 3.7).

Table 3.6: Coastal hazards associated with landsliding (Total weight: 15%).

Parameter	Weight	Description	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)	Justification for Weight	Data/ Methodology Source
Proximity to landslide (SLIDO)	1.50%	Distance (m) to nearest feature in SLIDO	>500	100 - 500	<100	Landslide feature intersects site (0)	Active landslide intersects site (-1)	High weight because the landslides require more complicated solutions and can result in regular damage to the highway. The seacliff can often be the toe of the slide and as that erodes, the landslide movements accelerate.	DOGAMI SLIDO
Frequency of Repair	3.75%	Repair frequency	N/A - no nearby slide	4-5 years (<10)	2-3 years (10-60)	1 year (60-90)	Multiple times per year (>90)	Sites requiring frequent repair and maintenance will be the most active	Based on ODOT unstable slopes database
Failure Hazard Score	2.25%	Unstable Slope Rating of Failure Hazard	N/A - no nearby slide	<10	10-30	30-90	>90	Sites with high failure hazard scores are more problematic	Based on ODOT unstable slopes database
Road Impact	2.25%	Unstable Slope Road Impact	N/A - no nearby slide	Contained in shoulder/ ditch (<10)	0–3-mile detour, 1 way traffic (10-60)	10–60-mile detour (60-90)	> 60-mile detour (>90)	Sites with more substantial road impacts/delays would have more consequences.	Based on ODOT unstable slopes database
Annual Cost	3.75%	Annual Cost in Unstable Slopes Database	N/A - no nearby slide	<$1,000	$1,000 to $10,000	$10,000 to $100,000	>$100,000	Sites with higher annual costs are likely more active.	Based on ODOT unstable slopes database
Landslide Suscept-ibility	1.50%	Burns Landslide Susceptibility (Mean)	Very Low (0)	Low	Moderate	High	Very High	High weight given that landslides require complicated solutions and can result in frequent damage to the highway. A seacliff can often be the toe, the erosion of which accelerates landslide movements.	DOGAMI, Burns et al. (2016)

3.2.4 Unstable slopes database

ODOT maintains a database of unstable slopes containing a variety of information such as estimated repair and maintenance costs, hazard scores, repair frequencies, etc. The May 19, 2021 version of this database (provided by ODOT) was queried to extract several components of information relative to each of the hazard sites. However, in many cases there were several unstable slopes within each of the hazard site zones. To relate these information and account for multiple unstable slopes within each of the identified Highway 101 vulnerable sites, all unstable slope point features within a 200 m buffer of the hazard site zones were aggregated for the analysis (Figure 3.3). The following fields of information were extracted as the parameters:

- *Frequency of repair* – the unstable slope with the most frequent repair interval governs for the site. The scoring system is defined in Table 3.8.
- *Failure Hazard Score* – the maximum failure hazard score governs for the site. The Failure Hazard Score is a composite of many different assessment scores.
- *Road Impact Score* – the maximum road impact score governs for the site. This score is based on the closure times observed from prior events or estimated for the site. The scoring system is defined in Table 3.9.
- *Annual Cost* – the annual maintenance costs for all unstable slopes were summed.
- These features capture how active and damaging the unstable slopes are within each site.

Table 3.7: Maintenance frequency scores in the ODOT unstable slopes database.

Maintenance Frequency	Score
5 times or more a year	100
4 to 5 times a year	94
4 times a year	88
3 to 4 times a year	81
3 times a year	75
2 to 3 times a year	69
2 times a year	63
1 to 2 times a year	56
once every year	50
once every 1 to 2 years	38
once every 2 years	25
once every 3 years	17
once every 4 years	13
once every 5 years or less	0

Table 3.8: Road Impact scores in the ODOT unstable slopes database.

Impact Type	Roadway Impact Score
landslide affects shoulder	3
landslide closure resulting in a >60-mile detour	100
landslide closure resulting in a 0–3-mile detour	54
landslide closure resulting in a 10–60-mile detour	85
landslide closure resulting in a 3–10-mile detour	70
landslide leaves 1-way traffic	27
landslide leaves 2-way traffic	9
rockfall contained in ditch	3
rockfall fills all or part of lane	100
rockfall no ditch, enters roadway	81
rockfall on roadway	27
rockfall onto shoulder	9

Figure 3.3: Example site with multiple unstable slopes within the zone that were aggregated to extract different hazard parameters.

3.2.5 SLIDO Proximity Analysis

The Statewide Landslide Database of Oregon (SLIDO, https://gis.dogami.oregon.gov/maps/slido/, DOGAMI (2020)) contains mapped polygons of landslide deposits and scarps uncovered through detailed geologic mapping efforts that have been aggregated into a single database. Most of these are currently mapped based on lidar elevation data given its ability to capture topography at high resolution to preserve landslide features in dense vegetation and follows the method established in Burns and Madin (2009). While these mapping efforts have been extensive, relatively small portions of the state have been mapped to-date from high-resolution (~1.0 m) lidar data. As a result, in many sections of the state, several landslides have yet to be mapped. This inventory also contains a point layer feature of historical landslides which includes landslides from major storm events in 1996-1997 and some of the landslides from ODOT's unstable slopes database.

To extract the risk to each site based on nearby landslide features, the *Proximity to Landslide* is computed as the distance between each hazard site polygon and landslide deposits (Figure 3.4). These distances were then classified based on the thresholds in Table 3.7. Notably, sites that intersected with landslides that have been active in the last few decades were given the highest score (4) while sites that intersected a landslide with no known movement were assigned a score of 3. Unfortunately, many landslides have limited documentation about recent or historic activity, thus we relied on the best available information (e.g., highway records, news reports, etc.) when available.

(a)

(b)

Figure 3.4: Example distance calculations for the hazard sites based on proximity to features in SLIDO. (a) landslides intersecting the trouble spot and (b) landslide in proximity to a trouble spot.

3.2.6 Landslide Susceptibility Analysis

While SLIDO is a massive landslide database, the inventory is far from complete given the challenges associated with landslide mapping resulting from the rugged terrain, dense vegetation, and prevalence of landslides throughout the state. Burns et al. (2016) produced a statewide landslide susceptibility layer at a scale of 1:8,000 (Figure 3.5), which is used to identify areas where landsliding is likely to occur. These maps were based on analysis of (1) slopes derived from a 10 m DEM, which was a composite of Oregon Lidar Consortium (OLC) data and the USGS national elevation dataset (NED), (2) geologic data, and (3) previously mapped landslides in SLIDO. Susceptibility is classified into four categories of Low, Moderate, High, and Very High. *Landslide Susceptibility* represents the hazard values mapped by Burns et al. (2016).

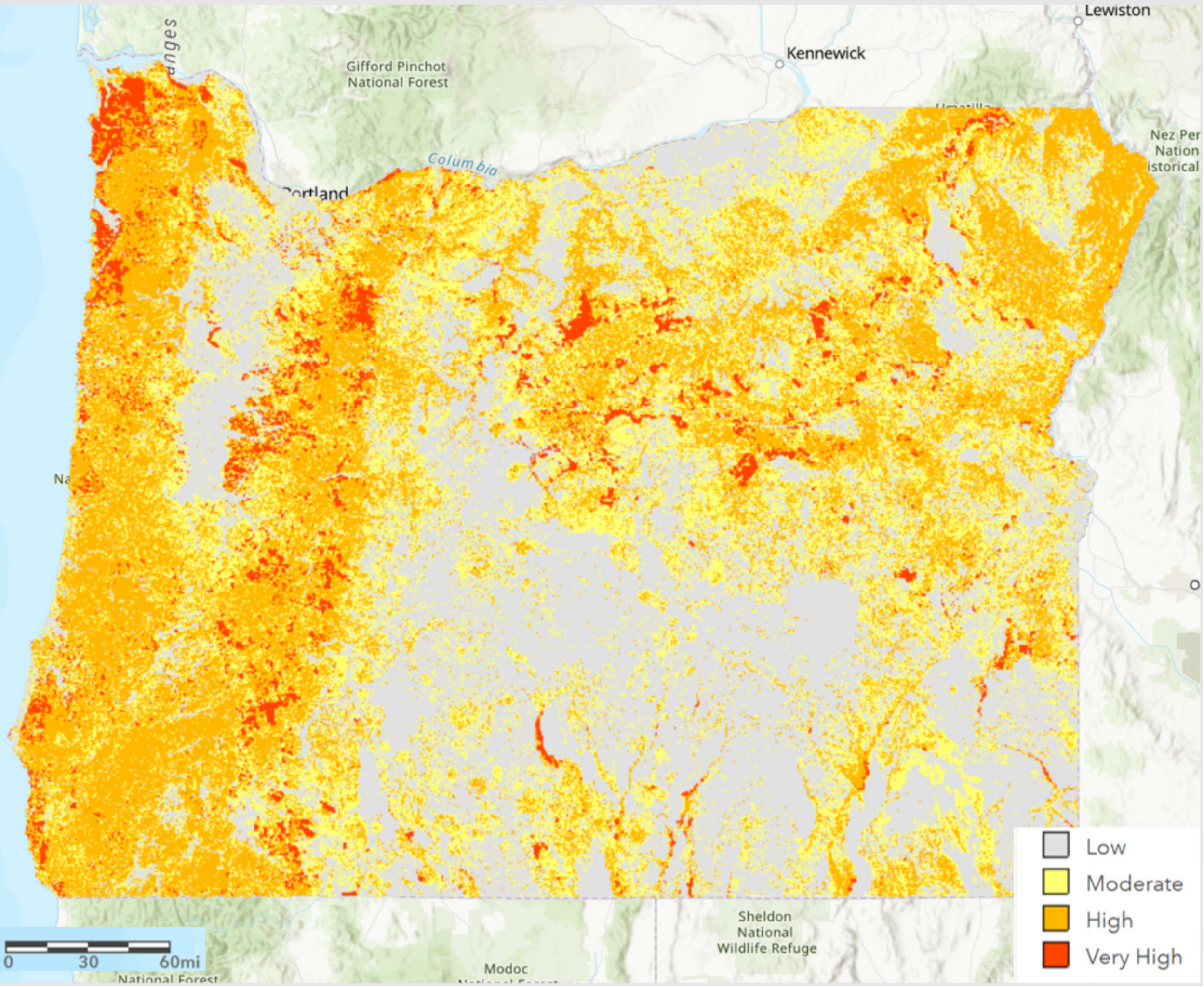
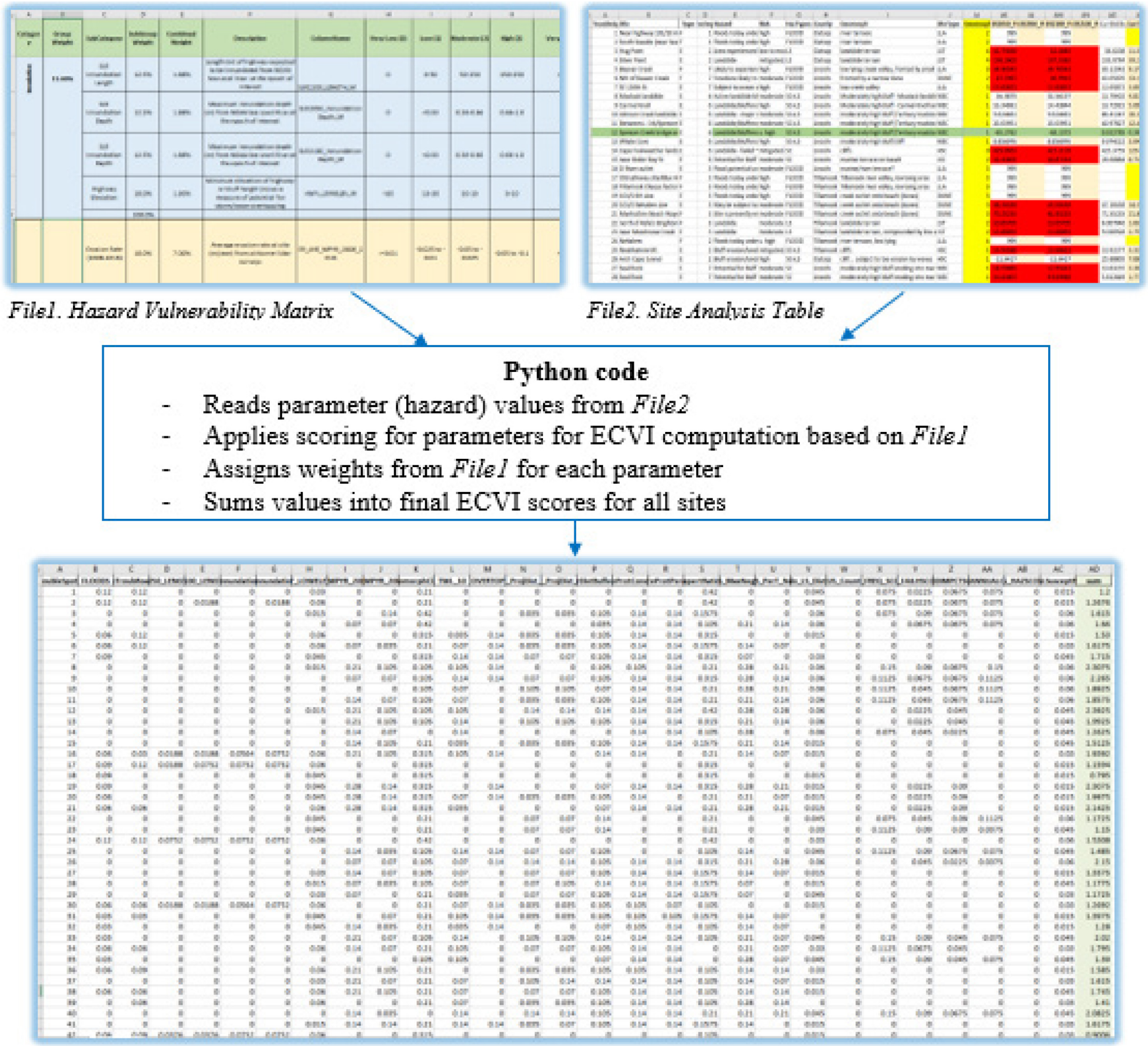


Figure 3.5: Burns et al. 2016 statewide landslide susceptibility layer.

3.3 ANALYSIS WORKFLOW

All parameters were compiled into a Site Analysis spreadsheet, which was integrated into a geodatabase feature class and provided as a digital file. A custom python script was developed to implement the analysis workflow (Figure 3.6). This script inputs the hazard vulnerability matrix and the site analysis table. It then applies the scoring following the classification thresholds in the hazard vulnerability matrix tables (Tables 3.4, Table 3.5, and Table 4.6) such that each parameter is converted to the range of 0-4. Those values are then multiplied by the weights for each parameter as outlined in those tables. The results are then summed to compute the ECVI score for each site following Equation 3.3b. Appendix C.3 contains the python script and associated input tables.



Python code

- Reads parameter (hazard) values from *File2*
- Applies scoring for parameters for ECVI computation based on *File1*
- Assigns weights from *File1* for each parameter
- Sums values into final ECVI scores for all sites

Figure 3.6: Analysis workflow inputs and outputs

4.0 EROSION RATE ANALYSIS

This section describes methods used to compute both short- and long-term erosion rates.

4.1 SHORT-TERM EROSION RATES

4.1.1 Available Airborne Lidar Datasets

Short-term erosion rates were estimated for 40 sites with primary erosion hazards of the 71 total trouble spot sites across the Oregon Coast. While there were 45 sites initially identified for this analysis, 5 sites were not feasible given that the airborne lidar data either did not capture the site (e.g., too far inland) or data were too sparse (e.g., no substantial seacliff or too much vegetation) at those sites. Appendix C.4 contains the detailed results of this assessment.

To compute the erosion rates, publicly available airborne lidar datasets from the Oregon Lidar Consortium (OLC) and NOAA Digital Coast were used (Table 4.1). Three epochs of suitable data were available across the entire Oregon Coast spanning the period from 2002 to 2016. While the 2002 NASA/USGS dataset was not as reliable from a resolution/accuracy perspective and had not been ground filtered to bare earth, this dataset was included in the analysis in order to increase the temporal range covered by the analysis. The OLC dataset consists of two subsets: a dataset collected south of Florence, OR in 2008 and a dataset collected north of Florence, OR in 2009. The 2008/2009 OLC datasets and the 2016 USGS dataset were found to be the most reliable, with high point density and reasonable accuracy values (Table 4.1). The resolution/accuracy of the 2014 USACE dataset was found to be inadequate especially compared to the 2016 USGS dataset collected at a relatively similar time window. As a result, two short term erosion rates (2002 to 2016 and 2008/9 to 2016) could be computed with the former providing a longer range in time and the latter based on higher quality data.

Table 4.1: Brief overview and Metadata of the airborne lidar datasets used to compute erosion rates at the selected sites across the Oregon Coast.

Collection Date	Agency source	Accuracy		Typical Point spacing (m)	Metadata link
		Hor. (m)	Vert. (m)		
2002/09/18 – 2002/10/03	NASA/ USGS	0.8	0.15	3	https://www.fisheries.noaa.gov /inport/item/49634; (OCM Partners 2022a)
2008/04/27 – 2009/04/05	DOGAMI	N/A	0.07	0.35	https://www.fisheries.noaa.gov /inport/item/49903; (OCM Partners 2022b)
2009/04/05 – 2009/08/09	DOGAMI	N/A	0.03	0.35	https://www.fisheries.noaa.gov /inport/item/49906; (OCM Partners, 2022c)
2014/07/30 – 2014/09/13	USACE	1.0	0.1	0.35	https://www.fisheries.noaa.gov /inport/item/49456 (OCM Partners, 2022d)
2016/04/28 – 2016/05/28	USGS	0.21	0.06	0.12	https://www.fisheries.noaa.gov /inport/item/48222; (OCM Partners, 2022e)

4.1.2 Computations

Short-term erosion rates were computed from airborne lidar datasets for all hazard sites that consisted of a well-defined seacliff or dune. Data were downloaded from the publicly available NOAA Digital Coast dataviewer website (https://coast.noaa.gov/dataviewer/) or OSU lidar data server. Data from the NOAA digital coast was downloaded as point clouds in the .laz format in the Oregon State Plane Coordinate system (NAD83(2011) Epoch 2010, meters, NAVD88 Geoid18) in either the North or South zone depending on the location of the site.

Seacliff extents for each point cloud were manually cropped using the segment tool in Cloud Compare v2.11 software (CloudCompare 2021). Long sections of cliffs or sections with complex geometry were divided into subsections. Large obstructions such as sections of vegetation were also removed using the segment tool. Data exported from Cloud Compare were further ground filtered using the RAMBO software (Olsen et al. 2021), followed by hole filling with a thin plate spline to help reduce data gaps within the model (Olsen et al., 2015). Change analysis (e.g., Figure 4.1) was then performed using the RAMBO software (Olsen et al. 2021), where a best fit plane was fit to the seacliff of the first data epoch to set a reference plane for the change analysis. A 1-m grid was then created on this plane and change was computed on a per cell basis. Changes values less than 0.1m (significant change threshold) were ignored in further analysis as they were assumed to be within the georeferencing error range for the datasets. The average change across the seacliff was then computed between the 2002 and 2016 datasets, and the 2008/2009 and 2016 datasets. The average change was then normalized by time to yield the time normalized average change (m/yr). The normalized average change (m/yr) between both the 2002 to 2016 (Table 4.2) and 2008/2009 to 2016 (Table 4.3) datasets was then used as an input of the Hazard Vulnerability Assessment (Section 3.0).

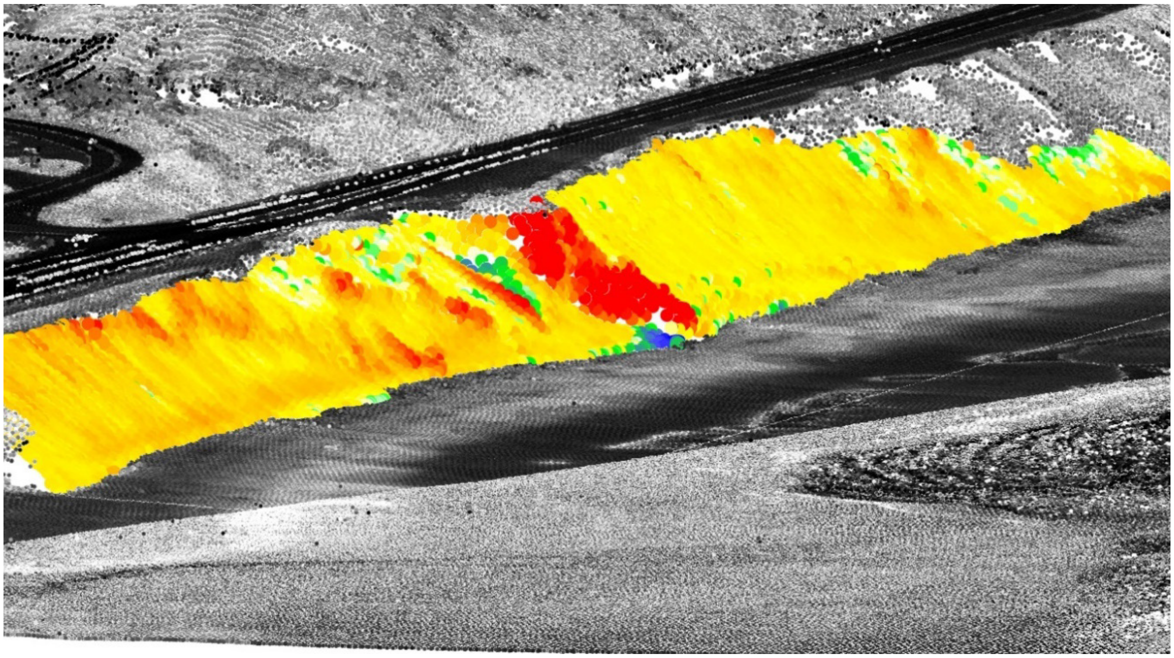


Figure 4.1: Example airborne lidar change detection analysis for Spencer Creek (2009 to 2016) showing example of cropped data. Red color denotes large change (erosion) while blue colors indicate accretion.

Table 4.2: Erosion Statistics for each site computed using the 2002 and 2016 airborne lidar datasets.

ID	Site Name	Section#	Length (m)	Change (m)				Normalized Change (m/yr)			
				Δ_{ave}	Δ_{std}	Δ_{min}	Δ_{max}	Δ_{ave}	Δ_{std}	Δ_{min}	Δ_{max}
3	Hug Point	0	223	-1.39	1.91	-9.31	1.48	-0.10	0.14	-0.68	0.11
4	SilverPoint	0	300	-0.49	0.80	-4.14	2.47	-0.04	0.06	-0.30	0.18
8	Moolack Landslide	0	714	-1.18	1.57	-9.66	3.74	-0.09	0.11	-0.71	0.27
9	Carmel Knoll	0	244	-0.41	0.95	-4.67	1.86	-0.03	0.07	-0.34	0.14
10	Johnson Creek landslide	0	352	0.00	0.74	-3.21	2.15	0.00	0.05	-0.24	0.16
11	Between J Crk/Spencer Creek	0	120	-0.41	0.59	-3.82	1.80	-0.03	0.04	-0.28	0.13
12	Spencer Creek bridge and seacliff	0	530	-0.82	0.65	-5.70	1.08	-0.06	0.05	-0.42	0.08
13	Whale Cove	0	N/A	No points on seacliff							
14	Cape Foulweather	0	325	-0.62	1.81	-21.59	17.00	-0.05	0.13	-1.58	1.25
15	near Boiler Bay St	0	120	-0.89	1.58	-8.37	3.44	-0.06	0.12	-0.61	0.25
21	Manhatten Beach Wayside	0	N/A	Dune, not seacliff - seems to be eroding very fast							
25	Neahkahnie Mt	0	450	-0.33	0.88	-9.62	8.75	-0.02	0.06	-0.71	0.64
26	Arch Cape tunnel	0	141	-0.63	0.65	-3.49	0.76	-0.05	0.05	-0.26	0.06
27	Seal Rock	0	140	-0.62	0.52	-2.74	0.60	-0.05	0.04	-0.20	0.04
		1	50	-0.58	0.59	-2.35	0.54	-0.04	0.04	-0.17	0.04
28	Seal Rock	0	180	-0.14	0.52	-2.65	2.29	-0.01	0.04	-0.19	0.17
29	intersect SW Whitecap Dr - Hwy 101	0	468	0.14	0.73	-4.68	2.56	0.01	0.05	-0.34	0.19
31	intersect SW Wakonda Beach Rd - Hwy 101	0	172	-0.69	0.77	-2.69	1.12	-0.05	0.06	-0.20	0.08
31	intersect SW Wakonda Beach Rd - Hwy 101	1	283	-0.30	1.03	-3.02	1.88	-0.02	0.08	-0.22	0.14
32	Annice Creek	0	110	-0.19	0.53	-2.30	1.64	-0.01	0.04	-0.17	0.12
33	Stonefield Beach	0	375	-0.37	0.99	-12.50	5.27	-0.03	0.07	-0.92	0.39
35	Ocean Beach	0	48	-0.51	0.61	-2.68	0.66	-0.04	0.04	-0.20	0.05
		1	57	0.85	1.25	-0.96	4.86	0.06	0.09	-0.07	0.36
37	Gywnn Creek	0	153	-0.68	1.26	-3.73	1.87	-0.05	0.09	-0.27	0.14
		1	60	0.08	0.29	-0.34	0.61	0.01	0.02	-0.03	0.04

ID	Site Name	Section#	Length (m)	Change (m)				Normalized Change (m/yr)			
				Δ_{ave}	Δ_{std}	Δ_{min}	Δ_{max}	Δ_{ave}	Δ_{std}	Δ_{min}	Δ_{max}
39	Big Creek	0	82	-0.25	0.32	-1.07	0.29	-0.02	0.02	-0.08	0.02
		1	56	0.17	0.34	-0.78	0.91	0.01	0.03	-0.06	0.07
40	Sea Lion Pt	0	390	-0.32	1.01	-6.81	3.51	-0.02	0.07	-0.50	0.26
41	North Depoe Bay	0	67	-3.34	3.43	-9.98	0.87	-0.24	0.25	-0.73	0.06
45	Port Orford to Gregory Point	0	260	-1.33	1.65	-7.60	3.38	-0.10	0.12	-0.56	0.25
		1	200	-0.23	1.61	-4.35	5.08	-0.02	0.12	-0.32	0.37
		2	315	-0.39	0.92	-4.00	2.52	-0.03	0.07	-0.29	0.19
46	Rocky Point to Coal Point	0	170	-0.80	0.71	-3.33	1.93	-0.06	0.05	-0.24	0.14
46		1	350	-0.21	0.83	-3.29	2.77	-0.02	0.06	-0.24	0.20
47	near Brush Creek	0	711	-0.14	1.02	-6.02	3.31	-0.01	0.08	-0.44	0.24
48	Arizona Inn	0	305	-4.47	2.01	-10.38	1.41	-0.33	0.15	-0.76	0.10
49	Sisters Rock to Devils Backbone	0	510	-0.47	1.03	-5.11	3.83	-0.03	0.08	-0.37	0.28
		1	140	-0.27	0.93	-3.96	3.52	-0.02	0.07	-0.29	0.26
		2	215	-0.19	0.86	-3.52	3.29	-0.01	0.06	-0.26	0.24
50-53	Ophir Beach	0	328	-0.96	1.35	-6.21	3.44	-0.07	0.10	-0.46	0.25
54	Nesika Beach	0	1600	-0.23	0.36	-2.16	1.65	-0.02	0.03	-0.16	0.12
56	South Side of Hunter Creek	0	Vegetated Dune (No Seacliff)								
57	Near Myers Creek	0	Vegetated Dunes (No Seacliff)								
58	Pistol River	0	544	-0.57	0.86	-3.87	2.10	-0.04	0.06	-0.28	0.15
59	Hooskanaden	0	305	-2.43	1.84	-6.01	3.02	-0.18	0.13	-0.44	0.22
		1	105	-2.52	1.63	-5.94	2.84	-0.18	0.12	-0.44	0.21
60	near Rainbow Rock (Taylor Creek)	0	535	-0.28	0.69	-4.88	2.67	-0.02	0.05	-0.36	0.20
61	near Seal Pt (Spruce Creek)	0	288	-0.26	0.76	-5.27	1.84	-0.02	0.06	-0.39	0.14
63	Alsea Bay	0	N/A	Since this is located in a bay (further inland), only the 2009 dataset contains coverage							
68	Squaw Creek	0	177	-0.61	0.95	-3.40	1.38	-0.04	0.07	-0.25	0.10
		1	402	-0.43	1.09	-8.62	2.18	-0.03	0.08	-0.63	0.16
69	Baker Beach slide	0	532	-0.86	1.40	-6.32	1.91	-0.06	0.10	-0.46	0.14

ID	**Site Name**	**Section#**	**Length (m)**	**Change (m)**				**Normalized Change (m/yr)**			
				Δ_{ave}	Δ_{std}	Δ_{min}	Δ_{max}	Δ_{ave}	Δ_{std}	Δ_{min}	Δ_{max}
70	Hubbard Creek	3	202	-0.41	0.65	-2.88	2.17	-0.03	0.05	-0.21	0.16
		4	93	-0.83	0.49	-2.33	0.47	-0.06	0.04	-0.17	0.03

Table 4.3: Erosion Statistics for each site computed using the 2008/2009 and 2016 airborne lidar datasets.

ID	**Site Name**	**Section#**	**Length (m)**	**Change (m)**				**Normalized Change (m/yr)**			
				Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}
3	Hug Point	0	223	-0.06	0.94	-4.73	3.94	-0.01	0.13	-0.66	0.55
4	SilverPoint	0	300	-0.15	0.51	-3.38	2.44	-0.02	0.07	-0.47	0.34
8	Moolack Landslide	0	714	-0.64	1.02	-6.00	2.61	-0.09	0.14	-0.84	0.36
9	Carmel Knoll	0	244	-0.15	0.63	-3.43	1.77	-0.02	0.09	-0.48	0.25
10	Johnson Creek landslide	0	352	0.05	0.57	-4.72	3.88	0.01	0.08	-0.66	0.54
11	Between J Crk/Spencer Creek	0	120	-0.33	0.30	-2.94	0.86	-0.05	0.04	-0.41	0.12
12	Spencer Creek bridge and seacliff	0	530	-0.41	0.42	-4.91	3.29	-0.06	0.06	-0.69	0.46
13	Whale Cove	0	N/A	*No points on seacliff*							
14	Cape Foulweather	0	325	-0.31	0.64	-8.01	10.45	-0.04	0.09	-1.12	1.46
15	near Boiler Bay St	0	120	-0.28	0.93	-8.16	4.21	-0.04	0.13	-1.14	0.59
21	Manhatten Beach Wayside	0	N/A	*Dune, not seacliff - seems to be eroding very fast*							
25	Neahkahnie Mt	0	450	-0.23	0.33	-17.97	5.80	-0.03	0.05	-2.51	0.81
26	Arch Cape tunnel	0	141	-0.08	0.29	-2.10	0.78	-0.01	0.04	-0.29	0.11
27	Seal Rock	0	140	-0.28	0.33	-2.14	1.08	-0.04	0.05	-0.30	0.15
		1	50	-0.33	0.36	-2.25	0.79	-0.05	0.05	-0.31	0.11
28	Seal Rock	0	180	-0.09	0.27	-2.21	1.97	-0.01	0.04	-0.31	0.28
29	intersect SW Whitecap Dr - Hwy 101	0	468	-0.09	0.72	-5.08	2.01	-0.01	0.10	-0.71	0.28
31	intersect SW Wakonda Beach Rd - Hwy 101	0	172	0.03	0.53	-1.44	1.39	0.00	0.07	-0.20	0.19

ID	Site Name	Section#	Length (m)	Change (m)				Normalized Change (m/yr)			
				Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}
31	intersect SW Wakonda Beach Rd - Hwy 101	1	283	0.33	0.69	-2.29	2.09	0.05	0.10	-0.32	0.29
32	Annice Creek	0	110	-0.25	0.53	-2.90	0.92	-0.04	0.07	-0.40	0.13
33	Stonefield Beach	0	375	-0.60	1.20	-19.83	2.80	-0.08	0.17	-2.77	0.39
35	Ocean Beach	0	48	-0.24	0.25	-1.55	0.69	-0.03	0.03	-0.22	0.10
		1	57	0.49	0.31	-0.18	2.06	0.07	0.04	-0.02	0.29
37	Gywnn Creek	0	153	-0.89	1.01	-4.68	1.73	-0.12	0.14	-0.65	0.24
		1	60	-0.24	0.27	-1.70	0.23	-0.03	0.04	-0.24	0.03
39	Big Creek	0	82	-0.15	0.14	-0.80	0.24	-0.02	0.02	-0.11	0.03
39	Big Creek	1	56	0.14	0.15	-0.32	0.81	0.02	0.02	-0.05	0.11
40	Sea Lion Pt	0	390	-0.27	0.59	-5.24	2.68	-0.04	0.08	-0.73	0.37
41	North Depoe Bay	0	67	-0.19	0.39	-3.35	2.61	-0.03	0.05	-0.47	0.37
45	Port Orford to Gregory Point	0	260	-0.26	0.98	-5.47	3.00	-0.03	0.13	-0.70	0.38
		1	200	-0.88	1.43	-6.43	1.38	-0.11	0.18	-0.82	0.18
		2	315	-0.16	0.35	-2.12	1.59	-0.02	0.04	-0.27	0.20
46	Rocky Point to Coal Point	0	170	-0.32	0.37	-2.04	2.00	-0.04	0.05	-0.26	0.25
		1	350	-0.22	0.54	-2.79	1.77	-0.03	0.07	-0.35	0.22
47	near Brush Creek	0	711	-0.49	1.24	-7.02	3.05	-0.06	0.16	-0.89	0.39
48	Arizona Inn	0	305	-2.31	1.52	-8.59	2.05	-0.29	0.19	-1.09	0.26
49	Sisters Rock to Devils Backbone	0	510	-0.22	0.54	-4.24	2.90	-0.03	0.07	-0.54	0.37
		1	140	-0.18	0.68	-2.58	4.04	-0.02	0.09	-0.33	0.51
		2	215	-0.24	0.34	-2.21	1.71	-0.03	0.04	-0.28	0.22
50-53	Ophir Beach	0	328	-1.02	1.21	-5.40	1.00	-0.13	0.15	-0.69	0.13
54	Nesika Beach	0	1600	0.03	0.13	-1.21	1.38	0.00	0.02	-0.15	0.18
56	South Side of Hunter Creek	0	*Vegetated Dune (No Seacliff)*								
57	Near Myers Creek	0	*Vegetated Dunes (No Seacliff)*								
58	Pistol River	0	544	-0.26	0.28	-2.00	0.90	-0.03	0.04	-0.25	0.11

ID	Site Name	Section#	Length (m)	Change (m)				Normalized Change (m/yr)			
				Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}	Δ_{ave}	Δ_{std}
59	Hooskanaden	0	305	-3.25	1.17	-6.39	0.17	-0.41	0.15	-0.81	0.02
		1	105	-1.22	1.06	-5.54	0.62	-0.15	0.13	-0.70	0.08
60	near Rainbow Rock (Taylor Creek)	0	535	-0.28	0.68	-5.03	2.60	-0.04	0.09	-0.64	0.33
61	near Seal Pt (Spruce Creek)	0	288	-0.19	0.32	-3.24	2.00	-0.02	0.04	-0.41	0.25
63	Alsea Bay	0	N/A	*Since this is in bay (further inland), only 2009 dataset contains coverage*							
68	Squaw Creek	0	177	-0.88	0.96	-5.02	0.81	-0.12	0.13	-0.70	0.11
		1	402	-0.47	0.84	-6.57	4.82	-0.07	0.12	-0.92	0.67
69	Baker Beach slide	0	532	-0.71	1.33	-23.92	10.01	-0.10	0.19	-3.34	1.40
70	Hubbard Creek	1	89	-0.48	0.89	-2.89	1.75	-0.06	0.11	-0.37	0.22
		2	43	-1.57	0.97	-3.33	0.45	-0.20	0.12	-0.42	0.06
		3	202	-0.29	0.29	-2.51	1.21	-0.04	0.04	-0.32	0.15
		4	93	-0.27	0.32	-2.44	0.89	-0.03	0.04	-0.31	0.11

4.2 LONG-TERM EROSION RATES

4.2.1 Overview

Over the past three decades a number of studies have attempted to define the patterns and rates of erosion for different rock lithologies for coastal seacliffs located along the Oregon coast (Table 4.4), including Seal Rock to Roads End in Lincoln County (Priest et al., 1994), Sisters Rock to North Gold Beach, Curry County (Priest et al., 2004), Cascade Head to Seal Rock, Lincoln County (Priest and Allan, 2004), Seal Rock to Cape Perpetua, Lincoln County (Witter et al., 2007), and in southern Clatsop County (Witter et al., 2009). In each case, discrete measurements of identified features in serial imagery are made, typically a house to seacliff top distance. Although these efforts provided extremely useful results, they inevitably lack sufficient spatial coverage and have potentially large uncertainties in the calculated rates of change as the temporal period of observation is limited to the period of study. For example, efforts by Priest and Allan (2004) use early 1939 aerial images where coverage is good, while other studies use 1967 aerial images to estimate change. Unfortunately, there is no sustained effort to document the long-term rates and patterns of coastal erosion on coastal seacliffs, which remains a limitation for projecting future erosion responses that may be used by resource managers and ODOT.

As noted in Section 1.0, a variety of studies have focused on documenting long-term patterns of coastal change by evaluating shoreline positions that may be derived from analyzing historical National Ocean Service (NOS) topographic “T” sheets depicting the mean high-water line on maps, extracting wet/dry shorelines from aerial imagery, and more recently by analyzing tidal datum-based (e.g. mean high water (MHW) or mean higher high water (MHHW)) shorelines from airborne lidar data (e.g., Allan et al., 2003; Ruggiero et al., 2013; Light, 2021). Nevertheless, these datasets have their own limitations. For example, the earliest NOS surveys of shorelines on the Oregon coast occurred in the late 1920s and were mapped at 1:20,000 scale. Uncertainties associated with the position of these shorelines are large, ~±20 m (Moore, 2000). Although coastwide aerial imagery of the Oregon coast was collected in 1939, georeferencing these data is extremely challenging, time consuming, and/or often not possible due to the absence of suitable ground control points. High-quality imagery did not begin to be collected until 1967, which would ultimately form the baseline from which many recent studies of coastal change have been based. The 1967 aerial photographs were flown for ODOT for the purposes of helping to delineate a shore zone boundary (Jung et al., 2022), and were eventually used to establish the “statutory vegetation line” for determining the permitting of coastal engineering structures. The images were flown at low altitude (1:6,000 scale, ~900 m elevation) between June and October 1967 and provide an excellent snapshot of the coastal strip at the time. In 2008, DOGAMI contracted with the Washington Department of Ecology to orthorectify the images. This was accomplished using Leica Photography Suite (LPS), from which a wet/dry shoreline was digitized. Since the 1990s, high-resolution orthorectified aerial imagery specifically for the coast has been collected on a more regular basis, the most recent of which was in 2018.

The main limitation of these datasets is that the imagery reflects discrete shoreline “snapshots” in time. Analyses of these imagery and the identified coastal changes, reveal large variability in the position of the shoreline due to its sensitivity to seasonal and interannual (e.g., El Niños) variations in ocean water levels and impacts from storms that are episodic in nature (Allan et al., 2003; Ruggiero et al., 2013). This makes determining reliable erosion rates from such data problematic, due to the large envelope of shoreline variability.

Table 4.4: Erosion rates defined for coastal seacliffs of different lithologic compositions from previous research.

Location	Lithology	Erosion Rate (m/yr)	Error (m/yr)	σ (m/yr)
[1]Clatsop County	Miocene Grande Ronde Basalt	-0.03	0.09	-
	Resistant sedimentary rock	-0.03	0.03	-
	Interbedded mudstone	-0.06	0.09	-
	Quaternary deposits	-0.08	0.08	-
[2]Tillamook County	Basalt and hard sandstone	-0.02	0.05	0.036
	Interbedded sandstone, siltstone, claystone	-0.06	0.08	0.039
	Soft quaternary sediments	-0.08	0.07	0.081
[3]Beverly Beach	Sedimentary rock (Astoria)	-0.25	0.12	0.024
[3]Holiday Beach to Lost Creek	Sedimentary rock (Nyems)	-0.09	0.04	0.006
[3]Lincoln City (Wecoma Beach)	Marine Terrace Sand	-0.09	0.06	0.003
[3]Gleneden Beach	Marine Terrace Sand	-0.09	0.11	0.003
[4]Headlands, Nesika Beach to Gold Beach	Hard Mesozoic Metamorphic Rocks	-0.02	0.09	0.021
[4]Seacliffs, south of Sisters Rock	Cretaceous and Jurassic sedimentary and metamorphic rocks	-0.02	0.09	0.034
[4]Euchre Creek to Nesika Beach	Marine terrace deposits over Jurassic sedimentary and metamorphic rocks	-0.40	0.09	0.003
[4]South Nesika Beach	Marine terrace deposits over Jurassic sedimentary and metamorphic rocks	-0.59	0.09	0.012
[4]Nesika Beach to Otter Point	Marine terrace deposits over Jurassic sedimentary and metamorphic rocks	0.26 0.16	0.09 0.09	0.098 0.064
[4]Otter Point to north jetty	Marine terrace deposits over Jurassic sedimentary and metamorphic rocks	-0.02	0.09	

Notes: [1]Witter et al., 2009; [2]Allan and Priest (2001); [3]Priest and Allan (2004); [4]Priest et al., (2004)

Beginning in 1997, high resolution airborne lidar data have been collected along the coast that complement the use of aerial imagery in evaluating coastal change in Oregon. As noted in Section 1, a combination of these various datasets was previously analyzed by Ruggiero et al. (2013) in order to assess coastal changes along the coast of Oregon and Washington. However, the analyses focused on the dune-backed beaches and hence did not evaluate erosion patterns on coastal seacliffs. Thus, large parts of the coast (e.g., Curry County) were not evaluated because of the dearth of data on which to define any changes that may be taking place.

Besides aerial imagery and lidar, recent efforts by DOGAMI have been directed at establishing a coastal monitoring program to document seasonal to interannual coastal change, which includes measurements undertaken at discrete beach profile sites as well as the collection of tidal datum-based shorelines. Currently, this is achieved using RTK-DGPS with monitoring now established at multiple locations along the Oregon coast, including the Rockaway and Clatsop littoral cells (Allan and Hart, 2008), Neskowin (Allan and Hart, 2007), Gold Beach-Nesika Beach-Netarts (Allan and Stimely, 2013), the Cannon Beach cell (Allan et al., 2018) and many other sites (http://nvs.nanoos.org/BeachMapping). Although such a rich dataset of coastal change is now established for many north coast beaches, with identified trends (e.g., Figure 4.2), regular, repeat surveys of many other sites (especially those on the south coast) do not have the same temporal resolution largely due to insufficient funding. Nevertheless, Figure 4.2 highlights certain important characteristics that are typical of PNW beach responses that provide guidance on the role of coastal processes in driving change. First, observations at the 3 m contour (nearest to the intertidal zone and hence the "shoreline"), demonstrate significant variability in the beach responses due to the strong seasonality of ocean waves and tides that characterize PNW beaches. These excursions can be very large (Figure 4.2), spanning many 10s of meters between summer and winter. This is further demonstrated in Figure 4.3, which is derived from RTK-DGPS surveys of the MHHW shoreline (light blue lines) collected by DOGAMI; the calculated change rate at the 3 m elevation at the Neskowin site is -1.21 ±0.71 m/year. These data highlight one of the challenges when using discrete "snapshots" of shorelines derived from aerial imagery, where the time intervals between measurements may be long, such that the results may be strongly affected by those few discrete measurements.

At higher elevations on the beach, such as the 6 m elevation located close to the dune or seacliff toe, there is much less variability (Figure 4.2) with a calculated erosion rate of -0.45 ±0.14 m/year. At these higher elevations, the erosion is now driven almost entirely in response to effects from extreme winter storms (coupled with high tides), which results in periodic abrupt landward movements in the position of the contour during the winter (e.g., 6 m contour in Figure 4.2), while highlighting a smoother, overall long-term trend. Although, monitoring efforts such as this are extremely valuable for dune-backed beaches where errors in the approach are low relative to the magnitude of changes being observed, the same cannot be said for performing RTK-DGPS measurements of seacliff profiles given that the approach of surveying down a seacliff face using GPS is prone to large errors and uncertainty due to the generally slower rates of change. Resolving this limitation can only be achieved by establishing a monitoring program that is founded on repeat measurements of the seacliff face using terrestrial lidar (as described in Section 6.1 and underway in SPR807).

In summary, many studies have identified estimates of short to long-term coastal change rates for different parts of the Oregon coast (Table 4.4), which have been derived from a variety of datasets, each with their own pros and cons. While it is not unreasonable to use these existing datasets to make projections of future changes along U.S. Highway 101, we chose to further evaluate the long-term change rates for each of the vulnerable sites along the highway.

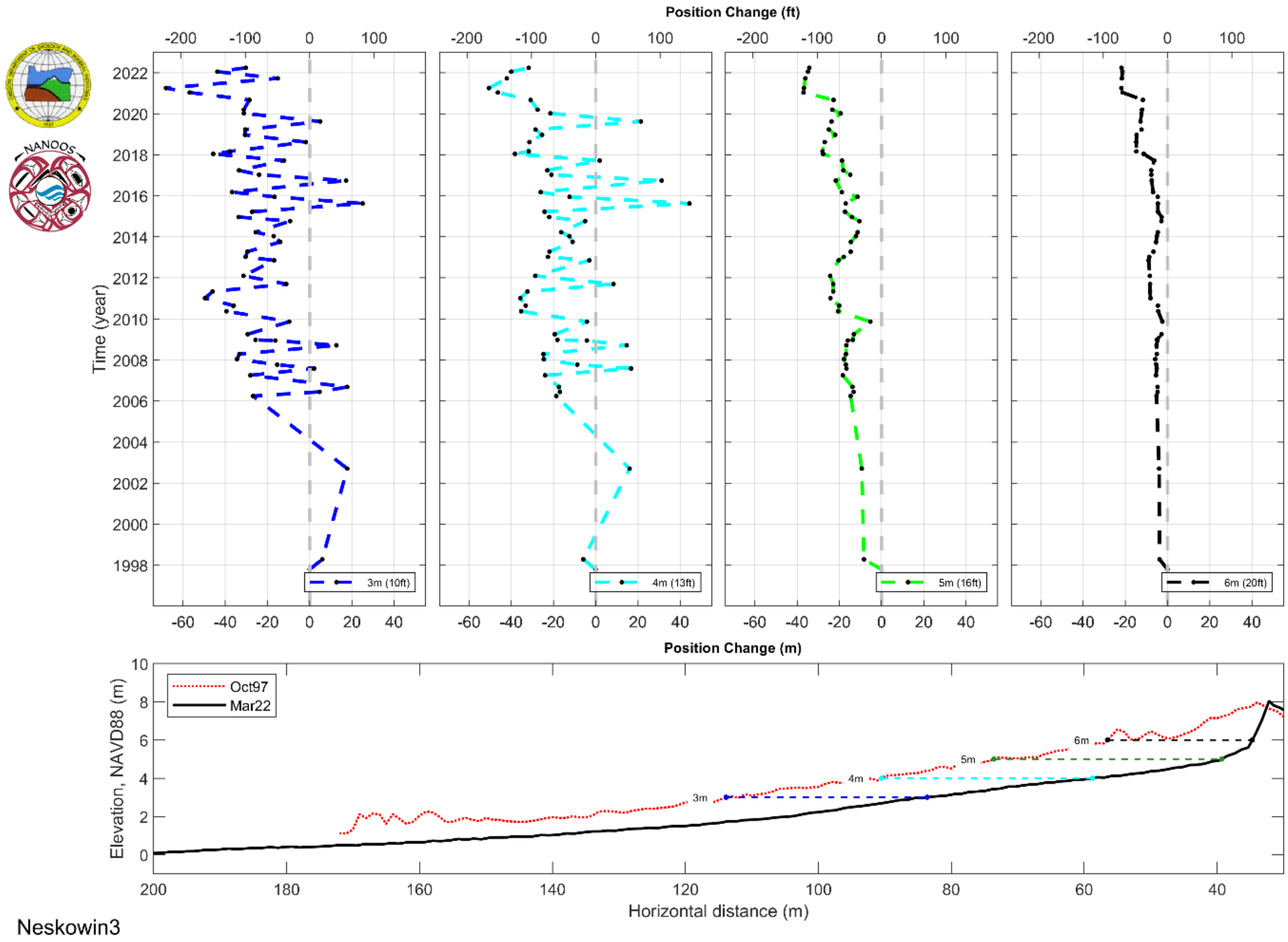


Figure 4.2: Seasonal surveys of beach responses in the Neskowin littoral cell at station Neskowin 3 (http://nvs.nanoos.org/BeachMapping). Plot shows the seasonal to interannual variability at different contour elevations across the beach. Negative positions in the contours indicate erosion, positive values denote accretion.

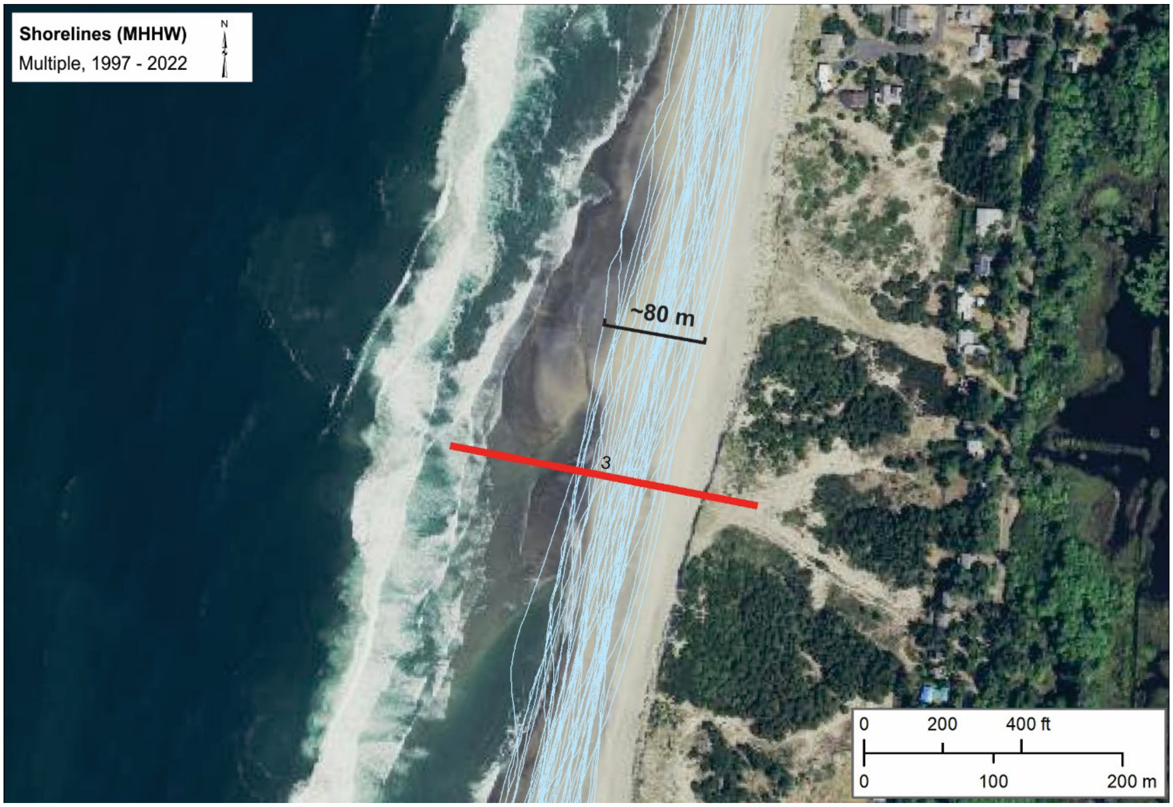


Figure 4.3: MHHW shorelines of the Neskowin shoreline derived from repeat surveys undertaken by DOGAMI. Red line denotes a long-term beach monitoring station (Neskowin 3).

4.2.2 Digitization

To evaluate long-term rates of coastal change, we used the 1967 orthorectified aerial images of the Oregon coast as our baseline, along with modern imagery collected by the State of Oregon in 2018 to characterize the most recent position of the seacliff top. According to metadata included with the 1967 imagery, the images were originally scanned at high resolution to yield a pixel resolution of 0.5 m. The imagery was then geo-referenced using Leica Photogrammetry Suite software, v9.1 with the aid of 2005 color orthoimages and local ground control points (e.g., road intersections or natural features such as large boulders on the beach) that could be identified in both the 1967 and 2005 imagery. Identified total RMS errors after processing the 1967 imagery was determined to average ~3 m (Table 4.5) with a maximum error of ~11 m; error in mapping the mean shoreline (wet/dry sand line) was determined to be ~10 m. Aerial imagery collected in 2018 have a reported accuracy of 0.9 m at the 95% confidence level when compared with true ground (Table 4.5).

We carefully digitized the seacliff-top/vegetation line in ESRI ArcGIS Desktop version 10.7 for each of the identified vulnerable sites (e.g., Manhattan Beach State Recreation Site, Figure 4.4). Mapping was undertaken typically at ~1:500 scale. Lidar data collected by the OLC in 2008/2009 and more recently in 2016 by the USACE were used to further evaluate and check our mapping of the 2018 seacliff-top/vegetation lines. At two locations (Ocean Beach, Lane County and Rainbow Rock, Curry County), we resorted to using 1995 aerial imagery due to large errors in the 1967 imagery. At the Ocean Beach site, a seam in the overlapping imagery contributed to considerable distortion, while at Rainbow Rock we were simply unable to define the vegetation line/seacliff top in the 1967 photo. To assess potential errors in our digitizing, we spot checked the identified vegetation/seacliff line at a number of sites by measuring additional lines either side of the originally determined bluff top. From these offsets, we determined that our mapping accuracy was typically better than 2 m (Table 4.5). In a few locations where it was difficult to identify the bluff top (identified in our GIS database) our mapping error increased to 3 to 4 m.

Table 4.4: Historical datasets used to compute erosion rates.

Imagery	Resolution (m)	Horizontal RMS Error (m)	Mapping Error
1967 aerial photographs, orthorectified. 1:6000 scale	0.5	2.96	Typically < 2m. Notably, a few sites had identified errors of ~3 to 4 m due to challenges in defining the seacliff top.
1995 orthophotos	1	7	Not evaluated
2016 lidar data	0.5	0.21	Not evaluated
2018 orthophotos	0.3	0.9	< 2m

Overall, we identify historical, long-term coastal seacliff changes at 45 applicable sites of the 71 trouble spot sites (primarily flooding hazard sites were not analyzed for erosion). We did not evaluate rates of change at several of the Highway 101 vulnerable sites, primarily because the 1967 imagery did not extend sufficiently far enough inland to map (1) landslide sites located up coastal estuaries (e.g., Nehalem estuary), (2) sites subject to combinations of riverine and tidal flooding (e.g., Nehalem, Alsea Bay, Necanicum River), or (3) along a few of the high seacliffs composed of basalt (e.g., Neahkahnie Mountain).

4.2.3 DSAS Analysis

Having mapped the vegetation/seacliff top features in a GIS, the results were processed using the Digital Shoreline Analysis System (DSAS) tool developed by the U.S. Geological Survey (Himmelstoss et al., 2021). The DSAS tool is an add-in to Esri ArcGIS Desktop version 10.4–10.7 that enables a user to calculate rate-of-change statistics from a time series of vector shoreline positions. DSAS includes an automated method to establish measurement locations, performs rate calculations, and evaluates the statistical data necessary to assess the reliability of the change rate calculations (Himmelstoss et al., 2021). To operate the tool, a user first defines a series of baselines along a coastline of interest. For the purposes of this study, this was undertaken for each of the 45 Highway 101 sites with primarily erosion hazards and was established landward of the seacliff top. Transects are then automatically cast by DSAS seaward and perpendicular to each baseline of interest. Although DSAS provides several functional controls that help account for areas subject to large shoreline curvature, we typically created shorter baselines, and manipulated the controls to ensure the transects were aligned shore-normal. For the purposes of this study, we chose to cast transects spaced 10 m apart. The tool then requires input of the shoreline features for change detection along with various metadata, which includes specification of any mapping errors (Table 4.5) associated with each line feature. Once the necessary data are input into the tool, DSAS is then run to define the rate-of-change statistics for the period of interest. This is accomplished by querying the position of each shoreline feature (with assigned dates) and its intersection with every transect line. Several statistics are then output from the tool, including net shoreline movement, end-point rate calculations, linear regression rates and weighted linear regression rates (e.g., see Table 10 in Himmelstoss et al., 2021).

Figure 4.4: Example of mapped vegetation lines on 1967 (top) and 2018 (bottom) orthoimagery at the Manhattan Beach State Recreation Site.

4.2.4 Results

Figure 4.5 provides an example of the change rates determined for transect sites near Ophir Creek on the southern Oregon Coast in Curry County. Red lines indicate erosion, blue indicates accretion, while gray lines indicate little to no change. As can be seen in the Ophir Creek example, the south-central portion of this particular area is dominated by erosion with the coastline receding by ~-0.3 to -2.1 m per year since 1967. In contrast, the northern portion of this area (blue lines) indicates significant accretion (>0.3 m/year) over the same period. Furthermore, in the southernmost area where Greggs Creek passes beneath U.S. Highway 101 and is where the highway is closest to the beach, it can be seen that there has been little overall change since 1967. This last response can be attributed to the stabilization of the beach backshore by European beach grass leading to the development and growth of dunes. The challenge with these data is that even within the confines of a single 'vulnerable site', it is visually apparent that there is a large variation in calculated change rates. To address this, we chose to focus mainly on those results that are specific to a particular study reach. That is, those areas where erosion is closest to the highway and is expected to impact the highway in the foreseeable future. The change rates were exported from the GIS and a maximum negative erosion rate identified, along with the proportion (percent) of transects that exhibit erosion (Table 4.6). Note that DSAS calculates both the percent eroding and accreting. Sites with 0% eroding indicate that 100% of the transects have experienced accretion since 1967.

Figure 4.5: Example of change rates determined for transect sites near Ophir Creek on the Southern Oregon Coast in Curry County.

Table 4.5: Quantified erosion parameters from the DSAS analysis results

ID	Site Name	Negative Transects (%) / Statistically Significant (%)	Max Negative Erosion Rate (m/year)
3	Hug Point	0.0 / 0.0	0.00
4	Silver Point	54.3 / 42.9	-0.27
6	Beaver Creek North	19.0 / 13	-0.10
7	SE 130th St	14.3 / 0.0	-0.01
8	Moolack landslide	90.5 / 68.4	-0.65
9	Carmel Knoll	89.3 / 50.0	-0.30
10	Johnson Creek landslide	78.8 / 51.5	-0.41
11	Beverly Beach North	65.6 / 42.6	-0.27
12	Beverly Beach South (Spencer Creek)	81.0 / 75.9	-0.36
13	Whale Cove	100.0 / 33.3	-0.20
15	Boilery Bay	66.7 / 22.2	-0.16
16	D River outlet	15.6 / 9.4	-0.08
19	Saltair Creek	63.6 / 54.6	-0.32
20	South Nehalem	24.0 / 20.0	-0.24
21	Manhatten Beach Wayside	78.8 / 90.9	-0.53
26	Arch Cape tunnel	100.0 / 90.9	-0.22
27	Seal Rock 1	20.7 / 3.5	-0.09
29	SW Whitecap Dr.	12.5 / 0.0	-0.02
31	SW Wakonda Beach Rd.	26.3 / 10.5	-0.06
32	Annice Creek	14.3 / 7.1	-0.09
33	Stonefeld Beach	57.9 / 15.8	-0.17
34	Rock Beach	100.0 / 75.0	-0.15
35	Ocean Beach	33.3 / 16.7	-0.30
36	Yachats River	78.6 / 42.9	-0.10
37	Gwynn Creek	92.3 / 23.1	-0.13
38	Cummins Creek	100.0 / 72.7	-0.11
39	Big Creek	68.8 / 68.8	-0.47
40	Sea Lion Pt	100 / 65.4	-0.15

ID	Site Name	Negative Transects (%) / Statistically Significant (%)	Max Negative Erosion Rate (m/year)
45	Port Orford (Gregory Point)	86.4 / 65.9	-0.74
46	Rocky Pt to Coal Pt	100.0 / 100.0	-0.37
47	Brush Creek	100.0 / 66.7	-0.58
48	Arizona Inn Landslide	100.0 / 95.4	-0.46
49	Sisters Rock to Devils Backbone	100.0 / 78.6	-0.35
50-53	Ophir Beach 1-4	96.6 / 93.1	-0.54
54	Nesika Beach	64.8 / 52.2	-0.36
55	North side of Hunter Creek	96.1 / 96.1	-2.07
57	Near Myers Creek	46.5 / 18.6	-0.16
58	Pistol River	50.8 / 31.7	-0.35
59	Hooskanaden Landslide	100.0 / 100.0	-0.76
60	Rainbow Rock (Taylor Creek)	51.6 / 0.0	-0.09
61	Seal Point (Spruce Creek)	100 / 87.5	-0.41

The identified rates of change presented in Table 4.6 vary significantly from little to no discernable change (e.g., Hug Point) to relatively high rates of erosion at several sites, including north of Hunter Creek, Curry County (-2.1 m/year), Hooskanaden, Curry County (-0.76 m/year), Gregory Point, Curry County (-0.74 m/year) and Moolack Beach, Lincoln County (-0.65 m/year) (Table 4.6). The GIS data and summary analysis results can be found in Appendix C.5.

4.3 PROJECTED SHORELINE CHANGE AT BEVERLY BEACH

A relatively simple analysis was undertaken at Beverly Beach/Spencer Creek to evaluate the potential loss in beach shoreline width due to future projections of regional sea level rise. The goal here was to evaluate the potential loss of beach width over time, which could have important implications for any coastal engineering proposed for the Spencer Creek area given the high recreation impact at Spencer Creek.

In performing this assessment, we first defined a mean shoreline position (±1 standard deviation (σ) of variability) from available shoreline data. These data include NOAA, USACE, and OLC lidar data, as well as repeat RTK-DGPS surveys of a tidal-datum based shoreline undertaken over the years by DOGAMI. For the purposes of this analysis, we used a tidal-datum based shoreline located at an elevation of 2.3 m, which approximates the MMHW elevation; Note that NOAA uses a slightly lower tidal-datum based shoreline at MHW. In the Newport area, DOGAMI has captured 10 epochs of data spanning the period between 1997 to the most recent survey completed in late summer 2021. These represent summer to summer periods.

To model sea level rise, we used the latest projections for the Newport area, which were derived from Sweet et al (2017). These projections are divided into low, moderate and high SLR estimates at years of 2030, 2050 and 2100.

- For 2030, the low SLR projection = 0.06 m was used.
- For 2050, the moderate SLR estimate = 0.34 m was used
- For 2100, we used a moderate SLR estimate = 1.02 m was used

If the high SLR estimates are used, the projected beach loss becomes very large, resulting in complete loss of the beach by 2100.

Next, the shoreline retreat was projected for each of the epochs using the Bruun model (Bruun, 1962, 1988; Dean and Houston, 2016), which simply divides the SLR component by the slope of the beach. The slopes were obtained from TLS surveys from SPR807 completed between 2016 and 2022. Note that this approach ignores any change in the overall beach sediment budget (i.e., sediment inputs versus losses), which in the case of Beverly Beach is a reasonable assumption given that there is very little sediment coming into the littoral cell, other than some nominal input from erosion of seacliffs at the south end of the littoral cell (Allan et al., 2015a).

Using this approach, we calculate a shoreline recession of:

- 2030 = 1.3 m erosion
- 2050 = 7.6 m erosion
- 2100 = 22.8 m erosion

Using these values, we can buffer from the mean shoreline and envelope of variability to define a projected future shoreline and envelope. Figure 4.6 shows the projected changes while Table 4.7 summarizes the beach widths.

Not surprisingly, by 2100 there are many areas south of Spencer Creek Bridge where one would expect to see very little to no beach over much of the year as a result of sea level rise. Nevertheless, the analysis is referenced to a MHHW tide so there would be some beach available for recreational activities at lower tides.

Table 4.7: Estimated beach widths North and South of the Spencer Creek Bridge based on sea level rise. The ranges, as expressed, reflect the distance to the mean projected shoreline (larger numbers) and to the mean – 1 sigma (lower numbers).

Trouble Spot ID	**Location**	**Beach Widths (m)**		
		2030	**2050**	**2100**
11	Beverly Beach North (North of Spencer Creek bridge)	~60 to 47 m	~54 to 40 m	~40 to 25 m
12	Beverly Beach South (South of Spencer Creek bridge)	~35 to 24 m	~30 to 17 m	~14 to 0 m

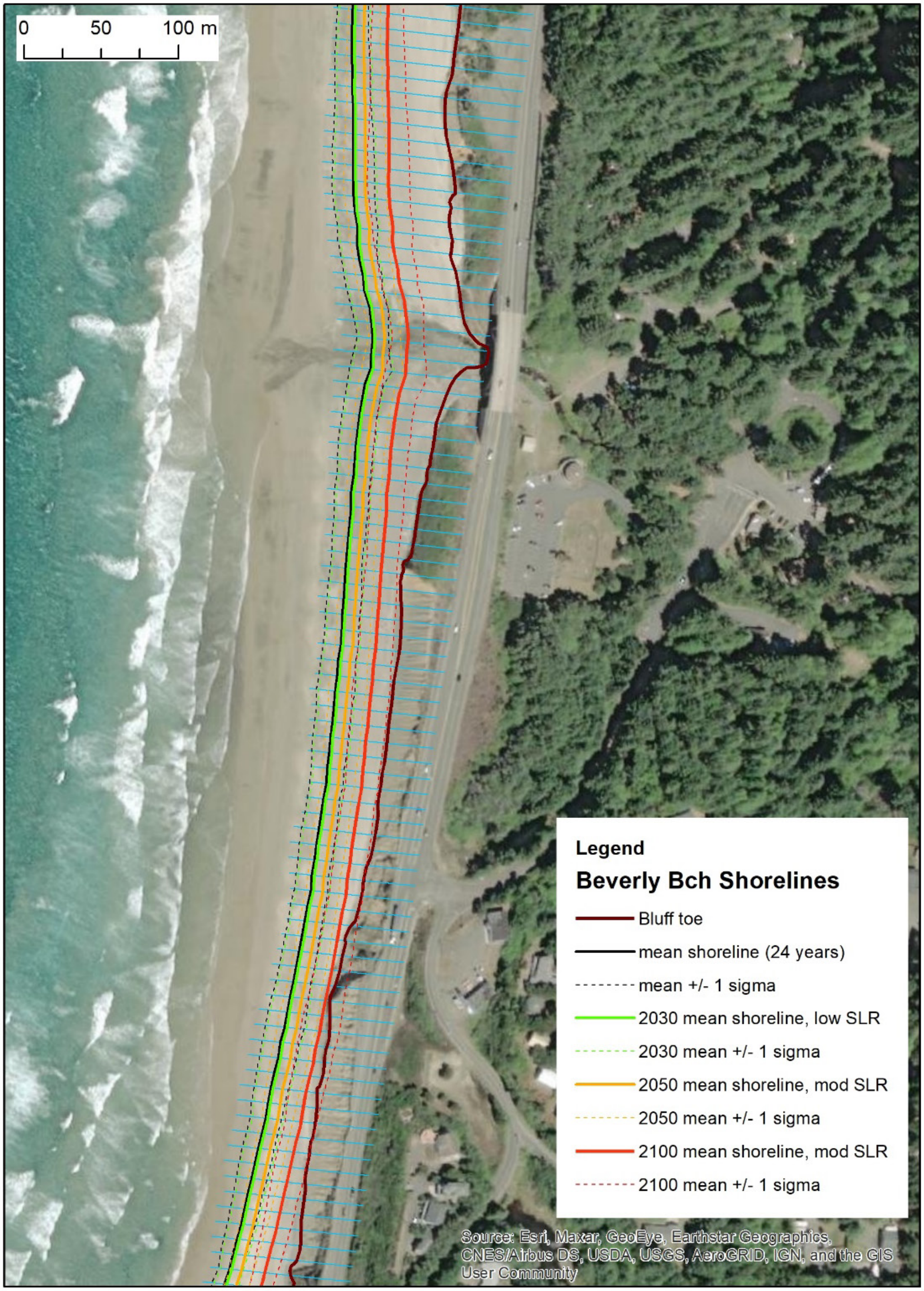


Figure 4.6: Beach shoreline analysis results at Beverly Beach for 2030, 2050, and 2100.

5.0 CLIFF EROSION FORECASTING

To forecast seacliff erosion for nineteen of the vulnerable sites along the coast, a physics-based methodology was developed. These nineteen sites are shown in Table 5.1 where the four Ophir Beach sites were combined for the analysis, resulting in sixteen analyses. Associated cross-sectional retreat data and other statistics are provided as a digital appendix (Appendix C.6). These subset of sites were chosen as they consist of seacliff-dominated geomorphology that is prone to retreat processes captured in the proposed model. Process-response models (Trenhaile, 2009, Walkden & Hall, 2005, M. J. Walkden & Hall, 2011) provide quantitative predictions of natural and human induced changes. This mode of predicting seacliff retreat has been applied within Southern California (Limber et al., 2018) and Southern Italy (Martino & Mazzanti, 2014) as well as for cohesive clay coasts (Trenhaile, 2009) and soft rock cliffs (Castedo et al., 2012). In comparison to other approaches such as statistical models, a physics-based model provides the advantage of capturing the short- and mid-term sporadic nature of seacliff retreat and is not reliant on long term training data as an input towards projections (compared to statistical models). Many conditions are expected to change due to climate change, such as sea level rise, wave scour and storm intensification, therefore, historical rates may not be accurate for predicting future trends. To evaluate the geomorphologic controls outside of current observations that dictate the magnitude and timescale of coastal retreat, such as those due to climate change, process-based models are best suited.

Within each priority site, cross sections are extracted to capture the seacliff geometry. The model considers geomorphologic (geology, cohesion, friction angle) and environmental (sea level rise and Total Water Levels (tide + wave runup)) controls to determine seacliff geometry over time. Three failure mechanisms are considered: undercutting, failure of overhanging terrain and full seacliff collapse. At each time step, seacliff geometry is evaluated against geomorphologic and environmental controls to test if the seacliff geometry remains unchanged or if the seacliff geometry evolves due to failure. A range of frictional strength scenarios are utilized to represent uncertainty in regional shear strength. This analysis provides key insights into seacliff evolution over time including anticipated retreat at various elevations, frequency of and distinct contribution to volumetric loss by the considered failure mechanisms and mean lateral retreat across all elevations within the profile.

Table 5.1: Sites and data inputs for cliff erosion forecasting

Site ID	Site Name	Sub-Section	# Cross Sections	TWL (Now)	TWL (2050)	TWL (2100)	Toe Erosion Rate (m/year)
26	Arch Cape Tunnel	-	23	7.83	8.00	8.46	-0.095
10	Johnson Creek Landslide	-	30	8.05	8.22	8.68	-0.036
11	Beverly Beach North	-	32	6.87	7.04	7.50	-0.043
12	Beverly Beach South (Spencer Creek)	A	21	7.66	7.83	8.29	-0.056
		B	18	9.25	9.42	9.88	-0.056
		C	18	7.11	7.28	7.74	-0.055
9	Carmel Knoll	A	9	10.12	10.29	10.75	-0.013
		B	19	7.31	7.48	7.94	-0.013
8	Moolack Landslide	A	10	9.60	9.77	10.23	-0.069
		B	13	9.30	9.47	9.93	-0.068
		C	27	9.58	9.75	10.21	-0.069
		D	18	9.95	10.12	10.58	-0.070
40	Sea Lion Pt.	A	42	10.43	10.6	11.06	-0.081
		B	14	16.77	16.94	17.4	-0.061
70	Hubbard Creek	A	11	8.47	8.64	9.10	-0.085
		B	28	8.47	8.64	9.10	-0.228
		C	32	8.47	8.64	9.10	-0.028
		D	6	8.47	8.64	9.10	-0.045
45	Port Orford (Gregory Point)	A	24	8.47	8.64	9.10	-0.020
		B	15	8.47	8.64	9.10	-0.100
		C	10	8.47	8.64	9.10	-0.018
46	Rocky Pt. To Coal Pt.	A	16	8.47	8.64	9.10	-0.048
		B	103	8.47	8.64	9.10	-0.014
47	Brush Creek	-	84	8.36	8.53	8.99	-0.020
48	Arizona Inn Landslide	-	82	8.36	8.53	8.99	-0.090
49	Sisters Rock to Devil's Backbone	A	69	8.36	8.53	8.99	-0.010
		B	69	8.36	8.53	8.99	0.034
		C	66	8.36	8.53	8.99	-0.0004
50-53	Ophir Beach	A	19	7.19	7.36	7.82	-0.061
		B	31	8.52	8.69	9.15	-0.071
		C	64	7.47	7.64	8.1	-0.061
54	Nesika Beach	A	9	8.13	8.3	8.76	-0.026
		B	84	11.38	11.55	12.01	-0.025
		C	2	10.14	10.31	10.77	-0.025
		D	45	10.14	10.31	10.77	-0.090
59	Hooskanaden Creek	A	34	8.29	8.46	8.92	-0.300
		B	1	8.29	8.46	8.92	-0.094
		C	22	9.04	9.21	9.67	-0.101

5.1 GENERATION OF INPUTS

For a given priority site, the model inputs consist of cross sections of the seacliff face (spaced 10 to 15 m apart), total water level projections, present erosion rates, and local geology. Figure 5.1 depicts the overall processes under consideration in the process-response model, including the key data inputs. Herein, details of the process used to perform retreat models are described.

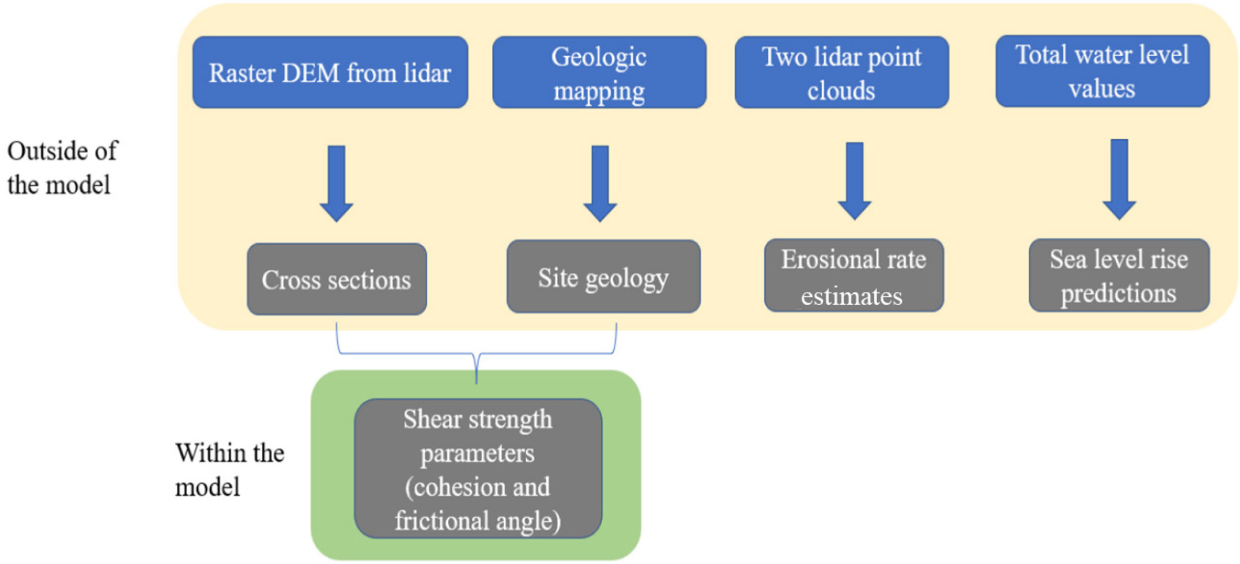


Figure 5.1: Development of inputs for the erosion projection model

5.1.1 Cross Sections

To generate cross sections, a bare earth digital elevation model (DEM) is processed through CliffMetrics (Payo et al., 2018). This open-source tool delineates and smooths shoreline vectors, generates orthogonal cross-sections to the shoreline and extracts the position of the cliff top and toe. Using a custom Python script, the cross sections, cliff toe points and cliff top points are thinned from their original spacing (1 m) to less dense data (10 to 15 m). Additionally, this script extends cross sections from their original length (100 m) to several hundred meters (ranging from 200 to 600 m depending on the site) to properly capture the entire geometry from the beach to well beyond the seacliff top where the erosion forecast model is applied. Lastly, the script generates points at 1 m interval along each cross section and outputs the elevation (in meters), northing and easting coordinates (NAD 1983 Oregon Statewide Lambert, Meters) for each point in a CSV file.

5.1.2 Total Water Level

Total water level values and associated sea level rise are determined based on a Coastal Flood Hazard Study conducted by DOGAMI within Lincoln County (Allan et al. 2015a). Wave data were collected from either the National Data Buoy Center (NDBC) or Global Reanalysis of Ocean Wave Fine Northeast Pacific Hindcast (GROW-FINE NEPAC) depending on the most relevant to the site. NDBC provides hourly wave statistics, while GROW-FINE NEPAC provides a continuous time series of wave and wind data. Shoaling, or the change in shape and behavior of waves as they travel through water of decreasing depth, is accounted for through a bathymetric-topographic digital elevation model (DEM) of the Central Oregon Coast by the NOAA National Geophysical Data Center (NGDC). The Simulating Waves Nearshore (SWAN) wave model (Booij et al. 1996) is used to transform deepwater waves to the nearshore and then linearly shoaled back into deep water to derive a refracted deepwater equivalent wave parameterization (wave height and peak period) that can be used to calculate runup levels. Total water level is then calculated as wave runup superimposed on the tidal level. After calculating total water levels, time-dependent interpolations of sea level rise were superposed to site-specific total water levels to account for potential increased erosion forcing.

5.1.3 Toe Erosion Rates

The erosion rate is computed for the toe for each cross section. Note that this process varies from that described in Section 4.1 given that the erosion rates are computed for the toe based on an elevation threshold set by the nearest TWL point rather than the entire cliff face. Two epochs of data are needed to serve as basis for change analysis. Point clouds corresponding to each epoch were downloaded from NOAA Digital Coast Data Access Viewer with the appropriate Oregon State Plane Zone (North or South) (NAD83(2011) Epoch 2010.00) as the coordinate system, the datum as NAVD88 (Geoid 18), and units of meters. Within *Cloud Compare* all points not located within the area of interest are cropped out for processing speed and accuracy. Additionally, points that capture large vegetation (e.g., trees, large shrubs) are manually removed. The resulting point clouds are then processed through the RAMBO software (Olsen et al., 2021), which calculates change between the two datasets by filling in data voids and filters the ground based on orientation of the best fit plane computed from the first point cloud. The erosional rate per cross section is calculated using a custom python script which computes the erosional statistics for each cross section by computing the average change across the cliff below the elevation of the most proximate total water level reading for each cross section. The average erosional rate is normalized to determine erosion rate per year in meters. From the total water level reading most proximate to each cross section, if the elevation value of the closest point cloud is less than the total water level, the average change over time is calculated. The average erosional rate is normalized to determine erosion rate per year in meters.

5.1.4 Geologic Information

Geologic information is determined using the Oregon Geologic Data Compilation (OGDC version 6, Smith and Roe, 2015). While sites contain multiple geologic units, the dominant lithology is noted in Table 5.2. A distribution of friction angles for the 10th, 25th, 50th, 75th, and 90th percentiles from Alberti et al. (2022b) are considered for each lithologic unit to represent uncertainty as described in Section 5.2.

Table 5.2: Overview of site lithologies and observed retreat rates.

Trouble Spot ID	Site	Lithology	Rate (cm/yr.)
26	Arch Cape Tunnel	Basalt	41.6
10	Johnson Creek Landslide	Mixed Grain Sediments	11.4
11	Beverly Beach North	Mixed Grain Sediments	2.3
12	Beverly Beach South (Spencer Creek)	Mixed Grain Sediments	94.6
9	Carmel Knoll	Mixed Grain Sediments	4.5
8	Moolack Landslide	Mixed Grain Sediments	6.8
40	Sea Lion Point.	Basalt	48.6
70	Hubbard Creek Slide	Mixed Lithologies	5
45	Port Orford (Gregory Point.)	Coarse Grained Sediments	35.3
46	Rocky Pt. to Coal Pt.	Mixed Lithologies	42.9
47	Brush Creek	Mixed Lithologies	41.8
48	Arizona Inn Landslide	Mixed Lithologies	36
49	Sisters Rock to Devils Backbone	Coarse Grained Sediments	30.4
54	Nesika Beach	Mixed Grain Sediments	42.6
50-53	Ophir Beach 1-4	Coarse Grained Sediments	11.6

5.2 STRENGTH BACK ANALAYSIS

Using the cross-sections, a back analysis is performed using a log spiral slope stability analysis (Stockton et al., 2019). The geometry of failure surface is assumed to follow a log spiral, determined as:

$$\boldsymbol{r = Ae^{-\theta \tan(\phi)}} \tag{5-1}$$

where r is the radius from the pole, A is the log spiral constant, θ is the rotation angle around the pole, and ϕ is the effective friction angle. The cohesion can be determined by satisfying moment equilibrium (and implicitly force equilibrium) as:

$$\boldsymbol{\frac{M_c}{M_w} = 1} \tag{5-2}$$

where M_C and M_W are the moments due to cohesion resistance and self-weight, respectively. For a given friction angle (ϕ), each cross-section is subject to a slope stability analysis where between 1,000 and 50,000 trial surfaces are considered, depending on its length and size. That is, exit points for failure surfaces were determined throughout the entire cliff face (starting at the toe and extending to the crest), and admissible surfaces were concave-up and within the length of the entire profile. For each admissible trial failure surface, the cohesion (c, i.e., strength from lithification) necessary to yield force and moment equilibrium are calculated using equation 5-2). Thus, a given cross-section will have many potential cohesion values, but the only cohesion value relevant to this parametrization is the maximum (Figure 5.2). As the estimated friction angle contains uncertainty and varies based on lithologic unit, the database of friction angles (Alberti et al. 2022b) is used based on its lithologic classification. From the distribution of friction angles in each lithologic unit, the 10th, 25th, 50th, 75th and 90th percentiles are determined along with their respective cohesion maxima. The vertical heights of the failure surface and maxima of cohesion are determined from all cross-sections, enabling creation of an envelope that relates cliff height and the strength of lithification (Figure 5.2). In other words, this enables creation of an envelope that characterizes the upper-bound of cohesion stemming from lithification with seacliff height. A convex hull relationship is used to constrain the upper limit of this relationship and is thereafter used to assign upper-bound cohesion along the envelope to all cross sections as a function of their height. In doing so, the heterogeneity of cementation for different heights of the seacliff face is captured. At shorter points within the seacliff profile, cementation is expected to be less compared with taller points.

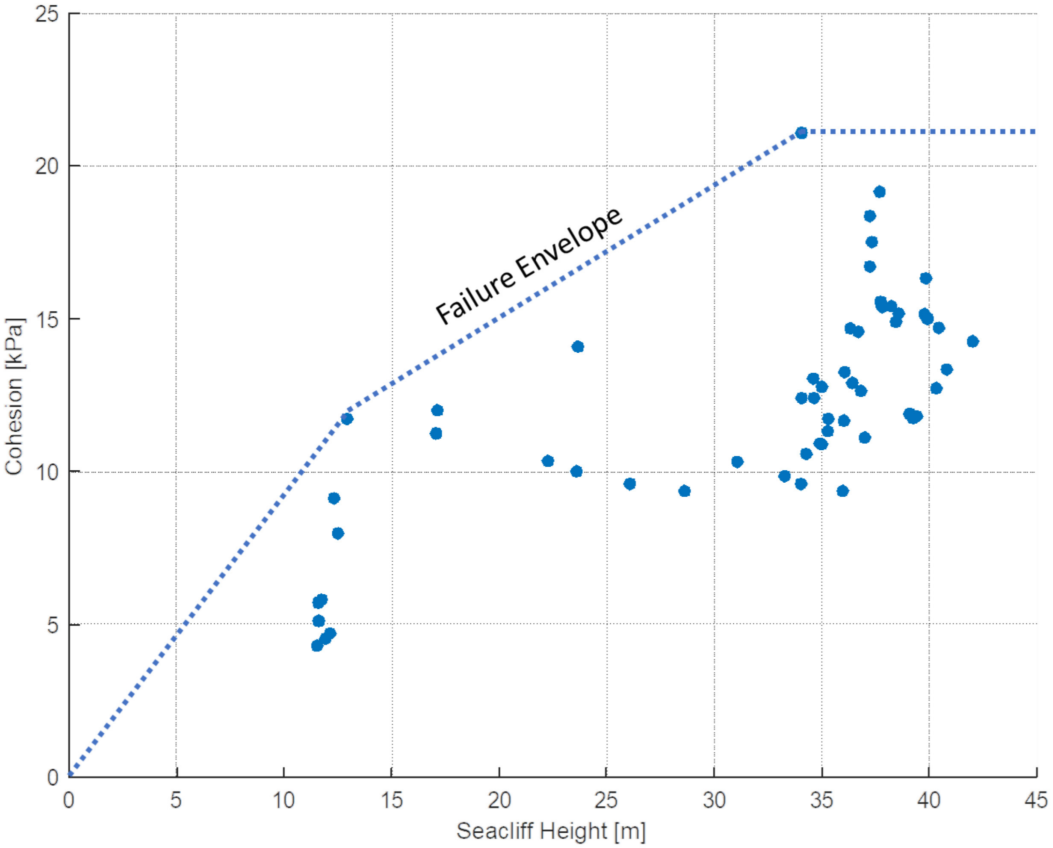


Figure 5.2: Example threshold relationship (failure envelope) between seacliff height and cohesion for a 50th percentile friction angle for Spencer Creek Bridge and Bluff. This threshold is used to assign initial cohesion values for cross sections used in retreat analyses.

5.3 RESULTS

5.3.1 Retreat projections

To visualize retreat over time, an elevation of interest must be chosen due to the high variability of retreat with elevation. For example, lower elevations (i.e., those below the total water level) are most impacted by wave scour. Higher elevations (i.e., those above the total water level) are less impacted by wave scour and more impacted by overhang failure or cliff collapse. Evaluating retreat at several elevations provides more explanatory power to the heterogeneity of retreat throughout the seacliff profile. For illustration purposes, three elevations are evaluated: 7 meters, 10 meters and 13 meters above mean sea level.

Figure 5.3 represents linear (left) and georeferenced (right) retreat for Spencer Creek for a period of 80 years, assuming sea level rise at a representative elevation of 7 m above mean sea level. Figure 5.4 represents linear (left) and georeferenced (right) retreat for a period of 80 years, assuming sea level rise and evaluating at an elevation of 10 m. Figure 5.5 represents linearized (left) and georeferenced (right) retreat for a period of 80 years, assuming sea level rise and evaluating at an elevation of 13 m. Each line represents retreat at a given epoch along the longitudinal profile of the site, where evenly spaced isolines reflect constant change stemming from wave scour, and larger, erratic gaps represent overhang or cliff collapse during an epoch.

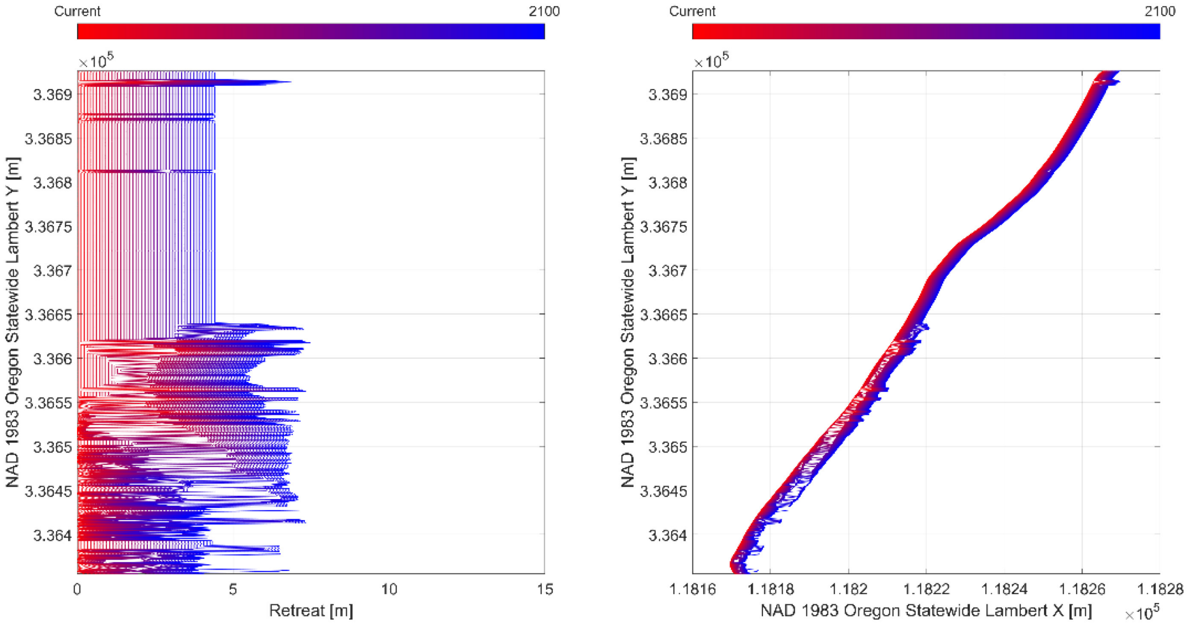


Figure 5.3: Linear (left) and georeferenced (right) retreat at an elevation of 7 m over 80 years, assuming sea level rise and the 50th percentile of strength

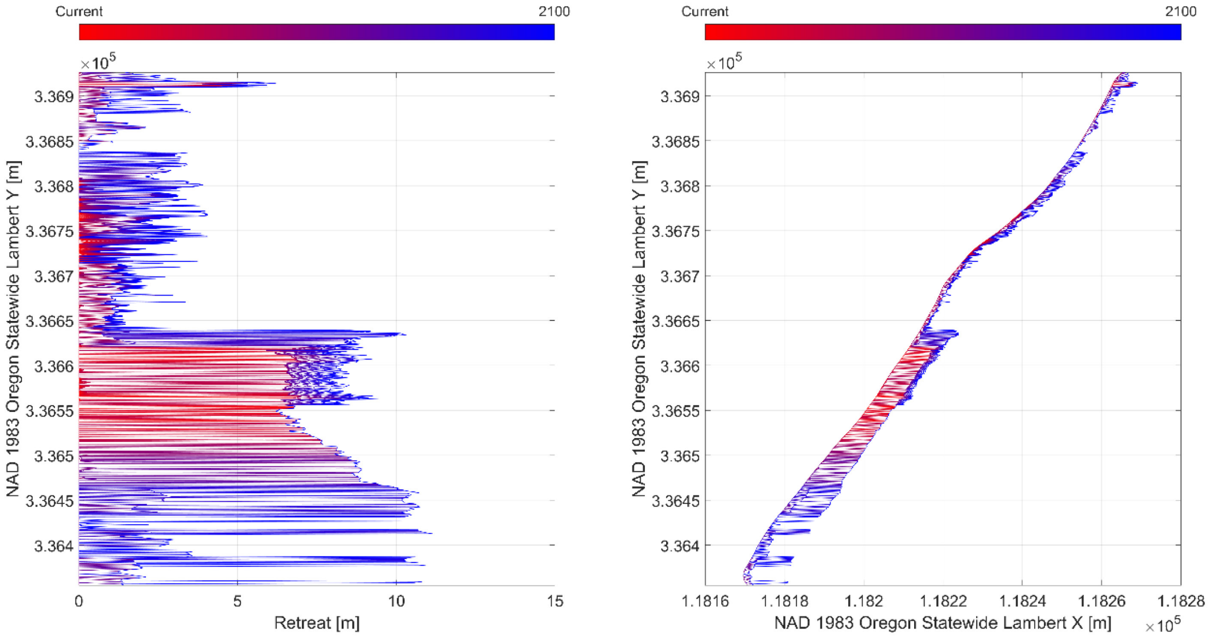


Figure 5.4: Linear (left) and georeferenced (right) retreat at an elevation of 10 m over 80 years, assuming sea level rise and the 50th percentile of strength

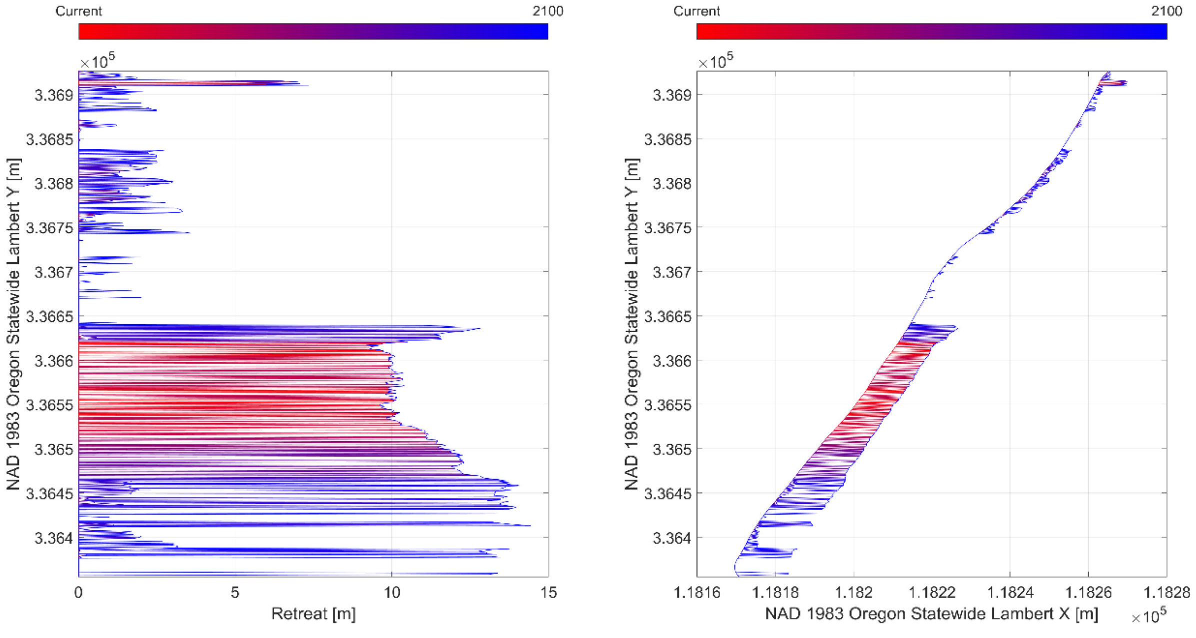


Figure 5.5: Linear (left) and georeferenced (right) retreat at an elevation of 13 m over 80 years, assuming sea level rise and the 50th percentile of strength

At lower elevations (Figure 5.3), within the northern extent of the seacliff profile, the isolines are generally evenly spaced, indicating constant, but gradual change reflective of site-specific toe erosion rates. In this portion of the seacliff, at an elevation of 7 m, inundation, and wave scour (both assumed to be constant within this model), dominate seacliff erosion. Within the southern extent, seacliff erosion is mostly driven by overhang failure (small jumps in isolines) with full cliff collapse (large jumps in isolines) occasionally yielding a large effect on the seacliff position at this elevation.

At mid elevations (Figure 5.4), the seacliff retreat is no longer constant. Erosion within the northern extent is dominated by overhang failure (small jumps in isolines), while full cliff collapse (large jumps in isolines) drives retreat at an elevation of 10 m. At even higher elevations (Figure 5.5), seacliff retreat continues to shift abruptly and erosion within both the northern and southern extents is driven by overhang failures (large jumps in isolines).

Within all three elevations, the southern portion of the study site exhibits both greater and faster erosion and retreat than the northern extent, which can be attributed to having steeper and more unstable geology. This is observed at all elevations but is most pronounced at higher elevations. Evaluating retreat at elevations of 7, 10, and 13 m, the fastest retreat for the northern portion of the site occurs at 10 m. This demonstrates that while wave scour might be relatively constant at lower elevations, other retreat mechanisms are sporadic with periods of activity and dormancy.

When evaluating retreat at the same elevations, but over longer time scales, similar patterns emerge. Figure 5.6 (elevation of 7 m), Figure 5.7 (elevation of 10 m) and Figure 5.8 (elevation of 13 m), present retreat over a 200-year time frame with the same assumption of the 50th percentile of strength as the 80-year time frame presented previously. Generally, the southern extent experiences greater retreat than the north. However, over a longer time period, the difference in retreat is lessened. At an elevation of 7 m (Figure 5.6), there is continued constant retreat in the northern extent and sporadic retreat in the southern extent, however the overall retreat is similar. Similar to 7 m, evaluating the seacliff profile at 10 m (Figure 5.7) and 13 m (Figure 5.8), the difference in retreat between the northern and southern extents is less distinct than the 80-year time scale. Over increasing time scales, the model effectively equilibrates.

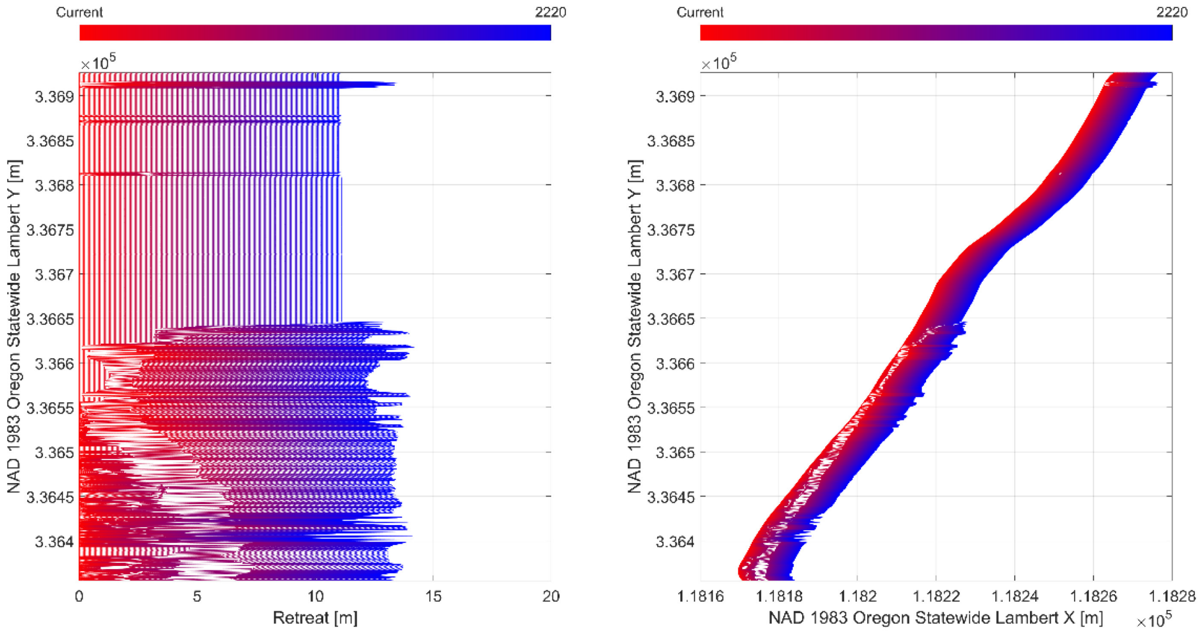


Figure 5.6: Linear (left) and georeferenced (right) retreat at an elevation of 7 m over 200 years, assuming sea level rise and the 50th percentile of strength

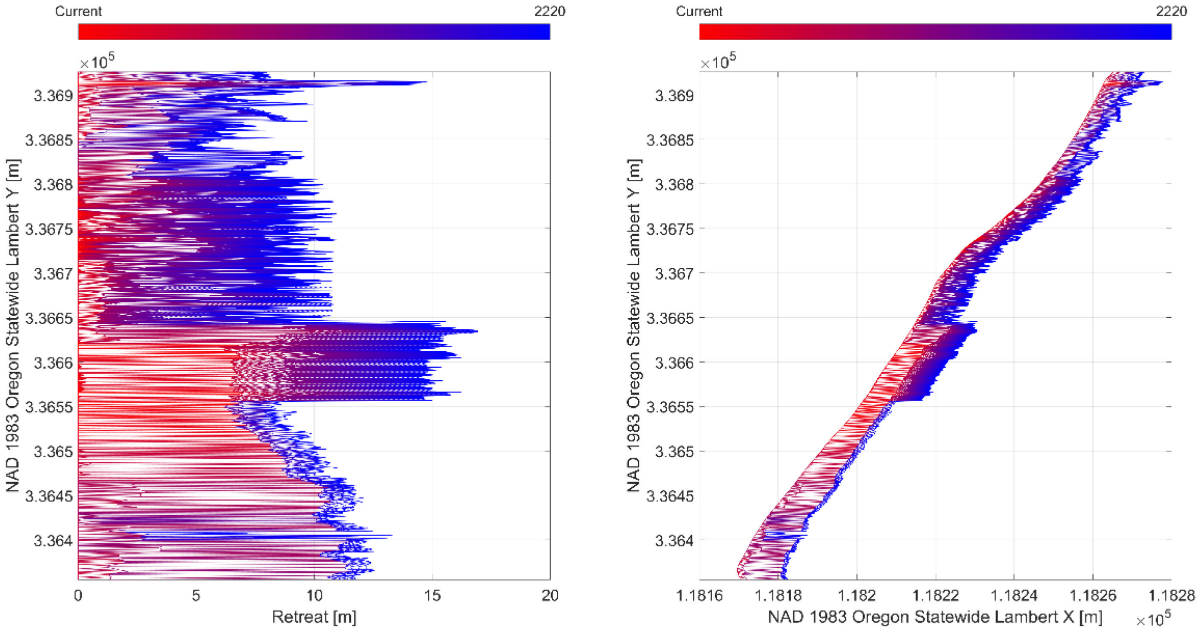


Figure 5.7: Linear (left) and georeferenced (right) retreat at an elevation of 10 m over 200 years, assuming sea level rise and the 50th percentile of strength

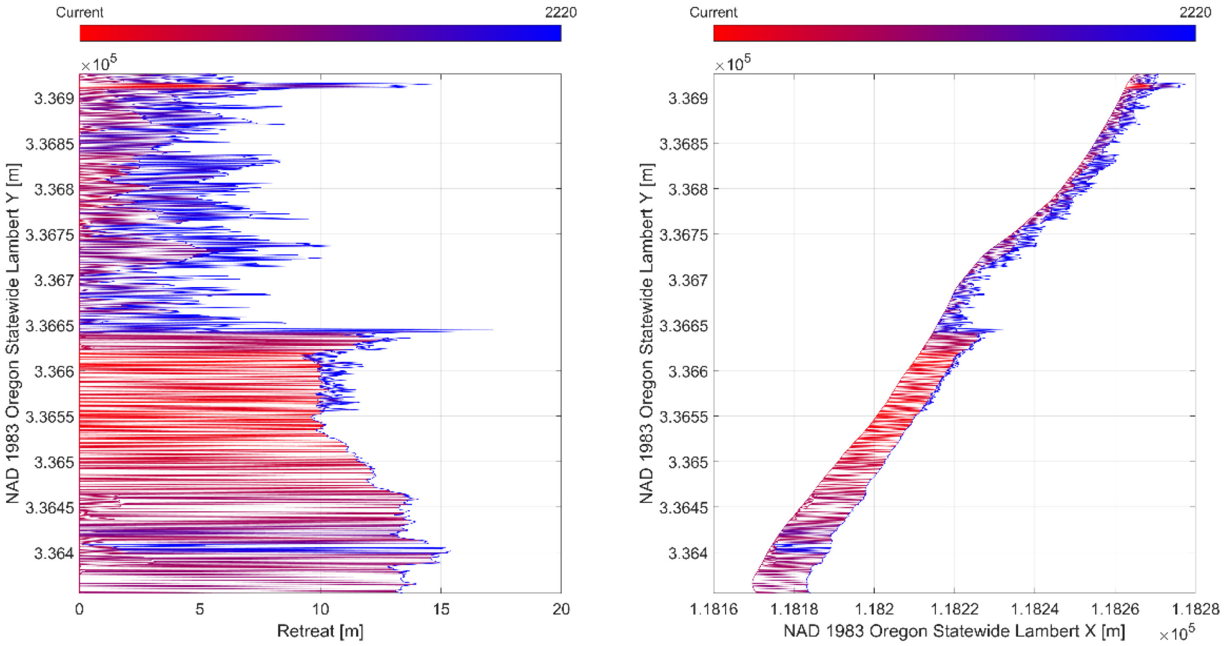


Figure 5.8: Linear (left) and georeferenced (right) retreat at an elevation of 13 m over 200 years, assuming sea level rise and the 50th percentile of strength

5.3.2 Erosional Mechanisms

Seacliffs serve as an important source of sediment (Young and Ashford, 2004, Haas et al. 2005); however, the relative magnitude by which various erosional mechanisms of seacliffs yield sediment is poorly constrained. One simplified means to describe sediment loss from weakly-cemented seacliffs is volume loss per linear meter of seacliff (m^3/m) versus time. These relationships are shown, starting at 2020 (Figure 5.9) and extending over an 80-year period. The dotted line represents mean volume loss due to wave scour from Total Water Levels (Allan et al., 2015) after accounting for sea level rise. By considering all five frictional strength percentiles (10th, 25th, 50th, 75th and 90th), Figure 5.9 represents the approximate range of possible volume loss for this given type of lithology (e.g., Nye mudstone/sandstone) considering a range of erosional mechanisms. Because the upper bound (e.g., high friction, low cohesion) and lower bound (e.g., high cohesion, low friction) represent the range of expected strength conditions for this site, this plot represents uncertainty of mean volume loss. The subplot on the left includes mean volume loss for all failure mechanisms (wave scour, overhang failure and full cliff collapse). The subplot in the middle includes mean volume loss only attributed to overhang failure and the subplot on the right includes mean volume loss only attributed to full cliff collapse.

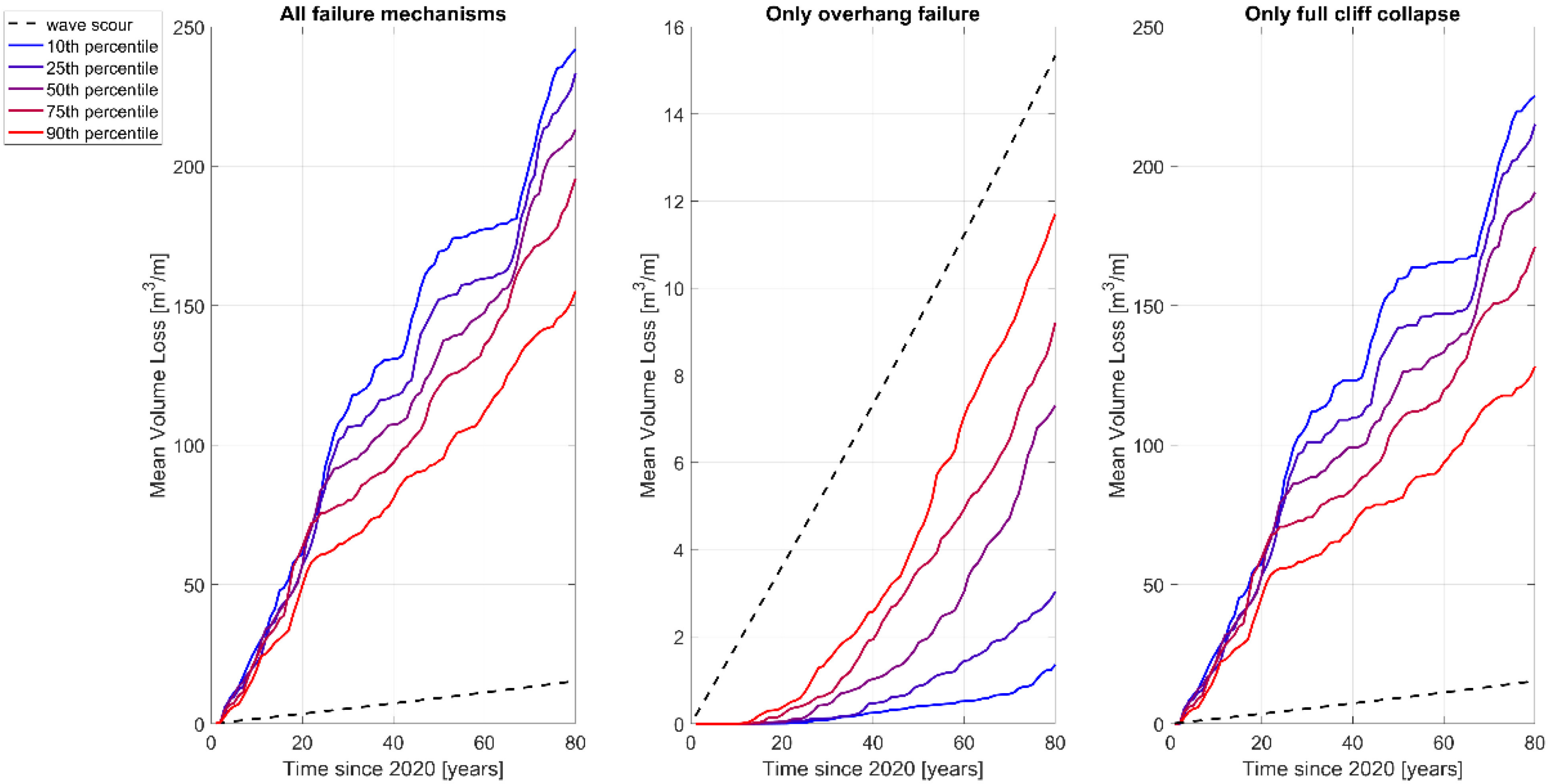


Figure 5.9: Mean volume loss for all failure mechanisms (left), only overhang failure (middle) and only full cliff collapse (right) for 80-year period assuming sea level rise. Note different scale on the Y-axis of the middle plot for visual clarity.

Distinct differences in trajectories in the mean volume loss are first evident beyond about 30 years after 2020 (Figure 5.9). After approximately 2050, patterns begin to emerge between strength percentiles. When evaluating the mean volume loss due to all failure mechanisms (left subplot in Figure 5.9), the 10th percentile representing high cohesion and low friction has the highest mean volume loss of approximately 240 ^{m3}/m at year 2100. Conversely, the 90th percentile representing high friction and low cohesion has the lowest mean volume loss of approximately 155 m^3/m at year 2100. The median strength scenario (50th percentile), as expected, demonstrates volume loss between the 10th and 90th percentiles for strength with a cumulative mean volume loss of approximately 215 m^3/m at year 2100. However, the relationship between strength and volume loss is evidently nonlinear – the median strength demonstrates 10% less and 39% more volume loss at 2100 than the 10th and 90th strength percentiles, respectively.

When evaluating mean volume loss due to only overhang failures (Figure 5.9, middle subplot), the 90th percentile representing high friction and low cohesion has the highest mean volume loss of approximately 11.9 m^3/m in 2100. The 10th percentile representing low friction and high cohesion has the lowest mean volume loss of approximately 0.5 m^3/m in 2100. The median strength scenario (50th percentile), as expected, demonstrates volume loss between the 10th and 90th percentiles for strength with a cumulative mean volume loss of approximately 7 m^3/m at year 2100.

When evaluating mean volume loss due to only full cliff collapse (Figure 5.9, right subplot), the 10th percentile representing high friction and low cohesion has the highest mean volume loss of approximately 225 m^3/m in 2100. The 90th percentile representing low friction and high cohesion has the lowest mean volume loss of approximately 125 m^3/m in 2100. The median strength scenario (50th percentile), as expected, demonstrates volume loss between the 10th and 90th percentiles for strength with a cumulative mean volume loss of approximately 190 m^3/m at year 2100.

Extending the time scale, more clear trends in the mean volume loss are evidenced between the strength percentiles. Figure 5.10 presents volume loss per linear meter of seacliff (m^3/m) for a 200-year period since 2020. Observed in Figure 5.10, patterns in trajectories of the percentiles are first evident around 30 years since 2020. However, in Figure 5.10, approximately 80 years after 2020, the trajectories become more distinct. When evaluating the mean volume loss due to all failure mechanisms (left subplot in Figure 5.10), the 10th percentile representing high cohesion and low friction has the highest mean volume loss of approximately 355 m^3/m at year 2220. Conversely, the 75th percentile representing high friction and low cohesion has the lowest mean volume loss of approximately 195 m^3/m at year 2220. The median strength scenario (50th percentile), as expected, demonstrates volume loss between the 10th and 75th percentiles for strength with a cumulative mean volume loss of approximately 315 m^3/m at year 2220. However, the relationship between strength and volume loss is evidently nonlinear – the median strength demonstrates 11% less and 62% more volume loss at 2220 compared with the 10th and 75th strength percentiles, respectively.

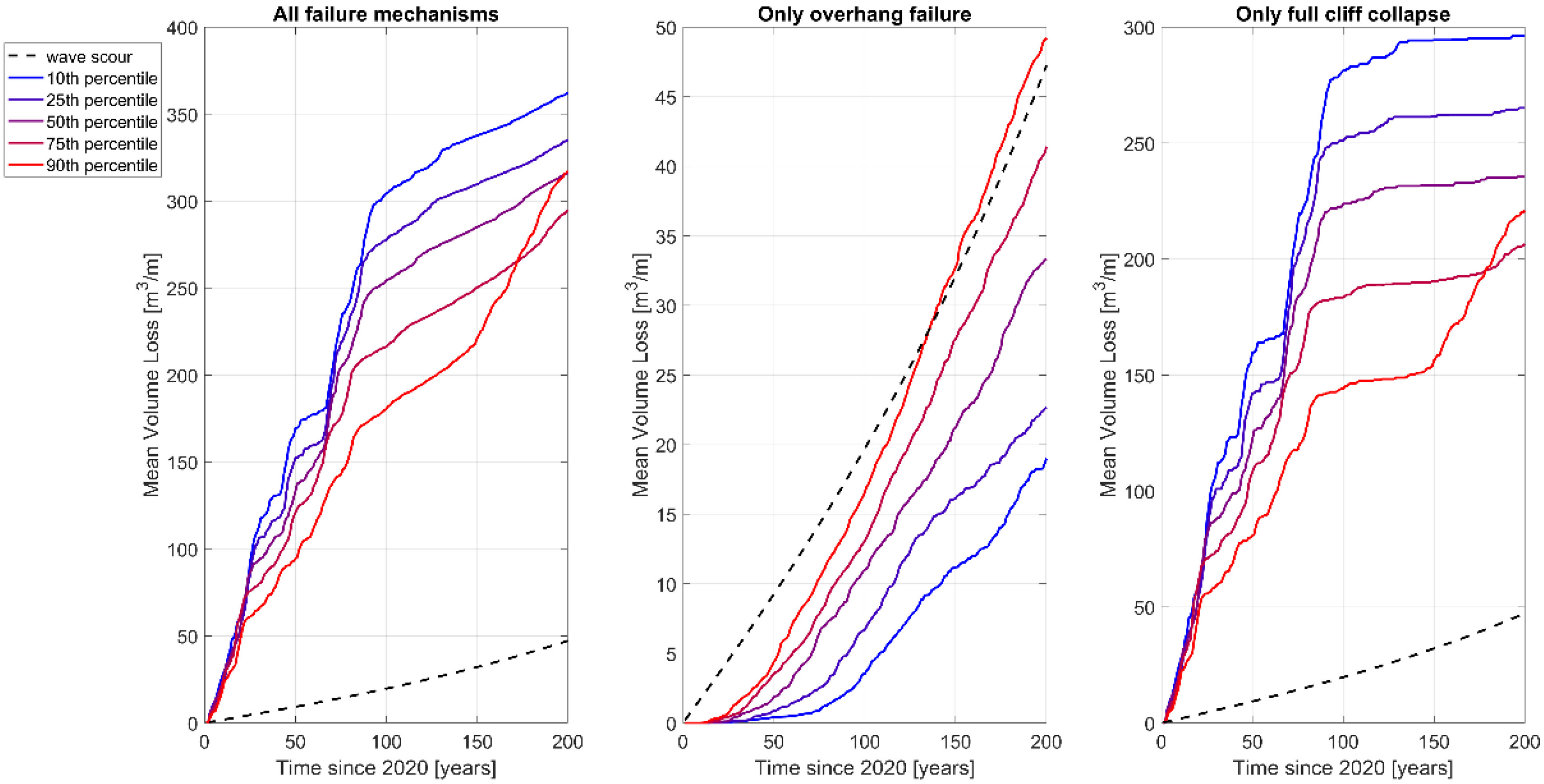


Figure 5.10: Mean volume loss for all failure mechanisms (left), only overhang failure (middle) and only full cliff collapse (right) for a 200-year period

When evaluating mean volume loss due to only overhang failures (Figure 5.10, middle subplot), the 90th percentile representing high friction and low cohesion has the highest mean volume loss of approximately 49 m^3/m in 2220. The 10th percentile representing low friction and high cohesion has the lowest mean volume loss of approximately 19 m^3/m in 2220. The median strength scenario (50th percentile), as expected, demonstrates volume loss between the 10th and 90th percentiles for strength with a cumulative mean volume loss of approximately 33 m^3/m at year 2220. When evaluating the mean volume loss due to only full cliff collapse (right subplot in Figure 5.10), the 10th percentile representing high cohesion and low friction has the highest mean volume loss of approximately 295 m^3/m at year 2220. Conversely, the 75th percentile has the lowest mean volume loss of approximately 220 m^3/m at year 2220. The median strength scenario (50th percentile), as expected, demonstrates volume loss between the 10th and 75th percentiles for strength with a cumulative mean volume loss of approximately 235 m^3/m at year 2220.

For both the 80-year and 200-year time periods since 2020, the trajectories of mean volume loss due to overhang failure (middle subplots in Figure 5.9 and Figure 5.10) and full cliff collapse (right subplots in Figure 5.9 and Figure 5.10) indicate their relative occurrence. Overhang failure (middle subplots in Figure 5.9 and Figure 5.10) is consistent and steadily occurs in each year. Full cliff collapse (right subplots in Figure 5.9 and Figure 5.10) is sporadic with periods of dormancy (flat portions of the curve indicating no full cliff collapse), followed by spikes in short time frames (indicating full cliff collapse). For overhang failures, the 90th percentile of strength (high friction, low cohesion) has the greatest mean volume loss. Conversely, for full cliff collapse, the 10th percentile of strength (high cohesion, low friction) results in the greatest mean volume loss. Because cohesion is the shear strength under zero normal stress and friction is the shear resistance of soils together with normal effective stress, high cohesion is necessary to prevent overhang failure as wave scour causes undercutting, or removal of mass at the base of the seacliff. Alternately, successive overhang failures lead to steepening of the seacliff where high friction angle prevents “mass wasting” or a full cliff collapse.

When determining the time frame by which steady state retreat occurs (i.e., the number of years needed for the model to reach a steady state), extending the time frame of the model better illustrates long-term trends in retreat. Observing 80 years since 2020, this period appears to be 30 years. However, extension to 200 years since 2020, suggests the model requires 80 years to remove noise and provide clear trends. Towards the end of the 200-year period, mean volume loss for all failure mechanisms (Figure 5.10, left subplot) and full cliff collapse (Figure 5.10, right subplot) for the 90th percentile for strength exceeds the mean volume loss for the 75th percentile. At the end of the 200-year period, mean volume loss for all failure mechanisms (Figure 5.10, left subplot) and full cliff collapse (Figure 5.10, right subplot) for the 75th percentile begins to increase. Likely over longer time scales, the strength percentiles may exhibit step patterns, where the mean volume loss of the lowest strength percentile rises first, followed by periods of increasing percentiles. However, all of these values eventually converge under long-term conditions. The step pattern represents the coalescence of many bluff failures (likely to occur under the weakest strength conditions, e.g. the 10th percentile), but is present in all strength percentiles as eventual over-steepening results in eventual extensive cliff collapse.

The contribution of full cliff collapse to the overall quantities of erosion, while sporadic, reflects an order of magnitude more sediment yield than both frequent overhang failures and wave scour. For an 80-year period, the median strength scenario (50th percentile) mean volume loss due to all failure mechanisms is approximately 215 m^3/m, while overhang failures constitute approximately 7 m^3/m and due to full cliff collapse approximately 190 m^3/m. Accumulated mean volume loss until 2100 assuming the 50th strength percentile, of approximately 215 m^3/m can be attributed approximately 88% due to full cliff collapse, 3% due to overhang failure and 9% due to wave scour. Similarly, accumulated mean volume loss until 2220 assuming the same 50th strength percentile, of approximately 315 m^3/m can be attributed approximately 71% due to full cliff collapse, 10% due to overhang failure and 19% due to wave scour. In determining the relative contributions of mean volume loss attributed to each failure mechanism, the percentages provided by the 200-year time frame are likely to be closer to the true value because it contains more years for the model to equilibrate.

5.3.3 Magnitude Frequency Relationships

Magnitude-frequency relationships for mass wasting (Hovius et al. 1997, Malamud et al. 2004, and Tebbens 2019) reflect the frequency of failure event size and their relative controls on sediment transport and landscape evolution. Figure 5.11 represents the frequency-volume relationships for the five strength percentiles for a 200-year period. The relationship between frequency density (m/m^3) and yearly event volume (in m^3/m) is shown as a gradient between overhang failure (green) and full cliff collapse (blue). A power-law regression is applied for each percentile by:

$$\boldsymbol{F\left(\frac{V}{L}\right) = \alpha\left(\frac{V}{L}\right)^{\beta}} \tag{5-3}$$

where F is the frequency function, V is volume (m^3), L is length (m), and α and β are power law coefficients. The subplot illustrating all regression lines (Figure 5.11, bottom right), indicates that there is limited variability between strength percentiles. As observed, all frequency-volume relationships demonstrate that small failures (predominantly overhang failures) are far more numerous and significantly smaller than full cliff collapse, which is infrequent and large in size. This is consistent with observations of failures in rockslopes and landslides (Malamud et al. 2004). For all strength percentiles, the fit of the regression line (R^2) is greater than 0.9, indicating that regardless of the strength percentile chosen, volume (m^3/m) of a yearly mass wasting events (e.g., overhang failure and/or full cliff collapse) is a strong predictor of frequency density (m/m^3).

Seacliff retreat varies along various elevations within its profile and trends at distinct elevations may be aggregated to determine generalized trend. Figure 5.12 summarizes mean retreat in m/m between the present and 2220 for each percentile of strength. The solid blue line is the observed retreat at the toe, while the effects of sea level rise are considered through increasing total water levels for the projected duration. After an initialization stage (about 70 years since 2020), the mean retreat trajectories become parallel to the observed retreat at the toe. The initial divergence likely stems from uncertainty in strength values; however, the parallel trajectory after time reflects that retreat rates are consistent with the rate of scour and the initial nonlinearity stems from the model reaching a steady state. These results suggest that mean scour may serve as a valuable metric for approximating seacliff retreat over longer time scales, but this contrasts the spatial (and temporal) heterogeneity in retreat demonstrated when considering different locations along the length of the seacliff.

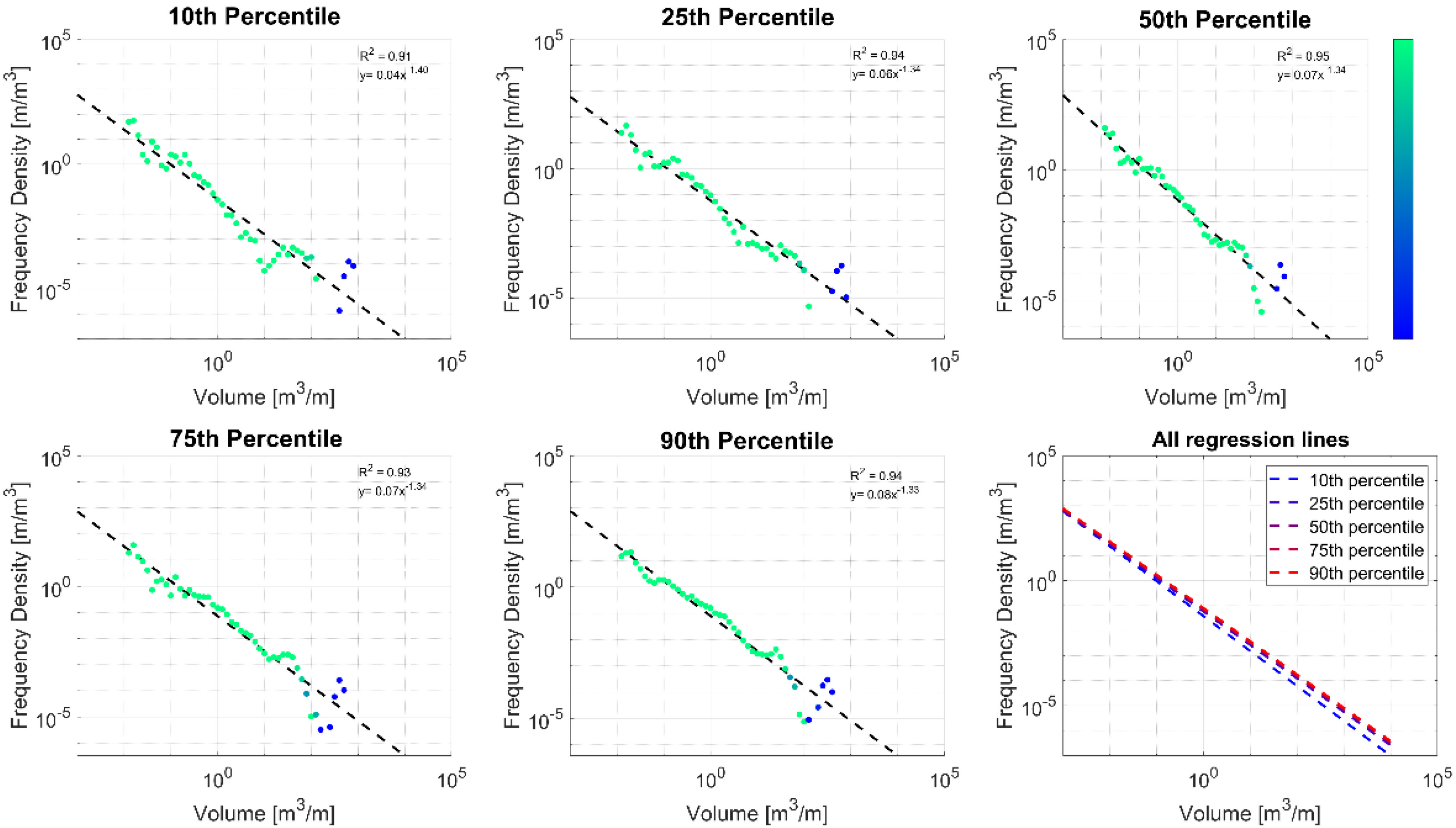


Figure 5.11: Yearly magnitude frequency relationship for mass wasting for each strength percentile over a 200-year period.

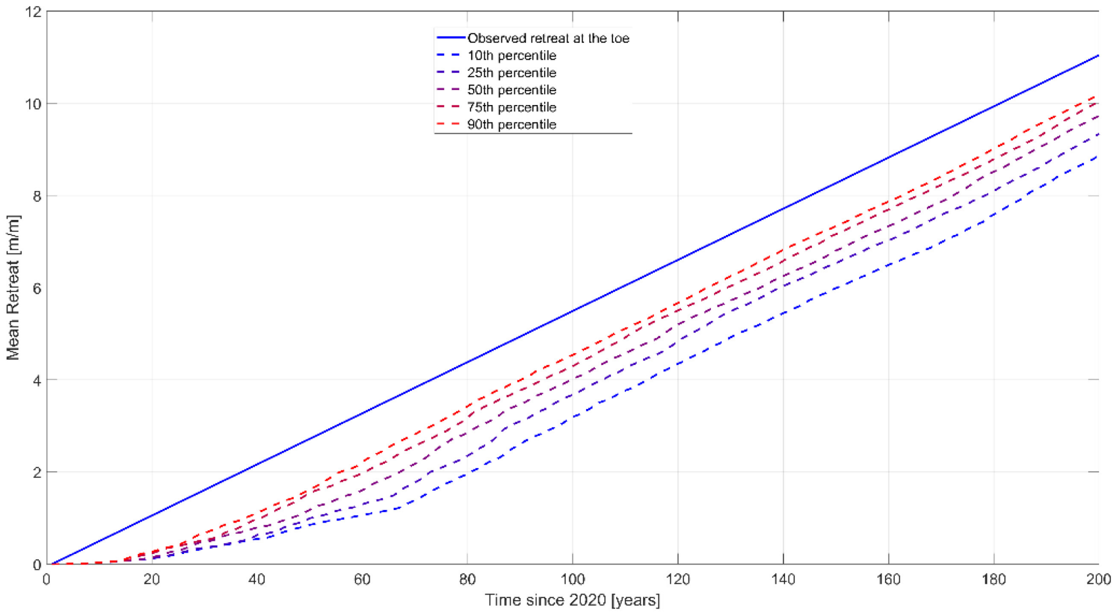


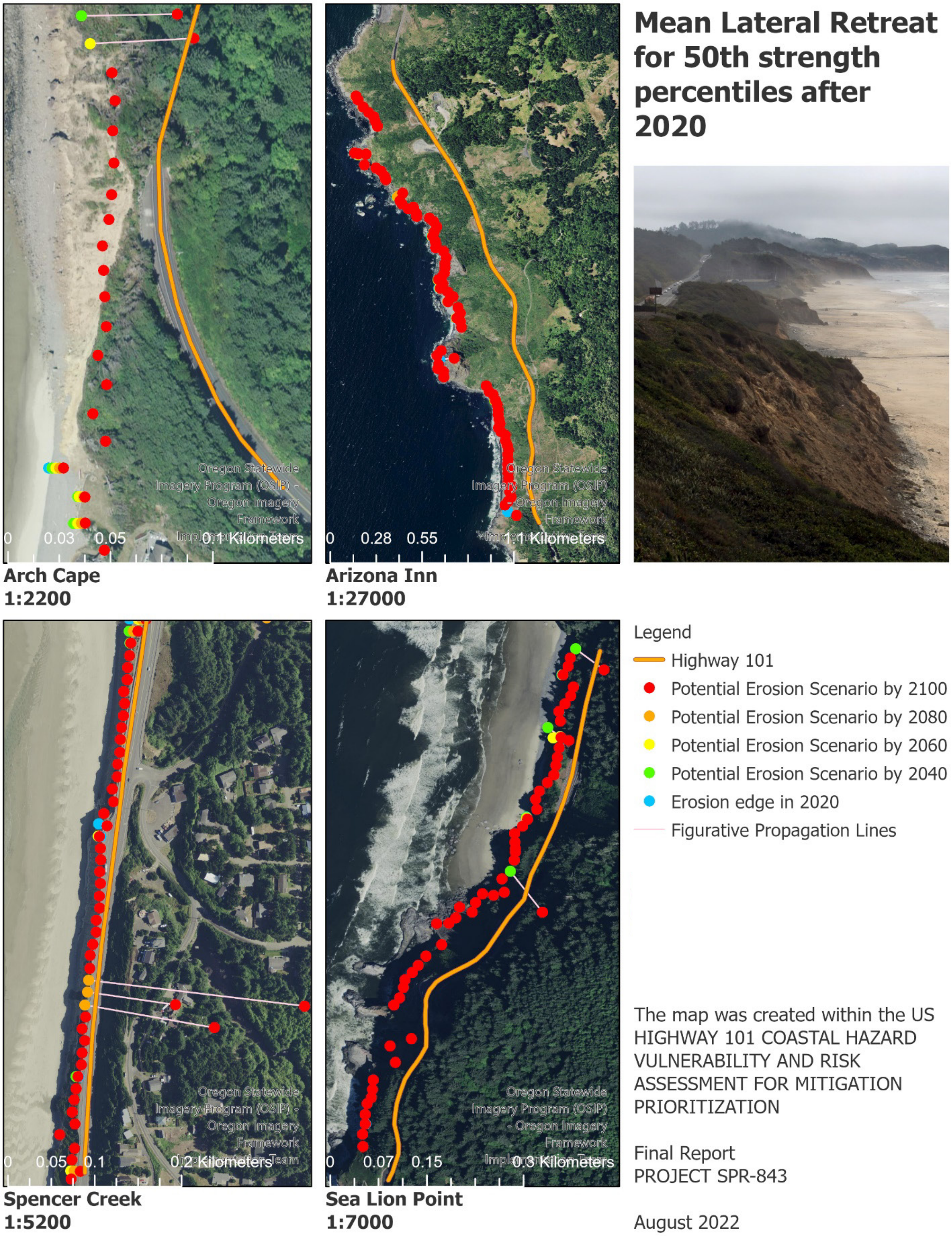
Figure 5.12: Mean lateral retreat (in m/m) for all strength percentiles for 200 years

The initial nonlinear behavior, followed by parallel retreat rates are likely an artifact of the assumed strength distributions and the time needed to reach a steady state retreat rate. However, the eventual retreat rates parallel to the toe retreat rate suggest that once at steady state, toe retreat is a reasonable metric for evaluating total cliff retreat over long timescales. However, as evidenced in Figure 5.9 and Figure 5.10, the source of the observed retreat (overhangs versus cliff collapse) and the periodicity of erosional episodes will vary depending on the seacliff's relative strength (e.g., low friction/high cohesion vs. high friction/low cohesion).

5.4 AGGREGATION AND INTERPRETATION OF RESULTS

The analysis presented in this chapter provides a wealth of information and values that can be used to estimate potential seacliff erosion into the future. However, in order to integrate within the vulnerability matrix described in Section 3.0, specific values to describe the entire site are needed. To this end, the projected seacliff crest at 2050 and 2100 were extracted based on the lateral retreat from the 50th percentile strength scenario (Figure 5.4 and Figure 5.5). The estimated crest position was then compared to the highway shoulder to compute the shortest a distance to serve as the metric, similar to the current distance in Section 3.2.2.3.

Figure 5.13 shows detailed examples of the analysis for four of the vulnerable Highway 101 sites while Figure 5.14 provides summary results of the buffer distance for all sites at the epochs of interest. Abnormally large retreats were ignored as outliers that stemmed from spurious cross section geometry, represented by the dots that are exceptionally far inland, particularly for 2100. We deem these points as overestimates as the geologic weathering (i.e. cohesion values) at these depths are likely slower (i.e. higher cohesion values) than the model is predicting. The model does capture well shallow bluff failures, however. Caution should be used when interpreting these results at the scale of a site. While the model employs rigorous physics, substantial uncertainty exists in model inputs for strength (which are inherently variable spatially) and even larger uncertainties exist when projecting these models towards very long timeframes. Hence, while the model is useful to relatively compare sites and understand which sites might experience sizable erosion and failures in the future, it should not be used to interpret the precise locations of where failures will occur at the distant time horizons.



The map was created within the US HIGHWAY 101 COASTAL HAZARD VULNERABILITY AND RISK ASSESSMENT FOR MITIGATION PRIORITIZATION

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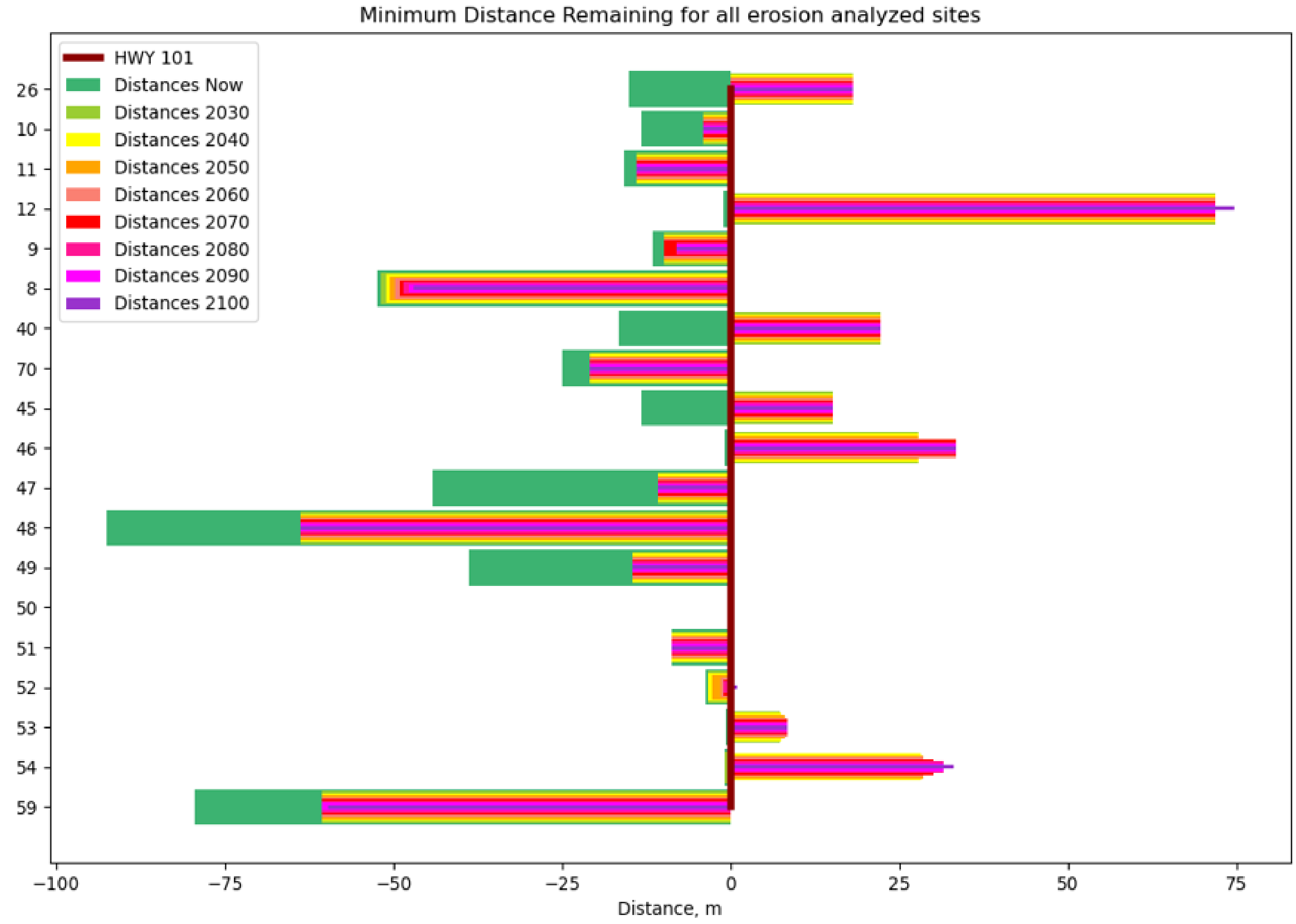
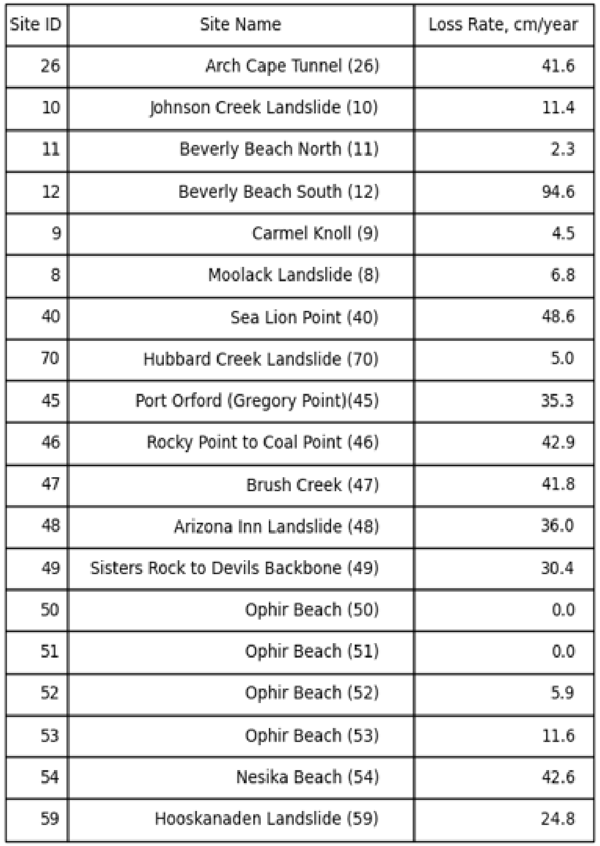
Figure 5.13: Example of projected erosion estimates at Arch Cape, Arizona Inn, Spencer Creek, and Sea Lion Point.





Site ID	Site Name	Loss Rate, cm/year
26	Arch Cape Tunnel (26)	41.6
10	Johnson Creek Landslide (10)	11.4
11	Beverly Beach North (11)	2.3
12	Beverly Beach South (12)	94.6
9	Carmel Knoll (9)	4.5
8	Moolack Landslide (8)	6.8
40	Sea Lion Point (40)	48.6
70	Hubbard Creek Landslide (70)	5.0
45	Port Orford (Gregory Point)(45)	35.3
46	Rocky Point to Coal Point (46)	42.9
47	Brush Creek (47)	41.8
48	Arizona Inn Landslide (48)	36.0
49	Sisters Rock to Devils Backbone (49)	30.4
50	Ophir Beach (50)	0.0
51	Ophir Beach (51)	0.0
52	Ophir Beach (52)	5.9
53	Ophir Beach (53)	11.6
54	Nesika Beach (54)	42.6
59	Hooskanaden Landslide (59)	24.8

Figure 5.14: Summary results of cliff top loss for all erosion analyzed sites for now, 2050, and 2100. These loss rates are computed as the difference in the minimum distance between the highway edge and the seacliff crest between 2100 and now divided by time.

6.0 VULNERABILITY ANALYSIS RESULTS

6.1 SITE RATINGS

Following Equation 3-3 using the weighting scheme established in Table 3.4 to Table 3.7, the ECVI scores for all sites were computed (Table 6.1). This weighting scheme prioritizes sites at risk from erosion and for consideration when exploring engineering needs under Goal 18. Thus, the associated erosion parameters receive the highest weight. In developing the results in Table 6.1, multiple weights were investigated, and the results were reviewed by the research team to ensure that they made sense relative to experience, judgment, and empirical observations.

Table 6.1: Ranking of priority sites, based on weighting scheme focused on erosion sites most relevant to Goal 18.

Rank	ID	Site	ECVI Value	ECVI Score	Mileposts		
					Start	End	Length
1	12	Beverly Beach South (Spencer Creek)	2.392	59.8%	133.89	134.34	0.45
2	59	Hooskanaden Landslide	2.385	59.6%	343.32	344.23	0.91
3	46	Rocky Point to Coal Point	2.360	59.0%	303.68	304.82	1.14
4	48	Arizona Inn landslide	2.340	58.5%	310.66	312.5	1.84
5	19	Saltair Creek	2.308	57.7%	51.30	51.34	0.04
6	8	Moolack landslide	2.308	57.7%	135.70	136.3	0.60
7	9	Carmel Knoll	2.265	56.6%	135.24	135.4	0.16
8	45	Port Orford (Gregory Point)	2.198	54.9%	302.78	303.68	0.90
9	52	Ophir Beach 3	2.153	53.8%	318.35	318.43	0.08
10	26	Arch Cape Tunnel	2.150	53.8%	35.90	35.97	0.07
11	21	Manhatten Beach Wayside	2.143	53.6%	49.01	49.25	0.24
12	51	Ophir Beach 2	2.125	53.1%	318.12	318.35	0.23
13	49	Sisters Rock to Devils Backbone	2.100	52.5%	314.09	315.81	1.72
14	40	Sea Lion Point	2.083	52.1%	178.57	179.13	0.56
15	33	Stonefeld Beach	2.020	50.5%	170.27	170.49	0.22
16	20	South Nehalem	1.998	49.9%	50.740	50.82	0.08
17	13	Whale Cove	1.993	49.8%	129.24	129.32	0.08
18	47	Brush Creek	1.958	48.9%	309.75	310.59	0.84
19	16	D River outlet	1.939	48.5%	114.86	114.96	0.10
20	68	Squaw Creek	1.918	47.9%	172.46	172.74	0.28
21	10	Johnson Creek landslide	1.893	47.3%	133.07	133.28	0.21
22	11	Beverly Beach North	1.858	46.4%	133.44	133.59	0.15
23	56	South side of Hunter Creek	1.850	46.3%	330.51	330.64	0.13
24	70	Hubbard Creek Landslide	1.838	45.9%	301.37	302.16	0.79
25	53	Ophir Beach 4	1.820	45.5%	318.43	318.59	0.16
26	55	North side of Hunter Creek	1.800	45.0%	330.12	330.48	0.36
27	34	Rock Beach	1.795	44.9%	174.36	174.43	0.07
28	38	Cummins Creek	1.745	43.6%	168.42	168.47	0.05
29	7	SE 130th St	1.715	42.9%	147.31	147.39	0.08

Rank	ID	Site	ECVI Value	ECVI Score	Mileposts		
					Start	End	Length
30	50	Ophir Beach 1	1.705	42.6%	317.49	318.12	0.63
31	4	Silver Point	1.660	41.5%	31.64	31.89	0.25
32	69	Baker Beach Landslide	1.648	41.2%	180.78	181.24	0.46
33	6	Beaver Creek North	1.618	40.4%	148.43	148.71	0.28
34	41	North Depoe Bay	1.618	40.4%	126.89	126.95	0.06
35	3	Hug Point	1.615	40.4%	32.41	32.56	0.15
36	37	Gwynn Creek	1.615	40.4%	168.03	168.12	0.09
37	36	Yachats River	1.585	39.6%	164.70	164.78	0.08
38	57	Myers Creek	1.570	39.3%	336.50	337.01	0.51
39	54	Nesika Beach	1.565	39.1%	319.36	320.62	1.26
40	25	Neahkahnie Mountain	1.555	38.9%	40.57	40.92	0.35
41	14	Cape Foulweather landslide	1.543	38.6%	130.70	130.84	0.14
42	24	North Nehalem	1.531	38.3%	44.97	45.08	0.11
43	5	Beaver Creek	1.530	38.3%	148.71	148.9	0.19
44	58	Pistol River	1.528	38.2%	338.06	339.07	1.01
45	15	Boiler Bay	1.513	37.8%	125.94	126.01	0.07
46	60	Rainbow Rock	1.430	35.8%	353.8	354.12	0.32
47	39	Big Creek	1.410	35.3%	174.88	175.05	0.17
48	31	SW Wakonda Beach Rd	1.398	34.9%	158.82	159.22	0.40
49	35	Ocean Beach	1.390	34.8%	174.15	174.23	0.08
50	61	Seal Point	1.350	33.8%	346.5	346.72	0.22
51	27	Seal Rock 1	1.338	33.4%	151.02	151.25	0.23
52	32	Annice Creek	1.280	32.0%	158.6	158.67	0.07
53	71	Nestucca Bay	1.276	31.9%	90.24	93.22	2.98
54	30	Big Creek	1.269	31.7%	160.13	160.19	0.06
55	2	South Seaside	1.268	31.7%	22.47	22.81	0.34
56	62	Fogarty Creek	1.260	31.5%	125.15	125.3	0.15
57	63	Alsea Bay	1.235	30.9%	156.17	156.52	0.35
58	1	HWY26 interchange	1.200	30.0%	24.3	24.85	0.55
59	28	Seal Rock 2	1.178	29.4%	151.29	151.41	0.12

Rank	ID	Site	ECVI Value	ECVI Score	Mileposts		
					Start	End	Length
60	22	North of Kelly's Brighton Marina	1.173	29.3%	45.66	46.06	0.40
61	29	SW Whitecap Dr	1.173	29.3%	157.7	157.99	0.29
62	17	Blue Heron Cheese	1.159	29.0%	64.53	65.44	0.91
63	23	Messhouse Creek	1.150	28.8%	46.88	47.01	0.13
64	67	Ten Mile Creek	0.955	23.9%	171.32	171.61	0.29
65	65	Coos Bay - north slough	0.924	23.1%	229.42	231.78	2.36
66	66	Coos Bay - downtown	0.904	22.6%	236.31	238.61	2.30
67	42	Siletz Bay South	0.901	22.5%	120.51	121.35	0.84
68	64	Gardner	0.886	22.1%	209.48	210.34	0.86
69	18	Tillamook Cheese Factory	0.795	19.9%	63.70	63.95	0.25
70	44	Siletz Bay North	0.760	19.0%	118.11	118.5	0.39
71	43	Siletz Bay Central	0.690	17.3%	119.38	119.98	0.60

6.2 ADAPTATION SITE SELECTION PROCESS

While the ratings and rankings in Section 6.1 are based on the cumulative hazard and vulnerability ratings for sites along US Highway 101, additional selection criteria were applied to identify those sites for which adaptation options would be evaluated as part of this study. Rather than focusing on the "Top 5" sites, the intent was to select a variety of sites capturing different situations across different areas of the state. Hence, this further selection process is not intended to change the priority levels, but rather show representative sites across the different regions at a suitable level of detail for use in the economic framework (Chapter 8).

In the course of this site selection process, other factors were considered such as commodity flows from the Transportation Planning Analysis Unit (TPAU) modeling (Appendix D) and the statewide ODOT equity layer (ODOT, 2021). It is worth noting that the TPAU commodity flow values are more or less similar for most of the sites within a corridor segment. The social equity index values were considered in the decision process but were relatively similar for most of the sites on Highway 101 (typically 0.9-1.0 compared with 0.3 to 1.94 across the state). After evaluating the social equity distribution of the sites, the selection process consists of the following steps:

1. Group sites by specific corridor segment between highways that intersect with HWY 101 (Table 6.2).
2. Rank the vulnerable sites within each corridor segment based on the hazard score computed in Section 6.1.
3. Next, select the site with the highest score in each segment as a proposed site unless there was a specific reason to exclude the site, such as:
    a. No sites were selected from corridors where (a) the hazards were primarily flooding controlled and thus not applicable for consideration under Goal 18, and (b) where the erosion hazards are significantly lower.
    b. For the South Coast segment, Hooskanaden had the highest score; however, it is highly unlikely that shoreline protection will be an effective solution given that the large landslide movements would overwhelm any benefits by the shoreline protection. The next highest ranked sites Rocky Pt to Coal Pt. (ECVI Score = 59.0) and Arizona Inn (ECVI Score = 58.5) had nearly identical ECVI scores. Arizona Inn was selected because (1) some new drainage installation work has already been undertaken at the site, (2) has higher annual maintenance costs, and (3) monitoring from research project SPR807 has shown that the site is showing high levels of movement and may require mitigation soon before a substantial failure occurs.

This approach for site selection has the following benefits:

1. Allows the economic framework to be applied at a broad range of locations across the entire coastline. The sites also have a broad range of challenges and scales.

2. Allows the economic framework to move forward for a representative site considered to be most likely to fail first within each main corridor section. In turn, that makes it simpler to extend the framework to the other sites in the future (outside of the scope of 843) as a significant portion of the economic data, assumptions, and considerations for the representative site could be readily adapted for the other sites in the corridor.

3. Allows the research team to focus in more detail on specific sites and implement more rigorous methodologies rather than perform very coarse analysis on a large number of sites clustered together. This former approach results in a more useful product for ODOT compared with a generalized approach that endeavors to evaluate many or all sites (with multiple options) resulting in a cruder analysis, characterized with broad assumptions. From this process, the five selected sites for the adaptation option economic analysis are summarized in Table 6.3.

Table 6.2: Erosion sites sorted by each corridor segment. Includes commodity flow, maintenance costs, and estimated repair costs for sites.

Corridor Segment	ID	Site	Site Primary Hazard Type	TPAU Annual Commodity Flow	Unstable Slopes		ECVI Score
					Annual Maintenance Cost	Estimated Repair Cost	
HWY 26 to 53	26	Arch Cape Tunnel	E	$263,769	$547.88	$668,531.52	53.8%
	4	Silver Point	E	$292,273	$6,562.33	$2,190,658.77	41.5%
	3	Hug Point	E	$292,273	$2,332.20	$201,476.84	40.4%
	25	Neahkahnie Mountain	E	$263,769	$5,266.96	$123,150,173.92	38.9%
HWY 6 to 53	19	Saltair Creek	E	$266,839	$-	$ -	57.7%
	20	South Nehalem	E	$229,812	$-	$ -	49.9%
	22	North of Kelly's Brighton Marina	E	$223,826	$20,318.28	$2,964,930.86	29.3%
	23	Messhouse Creek	E	$223,826	$715.30	$286,030.96	28.8%
Hwy 229 to 18	16	D River outlet	E	$3,107,055	$-	$ -	48.5%
HWY 20 to 229	12	Beverly Beach South (Spencer Creek)	E	$2,659,781	$-	$ -	59.8%
	8	Moolack landslide	E	$2,833,804	$277,710.89	$27,115,947.14	57.7%
	9	Carmel Knoll	E	$2,659,781	$44,708.51	$3,547,352.40	56.6%
	13	Whale Cove	E	$2,659,781	$-	$ -	49.8%
	10	Johnson Creek landslide	E	$2,659,781	$20,000.00	$3,599,109.13	47.3%
	11	Beverly Beach North	E	$2,659,781	$16,481.31	$943,910.32	46.4%
	41	North Depoe Bay	E	$2,682,582	$-	$ -	40.4%
	14	Cape Foulweather landslide	E	$2,659,781	$-	$ -	38.6%
	15	Boiler Bay	E	$2,682,582	$-	$ -	37.8%
HWY 34 to 20	7	SE 130th St	E	$2,507,292	$-	$ -	42.9%
	27	Seal Rock 1	E	$3,109,319	$-	$ -	33.4%
	28	Seal Rock 2	E	$3,109,319	$-	$ -	29.4%
	40	Sea Lion Point	E	$3,763,578	$6,549.90	$12,419,073.79	52.1%

Corridor Segment	ID	Site	Site Primary Hazard Type	TPAU Annual Commodity Flow	Unstable Slopes		ECVI Score
					Annual Maintenance Cost	Estimated Repair Cost	
HWY 126 to 34	33	Stonefeld Beach	E	$3,763,578	$9,755.29	$5,708,425.68	50.5%
	68	Squaw Creek	E	$3,763,578	$1,908.81	$268,243.12	47.9%
	69	Baker Beach Landslide	E	$3,763,578	$-	$ -	41.2%
	37	Gwynn Creek	E	$3,763,578	$-	$ -	40.4%
	35	Ocean Beach	E	$3,763,578	$2,081.92	$8,502,925.16	34.8%
	32	Annice Creek	E	$3,179,023	$-	$ -	32.0%
	29	SW Whitecap Dr	E	$2,996,789	$-	$ -	29.3%
HWY 199 to 42	59	Hooskanaden Landslide	E	$1,166,377	$490,178.40	$300,517,800.00	59.6%
	46	Rocky Point to Coal Point	E	$1,851,312	$181,597.44	$8,248,750.19	59.0%
	48	Arizona Inn landslide	E	$1,851,312	$376,219.89	$7,153,993.47	58.5%
	45	Port Orford (Gregory Point)	E	$1,851,312	$229,245.00	$10,871,877.16	54.9%
	52	Ophir Beach 3	E	$1,606,898	$-	$ -	53.8%
	51	Ophir Beach 2	E	$1,606,898	$-	$ -	53.1%
	49	Sisters Rock to Devils Backbone	E	$1,851,312	$397,600.72	$8,256,652.26	52.5%
	47	Brush Creek	E	$1,851,312	$61,794.24	$27,034,784.92	48.9%
	70	Hubbard Creek Landslide	E	$1,851,312	$-	$ -	45.9%
	53	Ophir Beach 4	E	$1,606,898	$-	$ -	45.5%
	50	Ophir Beach 1	E	$1,606,898	$-	$ -	42.6%
	54	Nesika Beach	E	$1,606,898	$-	$ -	39.1%
	60	Rainbow Rock	E	$1,220,588	$3,134.68	$3,071,569.81	35.8%
	61	Seal Point	E	$1,166,377	$-	$ -	33.8%

Table 6.3: Selected Sites for Adaption Option Economic Analysis

ID	Site Name	ECVI Value	ECVI Score	Mileposts			ODOT Region	Additional Notes
				Start	End	Length		
26	Arch Cape Tunnel	2.150	53.8	35.62	35.97	0.35	2	While TPAU commodity flow results are relatively low here compared with other sites, the tunnel is a significant infrastructure investment and unique case study. While the site may not handle much freight, it can have important implications connecting smaller communities on the coast for emergency response, tourism, and other purposes that are not captured in the TPAU results. The tunnel was originally built because there were very limited routing options. It was also included in an earlier ODOT adaption pilot study (ODOT, 2014).
19	Saltair Creek	2.308	57.7	51.30	51.34	0.04	2	Site regularly experiences erosion and flooding issues. A house at the site is also currently being considered for a Goal 18 exception.
12	Beverly Beach South (Spencer Creek)	2.392	59.8	133.89	134.34	0.45	2	This site is a very unique site on the Oregon Coast and has high tourism value with Beverly Beach State Park Campsite and Day Use Facilities. It also is a critical link between Newport and Lincoln City.
40	Sea Lion Point	2.082	52.8	178.57	179.13	0.56	2	This site experienced a recent failure that required an emergency repair in 2021.
48	Arizona Inn Landslide	2.340	58.5	310.66	312.50	1.84	3	Some new drainage installation work was underway, has high annual maintenance costs, and monitoring from research project SPR807 has shown that the site is showing high levels of movement and may require mitigation soon before a substantial failure occurs. Note that on January 9, 2023, long after the analysis of this project was completed, the landslide moved approximately 7 m, completely closing Hwy 101 for a week followed by an extended period of reduced operation with just a single gravel lane while rebuilding plans are determined.

***Note Mileposts (MP) are based on the ODOT 2016 milepost layer and approximate.

6.3 ALTERNATIVE ANALYSIS FOR FLOODING

For illustration purposes, an alternative weighting scheme was developed to identify those sites that experience the most significant inundation (flood) hazards (Table 6.4). Note that the thresholds used were the same as those presented in Tables 3.1 to 3.3. Only the weighting was modified. Many of these sites are not directly related to Goal 18, so they would be out of the scope of the project. However, these results are presented (1) as a reminder that they are still problematic sites that still need to be dealt with under Goal 16 constraints, and (2) show the impact of the weighting scheme based on the priorities of the analysis.

Table 6.4: Weights used for flooding analysis.

Category	Parameter	Weight
Inundation	Floods	14.00%
	Flooded Length	14.00%
	SLR Inundation Length, 2050	8.75%
	SLR Inundation Length, 2100	8.75%
	SLR Inundation Depth, 2050	8.75%
	SLR Inundation Depth, 2100	8.75%
	Highway Elevation	7.00%
Erosion	Erosion Rate (2008-2016)	1.50%
	Erosion Rate (2002-2016)	0.75%
	Geomorphology Class	2.25%
	Total Water Level	0.75%
	Overtopping	0.75%
	Projected Distance from Seacliff Edge to Highway (Average, 2050)	0.75%
	Projected Distance from Seacliff Edge to Highway (Average, 2100)	0.75%
	Current Distance to Seacliff Highway	0.75%
	Shoreline Protection	0.75%
	Shoreline Protection Length	0.75%
	Qualitative Field Change Analysis	2.25%
	Maximum Erosion Rate	1.50%
	Percentage of Transects	1.50%
Landslides	Proximity to landslide (SLIDO)	1.50%
	Unstable Slopes Frequency of Repair	3.75%
	Unstable Slopes Failure Hazard Score	2.25%
	Unstable Slopes Road Impact	2.25%
	Unstable Slopes Annual Cost	3.75%
	Landslide Susceptibility	1.50%

Table 6.5: Sites ranked based on flooding/inundation hazards.

Rank	ID	Site	ECVI Value	ECVI Score	Mileposts		
					Start	End	Length
1	24	North Nehalem	3.072	76.8%	44.97	45.08	0.11
2	71	Nestucca Bay	2.776	69.4%	90.24	93.22	2.98
3	64	Gardner	2.620	65.5%	209.48	210.34	0.86
4	17	Blue Heron Cheese	2.552	63.8%	64.53	65.44	0.91
5	66	Coos Bay - downtown	2.488	62.2%	236.31	238.61	2.3
6	42	Siletz Bay South	2.168	54.2%	120.51	121.35	0.84
7	2	South Seaside	2.012	50.3%	22.47	22.81	0.34
8	16	D River outlet	1.872	46.8%	114.86	114.96	0.1
9	30	Big Creek	1.864	46.6%	160.13	160.19	0.06
10	65	Coos Bay - north slough	1.820	45.5%	229.42	231.78	2.36
11	63	Alsea Bay	1.772	44.3%	156.17	156.52	0.35
12	1	HWY26 interchange	1.696	42.4%	24.30	24.85	0.55
13	6	Beaver Creek North	1.440	36.0%	148.43	148.71	0.28
14	5	Beaver Creek	1.420	35.5%	148.71	148.9	0.19
15	34	Rock Beach	1.412	35.3%	174.36	174.43	0.07
16	21	Manhatten Beach Wayside	1.372	34.3%	49.01	49.25	0.24
17	36	Yachats River	1.312	32.8%	164.7	164.78	0.08
18	43	Siletz Bay Central	1.240	31.0%	119.38	119.98	0.60
19	38	Cummins Creek	1.224	30.6%	168.42	168.47	0.05
20	55	North side of Hunter Creek	1.224	30.6%	330.12	330.48	0.36
21	19	Saltair Creek	1.208	30.2%	51.30	51.34	0.04
22	44	Siletz Bay North	1.144	28.6%	118.11	118.50	0.39
23	62	Fogarty Creek	1.096	27.4%	125.15	125.30	0.15
24	57	Myers Creek	1.076	26.9%	336.5	337.01	0.51
25	67	Ten Mile Creek	1.064	26.6%	171.32	171.61	0.29
26	7	SE 130th St	1.028	25.7%	147.31	147.39	0.08
27	8	Moolack landslide	1.016	25.4%	135.70	136.30	0.60
28	20	South Nehalem	1.008	25.2%	50.74	50.82	0.08

Rank	ID	Site	ECVI Value	ECVI Score	Mileposts		
					Start	End	Length
29	46	Rocky Point to Coal Point	0.984	24.6%	303.68	304.82	1.14
30	48	Arizona Inn landslide	0.936	23.4%	310.66	312.5	1.84
31	33	Stonefeld Beach	0.920	23.0%	170.27	170.49	0.22
32	59	Hooskanaden Landslide	0.900	22.5%	343.32	344.23	0.91
33	45	Port Orford (Gregory Point)	0.876	21.9%	302.78	303.68	0.90
34	9	Carmel Knoll	0.864	21.6%	135.24	135.4	0.16
35	39	Big Creek	0.860	21.5%	174.88	175.05	0.17
36	49	Sisters Rock to Devils Backbone	0.820	20.5%	314.09	315.81	1.72
37	40	Sea Lion Point	0.816	20.4%	178.57	179.13	0.56
38	51	Ophir Beach 2	0.804	20.1%	318.12	318.35	0.23
39	47	Brush Creek	0.804	20.1%	309.75	310.59	0.84
40	58	Pistol River	0.800	20.0%	338.06	339.07	1.01
41	18	Tillamook Cheese Factory	0.796	19.9%	63.7	63.95	0.25
42	68	Squaw Creek	0.792	19.8%	172.46	172.74	0.28
43	22	North of Kelly's Brighton Marina	0.788	19.7%	45.66	46.06	0.40
44	35	Ocean Beach	0.784	19.6%	174.15	174.23	0.08
45	31	SW Wakonda Beach Rd	0.780	19.5%	158.82	159.22	0.4
46	56	South side of Hunter Creek	0.776	19.4%	330.51	330.64	0.13
47	50	Ophir Beach 1	0.772	19.3%	317.49	318.12	0.63
48	10	Johnson Creek landslide	0.764	19.1%	133.07	133.28	0.21
49	23	Messhouse Creek	0.764	19.1%	46.88	47.01	0.13
50	52	Ophir Beach 3	0.764	19.1%	318.35	318.43	0.08
51	11	Beverly Beach North	0.756	18.9%	133.44	133.59	0.15
52	3	Hug Point	0.748	18.7%	32.41	32.56	0.15
53	12	Beverly Beach South (Spencer Creek)	0.716	17.9%	133.89	134.34	0.45
54	53	Ophir Beach 4	0.692	17.3%	318.43	318.59	0.16
55	25	Neahkahnie Mountain	0.676	16.9%	40.57	40.92	0.35
56	60	Rainbow Rock	0.660	16.5%	353.80	354.12	0.32
57	26	Arch Cape Tunnel	0.636	15.9%	35.90	35.97	0.07

Rank	ID	Site	ECVI Value	ECVI Score	Mileposts		
					Start	End	Length
58	32	Annice Creek	0.620	15.5%	158.60	158.67	0.07
59	4	Silver Point	0.616	15.4%	31.64	31.89	0.25
60	13	Whale Cove	0.564	14.1%	129.24	129.32	0.08
61	14	Cape Foulweather landslide	0.524	13.1%	130.70	130.84	0.14
62	70	Hubbard Creek Landslide	0.516	12.9%	301.37	302.16	0.79
63	37	Gwynn Creek	0.516	12.9%	168.03	168.12	0.09
64	69	Baker Beach Landslide	0.464	11.6%	180.78	181.24	0.46
65	41	North Depoe Bay	0.448	11.2%	126.89	126.95	0.06
66	27	Seal Rock 1	0.444	11.1%	151.02	151.25	0.23
67	29	SW Whitecap Dr	0.444	11.1%	157.70	157.99	0.29
68	54	Nesika Beach	0.436	10.9%	319.36	320.62	1.26
69	15	Boiler Bay	0.372	9.3%	125.94	126.01	0.07
70	28	Seal Rock 2	0.368	9.2%	151.29	151.41	0.12
71	61	Seal Point	0.360	9.0%	346.50	346.72	0.22

7.0 PROPOSED SITE ADAPTATION OPTIONS

7.1 OVERVIEW

This section describes the selected sites (Figure 7.1) and the adaptation options considered (Table 7.1). In general, adaption options include (1) an expensive but long-life option, (2) a mid-range option, (3) a quick and easy fix, and (4) a do nothing alternative. However, these options vary at some sites when they would not be applicable. In addition, they build upon recent ODOT efforts such as the Adaption Pilot for Arch Cape as part of the broader "Climate Change Vulnerability Assessment and Adaptation Options Study" (ODOT 2014) and the "Green Infrastructure Techniques for Resilience of the Oregon Coast Highway" (ODOT, 2017).

7.2 ASSUMPTIONS

Ultimately, the intent was to illustrate the process for realistic adaptation options rather than authoritatively estimate an optimal prioritization for the adaption options that are under consideration. To this end, several assumptions were made in these adaption options based on input from ODOT (Mohney, personal communication).

- Beach loss estimates are direct beach loss due to the placement of the engineering structure at the time of placement. It does not account for long-term, secondary effects in changing the dynamics of the beach morphology. Beach loss from sea level rise will also occur regardless of the adaptation option. An example of beach loss due to long-term projections of sea level rise is presented in Section 4.3.

- Substantial failures could occur multiple times over the next century at some sites (e.g., Spencer Creek, Arizona Inn), increasing in frequency due to changes in storm characteristics, specifically the intensity of storms (e.g., waves, precipitation) and sea level rise resulting from climate change. Many of the scenarios only considered one failure event.

- Sand replenishment and sand tubes considered in ODOT's prior adaptation study were not considered here as viable alternatives. Sand replenishment has many issues, not least of which is identifying suitable sand sources that may be 'borrowed' from, and barging the sand long distances increases its cost and disrupts the public beach. Furthermore, sand tubes are akin to seawalls and thus can also enhance scour when exposed (Mohamed Rashidi et al., 2021).

- The cost per mile for a general reroute was computed by ODOT (personal communication) based on the Pioneer Mountain - Eddyville project(s) and estimated as $27,528,000 per mile, which consisted of seven separate projects that occurred around 2013 ($33,584,000 per mile in 2022 dollars). An additional project on the west end of the project was outside of the reroute, addressed an existing alignment, and did not include the full roadway width so it was excluded. This figure includes all costs – construction, design, Right of Way (R/W), utilities, etc. Nevertheless, the project did not involve a lot of high-value R/W acquisition but did include more railroad payments than are typical for rural projects, likely balancing out.

- The mitigation of any existing slides on a reroute would be part of the initial cost and that other earthworks and structures associated with the upgrade would be constructed to current standards for heavy mitigations. For mid-range mitigations such as shear keys/buttresses, minimal maintenance is also assumed, which is primarily focused on occasional patching due to post-construction consolidation during the first five years after construction.

- Routine, generic maintenance costs that are not specific to an alternative design are not considered across the alternatives as they would be estimated to be similar across all options.

- Potential closure event date scenarios were determined by the research team and ODOT TAC after deliberating on documentation of previous events at each site, field observations (e.g., SPR807), the vulnerability assessment (Section 6.0), retreat modeling (Section 5.0), and judgement. Given the wide range of uncertainty, these were labeled into three categories, average (best estimate of the timing of a closure), best case situation (longest time before a closure that is likely to occur- e.g., relatively dry winters), and worst-case situation (shortest time before a closure is likely to occur-e.g., substantial rainfall from atmospheric rivers).

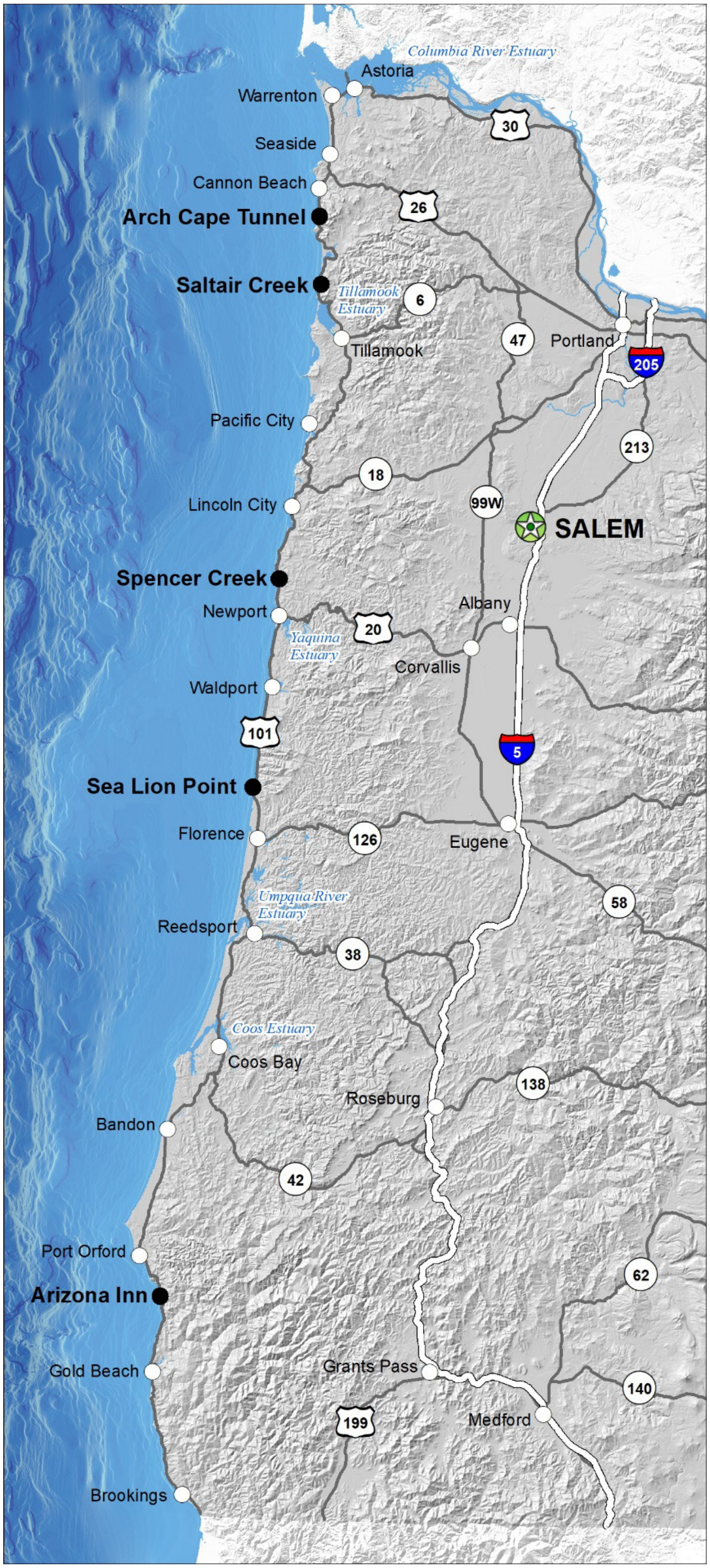


Figure 7.1. Map showing selected vulnerability sites for economic analysis.

Table 7.1: Specific simplifying assumptions used in the site adaptation option analysis.

Site	Closure Event			Closure Scenario for Repairs (Do Nothing Alternative)	Closure scenario for each adaptation strategy
	Average	Worst Case	Best Case		
Arch Cape Tunnel	2032	2023	2035	Repair work will likely not go past centerline; keep 1 lane open with 24/7 flagging; closed for 2 weeks	-
Saltair Creek	2027 -2028	2023	2032	Full closures resulting from flooding. Closures not expected to last a significant amount of time because of flooding. As repairs/cleanup can be done fairly quickly (hours); construction can be done under flagging.	Replace bridge with higher structure. Work performed in stages; build half at a time, so traffic can continue.
Spencer Creek	2030	2023	2035	Closed in 1 direction with flagging team for 6 weeks; worst case full closure for 3 months	Reroute: no disruption (assuming lack of road failure). Armoring/Shotcrete seawall: closed in 1 direction with flagging team for 2 months to enable construction of structure. Placing of riprap should not require closure.
Sea Lion Point	2027	2023	2035	Minimal clearance between road and cliff; could keep lane open for portions, but would require periods of full closure especially when using a crane to place equipment over the edge. 6 weeks closure per failure.	Requires specialized equipment hanging over side.
Arizona Inn Landslide	2025	2023	2030	Reroute; place temporary gravel road for access; 2 weeks (best case) to 3 months (worst case)	Reroute: HWY 42 to I-5 into CA and back

7.3 ARCH CAPE

7.3.1 Site Overview

The Arch Cape site is located on U.S Highway 101 (HWY 101) at Milepost 36 immediately south of the Arch Cape tunnel and approximately 1 mile south of the town of Arch Cape, Clatsop County, OR. At this site, HWY 101 runs roughly parallel to the shoreline and is separated by a steep coastal landslide deposit that is rapidly eroding. Figure 7.2 shows the section of road above the site, whilst Figure 7.3 shows the steep drop from the road to the shoreline. This site is a unique site with a critical structure (tunnel) for emergency response and tourism. Because of the limitations of vehicle size due to the tunnel, much of the freight and commodity transport takes alternate routes to the coast. Nevertheless, it is still an important lifeline to connect residents of communities.

The shoreline at this location (moving landward) changes from a small section of sandy beach, to a steep cobble/boulder berm around 15 m wide that is flush against the seacliff (Figure 7.4 and Figure 7.5). The cobbles decrease in angularity southward where they become well-sorted, smooth, rounded cobbles approximately 6” in diameter. The coastal seacliff itself is a landslide deposit around 35 m in height with a gradient of roughly 45˚ and contains sparse vegetation at its base up until around 10 m where vegetation increases. HWY 101 sits upon this seacliff and trees also appear on the slope at approximately the elevation of the highway.

Figure 7.2: US Highway 101 facing north just before the Arch Cape tunnel (near MP36, August 2016).

Figure 7.3: Facing west (towards to ocean) from Hwy 101, showing the steep coastal seacliff rapidly descending to the beach (near MP36, August 2016).

Figure 7.4: The coastal seacliff and cobble/boulder berm along the toe of the Arch Cape site (facing south east) (near MP36, August 2016). Note the decreasing angularity southward.

Figure 7.5: Steep seacliff, fronted by a lag of boulders and cobble at Arch Cape, looking northward.

Arch Cape lies within the Astoria Formation and is mainly composed of sandstone with some siltstone from the Miocene (Schilicker et al., 1972). Just north of the study area this formation is bounded by extrusive basalt from the Grande Ronde basalt formation (Niem and Niem, 1985). The beginning of this unit is visible in the topography as the elevation sharply rises due to the increased hardness of the basalt and corresponds roughly with the start of the Arch Cape tunnel. This Grande Ronde basalt, along with colluvial deposits in the older landslide unit, forms a large source of much of the cobbles and boulders that form the berm at the base of the seacliff in the study area.

Data from ODOT's unstable slope database shows this site as requiring repair once every five years with heavy precipitation cited as the primary cause of movement. Currently, temporary retaining walls and pavement patches are used to protect the highway at this location (Crook & Mohney, 2014); however, they are required to be replaced every 12-15 years (Crook & Mohney, 2014).

7.3.2 Adaptation Options

Four adaptation options were considered for this site (Table 7.2) including (1) do nothing, (2) buttressing, (3) soldier pile wall with protection, and (4) rerouting (Figure 7-6). Estimated construction costs are summarized in Table 7.3. For Alternative 3, ODOT does not typically consider maintenance on a structure such as this. The piezometric surface is below the retained section so the site would not require any extraordinary maintenance for drain cleaning. Hence, any maintenance on this structure would be of a general nature and not related to ongoing slide movement. Nevertheless, the structure may experience a reduced design life given its location.

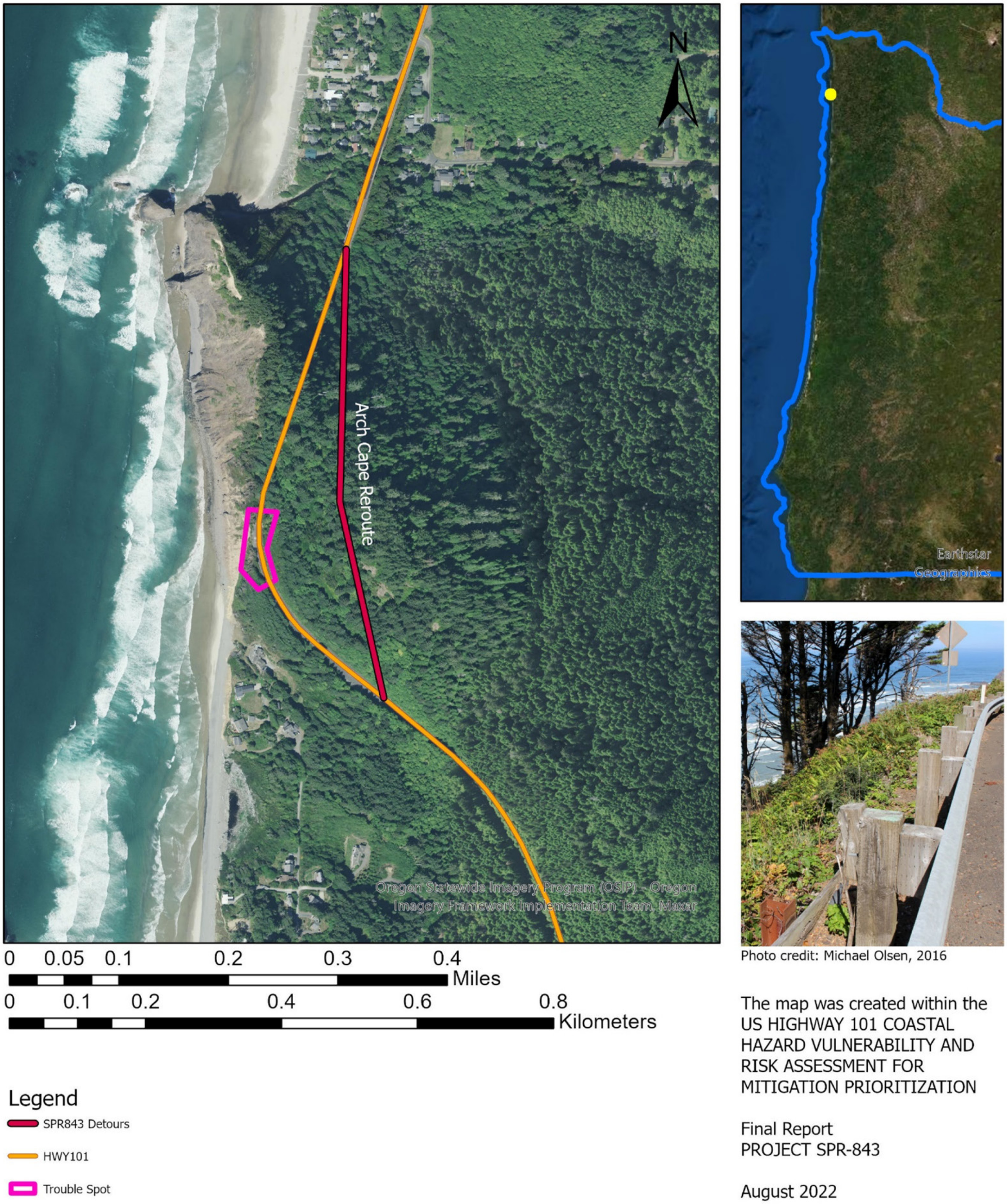


Photo credit: Michael Olsen, 2016

The map was created within the US HIGHWAY 101 COASTAL HAZARD VULNERABILITY AND RISK ASSESSMENT FOR MITIGATION PRIORITIZATION

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Figure 7.6: Potential re-route option used for Arch Cape

Table 7.2: Description and basic characteristics of adaptation options considered for Arch Cape

#	Alternative	Mitigation Effect	Relative Protection	Direct Loss of Beach Width (ft)	Relative Maint.	Initial Cost	Design Life (years)	Repair Length (ft)	RW Take (ft^2)
1	Do Nothing	No Effect - Failure continues to SB Lane, Traffic restricted to one-way flagger control for 8-hour period, 0.2 times per year	None	0	Very High	Low	0	0	0
2	Buttress Primary Slide, Reinforce Second Slide	Increase Resisting Force on Slide. Continue Maintenance Frequency with increased effort for Buttress Maintenance, Eliminate existing wall and wall maintenance. Reinforce Lower Slide to decrease rate of movement/maintenance requirements	Moderate	0	Low	Medium	20	365	0
3	Construct Soldier Pile Wall, Protect Slope	Support roadway with Soldier Pile Wall. Tiebacks support wall and roadway. Lower design life - marine environment. Secondary Slide is separated from roadway eliminating its effect. Add RipRap protection.	High	20	Low	High	50	365	13,485
4	Highway Re-rerouting	Re-route highway inland away from the coast	Very High	0	Low	Very High	75	2,192	Easement

Table 7.3: Cost estimates (2022 US$) of adaptation options considered for Arch Cape

#	Estimated Construction Cost (Total)	Estimated Cost (Per Linear Foot)	Construction Time (weeks)	Current			@30 years			Notes
				Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours	
1	$0	$0	0	$2,460	0.2	8	$5,747	0.25	8	-
2	$1,405,713	$3,851.27	4	$968	0.067	8	$2,559	0.08	8	-
3	$3,452,833	$9,459.82	14	$0	0	0	$0	0	0	High initial cost to result in minimal maintenance
4	$41,000,000	$18,704	75	$225,000	0.5	0	$266,391	0.2	0	-

7.4 SALTAIR CREEK

7.4.1 Site Overview

The Saltair Creek site is located just north of the intersection of Highway 101 and South 6th Avenue in Rockaway Beach, Oregon (Figure 7.7, Figure 7.8). One primary reason for selecting this site is that a house located nearby is the focus of a current Goal 18 exception. The site regularly experiences flooding at high tides, coupled with storm surges. The site is an existing problem since the original culvert design under Highway 101 is small and was designed primarily for water to be transported to the ocean, but not for incoming tides (Figure 7.9). It has experienced rapid erosion relative to the sections north and south of the site due to the small stream (Figure 7.10). Adjacent to the highway is a railroad bridge that was recently replaced at the time of this report. The stream channel has undergone restoration work to slow water velocities and help mitigate flooding (Figure 7.11, Figure 7.12). A wall of driftwood supported by steel railroad track segments has also been constructed to help protect waves from eroding the channel upstream, and from reducing the transport of flotsam (logs etc.) onto the highway (Figure 7.13).

The geology of this site consists primarily of Quaternary age fine-grained unconsolidated sediments, including alluvium, colluvium, river and coastal terrace, landslide, eolian deposits (Snavely et al. 1976).

Figure 7.7: Photograph showing the Saltair Creek site looking southward (July 2022).

Figure 7.8: Photograph showing the Saltair Creek site looking northward (July 2022).

Figure 7.9: Photograph showing the culvert under the highway (July 2022).

Figure 7.10: Aerial photograph showing accelerated erosion of the dunes observed at the Saltair Creek intersection site compared with adjacent dune morphology.

Figure 7.11: Photograph looking eastward at the Saltair Creek site showing the drainage channel restoration (July 2022)

Figure 7.12: Photograph looking westward at the Saltair Creek site showing the drainage channel restoration (July 2022)

Figure 7.13: Photograph showing the driftwood protection wall with steel railroad track supports (July 2022).

7.4.2 Adaptation Options

Four adaptation options were considered for this site (Table 7.4) including (1) do nothing, (2) buttressing, (3) soldier pile wall with protection, and (4) rerouting. Estimated construction costs are summarized in Table 7.5. For this site, the reroute would involve transferring ownership from a Tillamook County Road and upgrading a portion of a parallel city road to avoid this problematic location. It is assumed that the mitigation of any existing slides on the reroute would be included as part of the initial cost and that other earthworks and structures associated with the upgrade would be constructed to current standards. Any maintenance with this option is assumed to be generic, routine maintenance and not necessitated by slide movement.

Table 7.4: Description and basic characteristics of adaptation options considered for Saltair Creek

#	Alternative	Mitigation Effect	Relative Protection	Direct Loss of Beach Width (ft)	Relative Maint.	Initial Cost	Design Life (years)	Repair Length (ft)	Right of Way Take (ft^2)
1	Do Nothing	Continue with basic repairs and maintenance of the highway but no implementation of shoreline protection	None	None	Medium	Low	0	0	0
2	Shoreline Mitigation	Arrest debris at shoreline with barriers, widen and reinforce channels including RR bridges	Moderate	10	Medium	Medium-High	25-50	125	Easement
3	Erosion Control.	V-shaped, vegetated, armored slopes along north and south sides of stream. Riprap wall on westerly edge. Elevate and widen crossings including RR	High	10	Low	High	25-50	125	2,500
4	Highway Re-rerouting	Re-route – upgrade local road	Very High	None	Low	Very High	50	68,640	1,372,800

Table 7.5: Cost estimates (2022 US$) of adaptation options considered for Saltair Creek

#	Estimated Construction Cost (Total)	Estimated Cost (Per Linear Foot)	Construction Time (weeks)	Current			@30 years			Notes
				Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	
1	$0	$0	0	$3,378	5	4	$23,598	10	6	-
2	$5,550,000	$44,400	25	$2,565	5	2	$17,422	5	4	Debris barrier has 25-year design life. 50 years for all other. Length along highway centerline
3	$13,125,300	$105,002	50	$1,000	1	0	$3,582	2	0	Debris barrier has shorter design life
4	$19,400,000	$282.63	60	*Assumed minimal, routine maintenance only*						-

7.5 SPENCER CREEK

7.5.1 Site Overview

The Spencer Creek site is located immediately south of the Spencer Creek Bridge at Beverly Beach State Park, just north of milepost 134 on Hwy 101. The site has substantial recreational activity due to the State Parks campground and day use facilities. This section of Highway 101 is also a unique section with an open view of the ocean. It also serves as a vital lifeline connection between the cities of Newport and Lincoln City.

Figure 7.14 shows Hwy 101 running parallel to the coastline separated by a coastal seacliff at the site. Moving landward the area changes from a wide, gently sloping sand beach to a steep coastal seacliff around 20 m in height with a gradient of about 30˚, with varying amounts of vegetation. Representative examples of seacliffs are shown in Figure 7.15 and Figure 7.16. The typical front face of these seacliffs is shown in Figure 7.16, while Hwy 101 sitting on top of this seacliff is typically separated by a 5- to 10-foot-wide shoulder as shown in Figure 7-15. Nevertheless, several failures have cut into this shoulder (Figure 7.15).

Figure 7.14: Photograph showing Spencer Creek site, facing south, with Hwy 101 shown on the left separated from ocean by the crumbling coastal seacliff (Near MP 134, Aug 2016).

Figure 7.15: Mass movement and infrastructure damage along Hwy 101 at Spencer Creek, (facing south, near MP 134, August 2016).

Figure 7.16: Example coastal seacliff failure at Spencer Creek (facing east, near MP 134, August 2016).

The geology of this site consists primarily of siltstone and sandstone from the Astoria Formation, which dips around 20° to the east. This is overlain by interbedded estuary deposits consisting of layers of loose silt and sand interbedded with soft clayey silt and organics. The estuary deposits vary from around 90 feet thick (around Spencer Creek) down to 10 feet thick on the lateral edges of the site (Shannon & Wilson, Inc. 2015).

Previous studies by Priest (1999) estimates erosion rates in the seacliffs surrounding Spencer Creek to be 0.2 to 1.5ft per year. This combined with local mass movement events (Figure 7.15 and Figure 7.16) causes periodic problems for Hwy 101 along this stretch requiring frequent repaving of the highway. Whilst large failure events are unlikely, small cumulative events slowly build up causing damage to the road and infrastructure, including Spencer Creek Bridge, which was recently constructed in 2008 costing $20.2 million US.

7.5.2 Adaptation options

Five adaptation options were considered for this site (Table 7.6) including (1) do nothing, (2) a rip-rap revetment (3) cobble beach, (4) drainage blanket and (5) rerouting (Figure 7.17). Estimated construction costs are summarized in Table 7.7. Note that the beach loss values are directly associated with the adaptation option and does not include beach loss from sea level rise and natural erosional processes (Section 4.3), which will result in beach loss for all options. Given the particularly high recreational value at this site, beach loss is a critical consideration.

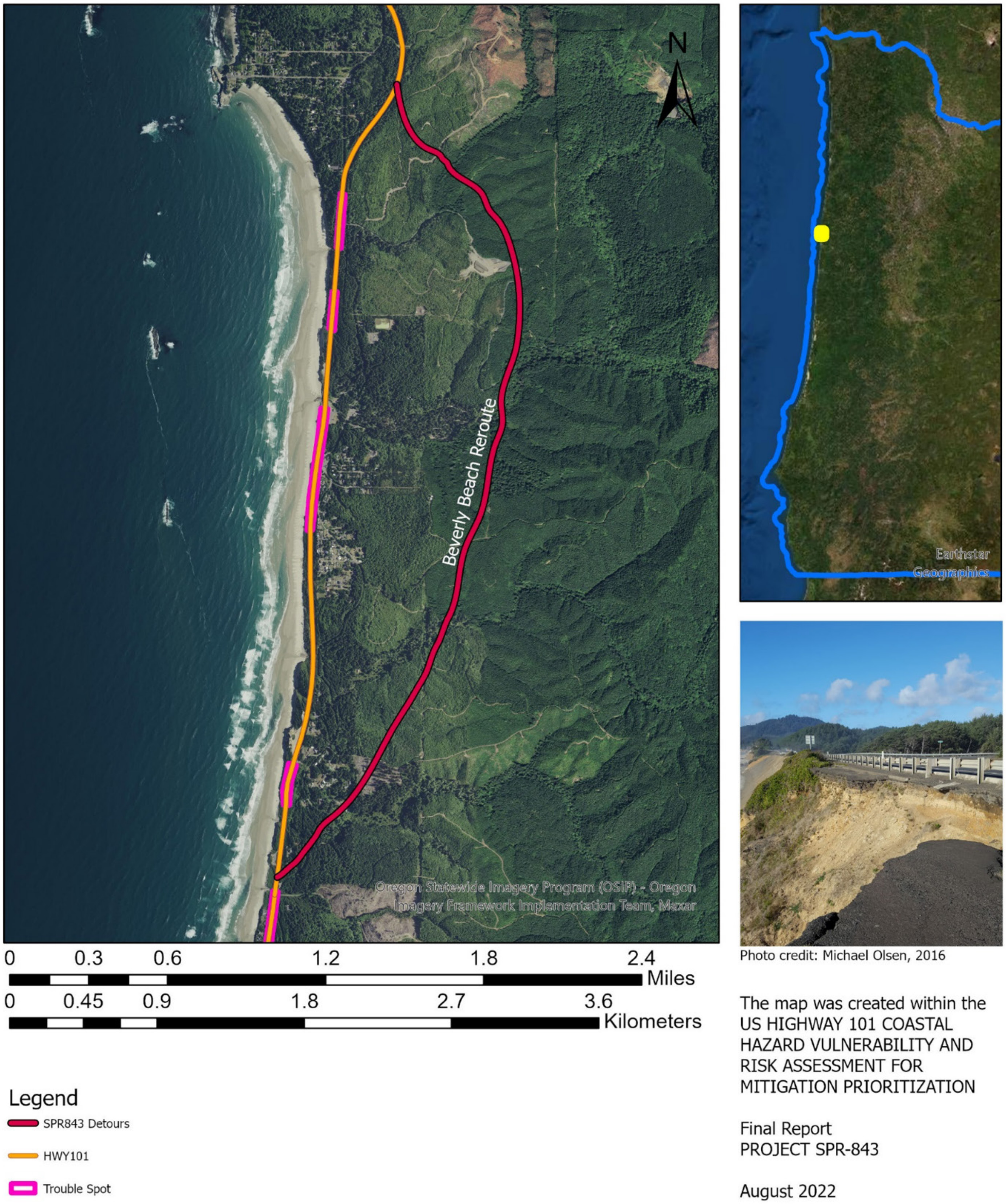

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Figure 7-1. Potential re-route option used for Spencer Creek

Table 7.1: Description and basic characteristics of adaptation options considered for Spencer Creek

#	Alternative	Mitigation Effect	Relative Protection	Direct Loss of Beach Width (ft)	Relative Maintenance	Initial Cost	Design Life (years)	Repair Length (ft)	RW Take (ft^2)
1	Do Nothing	Continue with basic repairs and maintenance of the highway but no implementation of shoreline protection	None	0	Very High	Low	0	0	0
2	Cobble beach, Jetty rock, riprap, drainage blanket, MSE slope with planted terraces or architectural face, and piles	Riprap will result in significant beach loss. Riprap will be perched on a thin veneer of sand	High	30 ft (potentially higher if structure is designed to fully mitigate runup)	Medium-Low	High	50	2507	Easement
3	Cobble beach with sheetpile wall behind face of slope.	Dynamic Revetment. Cobbles will make beach harder to navigate for recreation (State Park)	High	10 feet There will be a loss here as well as the upper beach is now cobble, reducing recreating space.	High	Med - High	30	2507	Easement

#	Alternative	Mitigation Effect	Relative Protection	Direct Loss of Beach Width (ft)	Relative Maintenance	Initial Cost	Design Life (years)	Repair Length (ft)	RW Take (ft^2)
4	Drainage blanket, wall feature with natural-looking shotcrete facing on upper slope, tiebacks	Best beach access.	High	15	Low	High	50	2507	Easement
5	Highway Re-rerouting	Re-route highway inland away from the coast	Very High	0	Low	Very High	75	17952	897,600

Table 7.7: Cost estimates (2022 US$) of adaptation options considered for Spencer Creek

#	Estimated Construction Cost (Total)	Estimated Cost (Per Linear Foot)	Construction Time (weeks)	Current			@30 years			Notes
				Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	
1	$0	$0	0	$16,481	1	0	$172,338	2	0	-
2	$41,000,000	$16,354	20	$1,402	0.2	0	$37,354	0.5	0	Could eliminate cobble armoring if using RipRap
3	$12,600,000	$5,026	16	$97,175	0.133	0	$391,983	0.25	0	Cobble Replacement drives maintenance cost
4	$60,170,000	$24,024	24	$956	0.2	0	$5,013	0.5	0	High-cost soldier pile wall behind existing slope. Riprap protection
5	93,500,000	$5,208.33	150	*Assumed minimal, routine maintenance only*						-

7.6 SEA LION POINT

7.6.1 Site Overview

Sea Lion Point is located between the cities of Florence and Yachats. It is located immediately North of the popular Sea Lion Caves tourist location. The site consists of tall, basalt cliffs protruding in the ocean (Figure 7.18). A recent failure happened in 2021 at this site, resulting in emergency repairs to install retaining walls (Figure 7.19). These repairs resulted in partial highway closures for several months. A major failure also occurred south of this site in 1999, adjacent to the Heceta Head tunnel (Priest, 2000), resulting in a 3-month closure to Highway 101 (The World, 2001).

The geology of this site consists primarily of subaerial porphyritic basalt lava flows from the Yachats Basalt formation from the upper Eocene epoch (Snavely & MacLeod, 1974). This is interbedded with tuffaceous siltstone and sandstone from the Nestucca formation (Schlicker & Deacon, 1974).

Figure 7.18: Southward view of Highway 101 from the Sea Lion Point pullout (June 2022).

Figure 7.19: Northward view from the Sea Lion Point pullout (June 2022). The section that was recently repaired is located in the center right of the photograph.

7.6.2 Adaptation options

Four adaptation options were considered for this site (Table 7.8) including (0) do nothing, (1) buttressing, (2) soldier pile wall with protection, and (3) rerouting map (Figure 7-20). Estimated construction costs are summarized in Table 7.9.

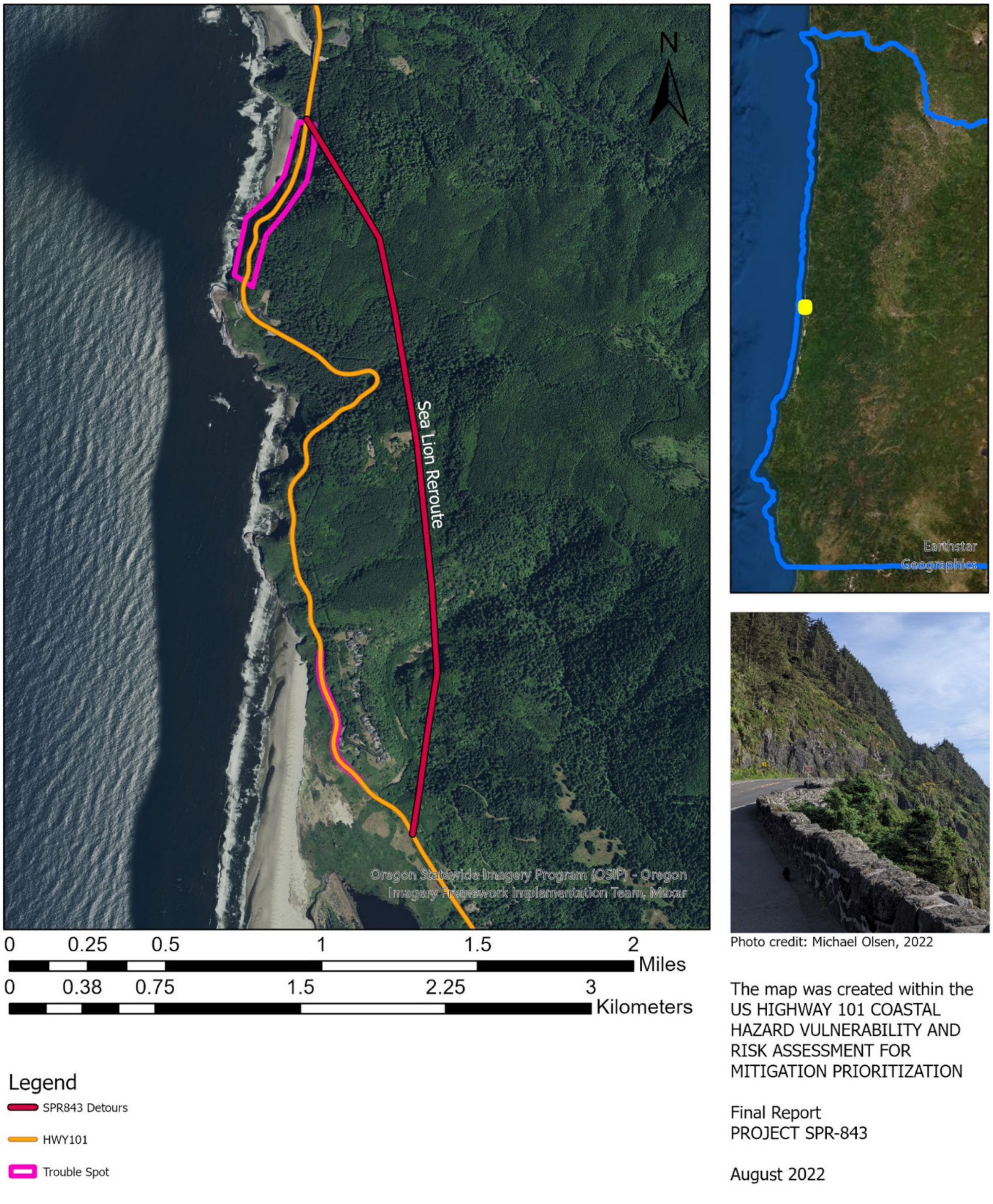

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Figure 7.20: Potential re-route option considered for Sea Lion Pt.

Table 7.8: Description and basic characteristics of adaptation options considered for Sea Lion Point

#	Alternative	Mitigation Effect	Relative Protection	Direct Loss of Beach Width (ft)	Relative Maint.	Initial Cost	Design Life (years)	Repair Length (ft)	RW Take (ft^2)
1	Do Nothing	Continue with basic repairs and maintenance of the highway but no implementation of shoreline protection	None	-	Very High	Low	0	0	0
2	Buttress and Shear key with riprap	Arrests most movement. Very Slight ongoing deformation	Medium-High	20'	Medium	High	35 years	528	Easement
3	Tiebacks, sheetpile wall, and riprap. Repair slides in north section. Drainage system.	Complete Mitigation	High	20'	Low	High	50 years	528	Easement
4	Highway Re-rerouting	Re-route highway inland away from the coast	Very High	-	Low	Very High	75 years	11,612	580,600

Table 7.9: Cost estimates (2022 US$) of adaptation options considered for Sea Lion Pt

#	Estimated Construction Cost (Total)	Estimated Cost (Per Linear Foot)	Construction Time (weeks)	Current			@30 years			Notes
				Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	
1	$0	$0	0	$10,792	0.5	8	$56,065	1.5	24	"C" slides triggered by additional rainfall
2	$1,975,248	$3,741	6	$3,000	0.2	0	$15,732	0.25	0	-
3	$2,166,513	$4,103	12	$0	0	0	$0	0	0	3 sites with Retaining walls
4	$60,560,000	$5,215	130	*Assumed minimal, routine maintenance only*						-

7.7 ARIZONA INN LANDSLIDE

7.7.1 Site Overview

Arizona Inn is located approximately 14.5 miles north of Gold Beach between Hwy 101 Mileposts 315 and 316. The photograph in Figure 7.21 is taken from the landslide, looking down on the highway running parallel to the coastline, separated by a steep seacliff.

Figure 7.21: Photograph showing Hwy 101 running through Arizona Inn (facing south from the upper section of the landslide deposit). Note the freshly paved section as a repair to the creeping landslide movement (August 2016).

The study area extends south from Lookout Rock about 650m and extends landward around 350m from Hwy 101 to cover the Arizona Inn landslide. Moving landward, the site extends from a narrow sandy beach to a cobble/boulder beach about 10m wide before reaching the seacliff (Figure 7.22). The seacliff at this site is around 50m in height, sparsely vegetated at its base and more heavily vegetated towards the top where Hwy 101 sits. East of Hwy101, there is a large landslide around 120m in height, and about 600m wide.

Figure 7.22: Photograph showing beach and coastal seacliff at Arizona Inn (facing south, August 2017).

Arizona Inn's geology consists of approximately 45˚, southwest dipping, Humbug Mountain Conglomerate from the Elk Subterrane of the Western Klamath terrane that was deposited during the Lower Cretaceous (McClaughry et al. 2013). Towards the coast this deposit is overlain by anthropogenic landslide deposits. Below the Humbug Mountain Conglomerate there is Colebrooke Schist from the Pickett Peak terrane from the Upper Jurassic. At this location Elk subterrane has been thrust on top of the Pickett Peak terrane. This is evident from the thrust sheet window present at higher elevations to the east (McClaughry et al, 2013) as well as core logging conducted along the landslide. The south extent of the landslide is bounded by a planar shear surface that forms the north face of a large rock mass that forms the headland in the south, which also bounds the landslide below the ground (Squier et al. 1994).

Arizona Inn failed catastrophically in 1993, closing Hwy 101 for 2 weeks (Squier et al, 1994). Aside from catastrophic failures, Arizona Inn exhibits creep style mass movement that results in small but cumulative damage that builds up over time. Large Catastrophic failures generally correlate with large rainfall events similar to much of Oregon (Squier et al. 1994).

Based on detailed monitoring and repeat site visits from SPR-807, the site has shown significant activity including (1) undermining a recently installed (2021) retaining wall (Figure 7.23) and (2) several new and expanding tension cracks at the surface (Figure 7.24), and (3) substantial erosion and landslide movement causing shifting of pavement and guardrails (Figure 7.25).

Figure 7.23: Undermining of a recently installed (2021) wall at the north end of Arizona Inn. (Photograph looking south east, July 2022)

Figure 7.24: Large tension cracks present at the site (Photograph looking northwest, immediately west of the highway southbound lane & shoulder, July 2022)

Figure 7.25: Shifts observed in guardrail and additional cracking (Photograph looking southeast, immediately west of the highway southbound lane & shoulder, July 2022)

Note that on January 9, 2023, after the analysis of this project was completed, the landslide moved approximately 7 m, completely closing Hwy 101 for a week (Figure 7.26). This full closure was followed by an extended period of reduced operation with just a single gravel lane while rebuilding plans are determined. In 1993, a major failure occurred at the site that also closed Hwy 101 completely for a week.

(a)

(b)

Figure 7.26: Photographs of the damages to Highway 101 at the Arizona Inn landslide surge event on January 9, 2023 from different vantage points on the slide. (a): Looking northward adjacent to highway. (b): Looking southwest from the upper slow. A temporary, single gravel lane was built after movements slowed in order to allow access to motorists. (Photographs acquired on site January 20, 2023).

7.7.2 Adaptation options

Four adaptation options were considered for this site (Table 7.10) including (1) do nothing, (2) buttressing, (3) soldier pile wall with protection, and (4) rerouting map (Figure 7-27). Estimated construction costs are summarized in Table 7.11.

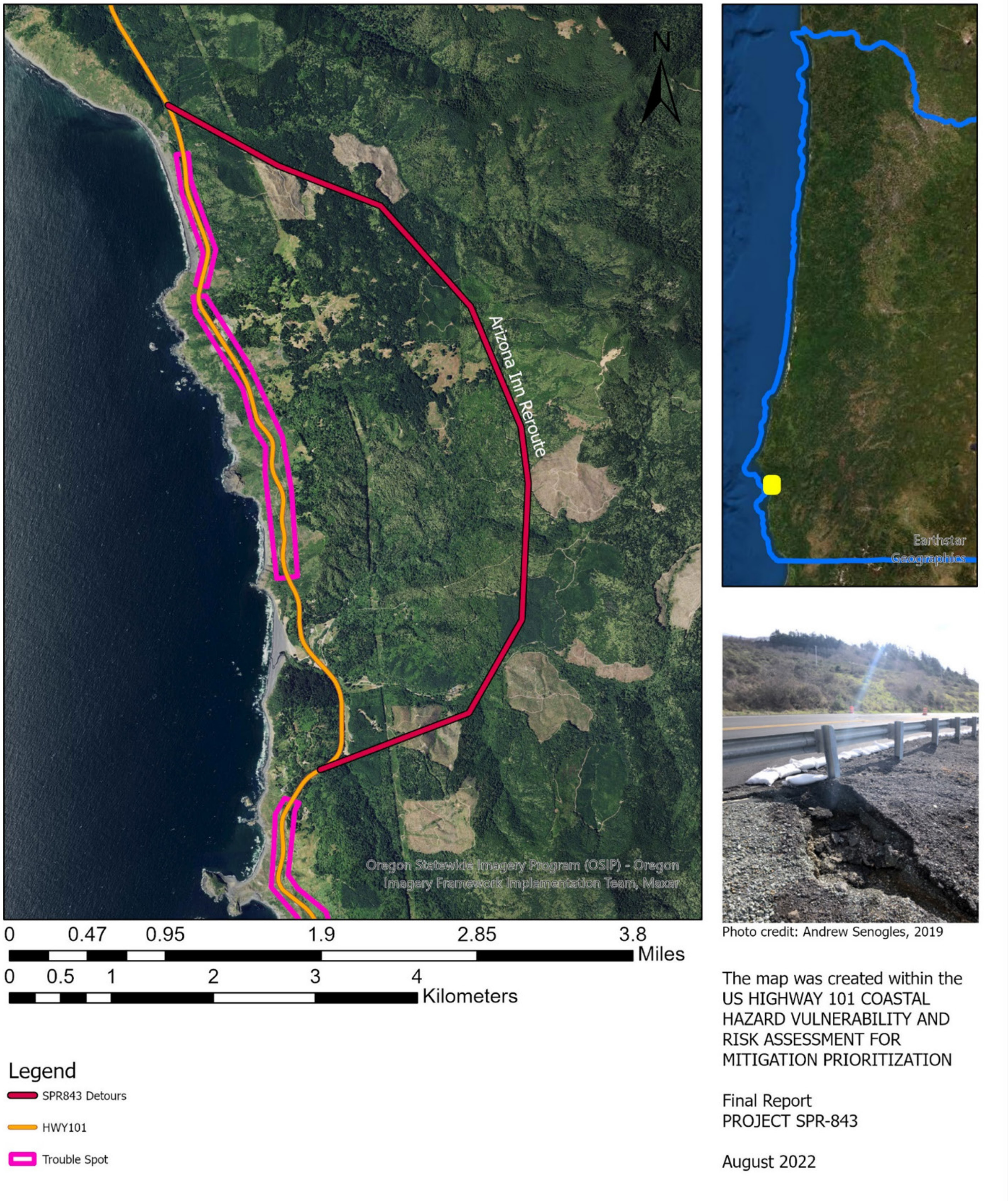

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Figure 7-2. Potential re-route option considered for Arizona Inn

Table 7.10: Description and basic characteristics of adaptation options considered for Arizona Inn

#	Alternative	Mitigation Effect	Relative Protection	Direct Loss of Beach Width (ft)	Relative Maint.	Initial Cost	Design Life (years)	Repair Length (ft)	RW Take (ft^2)
1	Do Nothing	Continue with basic repairs and maintenance of the highway but no implementation of shoreline protection	None	0	Very High	Low	0	0	0
2	Riprap & drainage system	Riprap to slow erosion at base and drainage system to slow landslide movement	Moderate	30	High	Med-High	30	2,455	Easement
3	Retention	Three rows of tied-back soldier piles, Riprap shoreline, enhanced drainage	High	30	Medium	High	40	2,455	575,000
4	Highway Re-routing	Re-route highway inland from the coast	Very High	0	Low	Very-High	60	25,819	1,550,000

Table 7.11: Cost estimates (2022 US$) of adaptation options considered for Arizona Inn

#	Estimated Construction Cost (Total)	Estimated Cost (Per Linear Foot)	Construction Time (weeks)	Current			@30 years			Notes
				Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	Annual Maint. Cost	Maint. Frequency (Repairs/Year)	Maint. Closure Time (Hours)	
1	$0	$0	0	$131,929	5	0	$691,830	12	24	-
2	$12,794,000	$5,211	30	$5,000	0.5	0	$18,878	1	6	Includes new drainage shaft
3	$86,000,000	$35,030	105	$1,000	0.2	0	$3,671	0.25	0	Constructability is questionable
4	$136,920,000	$25,932	180	*Assumed minimal, routine maintenance only*						-

8.0 ECONOMIC DECISION FRAMEWORK

Prior sections of this report have analyzed vulnerability to coastal natural hazards to identify five priority locations along US 101 for which several site-specific adaptation options have been proposed. Each site has a high potential of failure in the near future. This section first presents an economic decision framework, cost-benefit analysis (CBA), to think about how to prioritize investments in these adaptation options. Next, output from ODOT's Statewide Integrated Model (SWIM) using future scenarios demonstrating the effects of closures on US 101 at the five locations is summarized to characterize key potential long-term economic impacts of road failures (e.g., GDP, population, employment, traffic volume). Then benefits of avoiding closures (detours, recreation, etc.) and the costs of each adaptation option are discussed for each of the five sites. Lastly, closure scenarios and the CBA framework are applied to all sites to illustrate the decision framework.

8.1 COST BENEFIT ANALYSIS

Since 1981 with Presidential Executive Order 12291 (Exec. Order No. 1229, 1981), cost-benefit analysis (CBA) has been a key component of federal regulatory impact analysis and social decision-making. CBA is a comprehensive assessment method that quantifies the social benefits and costs of a policy change or investment in monetary terms. This process aids in understanding the economic tradeoffs across policy or investment options as well as providing a metric (***net benefits*** = social benefits – social costs) to inform allocation of resources. Often, investments have clearly defined costs in dollars and the challenge is to understand the monetary benefits that would be provided to society. This has required the development of economic methods to quantify the monetary value of potential changes in both market and nonmarket goods and services that result from economic activity and policies. Such a need was further validated in an October 2015 Memorandum for Executive Departments and Agencies that explicitly directed federal agencies to "develop and institutionalize policies to promote consideration of ecosystem services, where appropriate and practicable, in planning, investments, and regulatory contexts" (Memorandum 2015, p. 1). In Spring 2023, the Biden administration issued Executive Order 14094 (Exec. Order No. 14094, 2023) directing federal agencies to modernize regulatory review. As part of that process, the Office of Management and Budget (OMB) issued an update to Circular A-4 (OMB, Circular A-4 2023) on November 9th, 2023. This document updates guidance about the use of discount rates in economic analyses of proposed projects and policies. Under prior guidance, the recommendation was the use of a 7% discount rate for capital projects and a 3% discount for projects that impact consumption. The new federal guidance establishes a single default rate of 2% for measuring all impacts from now through 2053, and this recommended rate will be updated every three years moving forward. Analyses presented in this report follow this new federal guidance and use a 2% discount rate.

For US 101 adaptation options, an *ex-ante*, or before the event, CBA could help identify the relevant impacts and directly inform decisions on allocation of scarce resources. In other words, an *ex-ante* CBA can help project-specific decision making. That said, at this stage there is considerable uncertainty about the actual impacts of a proposed project and CBAs conducted after project adoption could estimate net benefits more accurately. To provide a manageable guide for a CBA process, we adapt the basic steps of a CBA from Boardman et al. (2018) and apply them to decision making on adaptation strategies for US 101 in Oregon.[1]

8.1.1 Step 1: Define The Set of Options

This first step requires relevant decision makers specify the set of potential alternative projects. This stage of the process is not trivial, as the set of possible alternatives could be quite large. Best practices suggest using as few alternatives as is reasonable to limit the cognitive burden on decision makers who will have to make informed choices across the alternatives after the CBA. For US 101 adaptation options, this step includes much of the prior work documented in this report (e.g., Section 7.0) that include: 1) estimating site vulnerability and then choosing five locations at high risk of future road failures; and 2) establishing different adaptation options for mitigating the hazard risk at each location. Table 8.1 summarizes the set of options for this exercise for US 101 in Oregon, omitting the “do nothing” option, which can be evaluated as the status quo for each site.

Table 8.1: US 101 Set of Project Alternatives – CBA Step 1

Location	Alternative #1	Alternative #2	Alternative #3	Alternative #4
Spencer Creek	Rip-rap Revetments	Cobble Beach (Dynamic Revetment)	Drainage Blanket & Wall	Highway Reroute
Arizona Inn	Rip-rap Revetments & Drainage System	Retention	Highway Reroute	-
Arch Cape	Buttress Landslides	Solider Pile Wall	Highway Reroute	-
Sea Lion Point	Buttress & Rip-rap Revetments	Tiebacks, Sheet Pile Wall, Rip-rap Revetments	Highway Reroute	-
Saltair Creek	Shoreline Mitigation	Erosion Control	Highway Reroute	-

8.1.2 Step 2: Decide Who Has Standing

The second step is to decide whose benefits and costs are to be included in the CBA calculations. This is often a contentious decision in CBA as the scale at which the analysis is done could have implications for the estimated net benefits of each alternative, and thus on the ultimate investment decision. Given that (1) US 101 is a federal highway that connects multiples states on the US West Coast, (2) any alternative investment is likely to be supported by federal funds, and

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[1] It is important to note that a comprehensive and rigorous CBA when projects, such as the US 101 adaptation to climate risk, are complex undertakings is beyond the scope of this project. Large federal CBAs to evaluate existing or new programs often cost millions to undertake.

(3) visitors from around the country enjoy visiting the Oregon Coast, this analysis takes a broad perspective when considering costs and benefits of alternative actions.

8.1.3 Step 3: Identify Impacts

This third step focuses on identifying all impacts of the alternatives and classifying them as a potential cost or benefit. In some cases, impacts are intuitive and clearly defined. For the five vulnerable locations on US 101, potential closures under the status quo and the adaptation options themselves are likely to generate both individual and social impacts associated with potential road closures. A closure or construction operations would necessitate a detour, where costs to individuals would include added fuel cost, depreciation of the vehicle due to extra mileage, and the added time to an individual's trip. For the social cost, we consider the impacts of additional greenhouse gas (GHG) emissions due to the additional miles driven from detours. Also, understanding the impact of potential closures on local and state economic output, population, traffic volume and employment are important impacts to consider. In this exercise, these four factors are approximated using long-term closure simulations in ODOT's SWIM system.

There are often relevant impacts that may be omitted in a CBA because these impacts lack a clear causal connection to the project alternatives. In other words, for impacts to be identifiable and measurable (see steps 4 and 5 below), we must know the relationship between each alternative and its effect on society. This is a high bar to pass and often requires extensive reviews of prior literature and new primary analyses to demonstrate these relationships. In this exercise, the recreation effects of different adaption options are impacts that required such steps to establish this relationship. Using recreation data from Oregon Parks and Recreation Department (OPRD), we can estimate the economic impact of potential US 101 closures on recreation opportunities at Oregon State Park locations for both overnight (camping/RV) and day-use visitors. Additionally, some adaptation alternatives (e.g., rip-rap revetments) will result in loss of beach width at or near beach recreation locations. One potential impact, the effect of closures and/or adaptation options (e.g., highway re-routes) on land markets, is not included here as extensive effort in data curation and a new econometric analysis to establish the causal relationship between the CBA options and land prices would be necessary. Table 8.2 provides a summary of the impacts compiled for this exercise.

8.1.4 Step 4: Predict Impacts Quantitatively Over Time

Each adaptation option for US 101 would lead to impacts that would occur over time. The next step in a CBA is to quantify impacts in all relevant time periods. This step is a key element of a CBA but is often difficult in practice. Quantitatively predicting impacts over time increases in difficulty with projects like highway construction/maintenance that have long time horizons, unique adaptation options, and complex relationships between alternatives and the ocean environment. In this exercise, we use best available information to predict impacts over a 30-year time horizon (2022 – 2052) for all sites and 50-year time horizon for Spencer Creek for a few more complex scenarios.

Table 8.2: Impacts of Potential Closures – CBA Step 3

Impact	Description	Data (Source)
Traveler Cost due to Detours	Time and vehicle operating costs from additional miles traveled	Detour routes, Average Annual Daily Traffic (AADT), and SWIM detour mileage predictions (ODOT)
Social Cost due to Detours	Additional carbon emissions due to additional miles traveled	Detour routes & AADT (ODOT); Fleet average MPG (DOE 2022) CO_2 emissions/gallon of gasoline (EPA 2018); Social Cost of Carbon (IWG 2021)
Recreation Impacts of Closures	Changes to both camping and day-use recreation near potential closure areas	Camping reservation and day-use data (Oregon Parks and Recreation Dept.)
Recreation Impacts of Adaptation Options	Effects on both camping and day-use recreators of reduced beach width from some adaptation options	Remote sensing and GIS data on shorelines (NOAA, DOGAMI, Oregon State University)
Economic Output	Local, state, and regional effects of closures on gross domestic product (GDP)	SWIM 10-year closure analysis (ODOT)
Traffic Volume Change	Predicted traffic flow changes from closures on US 101 and nearby major roads	SWIM 10-year closure analysis (ODOT)
Population Change	Predicted population change from closures	SWIM 10-year closure analysis (ODOT)
Employment Change	Predicted employment changes from closures	SWIM 10-year closure analysis (ODOT)

8.1.5 Step 5: Monetize Impacts

The fifth step of a CBA is to monetize the impacts in each period. Estimating all impacts in dollars allows for an apples-to-apples comparison of both benefits and costs of a potential alternative over time. Environmental benefits are often the most difficult to monetize as markets often do not exist.

In all cases, this step requires a quantity of a change and the price of a unit of that change to calculate the impact. In this exercise, we need to monetize each unit of time lost to detours, the impacts of additional carbon emissions, and the recreation impacts, among others. To provide an example, we can look at these latter two in more detail.

Monetizing the additional carbon emissions from road closures (a quantity) requires an estimate of the economic damages of those emissions (a price). These damages are calculated at the federal level by using the social cost of carbon (SCC), which provides a value for the effect of each additional ton of GHGs emitted per year (IWG 2021). The Interagency Working Group (IWG) on the Social Cost of Greenhouse Gases recommends a range of values that depends on an assumed discount rate (see Step 6). Integrated Assessment Models (IAMs) that estimate the SCC often use discount rates between 2.5 and 5 percent (National Academies of Sciences 2020) although more recent efforts use 1.5 to 3 percent (Rennert et al. 2022; EPA 2022). For recreation impacts, we observe the number of visits per year to potentially impacted sites (a quantity) and estimate a travel cost model to reveal a demand curve for beach recreation, which yields a per visit value for recreation (a price). Prior research has also found loss of beach width at a recreation site (a quantity) can reduce the value (a price) of a recreational visit (e.g., Whitehead et al. 2008). In each of these examples, we predict the impacts and either estimate new values or use values from prior research to monetize the impacts of each alternative scenario.

8.1.6 Step 6: Apply a Discount Rate to Obtain Present Values for all Impacts

Since any US 101 adaptation project is likely to have impacts that occur over time, we need to aggregate the impacts (benefits and costs) across time into a common unit for CBA. The typical common unit is to convert future benefits and costs into their present values (PV). This means that future impacts are discounted relative to current impacts. Discounting is common because people, in general, are impatient and prefer benefits now rather than waiting for them in the future (Boardman et al. 2018). The act of discounting brings all monetized project impacts into a common unit (present values) to aid decision making. Specifically, each future impact in year *t* is converted to a PV by dividing it by a chosen discount rate (*r*). We can estimate a PV for both benefits (b) and costs (c) of an alternative across T years as:

$$\boldsymbol{PV(b) = \sum_{t=0}^{T} \frac{b_t}{(1+r)^t}} \quad ; \quad \boldsymbol{PV(c) = \sum_{t=0}^{T} \frac{c_t}{(1+r)^t}} \tag{8-1}$$

The assumption needed to operationalize this step is the choice of a discount rate. Both theoretical and empirical evidence suggests uncertainty about future benefits and costs and for projects that are intended to span multiple generations, a lower discount rate (e.g., 3%) is recommended for public policy analysis (US Council of Economic Advisors 2017; Li et al., 2018). Prior federal guidance to state transportation departments from the Office of Management and Budget (OMB Circular A94, 1992) suggested using a 7% discount rate in CBA and using 3% as a sensitivity analysis (see step 8). The prior use of a high discount rate (e.g., 7%) favors projects that deliver short-term solutions at low cost by giving lower present value to benefits and costs accruing in the future. Long-term capital and infrastructure projects have the potential to impact people who cannot take part in the decision-making process today, and a higher discount rate minimizes the consideration of these effects. New guidance from OMB released in November 2023 suggests using 2% discount rate for any capital project that will impact society from present day to 30 years in the future (OMB Circular A-4, 2023). This change increases the present value of future benefits and costs in current decision-making. Practically speaking for this report, a lower discount rate suggests project alternatives that generate costs each year (e.g., rip-rap revetments reducing future recreation opportunities) are now more costly in present value terms. All analyses below are conducted using a 2% discount rate in line with current federal guidelines.

8.1.7 Step 7: Calculate Net Present Value of Each Alternative

Taking the difference between the present value of benefits and the present value of costs yields the *net present value (NPV= PV(b)-PV(c)).* This metric provides some basic decision rules for decision-makers:

1. For a project with a single alternative, move forward with the change if the NPV is positive (i.e., benefits exceed costs).
2. For a project with multiple alternatives, chose the alternative that has the largest positive NPV.

8.1.8 Step 8: Perform Sensitivity Analysis around key assumptions

At this point, it is important to remember that NPVs used for decision-making are just estimates, subject to assumptions and uncertainty. Uncertainty could reside in predicting impacts over time, the prices used for monetizing impacts, or the appropriate discount rate to use for the analysis. Conducting additional analyses to understand NPV sensitivity to assumptions is an important step to account for these uncertainties. Nearly every assumption or prediction could be varied, so it is important to focus sensitivity analyses on the most important assumptions. Often, NPVs are calculated with a range of potential discount rates to determine if the guidance offered by a CBA is contingent on that choice. The final step is to then select the alternative with the highest NPV that has survived any sensitivity checks.

The next three sections discuss results from ODOT's SWIM model simulating a 10-year closure at each of the five selected sites (Section 8.2), the benefits and costs of adaptation options defined for each site (Section 8.3) and lastly, the CBA process applied to the project alternatives and closure scenarios at the five sites (Section 8.4).

8.2 STATEWIDE INTEGRATED MODEL (SWIM) SUMMARY

ODOT's SWIM model (Donnelly, 2017) represents the interactions between Oregon's transportation infrastructure and the economic behavior (e.g., shipping, traveling) that uses that infrastructure. SWIM is a dynamic model that integrates many components, including demographics, population, personal and commercial travel to simulate how changes to the system may impact Oregon's economy and communities. For this exercise, ODOT used SWIM to simulate long-term economic impacts (GDP, traffic volumes, population, and employment) of a roadway failure at each of our five sites. The impacts of two simplified scenarios, an unimpeded roadway and a complete road closure, were considered for a ten (10) year period. The comparison allows for the establishment of baseline data to begin to describe the possible impacts to local and regional economies of any road closure. It is important to note that under current conditions, a major roadway failure at any of the five sites would likely be repaired by ODOT within 3 months. Therefore, this modeling exercise is designed to provide context about the relative importance of maintaining US 101 at these five locations in terms of economic output, traffic volumes, employment, and population. Reported impacts focus on the difference between average percent changes with and without roadway failures over a hypothetical ten-year period based on SWIM scenario forecasts.

8.2.1 Economic Output

A commonly used measure of the value of goods and services produced within an economic system is gross domestic product (GDP). A significant disruption to a major highway like US 101 is likely to reallocate economic activity (and GDP) across space, depending on the severity and length of the disruption. SWIM output (Appendix D) suggests changes in GDP at varying spatial scales, ranging from county-level to state-level within the region.

The impact to GDP for a long-term closure varies significantly across the five sites:

- For a long-term closure at Spencer Creek, we may expect to see a 1% loss for the state of Oregon. Losses would be concentrated in coastal counties (- 5%) and partially offset as economic activity would shift to the Willamette Valley and Portland Metro regions (+ 3%).

- For Arizona Inn, a long-term closure would reduce Oregon's GDP by 1%, with losses again concentrated in Oregon's coastal counties (- 6%). Economic activity would shift to the Willamette Valley (+ 5%), Portland Metro (+ 3%) and neighboring states (CA, WA, ID).

- A closure at Arch Cape tunnel would lead to a 1% increase in GDP for Oregon and 2% increase for the Willamette Valley. One percent reductions in GDP would be forecasted for all coastal counties as a whole, Clatsop and Tillamook counties, and Portland Metro.

- For a long-term closure at Sea Lion Point, losses are projected for coastal counties (-4%) and gains predicted for the Willamette Valley (+ 4%) and Portland Metro (+3%).

- Lastly, the GDP impacts from a closure at the Saltair Creek location would be minimal. There is no predicted impact to Oregon or coastal counties and a 1% increase projected for the Willamette Valley.

- Figure 8-1 summarizes these potential impacts to GDP for Oregon, the Willamette Valley and coastal counties.

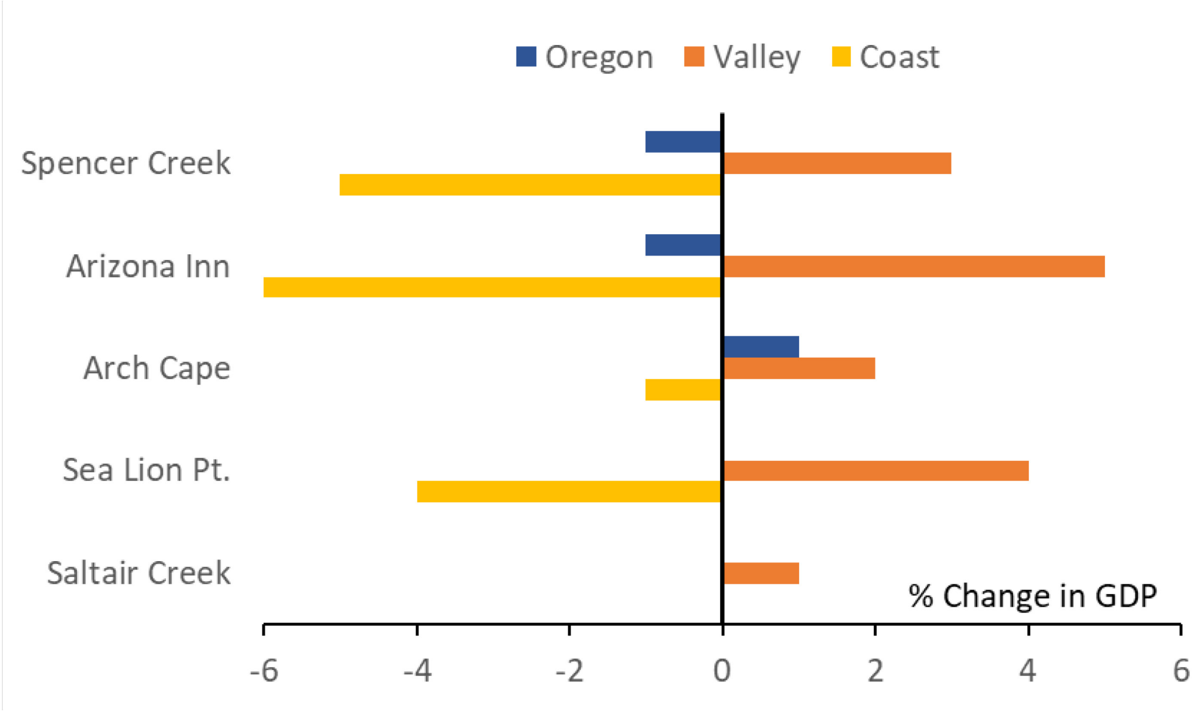

Figure 8.1: GDP Impacts from 10-year Closure Simulations at Five US 101 Sites.

Note: Estimates reported here are authors' calculations of average effect based on SWIM output provided by ODOT (Appendix D).

To provide some context for the size of these potential impacts, we use GDP data from the St. Louis Federal Reserve from 2019.[2] For long-term closures at two sites (Spencer Creek, Arizona Inn), SWIM predicts a 1% loss of GDP to the state of Oregon. Since Oregon's state GDP in 2019 was approximately $220 billion dollars, a 1% loss is $2.2 billion annually. Given the worst-case scenario for a full closure at any of the five sites in this report is three months, a rough estimate of the state-level GDP impacts for such a closure at Spencer Creek or Arizona Inn would be approximately $550 million dollars. For Saltair Creek and Sea Lion Point, there was no predicted impact on state-level GDP and for a closure at Arch Cape Tunnel, SWIM output suggests a 1% gain in Oregon GDP.

The state-level numbers do obscure potentially large negative impacts on Oregon coastal counties and communities near these five sites. The state-level impacts trend toward smaller percentages because losses at the coast suggest economic activity will shift elsewhere. The SWIM predictions bear this out as we see predicted GDP gains for the Willamette Valley in response to long-term US 101 closures for all sites. For three sites (Spencer Creek, Arizona Inn, and Sea Lion Point), impacts on Oregon's coastal counties range from – 4% to – 6%. For a three-month closure at these sites, the coast-wide county-level GDP losses could range from $250 million to $375 million. However, these projections are likely overestimates because it includes

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[2] The St. Louis Federal Reserve (FRED Economic Data) publishes county-level GDP data. The most recent available data is 2020, so 2019 is used here to avoid the temporary impacts of the COVID-19 pandemic in 2020. Data can be accessed here: https://fred.stlouisfed.org/release/tables?rid=397&eid=1081287&od=2019-01-01#

Lane and Douglas counties since they are coastal counties, but a majority of economic activity occurs in cities away from the coasts (e.g., Eugene/Springfield for Lane County and Roseburg for Douglas County) and not likely to be impacted by a closure. The GDP loss estimates when excluding those two counties for a three-month closure are $72.5 million to $109 million.

Related to GDP loss, SWIM also estimates the value of the daily commodity flows on each section of US 101. The value of commodity flows at each site adjusted to 2022 dollars are $3.4 million at Spencer Creek, $2.4 million at Arizona Inn, $340,000 at Arch Cape, $4.9 million at Sea Lion Point, and $344,000 at the Saltair Creek site. Without additional modeling efforts, we do not know how closures will shift these commodity flows specifically but the shift of GDP from the coast to the Willamette Valley does provide some insight on how commodity flows might change due to long-term closures on US 101.

Another factor that likely contributes to the impacts and shift in economic output is the change in traffic volumes that would result from closures. SWIM outputs also track the change in traffic volumes long-term closures may generate. Long term closures result in users taking routes that are longer in distance and time. These detours increase transportation costs, which may result in businesses and households relocating over time as people look for cheaper alternatives. Thus, SWIM estimates of traffic volume change is a result of system use changes over time due to changes in land use.

- For a Spencer Creek closure, we may expect to see large (27 to 50%) reductions in use of US 101 in and around Newport (Lincoln County). The most likely route to be used around the closure area is the Siletz Highway, which would see major increases in traffic volume. US 20 would also experience large (up to 26%) increases in traffic volumes.

- At Arizona Inn, major reductions in traffic on US 101 would occur from Brooking to Coos Bay. The largest impact would be on US 101 between Gold Beach and Port Orford (~ 80% reductions). Routes that provide alternative passage between inland areas and the coast would see major increases in traffic, including US 20, US 199, OR 18 and OR 6.

- A closure at Arch Cape tunnel would see small reductions in traffic on US 101 near the closure (3 to 13%) and increases on alternative highways like US 26 and OR 6.

- A long-term closure at Sea Lion Point would reduce traffic volume on US 101 between Florence and Newport by 24 to 26% and between Florence and Reedsport by nearly 10%. SWIM output reports traffic volume increases on OR 38, OR 126 and Interstate 5.

- Lastly, a closure at Saltair Creek would result in a volume decrease on US 101 north of Tillamook (-17%) and a gain on US 101 south of Nehalem up to 17%. There are also predicted losses in volume on OR 6 and gains on US 26.

8.2.2 Employment Impacts

A long-term closure at US 101 locations could also disrupt the local employment market. Employment may change because businesses are likely to relocate to more affordable or lucrative locations, taking jobs with them and households will relocate to follow the jobs. Any disruption to transportation infrastructure leads to potential for land use, population, and employment changes in the local economy. SWIM predictions suggest impacts to employment at scales ranging from areas directly around the closure site to county-level changes. As with GDP, the largest impacts likely occur with long-term closures at Spencer Creek and Arizona Inn. For Spencer Creek, SWIM predicts employment reductions of 32% in the closure zone and nearly 24% in Depoe Bay, located 6.6 mi north of Spencer Creek. The job losses for Lincoln County from this closure are estimated to be approximately 8%. For Arizona Inn, significant losses near - 80% are predicted for the areas immediately adjacent to the closure site and -12 % losses in Curry County. A closure at Arch Cape could lead to a loss of employment north of the closure (-14%) and a gain (+ 2%) south of the closure. The county-level impact in this case for Clatsop is predicted to be a 0.5% loss. For a Sea Lion Point closure, localized impacts are a less than 2% loss with a – 5% impact on employment in nearby Lincoln County (Data were not avaialble for Lane County). Lastly for the Saltair Creek site, the employment impacts would be minimal. SWIM predictions suggest a - 0.9% loss in the closure zone and no county-level impacts. Figure 8.2 summarizes employment impacts for the immediate closure zone and the county where the closure occurs.

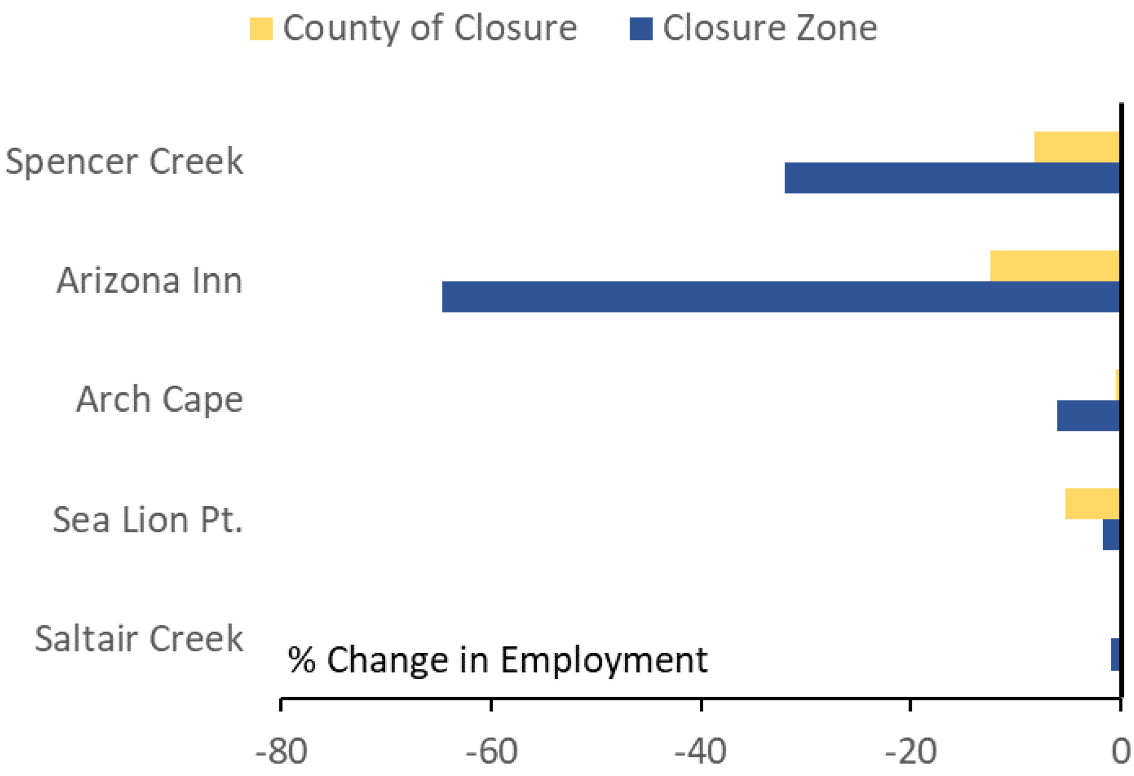

Figure 8.2: Employment Impacts from 10-year Closure Simulations at Five US 101 Sites.

Note: Estimates reported here are authors' calculations of average effect based on SWIM output provided by ODOT (Appendix D).

8.2.3 Population Impacts

Population levels may also be affected by a long-term closure along US 101. SWIM predictions for population change operate at similar scales to the employment estimates and impacts to the immediate vicinity of the closure and county of closure are reported here. For a Spencer Creek closure, population in the immediate area around the closure is predicted to decrease by 15% with Lincoln County projected to have a loss of 3.8%. A large loss is predicted by SWIM for a closure at Arizona Inn, with estimates suggesting a 65 % loss for areas in the immediate vicinity of the closure zone and a 12 % loss for Curry County. For Arch Cape, the population change predictions are for a 12 % loss in the closure zone and 0.5% loss in Clatsop County. A closure at Sea Lion Point would result in small population changes around the closure (small loss north -0.2% and small gain south 1.6%) and a 1.3% gain in population to Lincoln County. Lastly, a Saltair Creek closure would reduce population by 2.7 % near the closure and not impact county-level population estimates. Figure 8.3 summarizes population impacts for the immediate closure zone and the county where the closure occurs.

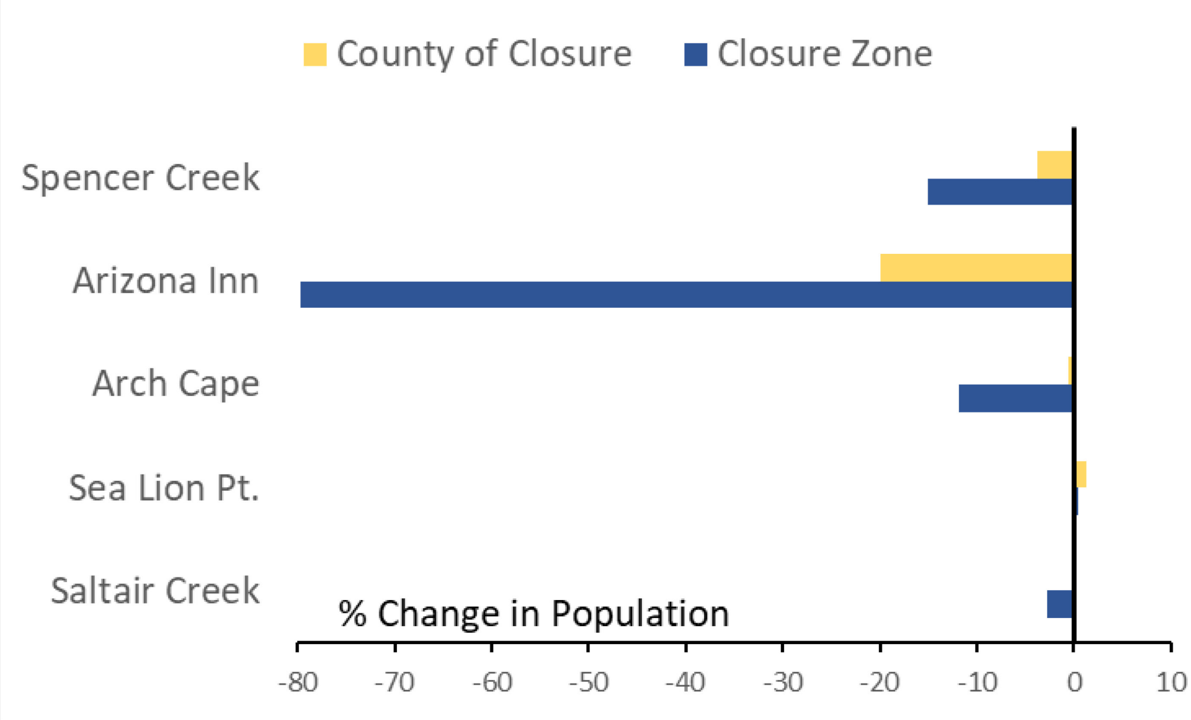

Figure 8.3: Population Impacts from 10-year Closure Simulations at Five US 101 Sites.

Note: Estimates reported here are authors' calculations of average effect based on SWIM output provided by ODOT (Appendix D).

8.3 SITE-SPECIFIC BENEFITS AND COSTS

In this section, we catalogue the site-specific impacts that we can measure and potentially use in a CBA of adaptation options. Four of those impacts were described in the previous section, although three (traffic volume, employment, and population) are not able to meet requirements for steps 4 (predict impacts quantitatively over the life of the project) and 5 (monetize impacts) of the CBA process and will not be considered further. For each site, we describe the benefits as the avoided costs of road closures in terms of traveler and social costs due to detours, the impacts of closures and construction of adaptation options on beach recreation, and estimated GDP impacts (described above in Section 8.2.1), and the costs as the initial construction costs and annual maintenance costs of the project alternatives.

First, we review data, assumptions and values that are applied to generate site-specific benefits and costs. To estimate traveler costs due to detours, we use, for both autos and trucks, the total estimated detour mileage (*DM*) and delay times (*DT;* in hours) predicted by ODOT's SWIM model (Appendix D) for a full day closure, an estimate of the value of time (*VT*) in 2022 dollars (ODOT 2019), and estimates for operations costs (*OC*) for autos from AAA (2022) and for trucks from the American Transportation Research Institute (ATRI 2022) in 2022 dollars. We calculate this estimate ($IndCosts_{detour}$) as follows:

$$\boldsymbol{IndCosts_{detour}} = (\boldsymbol{DM_{auto}} \times \boldsymbol{OC_{auto}}) + (\boldsymbol{DT_{auto}} \times \boldsymbol{VT_{auto}}) + (\boldsymbol{DM_{truck}} \times \boldsymbol{OC_{truck}}) + (\boldsymbol{DT_{truck}} \times \boldsymbol{VT_{truck}}) \tag{8-2}$$

In addition to individual costs of detours, there are also social costs associated with increased vehicle emissions from additional miles traveled. To calculate this, we use total detour mileage (*DM*) predicted by ODOT's SWIM (Appendix D) for a full day closure, the average fuel economy in miles per gallon (*AvgMPG*) for autos (24 mpg) and trucks (6.2 mpg) (Department of Energy, DOE 2022), and an EPA estimate of the carbon dioxide (CO_2) emission from each gallon of gas (8,887 grams → 0.0098 tons; EPA 2018). To monetize this impact, we then multiply the increased emissions from the detours by the social cost of carbon (*SCC*), using \$50/ton from current IWG guidance[3] as follows:

$$\boldsymbol{SocCosts_{detour}} = \left[\left(\left(\frac{\boldsymbol{DM_{auto}}}{\boldsymbol{AvgMPG_{auto}}}\right) \times \boldsymbol{CO_2}\right) + \left(\left(\frac{\boldsymbol{DM_{truck}}}{\boldsymbol{AvgMPG_{truck}}}\right) \times \boldsymbol{CO_2}\right)\right] \times \boldsymbol{SCC}. \tag{8-3}$$

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[3] At the time of this writing, the official federal estimate of the SCC is \$50/ton. However, a new draft Environmental Protection Agency estimate (https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf) that is currently under review suggests this number is likely to increase to \$190/ton in the near future, which would increase the costs due to detours in the analysis and may change the prioritization outcomes (EPA 2022). A 2022 academic article in the journal *Nature* also estimates a SCC value near \$190/ton (Rennert et al. 2022). That said, the social costs in this analysis are small relative to other costs, so even the near quadrupling of the SCC is not likely to impact the overall findings contained in this document.

Table 8.3 displays the estimated values of time (*VT*) and operation costs (*OC*) for both autos and trucks that are used in this chapter.

Table 8.3: Estimated Values (2022 US$) for Traveler and Social Costs due to Detours

Parameter	Auto	Truck	Source
Value of Time/Hour (\$2022 USD)	\$31.96	\$39.37	ODOT (2019)
Vehicle Operation Costs/Mile (\$2022 USD)	\$0.25	\$1.09	Driving costs for autos (AAA 2021) and trucks (ATRI 2022)

We also assess the potential impacts on beach recreation, an important activity with significant economic value that may be affected by road closures or construction of adaptation options. For the impact of road closures, we obtained data from OPRD on camping reservations and day-use visitor counts for 2018 and 2019 for Beverley Beach State Park. This park is located at the Spencer Creek site and would be directly impacted by any road failure or construction activities. For the value of camping recreation, we estimate a recreation demand model using a travel cost approach. Details and results are provided in the next section below (Section 8.3.1). Estimates of the value of a beach camping trip calculated for the Spencer Creek site are applied to other sites if there is significant recreation activity that may be affected by a closure or construction. To monetize the value of day-use trips, we use a unit value benefit transfer from a study on the value of a beach recreation daytrip from California (Lew and Larson 2005). That survey was conducted in 2001 and adjusting their estimate to 2022 dollars suggests a value of $47.83 per day trip. In spring 2022, an Oregon-specific beach recreation survey was fielded by Oregon State University so there is likely an opportunity to update this value with a current Oregon-specific value once results are available.

Adaptation options for each site also have potential to impact beach recreation. For example, ODOT engineers estimate that a rip-rap revetment to protect US 101 would likely require 30 feet of space on the beach to properly install the structure. Prior economic research suggests a loss of beach width at a recreation site is likely to generate costs to recreators. We use estimates from the literature that suggest a loss in value of $0.17 to $0.23 per foot per trip (Whitehead et al. 2008) from a permanent beach width loss. Adjusting those estimates to 2022 dollars suggests a range of $0.27 to $0.37. For simplicity and illustrative purposes, we use an average ($0.32/foot/trip) as our value estimate for beach width reductions from adaptation options.

For the costs of each adaptation strategy, we obtain estimated construction costs and annual maintenance costs for the next 30 years from ODOT.

8.3.1 Spencer Creek

To operationalize estimation of site-specific benefits and costs for Spencer Creek, we start with the estimated daily traffic flows at the site. Currently, ODOT estimates that 4,139 autos and 361 trucks use US 101 at Spencer Creek in each direction (8,278 autos and 722 trucks total) each day. SWIM model output suggests a single day closure at this site would generate a detour likely to add an additional 206,340 miles driven and 4,386 hours of driving time for autos and 40,086 miles and 443 hours for trucks. Using these estimates and our assumed values for lost time and vehicle operation costs (Table 8.3) we calculate the individual costs associated with a Spencer

Creek closure to be approximately $253,000 per day. The added social costs from the additional emissions are around $7,400 per day. Estimates are presented for a single day closure and a 3-month closure (worst-case scenario) in panel A of Table 8.4. GDP estimates for a 1-day and 3-month closure are calculated from SWIM model estimates described in Section 8.2.1 and are presented in panel B.

Spencer Creek has unique qualities for this analysis due to the fact it is in the same location as a popular state park. Beverly Beach State Park's (BBSP) campground is one of the state's largest managed parks with over 280+ sites available for recreational travelers. BBSP includes access to a day-use area with miles of ocean beach, extending from Yaquina Head to Otter Rock, and is centrally located to whale watching viewpoints, tidepools, the Oregon Coast Aquarium, and shops and restaurants in Newport. Any disruption to US 101 at this location is likely to have significant impacts on beach recreation opportunities. Here, we estimate a single-site recreation demand model using administrative data collected by OPRD to estimate the value of camping trips to BBSP. Given this effort was conducted for this report specifically, we provide details below of the data, modeling framework and results before providing the monetized impacts for the CBA.

Table 8.4: Benefits of Avoiding Road Closures at Spencer Creek

	1- Day Closure	3-month Closure
Panel A. Detour Impacts		
Individual	$252,880	$23,012,080
Social	$7,380	$671,580
Panel B. GDP (SWIM model estimates)		
Statewide	$6,027,397	$550,000,000
Coastal	$993,998	$90,702,300
Panel C. Recreation Impacts		
Camping	$12,773	$1,165,500
Day Use	$27,519	$2,511,075

Note: All values reported in 2022 dollars. Actual costs incurred by detours varies by traffic volumes, which vary by time of year and during special events. The highest volume months are typically in the summer, and lower volumes in the winter months.

First, we obtain the reservation data for overnight camping trips in 2018-2019 at BBSP. Each observation in the data provides the home zipcode of the individual making the reservation (i.e., where they travelled from to recreate at BBSP), how many people were in the party, the amount paid for the camping site, the type of site (RV or tent) and the days they arrived and departed. Since the seminal work of Hotelling (1949), economists have considered travel costs as an implicit price demonstrating what recreators are willing to give up in order to recreate at a given location. Travel costs are calculated using the round-trip money and time cost of traveling from a visitor's home to the recreational site. Camping recreators to Beverly Beach in our dataset came from all over the United States (Figure 8.4) demonstrating the popularity and the national draw of the Oregon coast and specifically, BBSP. Travel cost models work best when a common mode of travel to the site (e.g., driving) can be assumed. Given the large distance traveled for recreators outside the Pacific Northwest likely necessitated some air travel, we restrict this analysis to all home zip codes within 750 miles of BBSP following English et. al (2018). This restriction still contains over 88 percent of observed camping trips during 2018-19 and leaves us with nearly 37,000 observations for the analysis.

Driving distances and time spent travelling to BBSP for each reservation were calculated using Google’s Distance Matrix API. The recreators were assumed to originate from the zipcode provided in the reservation. Weekly gas prices were collected from the US Energy Information Administration (EIA 2022) for both regional areas within the 750-mile area, PADD5 (West) and PADD4 (Mountain). These prices were matched with the weekly arrival and departure date that each recreator faced the day of travel to the recreational site. The per-mile gasoline cost was divided by the average fuel economy of vehicle type based on reservation site type: 1) tent sites are assumed to be an average sedan and 2) RV sites were assumed to be standard RV. Vehicle depreciation cost from driving were gathered from AAA, which provide annual weighted estimates of operation costs for different vehicle types. The American Community Survey from the US Census Bureau was used to obtain demographic data from each zipcode in the study area including median income, unemployment, population and age. The opportunity cost of time is calculated using zipcode-level annual average household income (Lupi et al. 2020), which is then adjusted to be between 1/3 and 2/3 the hourly wage rate, consistent with previous research (Fezzi et al. 2014).

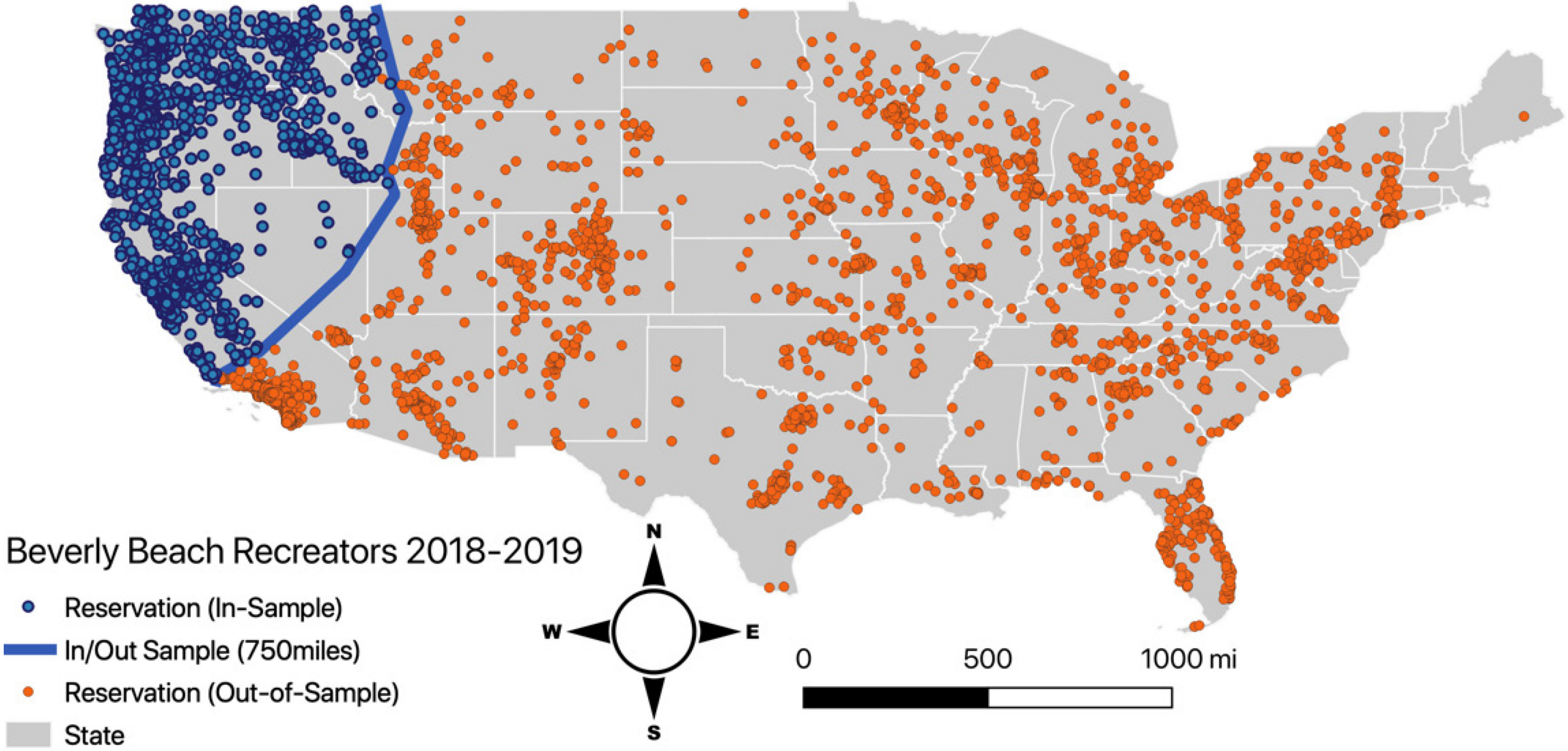

Figure 8.4: Locations of Reservations for Beverly Beach State Park 2018 - 2019

The count of overnight reservations from each zip code within 750 miles are treated as the quantity of trips and the travel cost is treated as the price, allowing for estimation of a conventional demand function. Since the dependent variable in this analysis is in count data form (i.e., non-negative integers), we specify a single-site recreation demand modeling framework (e.g., Boxall et al 1996; Lupi et al 2020) as follows:

$$\boldsymbol{x_n = f(p_n, D_n)} \tag{8-4}$$

where x_n is the number of trips taken from location *n* (zipcode) to the site. The number of trips is expressed as a function of p_n, the round-trip travel cost (i.e., price) based on the reservation (paid amount, vehicle type) and D_n, a vector of zipcode characteristics (e.g., population, education-level, etc.) assumed to influence the number of trips taken.

The model is estimated with two different frameworks for using count data (Poisson, Negative Binomial) and two assumptions for the opportunity cost of time (1/3 and 2/3 hourly wage rate). Results under these different assumptions produce a range of estimates for the value of a camping trip to BBSP from $144 to $270, with an average of $202 per trip. Converting that average value to 2022 dollars yields a value of $210 per trip. Using this mean estimate of the value of a camping trip, we can approximate the recreation benefits associated with avoiding a closure of the park. In our data, we observe 44,378 unique camping trips to BBSP in 2018 and 2019 (~22,200 per year). This suggests the economic value of camping trips per year to BBSP is approximate $4.7 million dollars.

For day use to BBSP, we only observe the number of visits, so we are unable to perform a similar analysis as the camping reservation data to estimate an economic value for this type of recreation. Therefore, we use a unit value benefit transfer from a study that estimated the value of a beach day trip from another US West Coast beach (Lew and Larson 2005). This survey was conducted in 2001 and adjusting the estimate to 2022 dollars suggests a value of $47.83. From 2010 - 2019, BBSP averaged around 17,500 visits each month, or 210,000 per year. Using these price and quantity values, we can estimate the annual economic value of daytrips to BBSP at $10 million per year. Combining the value for camping trips and day trips at BBSP suggests the annual economic value of recreation at the site is approximately $14.7 million dollars. To bring this to a time scale more relevant to potential closures of US 101, the aggregate economic value per day is ~ $40,300. The worst-case scenario for a closure at Spencer Creek location would be 3 months, suggesting the upper bound on recreation impacts could be around $3.7 million. These estimates are provided in Panel C of Table 8.4.

It is important to note that while recreation on the Oregon Coast occurs year-round, there is seasonal variation to visitation. The estimates from the above analysis are averages across a year but when the closure occurs (summer v. winter) will be important for estimating the recreation costs associated with that specific closure. In the camping data, we observe 1,850 trips per month. However, in July the average is 3,580 trips (93% higher than average) and in January the average is 605 trips. In the day-use visitation data, we observe 17,500 trips on average per month. In July, this average increases to 39,500/month (230% higher than average). In January, BBSP only receives an average of 6,500 trips. What this implies is that a closure in the summer is likely significantly costlier in terms of lost recreational value than a winter closure. In the summer, the cost of a 1-day (3-month) closure would increase from $40,300 ($3.7 million) to $86,400 ($7.9 million). In the winter, the cost of a 1-day (3-month) closure would decrease from $40,300 ($3.7 million) to $14,300 ($1.3 million). In other words, the timing of a road failure or other construction activities that would close US 101 matters when quantifying the potential impacts to beach recreation.

For Spencer Creek, two of the proposed mitigation strategies, a rip-rap revetment and a cobble beach, will likely result in permanent loss of beach width of approximately 30 feet to allow for installation of the structures. A third approach, a drainage blanket wall feature, would potentially result in 15 feet of permanent beach loss. Any loss of beach width will result in impacts to recreational access and users of the beach. Using a value from prior research, estimated at approximately $0.32 (in 2022 dollars) per foot per trip (Whitehead et al. 2008) we can estimate these potential impacts for day use visitors. The annual impact of a permanent 30 (15) foot loss of beach width would be $2 million ($1 million). Given the prospect of sea-level rise, the beach width in BBSP (and the recreational value of the beach) are likely to decline in the future without construction interventions (see Section 4.3) but such structures would generate an immediate and lasting impact.

Other potential benefits of avoiding closures and/or adaptation measures that we are unable to capture in this analysis for Spencer Creek and all four other sites could be reflecting in maintaining housing prices in the communities near potential closures, small businesses remaining open for business and ecological benefits to coastal habitats that are not impacted by construction activities.

Lastly, we present estimated construction costs and annual maintenance costs for the five alternative adaptation strategies proposed for Spencer Creek (Table 8.5). Option 1 is to “do nothing” and continue with increasing annual maintenance costs. Options 2 through 4 propose alternatives that would alter the shoreline through various engineering, including: rip-rap revetments (#2), cobble beach (#3) or a drainage blanket wall feature (#4) to protect US 101. Each has an estimated construction cost, cost associated with annual maintenance, along with estimates of lost beach width from construction activities. The final option (#5) is for a complete re-routing of US 101 around Spencer Creek to avoid the erosion hazards and maintain traffic flow on US 101. Here we were provided an estimated construction cost but not annual maintenance estimates.

Table 8.5: Estimated Costs for Adaptation Strategies at Spencer Creek

Alternative	Design Life	Estimated Construction Cost (Total)	Annual Maintenance Cost (Current)	Annual Maintenance Cost in 2052[a]
1: Do Nothing	0	$0	$16,481	$172,338
2: Jetty rock, riprap, drainage blanket, MSE slope with planted terraces or architectural face, & piles	50	$41,000,000	$1,402	$7,354
3: Cobble beach with sheet pile wall behind face of slope.	30	$12,600,000	$97,175	$391,983
4: Drainage blanket, wall feature with natural-looking shotcrete facing on upper slope, tiebacks	50	$60,170,000	$956	$5,013
5: Highway Re-rerouting	75	$93,500,000	Assumed Minimal	Assumed Minimal

[a] Annual maintenance costs in the future are adjusted assuming 2.5% annual inflation.

8.3.2 Arizona Inn

For site-specific benefits and costs for Arizona Inn, we again start with the estimated daily traffic flows at the site. ODOT estimates that 2,211 autos and 289 trucks use US 101 at Arizona Inn each day in each direction (4,422 autos and 578 trucks total). A closure here would generate a significant detour with a lengthy trip inland to reconnect with US 101. SWIM model output suggests a single day closure at this site would add an additional 796,514 miles driven and 8,393 hours of driving time for autos and 64,706 miles and 627 hours for trucks. Using these estimates and our assumed values for lost time and vehicle operation costs (Table 8.3) we calculate the individual costs associated with an Arizona Inn closure to be approximately $563,000 per day. The added social costs from the additional emissions are around $21,400 per day. Discussions with ODOT suggest a closure event at this location would take between 2 weeks and 3 months to re-open the highway. Estimates are presented for a 2-week closure and a 3-month closure in panel A of Table 8.6. GDP estimates for a 2-week and 3-month closure are calculated from SWIM model estimates described in Section 8.2.1 and are presented in panel B.

Table 8.6: Benefits of Avoiding Road Closures at Arizona Inn

	2-Week Closure	3-month Closure
Panel A. Detour Impacts		
Individual	$7,875,840	$51,192,960
Social	$299,320	$1,945,580
Panel B. GDP (SWIM model estimates)		
Statewide	$84,383,558	$550,000,000
Coastal	$16,699,158	$107,351,730
Panel C. Recreation Impacts		
Camping	$70,252	$457,905
Day Use	$147,500	$961,383

Note: All values reported in 2022 dollars. Actual costs incurred by detours varies by traffic volumes, which vary by time of year and during special events. The highest volume months are typically in the summer, and lower volumes in the winter months.

This location on US 101 also has two state parks in the general proximity of the high-risk closure area: Humbug Mountain State Park (HMSP, 3 miles north) and Arizona Beach Recreational Area (ABRA 0.5 miles south). Southbound traffic on US 101 would not be able to access ABRA whereas northbound traffic would not be able to access HMSP in the event of a closure. For simplicity, we assume park closures would accompany a road failure at Arizona Inn.

HMSP has a campground with 95 reservable campsites. OPRD data observed on average 8,722 unique camping trips in 2018 and 2021 at the site. Using the willingness to pay for a camping trip calculated in the analysis for BBSP ($210/trip 2022 dollars), the economic value of camping trips per year to HMSP is approximate $1.83 million dollars. The relevant estimates here are for a 2-week and 3-month closure, and the benefits of avoiding those closures are approximately $70,000 and $458,000, respectively.

HMSP also has a day-use area that receives 4,100 recreators per month and 49,200 per year. ABRA is a day-use park and receives 2,600 day-use recreators per month or 31,200 per year. Using the same unit value benefit transfer method from BBSP, we estimate the annual economic value of daytrips to HMSP and ABRA at $3.85 million per year. This would translate to a benefit of avoiding a 2-week (3-month) closure of $147,500 ($961,400). These impacts are presented in panel C of Table 8.6. Similar to BBSP, recreation is seasonal here and a summer closure would be more costly than a winter closure.

Two of the mitigation strategies (rip-rap revetment, retention wall) will result in permanent beach width loss of approximately 30 feet. The beach at this location is not formally labeled as a dedicated state park like Spencer Creek; hence, we do not have a credible way to estimate how recreators may be affected by beach loss at this site. Beach access is also highly limited at this site to low tide conditions. For example, if the loss of beach width impacts visitors at ABRA, they may substitute their day-use recreation activities to HMSP (3.5 miles away) where the beach would be unaffected by construction activities. Additional research would be needed to estimate this substitution potential to assess the economic impact of beach loss in this area, although the impacts are likely minimal as access to the beach at this site is difficult.

Here we also present estimated construction costs and annual maintenance costs for the four alternative adaptation strategies proposed for Arizona Inn (Table 8.7). Option 1 is to “do nothing” and continue with increasing (and large) annual maintenance costs. Options 2 and 3 propose alternatives that would alter the shoreline through rip-rap revetments (#2) or a retention feature (#3) to protect US 101. Each has an estimated construction cost and annual maintenance costs, along with estimates of lost beach width from construction activities. The final option (#4) is for a complete re-routing of US 101 around Arizona Inn to avoid the landslide and erosion hazards and maintain traffic flow on US 101. Here we were provided an estimated construction cost but not annual maintenance estimates.

Table 8.7: Estimated Costs for Adaptation Strategies at Arizona Inn

Alternative	Design Life (years)	Estimated Construction Cost (Total)	Annual Maintenance Cost (Current)	Annual Maintenance Cost in 2052 [a]
1: Do nothing	-	-	$131,929	$691,830
2: Riprap & drainage system	30	$12,794,000	$5,000	$18,878
3: Retention	40	$86,000,000	$1,000	$3,671
4: Highway Re-rerouting	60	$136,920,000	Assumed Minimal	Assumed Minimal

[a] Annual maintenance costs in the future are adjusted assuming 2.5% annual inflation.

8.3.3 Sea Lion Point

US 101 at Sea Lion Point has estimated daily traffic flows of 2,261 autos and 239 trucks each day in each direction (4,522 autos and 478 trucks total). SWIM model output suggests a single day closure at this site would add an additional 376,258 miles driven and 4,751 hours of driving time for autos and 29,223 miles and 305 hours for trucks. Using these estimates and our assumed values for lost time and vehicle operation costs (Table 8.3) we calculate the individual costs associated with a closure at Sea Lion Point to be approximately $289,750 per day. The added social costs from the additional emissions are around $9,900 per day. Discussions with ODOT suggest a closure event at this location would take between 1 day and 6 weeks to re-open the highway. Estimates are presented for a 1-day closure and a 6-week closure in panel A of Table 8.8. GDP estimates for a 1-day and 6-week closure are calculated from SWIM model estimates described in Section 8.2.1 and are presented in panel B.

Table 8.8: Benefits of Avoiding Road Closures at Sea Lion Point

	1-Day Closure	6-Week Closure
Panel A. Detour Impacts		
Individual	$289,750	$12,169,500
Social	$9,900	$415,800
Panel B. GDP (SWIM model estimates)		
Statewide	$0	$0
Coastal	$795,198	$33,398,316

Note: All values reported in 2022 dollars. Actual costs incurred by detours varies by traffic volumes, which vary by time of year and during special events. The highest volume months are typically in the summer, and lower volumes in the winter months.

Sea Lion Point has a few recreational opportunities in close proximity to the potential failure point, the Sea Lion Caves and Heceta Head Lighthouse Scenic Viewpoint (HHLSV). Sea Lion Caves is a privately-owned facility and we do not have visitation data. HHLSV is located south of Sea Lion Point and a closure would likely lower the nearly 24,000 monthly day use visits made to the site. At this time, we do not have the data to understand how much visitation would be reduced by a closure and since HHLSV offers many different recreation opportunities (hiking, visiting the lighthouse) in addition to beach recreation, applying a single value to a day trip to the site would also be problematic. Therefore, we are not able to estimate recreation benefits of avoiding a closure a Sea Lion Point.

Two of the mitigation strategies (buttress with rip-rap revetment, sheet pile wall) would result in permanent beach width loss of roughly 20 feet. However, the limited sandy beaches near this site are likely not accessible to the public and therefore would not be likely to have any impacts of recreation.

The estimated construction costs and annual maintenance costs for the four alternative adaptation strategies proposed for Sea Lion Point are presented in Table 8.9. Option 1 is to "do nothing" and continue with increasing annual maintenance costs. Options 2 and 3 propose alternatives that would alter the shoreline through a buttress with rip-rap revetments (#2) or tiebacks with a sheetpile wall (#3) to protect US 101. Each has an estimated construction cost and annual maintenance costs. The final option (#4) is for a complete re-routing of US 101 around Sea Lion Point to avoid the landslide and erosion hazards and maintain traffic flow on US 101. Here we were provided an estimated construction cost but not annual maintenance estimates.

Table 8.9: Estimated Costs for Adaptation Strategies at Sea Lion Point

Alternative	Design Life (years)	Estimated Construction Cost (Total)	Annual Maintenance Cost (Current)	Annual Maintenance Cost in 2052 [a]
1: Do Nothing	-	-	$10,792	$56,592
2: Buttress and Shear key with riprap	35	$1,975,248	$3,000	$15,731
3: Tiebacks, sheetpile wall, and riprap. Repair slides in north section. Drainage system.	50	$2,166,513	Assumed Minimal	Assumed Minimal
4: Highway Re-rerouting	75	$60,560,000	Assumed Minimal	Assumed Minimal

[a] Annual maintenance costs in the future are adjusted assuming 2.5% annual inflation.

8.3.4 Arch Cape Tunnel

Estimated daily traffic flows at Arch Cape Tunnel are 2,307 autos and 193 trucks each day in each direction (4,614 autos and 386 trucks total). SWIM model output suggests a single day closure at this site would add an additional 77,728 miles driven and 915 hours of driving time for autos and 19,304 miles and 157 hours for trucks. Using these estimates and our assumed values for lost time and vehicle operation costs (Table 8.3) we calculate the individual costs associated with a closure at Arch Cape Tunnel to be approximately $75,900 per day. The added social costs from the additional emissions are around $3,110 per day. Discussions with ODOT suggest a closure event at this location would take between 1 day and 2 weeks to re-open the highway. Estimates are presented for a 1-day closure and a 2-week closure in panel A of Table 8.10. GDP estimates for a 1-day and 2-week closure are calculated from SWIM model estimates described in Section 8.2.1 and are presented in panel B.

Table 8.10: Benefits of Avoiding Road Closures at Arch Cape Tunnel

	1- Day Closure	2-week Closure
Panel A. Detour Impacts		
Individual	$75,880	$1,062,320
Social	$3,110	$43,540
Panel B. GDP (SWIM model estimates)		
Statewide	$0	$0
Coastal	$198,800	$2,783,200

Note: All values reported in 2022 dollars. Actual costs incurred by detours vary by traffic volumes, which vary by time of year and during special events. The highest volume months are typically in the summer, and lower volumes in the winter months.

The location of this site is directly north of a popular recreation destination, Oswald West State Park (OWSP), and a closure may impact access to the park. OWSP is one of the most popular parks within the OPRD system with an on-average 14,400 day-use recreators per month. Given current predictions about short closure lengths or 24/7 flagging to keep at least one lane open, the specific impacts to recreation at the park are unclear at this time. One mitigation strategy will result in permanent beach width loss of roughly 20 feet; however, the beach is difficult to access and there are not likely to be many recreators that would be affected by this loss.

The estimated construction costs and annual maintenance costs for the four alternative adaptation strategies proposed for Arch Cape Tunnel are presented in Table 8.11. Option 1 is to "do nothing" and continue with minimal annual maintenance costs. Options 2 and 3 propose alternatives that would alter the shoreline through a buttress (#2) or soldier pile wall (#3) to protect US 101. Each has an estimated construction cost and annual maintenance costs were provided for option 2. The final option (#4) is for a complete re-routing of US 101 around Arch Cape to avoid the landslide and erosion hazards and maintain traffic flow on US 101. We were provided an estimated construction cost and annual maintenance estimates.

Table 8.11: Estimated Costs for Adaptation Strategies at Arch Cape

Alternative	Design Life	Estimated Construction Cost (Total)	Annual Maintenance Cost (Current)	Annual Maintenance Cost in 2052 [a]
1: Do Nothing	0	$0	$2,460	$5,747
2: Buttress Primary Slide, Reinforce Second Slide	20	$1,405,713	$968	$2,559
3: Construct Solider Pile Wall, Protect Slope	50	$3,452,833	Assumed Minimal	Assumed Minimal
4: Highway Re-rerouting	75	$41,000,000	$225,000	$266,391

[a] Annual maintenance costs in the future are adjusted to 2022 dollars assuming 2.5% annual inflation.

8.3.5 Saltair Creek

This US 101 site is in the southern part of Rockaway Beach, close to restaurants (e.g., The Original Pronto Pup) and lodge accommodations (e.g., hotels and vacation rentals). Estimated daily traffic flows at this site are 3,176 autos and 124 trucks each day in each direction (6,352 autos and 248 trucks total). SWIM model output suggests a single day closure at this site would add an additional 79,077 miles driven and 1,537 hours of driving time for autos and 12,166 miles and 143 hours for trucks. Using these estimates and our assumed values for lost time and vehicle operation costs (Table 8.3) we calculate the individual costs associated with a closure at Saltair Creek to be approximately $87,800 per day. The added social costs from the additional emissions are around $2,600 per day. Discussions with ODOT suggest a closure event at this location would be related to flooding and most closures could be remedied within hours. Therefore, estimates are presented for a 1-day closure only in panel A of Table 8.12. A closure at this site was not predicted to have any impact on Oregon or coastal GDP (panel B).

Table 8.12: Benefits of Avoiding Road Closures at Saltair Creek

	1- Day Closure
Panel A. Detour Impacts	
Individual	$87,760
Social	$2,580
Panel B. GDP (SWIM model estimates)	
Statewide	$0
Coastal	$0

Note: All values reported in 2022 dollars. Actual costs incurred by detours varies by traffic volumes, which vary by time of year and during special events. The highest volume months are typically in the summer, and lower volumes in the winter months.

There would likely be impacts to beach recreation associated with a closure, but due to the anticipated short closure times and lack of specific data on beach visits in this area, we cannot assess recreational impacts. Two of the mitigation strategies (shoreline mitigation and erosion control) will result in permanent beach width loss of roughly 10 feet, but again due to the lack of data on the quantity of recreational visits to this area, we cannot assess the potential impacts.

The estimated construction costs and annual maintenance costs for the four alternative adaptation strategies proposed for Saltair Creek are provided in Table 8.13. Option 1 is to "do nothing" and continue with minimal annual maintenance costs. Options 2 and 3 propose alternatives that would alter the shoreline through shoreline mitigation (#2) or erosion control (#3) to protect US 101. Each has an estimated construction cost and annual maintenance costs. The final option (#4) is for a complete re-routing of US 101 around this section to avoid the flooding hazards and maintain traffic flow on US 101. Here we were provided an estimated construction cost but not annual maintenance estimates.

Table 8.13: Estimated Costs for Adaptation Strategies at Saltair Creek

Alternative	Design Life	Estimated Construction Cost (Total)	Annual Maintenance Cost (Current)	Annual Maintenance Cost in 2052[a]
1: Do Nothing	0	$0	$3,378	$23,598
2: Shoreline Mitigation	25-50	$5,550,000	$2,565	$17,934
3: Erosion Control	25-50	$13,125,300	$1,000	$3,671
4: Highway Re-rerouting	50	$19,400,000	Assumed Minimal	Assumed Minimal

[a] Annual maintenance costs in the future are adjusted assuming 2.5% annual inflation.

8.4 APPLYING CBA TO CLOSURE SCENARIOS AT EACH SITE

Application of steps 1 to 5 of this CBA exercise for each site were reported in prior sections. To complete the analysis framework, this section applies the final three steps for the adaptation options at each US 101 site. Given current OMB guidelines under the recently updated Circular A4, we proceed here by assuming a 2 percent discount rate and use 1 percent and 3 percent to check the sensitivity of the results to this assumption (OMB Circular A-4, 2023). We estimate benefits of avoided closures using individual, social and recreation (if applicable) impacts at each site, which can be viewed as a probable lower bound on the estimated benefits. To explore the upper bound, we include GDP impacts from SWIM output, under the assumption that the daily GDP impacts from a 10-year closure of a road segment, in percentage terms, would be equivalent to a short-term closure. GDP is an aggregate economic measure of the market impacts of goods and services produced in an economy and typically include corporate profits, consumer expenditures, government consumption and investments, wages, and rental income. While the above assumption may be implausible, it is practical as it is important to include this type of measure as a very broad indicator for economic activity and as such, it is likely to overstate the economic impact of short-term US 101 closures. More site-specific research is likely needed to understand the short-term economic impacts of US 101 closures; hence, caution is urged with interpreting these findings.

Importantly, this exercise uses simple, yet plausible, ODOT-provided closure scenarios, ranging from worst case (failure happens soon) to most likely and then best case (failure does not happen in near future) at each site. Given the benefits for this analysis are based on avoiding a closure, the timing and the duration of the closure scenarios strongly influence the economic impacts. It is also important to note we consider one closure event per scenario, although multiple events are likely if no mitigation strategy is adopted at some sites. **Given the large uncertainty about when (and how many) closure events might occur, the following should be viewed as an illustrative example of a CBA decision framework to encourage thinking about the economic implications of each choice and the rankings presented should not be considered policy recommendations.** To illustrate these challenges, we explore more complex and realistic closure scenarios over a longer time horizon to demonstrate the importance of assumptions with additional exercises at Spencer Creek.

To summarize, we present net present value (NPV) calculations using a 2% discount rate with benefits measured with and without GDP impacts for all adaptation options at each of the 5 potential closure sites on US 101, based on three to four closure scenarios at each site, with additional scenarios included for Spencer Creek. The data and method behind these calculations are provided as a spreadsheet in Appendix C.7.

8.4.1 Spencer Creek

For this site, four (4) closure scenarios are explored (Table 8.14), each with benefits estimated with and without GDP impacts to the state included. Figures are used to display results with NPV in millions of 2022 dollars on the y-axis and the year of installation/construction of the alternative project on the x-axis.

Table 8.14: Spencer Creek Closure Scenarios

Alternative	Year of Failure	Type of Closure	Duration of Closure
Best Case	2035	1 direction with flagging	6 weeks
Most Likely #1	2030	1 direction with flagging	6 weeks
Most Likely #1	2030	Full closure	3 months
Worst Case	2023	Full closure	3 months

For the best-case scenario (6-week single lane closure in 2035), NPV calculation without GDP for each adaptation option are negative, suggesting there is not an economically viable strategy (Figure 8-5, panel A).[4] When GDP is included in the benefits (panel B), all options have a positive NPV for installation in 2022. Over this short time horizon, a cobble beach (orange line) installed in 2035 before the closure occurs has the highest NPV of the 4 alternatives. Note the patterns shown here are due to the recommended lower discount rate. With the formerly recommended discount rate of 7%, the present value of future costs would be lower, increasing overall net benefits.

For the two most-likely scenarios (2030 failure with different closing durations), Figure 8-6 displays the NPV of each alternative. In panel A, the scenario is a closure in 2030 that is 6 weeks in duration with 1 lane closed. In panel B, the closure in 2030 is a full closure for 3 months. In both scenarios, all alternatives have a positive NPV for immediate installation.

In all scenarios in this exercise, the cobble beach option has the highest NPV with a 2 percent discount rate when GDP impacts are included in the benefit estimates of avoided closures. All options have a negative NPV in all time periods when GDP is not included. The results are not affected if the discount rate is modified to either 1% or 3%. Scenarios over short time horizons such as these penalize construction options with high initial costs (e.g., highway re-route) so it is important to consider design life of projects and more realistic time horizons/closure scenarios when using CBA to evaluate options.

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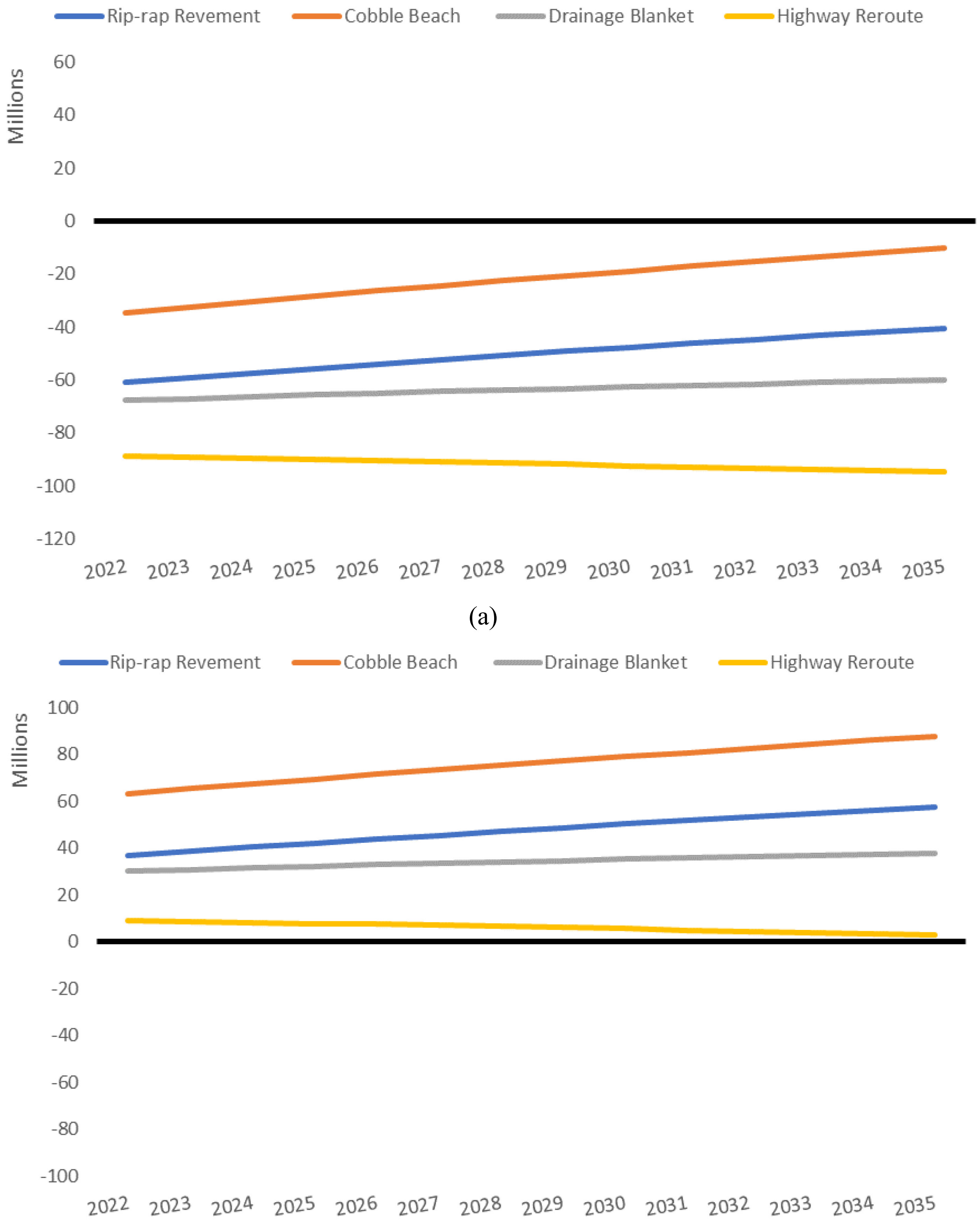
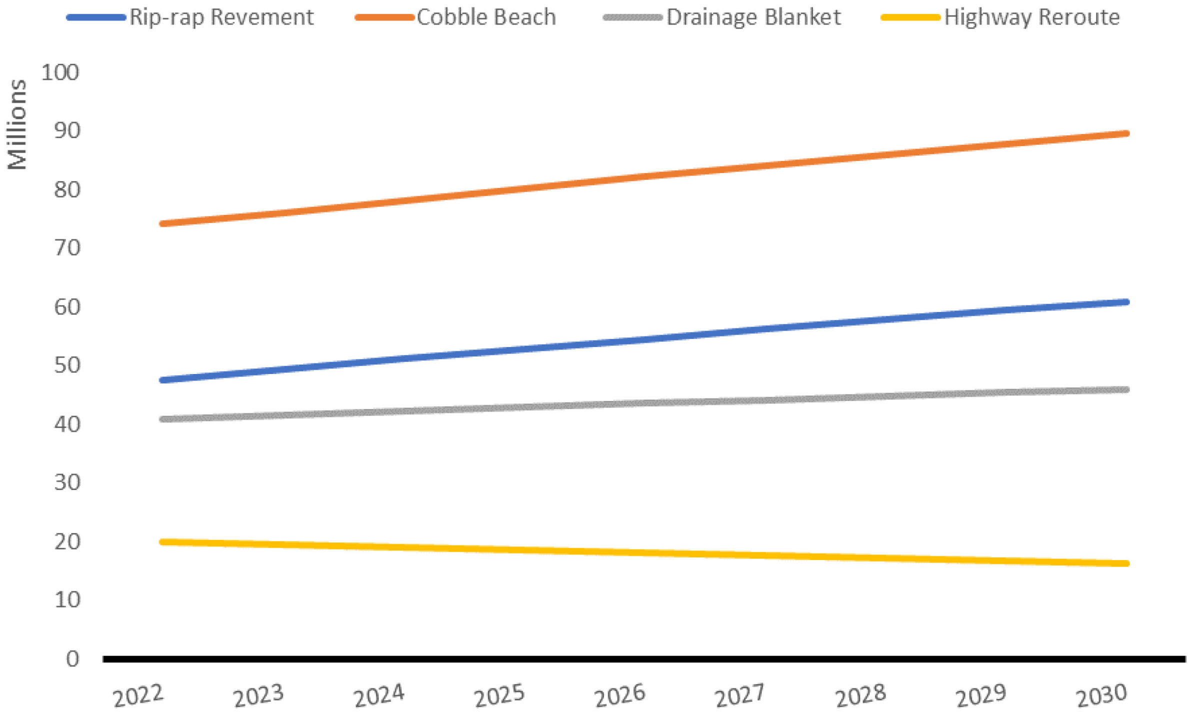
[4] This remains true for all remaining scenarios for Spencer Creek so graphs without GDP are not shown for those options.



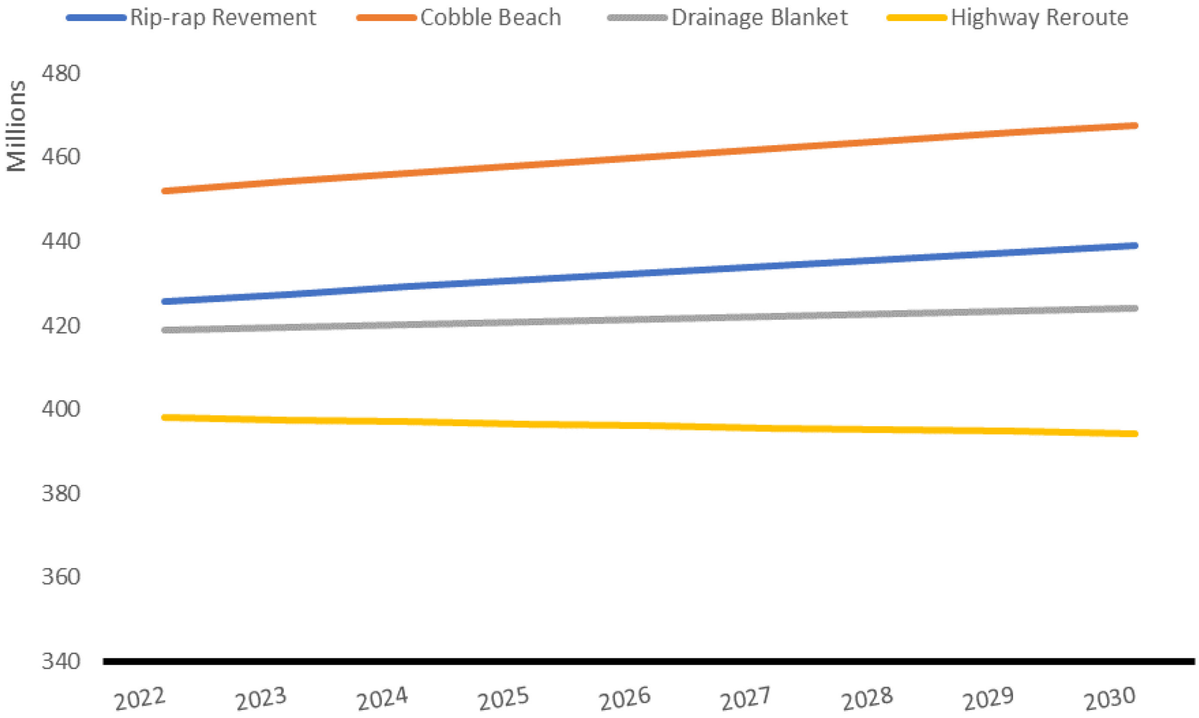
(a)

(b)

Figure 8.5: Net Present Value Estimates for Spencer Creek Adaptation Options under "Best-Case" Closure Scenario with (a) GDP not included and (b) GDP included.



(a)



(b)

Figure 8.6: Net Present Value Estimates for Spencer Creek Adaptation Options under "Mostly Likely" Closure Scenarios with GDP included for (a) a closure in 2030 that is 6 weeks in duration with 1 lane closed and (b) a full closure in 2030 lasting 3 months.

8.4.1.1 Additional Closure Scenarios

We explore four (4) additional scenarios at Spencer Creek over a 50-year time horizon to highlight the ability of the framework to handle longer time periods and multiple closures. Similar to the prior exercises, we develop four alternatives ranging from best-case (fortuitous) to worst-case (extreme) that include multiple closures over the next 50 years. Table 8.15 provides the details of these scenarios for this exercise. Figures are used to display results with NPV in millions of 2022 dollars on the y-axis and the year of installation/construction of the alternative project on the x-axis. Benefits are assumed to include GDP in all scenarios for this exercise and a 2% discount rate is used. Other assumptions underpinning these results are that each adaptation strategy is effective at preventing all closures in the scenario after it is installed, that each adaptation has a design life limit, and repair costs for failure events would be similar to recent US 101 closures.

Table 8.15: 50 Year Closure Scenarios Considered at Spencer Creek

Alternative	Description	Years of Failure	Type of Closure	Duration of Closure
Best Case	Small, localized failures every 20 years, no major failures	2035	1 direction w/ flagging	3 weeks
		2055	1 direction w/ flagging	3 weeks
Highly Likely #1	Small, localized failures every 10 years, no major failures	2030	1 direction w/ flagging	3 weeks
		2040	1 direction w/ flagging	3 weeks
		2050	1 direction w/ flagging	3 weeks
		2060	1 direction w/ flagging	3 weeks
		2070	1 direction w/ flagging	3 weeks
Highly Likely #2	Periodic small, localized failures, with 1 major failure in ~ 25 years	2030	1 direction w/ flagging	3 weeks
		2040	1 direction w/ flagging	3 weeks
		2050	Full Closure	3 months
		2060	1 direction w/ flagging	3 weeks
		2070	1 direction w/ flagging	3 weeks
Worst Case	Periodic small, localized failures, intermixed with multiple larger failures	2023	1 direction w/ flagging	3 weeks
		2033	Full Closure	3 months
		2043	1 direction w/ flagging	3 weeks
		2053	Full Closure	3 months
		2063	1 direction w/ flagging	3 weeks

For the “best-case” scenario (Figure 8.7, panel A), NPV calculation suggest that no option has a positive NPV initially, with only the highway re-route option (yellow line) having a positive NPV if installed immediately before the first closure in 2035. These results suggest that if we have an optimistic view about the future of US 101 at Spencer Creek (i.e., only 2 short duration closures in the next 50 years), many of the options would not be worth the cost to install. For the first “highly likely” scenario (Figure 8-7, panel B), every alternative has a positive NPV for immediate installation, with highway re-route having the highest NPV, followed by the drainage blanket, then cobble beach, and lastly rip-rap revetment. Only the highway re-route remains a net benefit immediately after the first closure but all alternative return to a positive NPV if installed soon before the next closure in 2040. The NPV is negative for all options if installation occurs after the second road failure, suggesting action in the near term would have some net benefits. For the second “highly likely” scenario which includes a major 3-month failure in 2050 (Figure 8.7, panel C), all options have a positive NPV immediately and up until the major closure in 2050, with the ordering remaining the same as the first two scenarios. This suggests that any adaptation options that can prevent a full 3-month closure of US 101 at Spencer Creek by 2050 would generate net benefits from installation. NPV is highest for near-term installation that would also prevent two small closure events prior to the major closure in 2050. The NPV for installation of any option becomes negative if installed after a major closure. The same is true for the “worst case” scenario (Figure 8-7, panel D). In all scenarios, again assuming a 2% discount rate and full efficacy of all options at preventing future closures, the highway re-route option provides the highest NPV. For comparison, the NPV of the highway re-route option under each scenario is shown in Figure 8.8.

For our sensitivity analyses, we also change our baseline assumptions that may alter the policy implications of the analysis. First, varying the discount rate between 1% and 3% does not substantively change the outcomes of these scenarios, though use of the formerly recommended discount rate of 7% does substantially change the outcomes of these scenarios. Second, a maintained assumption across these scenarios was that, once installed, every adaptation option would prevent all future closures with 100% efficacy. This assumption might be likely to hold with a highway re-route where the road is moved away from the coastal hazard area, but it may be less realistic for solutions that would remain subject to wave action, sea-level rise and increases in erosion (i.e., cobble beach, rip-rap, drainage blanket) or re-routed through landslide prone terrain. To illustrate this concern, we compare scenarios where we assume 100 percent efficacy to one where we assume a cobble beach would lose efficacy to prevent closures due to sea-level rise after 2050. Figure 8.9 compares highly likely #2 scenario across these assumptions. In panel B where efficacy of the cobble beach ends after 2050, the NPV patterns and some rankings of projects change, with cobble beach now ranked last among the four options. This comparison is provided for illustrative purposes and to simulate how the decision framework can be altered by assumptions to present potentially more realistic scenarios.

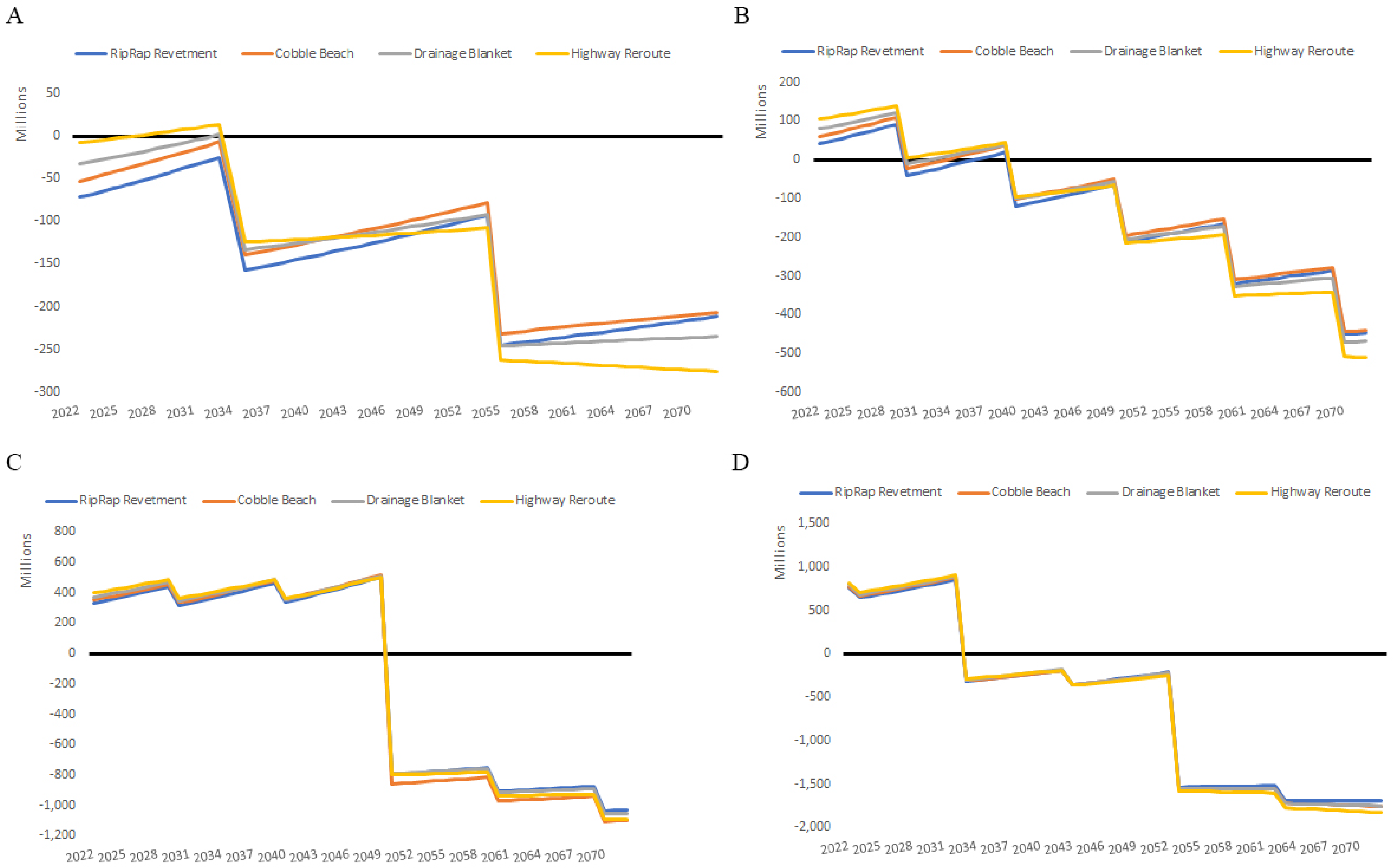


Figure 8.7: Net Present Value Estimates for Spencer Creek Adaptation Options under 50-year (a) best case, (b) most-likely #1, (c) most-likely #2, and (d) worst case closure scenarios.

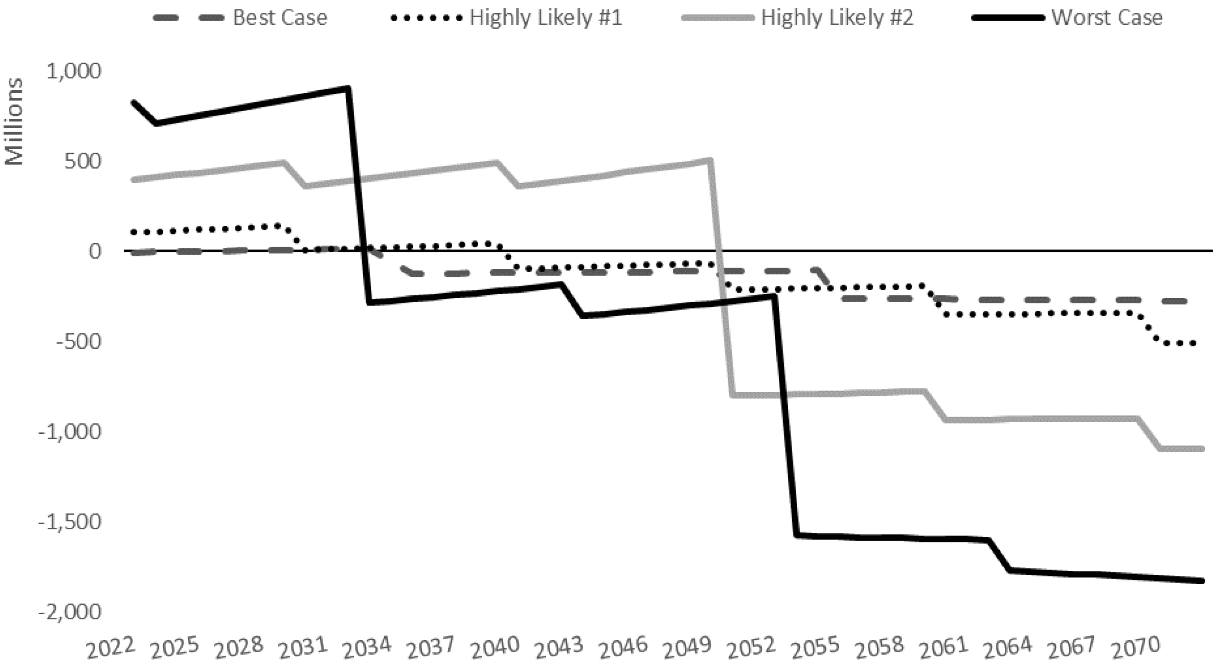
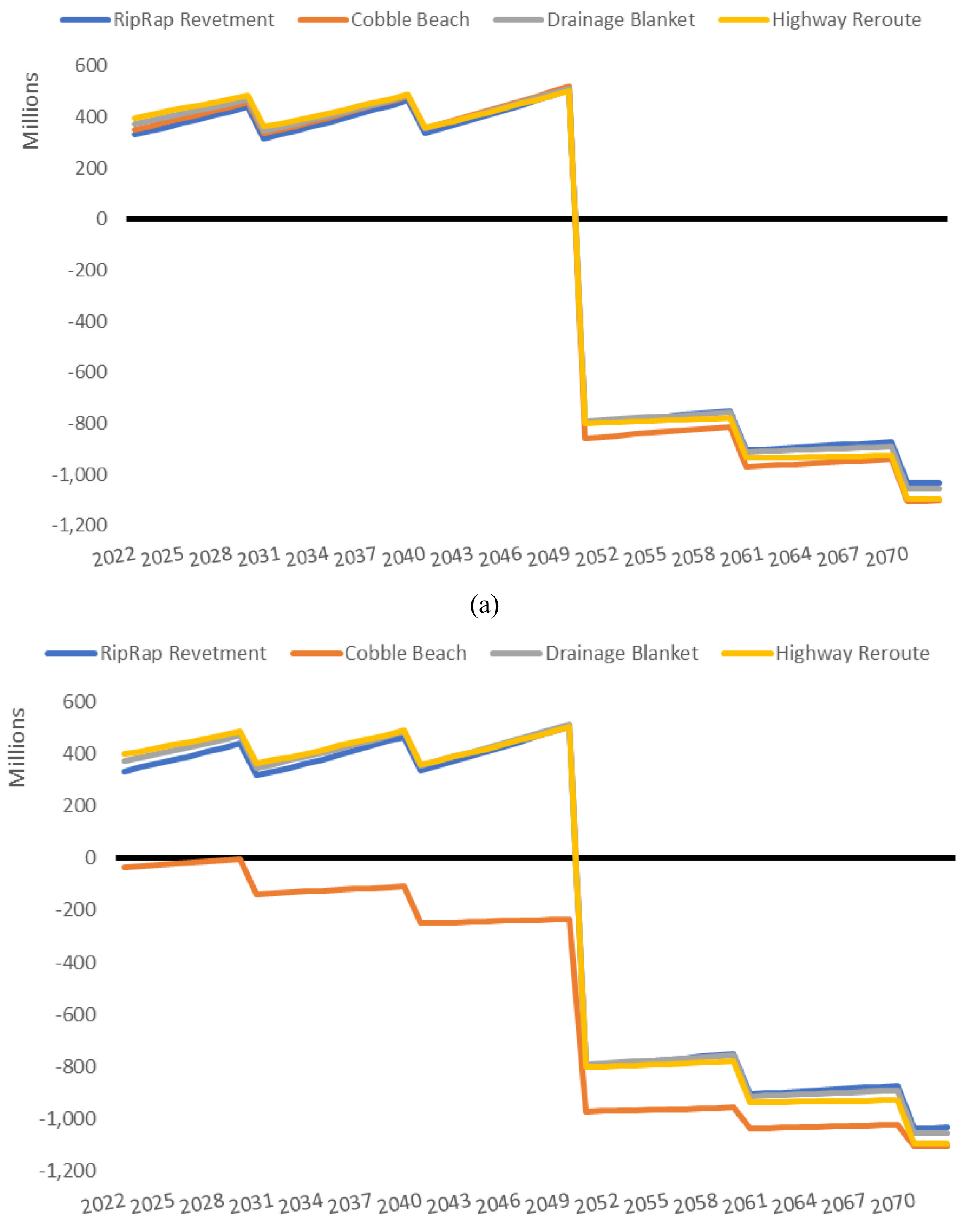


Figure 8.8: Net Present Value Estimates for Highway Re-Route at Spencer Creek under 50-year closure scenarios



(a)

(b)

Figure 8.9: Comparison of Highly Likely #2 Scenario with Differing Assumptions on Cobble Beach Efficacy. (a) no loss and (b) loss after 2050.

8.4.2 Arizona Inn

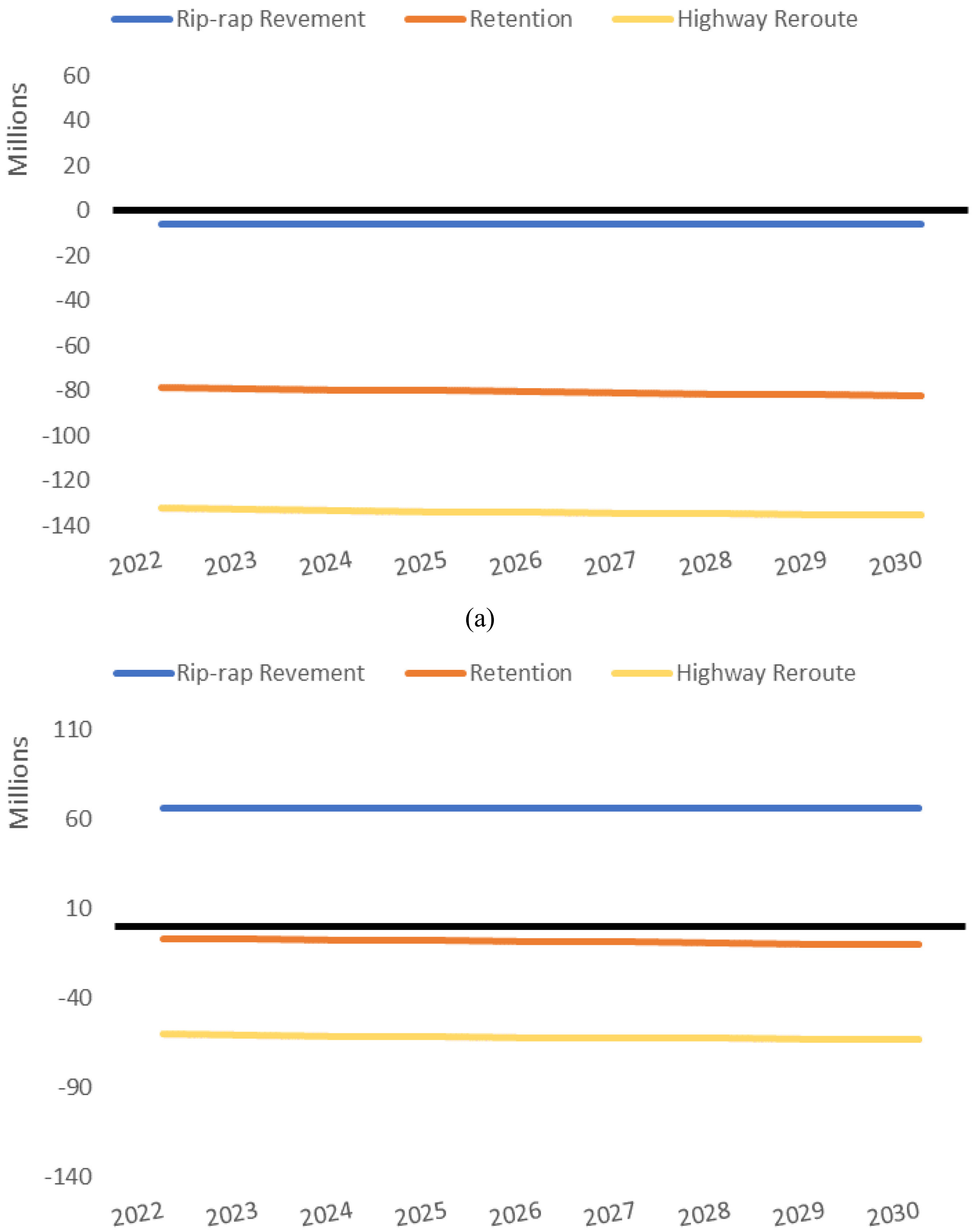
For Arizona Inn, there were three (3) closure scenarios evaluated (Table 8.16), each with benefits estimated with and without GDP impacts to the state included. Figures are used to display results with NPV in millions of 2022 dollars on the y-axis and the year of installation/construction of the alternative project on the x-axis.

Table 8.16: Arizona Inn Closure Scenarios

Alternative	Year of Failure	Type of Closure	Duration of Closure
Best Case	2030	Full closure	2 weeks
Most Likely	2025	Full closure	2 weeks
Worst Case	2023	Full closure	3 months

For the best-case scenario (2030 full closure for 2 weeks), NPV calculations without GDP for each adaptation option are negative, suggesting there is not an economically viable strategy (Figure 8.10, panel A). When GDP is included in the benefits (Figure 8.10, panel B), the rip-rap revetment option (blue line) has positive NPV for immediate construction. Both retention (orange line) and re-routing the highway (yellow line) in this scenario have a negative NPV across all time periods. In this scenario, altering the discount rate does not change these results in any meaningful way. For the most-likely (2025 2-week full closure) scenario, both a rip-rap revetment and retention measure have positive NPV in all time periods with the re-route remaining with negative NPV in all periods (Figure 8.11). Under the worst-case (2023 3-month full closure) scenario, all options have a positive NPV immediately and rip-rap revetment even has a positive NPV when GDP is not included in the benefits (Figure 8.12, panel A). Once again, these findings are not sensitive to altering the discount rate.

To summarize, in all scenarios in this exercise, the rip-rap revetment option has the highest NPV, and it is always positive with a 2 percent discount rate when GDP impacts are included in the benefit estimates of avoided closures. All options have a negative NPV in all time periods when GDP is not included in the benefits, with the lone exception of rip-rap in the worst-case scenario. As shown with Spencer Creek, expanding the time horizon in scenarios at Arizona Inn may alter the NPV prioritization of the alternative options.



(a)

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Figure 8.10: Net Present Value Estimates for Arizona Inn Adaptation Options under "Best Case" Closure Scenario with (a) GDP not included and (b) GDP included.

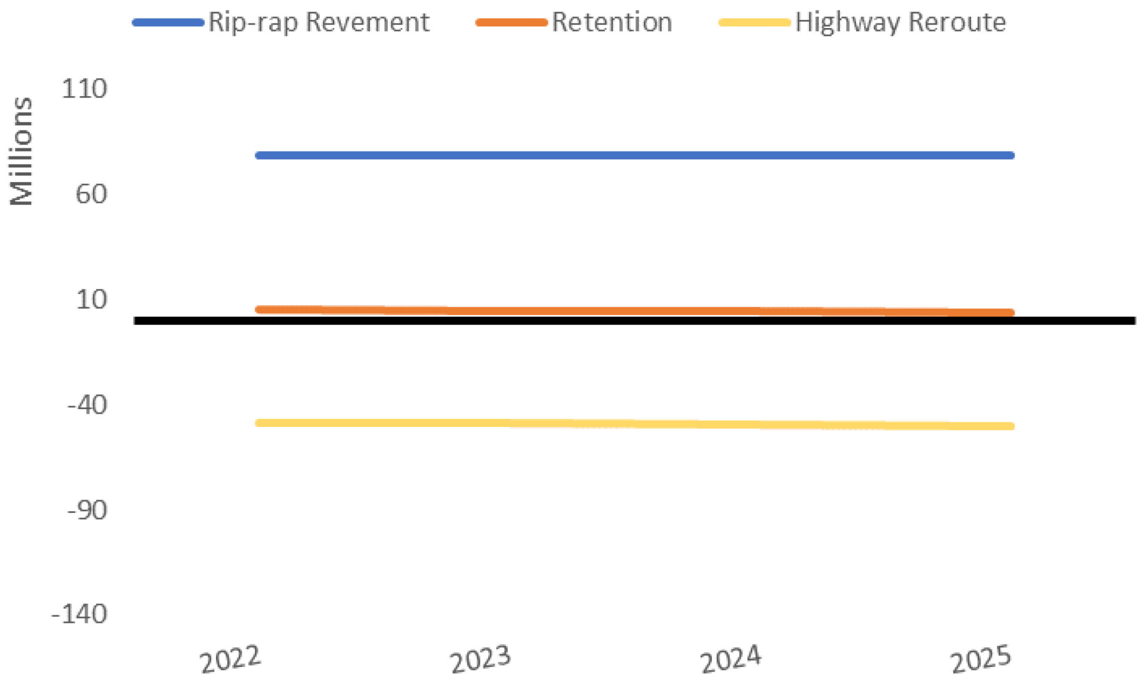
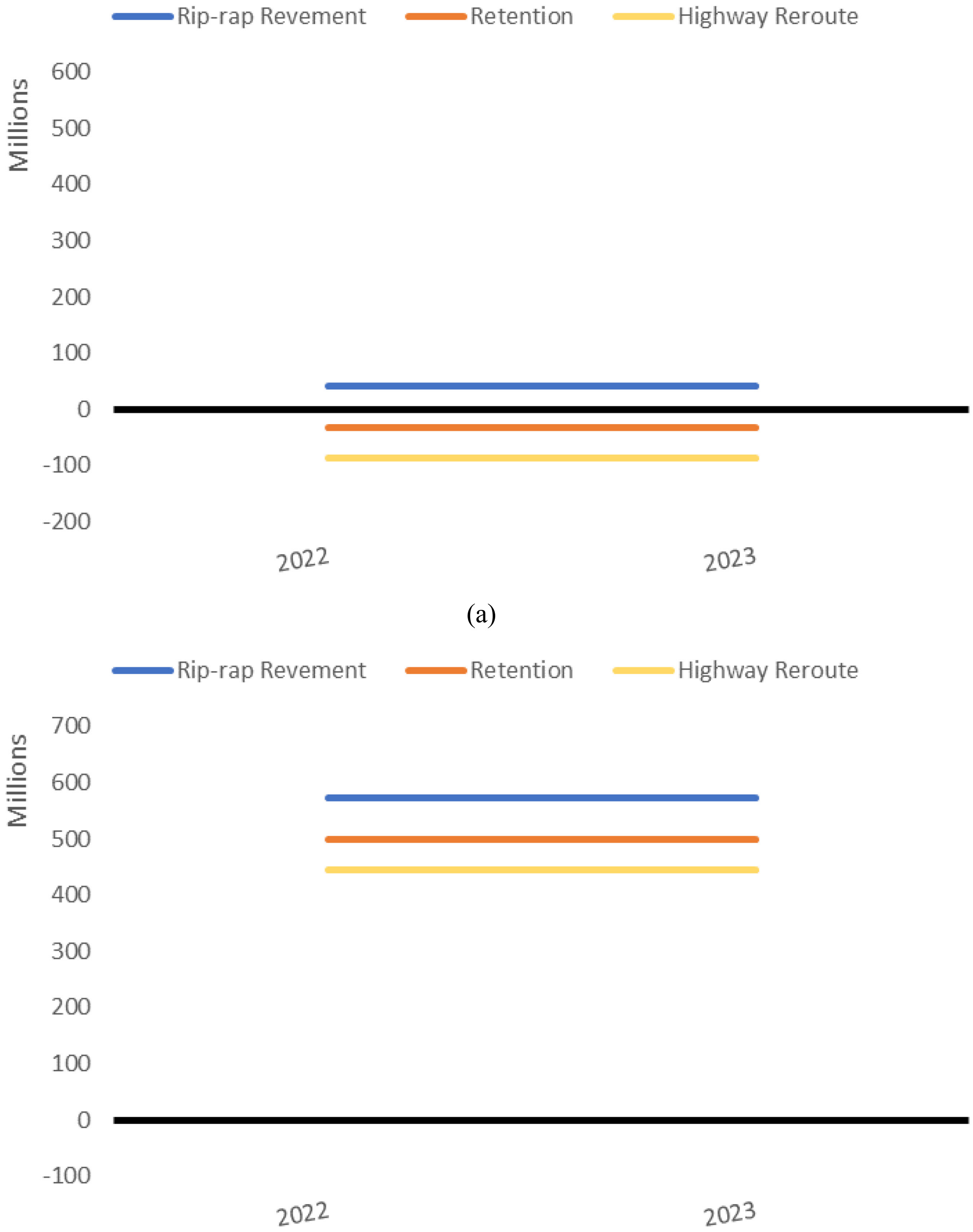


Figure 8.11: Net Present Value Estimates for Arizona Inn Adaptation Options under "Most Likely" Closure Scenario



(a)

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Figure 8.12: Net Present Value Estimates for Arizona Inn Adaptation Options under "Worst Case" Closure Scenario with (a) GDP not included and (b) GDP included.

8.4.3 Sea Lion Point

At Sea Lion Point, three (3) closure scenarios were evaluated (Table 8.17), each with benefits estimated with and without GDP impacts to the state included. Figures are used to display results with NPV in millions of 2022 dollars on the y-axis and the year of installation/construction of the alternative project on the x-axis.

Table 8.17: Sea Lion Point Closure Scenarios

Alternative	Year of Failure	Type of Closure	Duration of Closure
Best Case	2035	Full closure	2 weeks
Most Likely	2027	Full closure	6 weeks
Worst Case	2023	Full closure	6 weeks

For the best-case scenario (2035 full closure for 2 weeks), NPV calculation without GDP are marginally positive for the buttress (blue line) and tieback (orange dashed line) options while highway re-route is negative (Figure 8.13, panel A). When GDP is included in the benefits, the buttress and tieback options both have positive NPV for immediate construction. In all scenarios, the NPV for the buttress and tieback options are nearly identical given the limited cost information provided. Highway re-route (yellow line) would have negative NPV in all time periods. In both the most likely (Figure 8.14) and worst-case (Figure 8.15) scenarios, the buttress and tieback options have positive NPV in all time periods and re-routing the highway in negative all time periods. This holds for both benefit estimates (with and without GDP impacts) and all discount rates.

To summarize, in all scenarios in this exercise, the buttress and tieback options both have positive NPV with a 2% discount rate when GDP impacts are included in the benefit estimates of avoided closures (and even most scenarios when GDP is not included). The highway re-route option at this location has negative NPV in all periods regardless of GDP inclusion, once again due to the very short time horizon and high initial cost.

(a)

(b)

Figure 8.13: Net Present Value Estimates for Sea Lion Point Adaptation Options under "Best Case" Closure Scenario with (a) GDP not included and (b) GDP included.

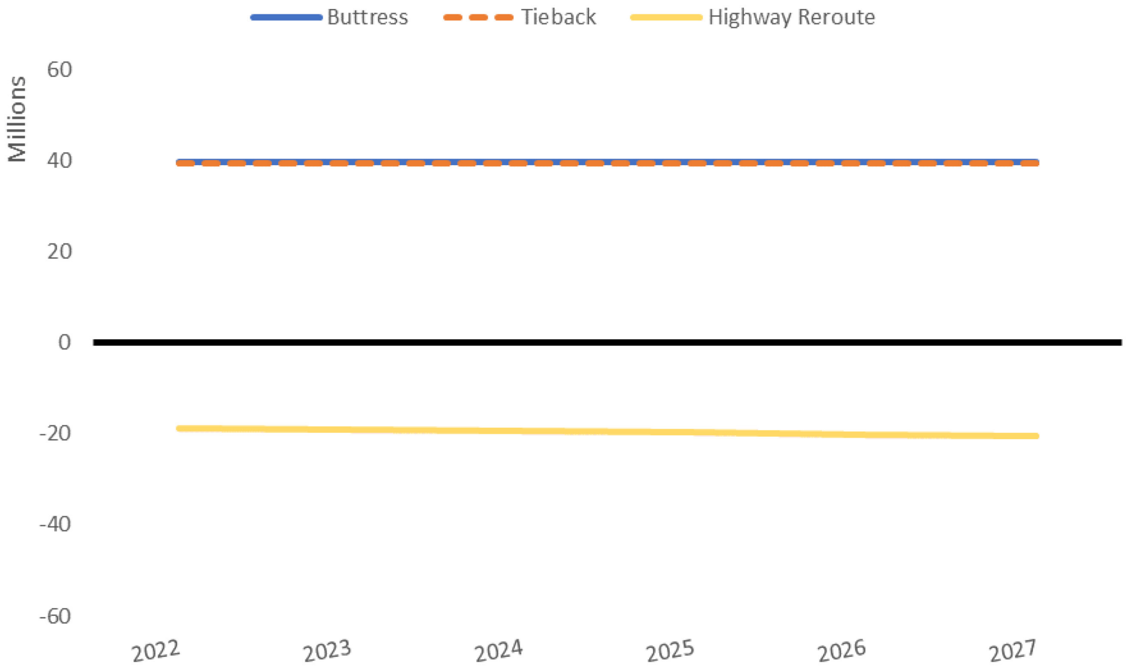

Figure 8-14: Net Present Value Estimates for Sea Lion Point Adaptation Options under “Most Likely” Closure Scenario

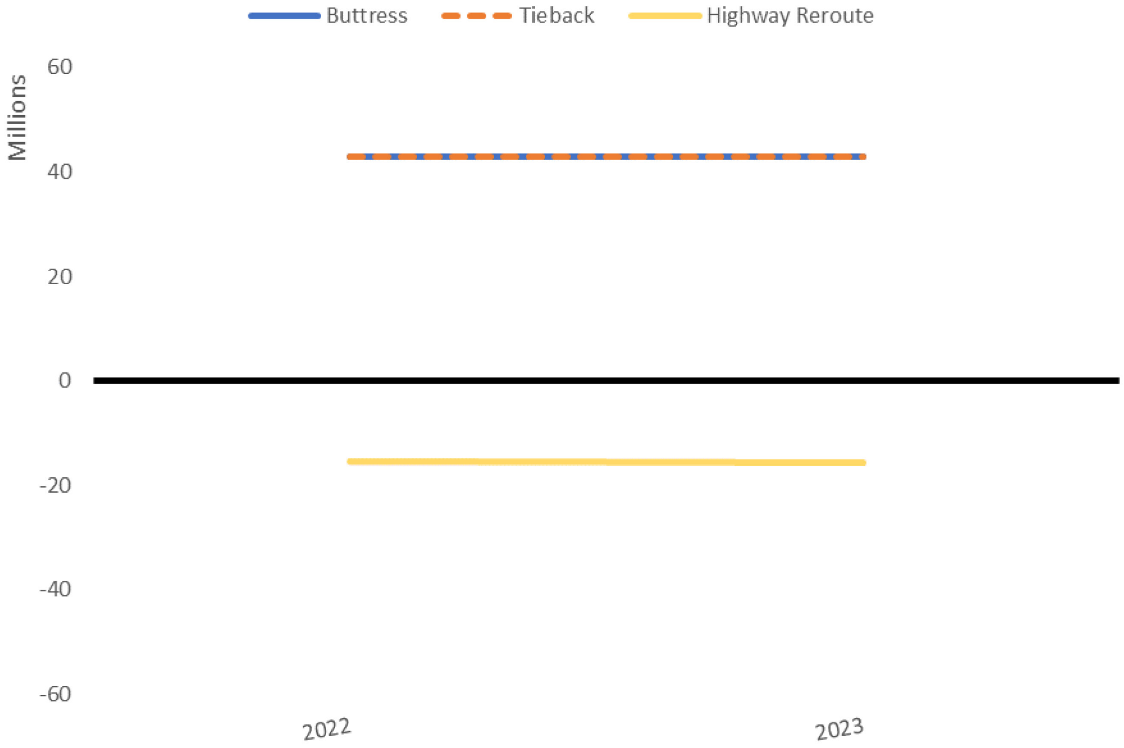

Figure 8.15: Net Present Value Estimates for Sea Lion Point Adaptation Options under “Worst Case” Closure Scenario

8.4.4 Arch Cape Tunnel

For Arch Cape, there were three (3) closure scenarios evaluated (Table 8.18), each with benefits estimated with and without GDP impacts to the state included. Figures are used to display results with NPV in millions of 2022 dollars on the y-axis and the year of installation/construction of the alternative project on the x-axis.

Table 8.1: Arch Cape Closure Scenarios

Alternative	Year of Failure	Type of Closure	Duration of Closure
Best Case	2035	1 direction with flagging	2 weeks
Most Likely	2032	Full closure	2 weeks
Worst Case	2023	Full closure	2 weeks

For the best-case scenario (2035 1 direction closed for 2 weeks), all options have a negative NPV when GDP is not included in the benefits (Figure 8.16, panel A).[5] When GDP is included, the buttress (blue line) and soldier pile wall (orange dashed line) options both have positive NPV for immediate construction (Figure 8.16, panel B). In the GDP inclusion set, the highway re-route option has negative NPV. In all scenarios, the NPV for the buttress is slightly higher but relatively similar to the soldier pile wall option. In the most likely scenario (2032 full 2-week closure), the buttress, soldier pile wall, and the highway re-route all have positive NPV across the time period (Figure 8.17). All options have negative NPV in the no GDP calculations. Lastly, the worst-case scenario at Arch Cape (2023 full 2-week closure; Figure 8.18) suggests all adaptation options have positive NPV.

To summarize, the buttress and soldier pile wall options both have positive NPV in all scenarios with a 2% discount rate when GDP impacts are included in the benefit estimates of avoided closures, with the NPV of the buttress option slightly higher. The highway re-route option at this location has positive NPV in in the most likely and worst-case scenarios when GDP is included.

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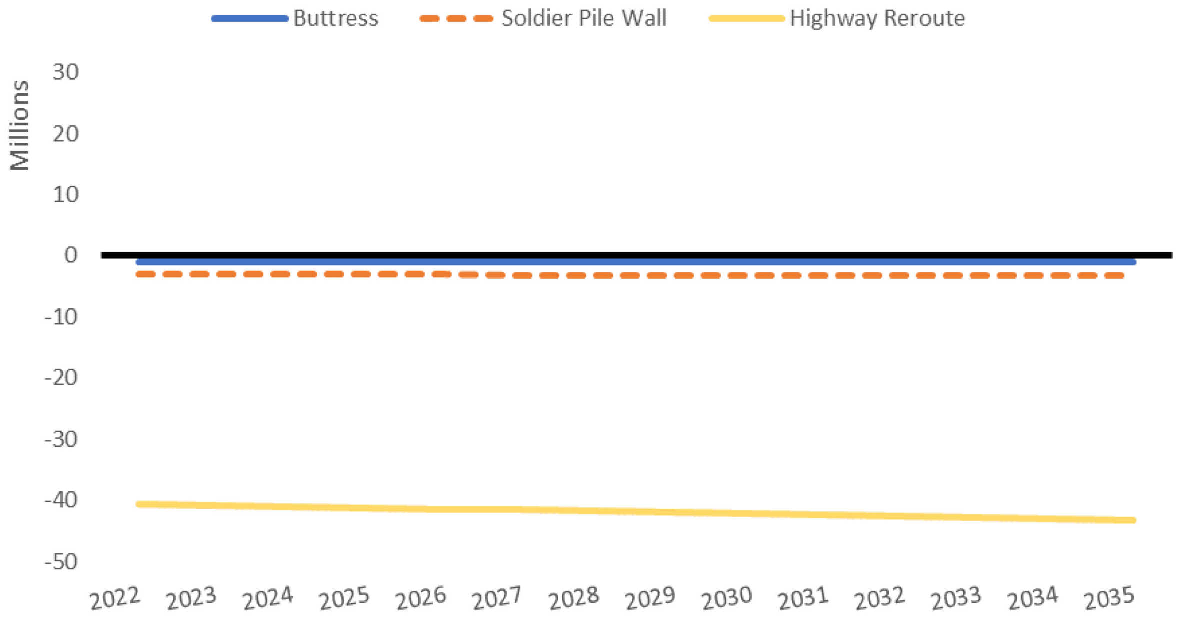
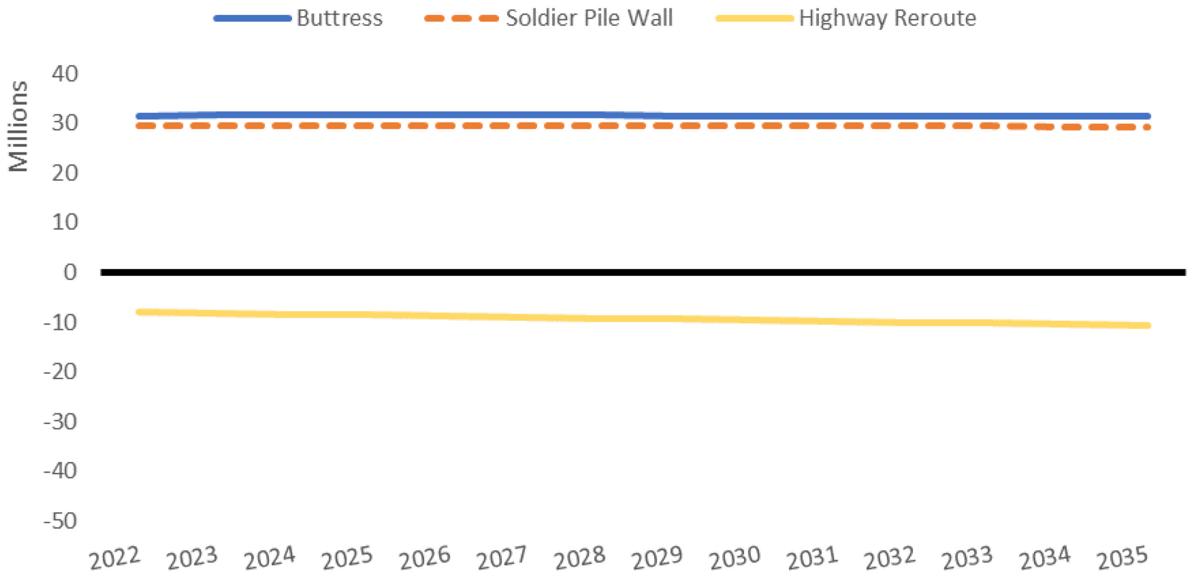
[5] This remains true for all remaining scenarios for Arch Cape so graphs without GDP are not shown here.



(a)



(b)

Figure 8.16: Net Present Value Estimates for Arch Cape Adaptation Options under "Best Case" Closure Scenario

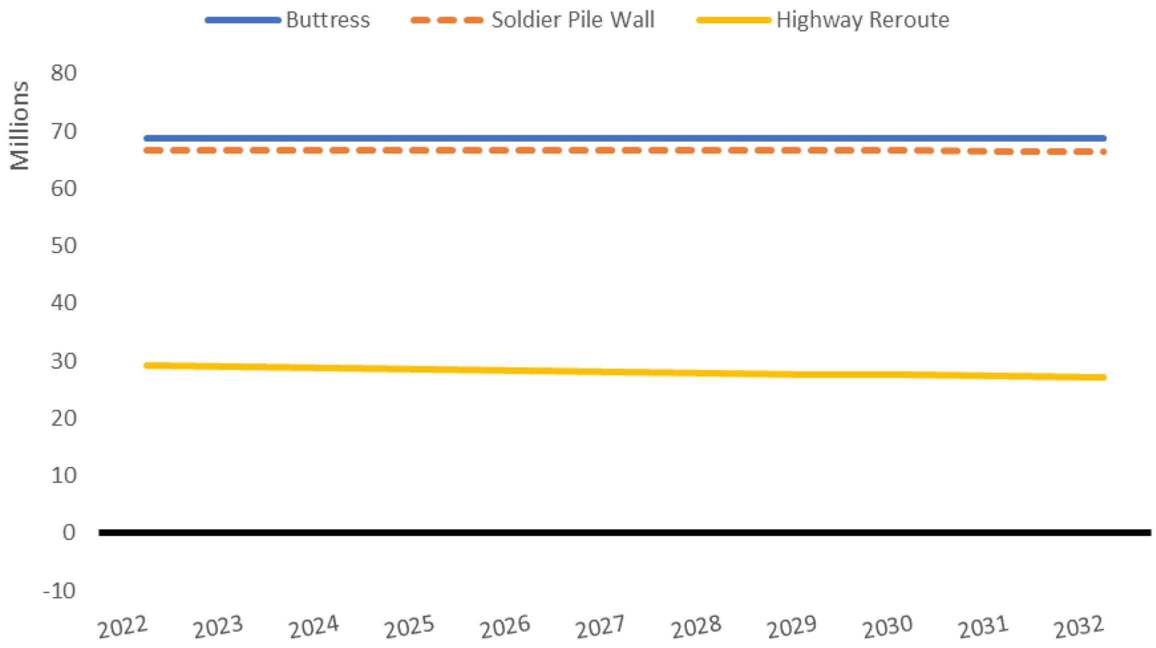


Figure 8.17: Net Present Value Estimates for Arch Cape Adaptation Options under "Most Likely" Closure Scenario

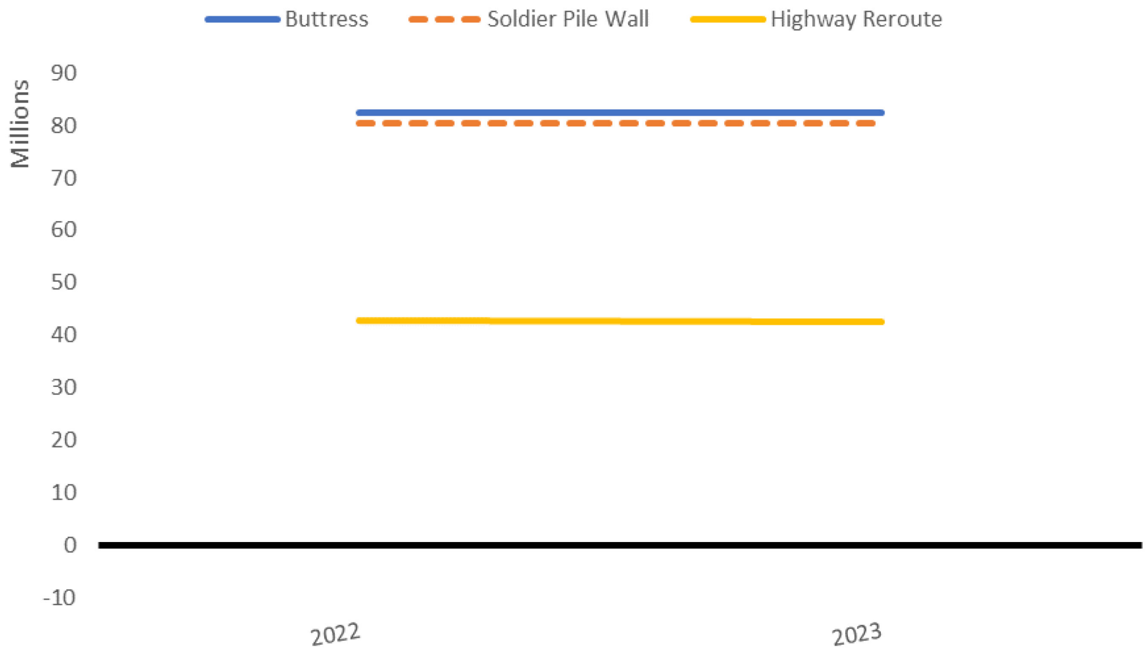


Figure 8.18: Net Present Value Estimates for Arch Cape Adaptation Options under "Worst Case" Closure Scenario

8.4.5 Saltair Creek

Lastly for Saltair Creek, three (3) closure scenarios were evaluated (Table 8.19). Since SWIM did not project any state or coast-level GDP impacts, the benefits used here do not contain any change in this measure. Figures are used to display results with NPV in millions of 2022 dollars on the y-axis and the year of installation/construction of the alternative project on the x-axis.

In all closure scenarios, the NPV for all three options is negative. Best-case, most likely, and worst-case scenario results are presented in Figure 8.19, Figure 8.20, and Figure 8.21, respectively. These results are not sensitive to different discount rate assumptions. This suggests that any proposed adaptation project at this location is likely to have net costs for Oregon.

Table 8.19: Saltair Creek Closure Scenarios

Alternative	Year of Failure	Type of Closure	Duration of Closure
Best Case	2032	Full closure	1 day
Most Likely	2027	Full closure	1 day
Worst Case	2023	Full closure	3 days

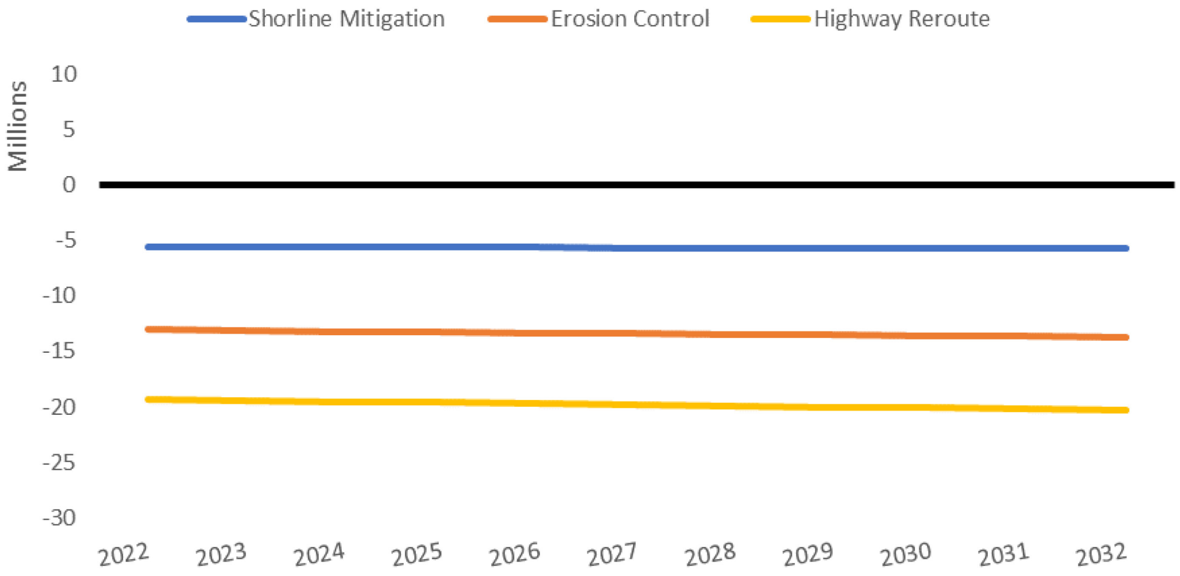


Figure 8.19: Net Present Value Estimates for Saltair Creek Adaptation Options under "Best Case" Closure Scenario

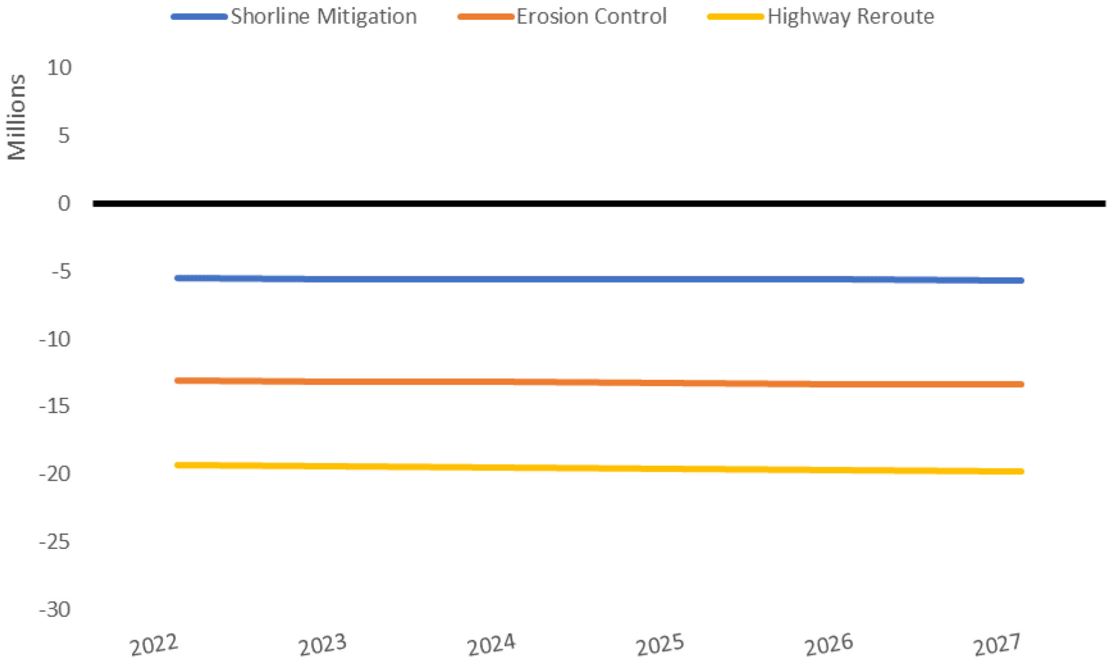


Figure 8.20: Net Present Value Estimates for Saltair Creek Adaptation Options under "Most Likely" Closure Scenario

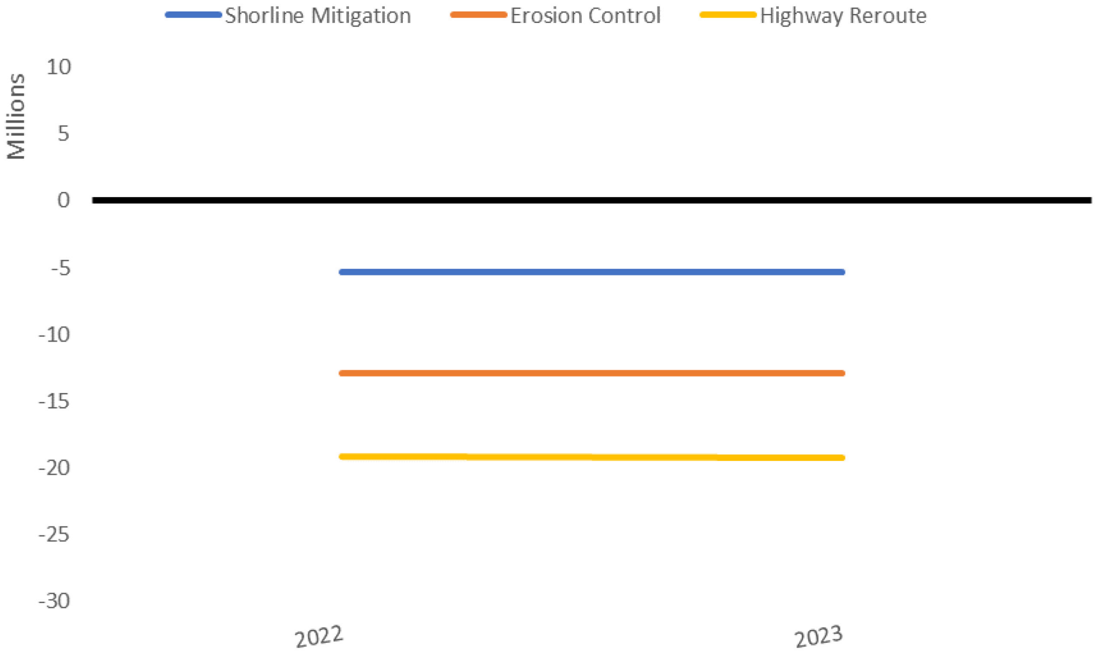


Figure 8.21: Net Present Value Estimates for Saltair Creek Adaptation Options under "Worst Case" Closure Scenario

8.5 CONCLUDING REMARKS

In this CBA exercise, adaptation options were identified with positive net benefits to Oregon at each US 101 site, except Saltair Creek. However, these occurred only when we included SWIM estimated long-term GDP impacts as short-term benefits of avoided road closures. The following discussion focuses on results from the most likely scenario from each site, and again assuming a short time horizon, 100% efficacy of adaptation options and a 2% discount rate, except for the more complex scenarios at Spencer Creek.

For Spencer Creek, the short-term scenarios suggest a cobble beach a has a positive NPV for immediate construction (+$74 million) but NPV is maximized (+$87.8 million) if construction can be delayed to 2029 (the year before the closure in this scenario). Additional 50-year scenarios with multiple closures at Spencer Creek do not support a cobble beach intervention because of the long-term annual recreation impacts created by construction. In the longer term, all scenarios support a highway re-route as the option with highest NPV. For the remaining sites, all scenarios are short term. At Arizona Inn, a rip-rap revetment has a positive NPV for immediate construction (+$78.1 million), while a buttress (+$39.6 million) and tieback option (+$39.5 million) are both economically viable for immediate construction at Sea Lion Point. These two options are so similar due to comparable installation costs and minimal (buttress) or missing (tieback) annual maintenance costs. Lastly, the buttress option (+$68.7 million) and the soldier pile wall (+$66.7 million) have similar positive NPVs for initial construction at Arch Cape. As with Sea Lion Point, these options are similar due to comparable initial costs and minimal/missing annual maintenance costs.

To move this forward, site-specific economic impacts should be investigated and estimated to refine steps in this framework to be more accurate compared with providing a range from no impacts to long-term GDP-level impacts. A better understanding of these impacts is likely to change the NPV calculations and even the ranking of options at each site. This exercise was also based on simple short-term closure scenarios - more complex longer-term scenarios that include multiple closures and efficacy considerations of project options (i.e., what is the probability a cobble beach investment will prevent road failure for 30 years) would add more realism to this exercise and is likely to change results. In the case of Spencer Creek, the short-term simple scenarios penalize high initial costs projects and artificially inflate other construction projects with long-term recurring costs (e.g., rip-rap revetments limiting recreation). The longer-term scenarios demonstrate this, showing the prioritization supporting a highway re-route (higher initial costs, but lower recurring impacts over time). As noted earlier in this section, this exercise is intended as an illustrative example of a CBA decision framework to encourage thinking about the economic implications of each choice and the rankings presented should not be considered policy recommendations.

9.0 COMMUNITY ENGAGEMENT

9.1 INTERACTIVE WEB-MAP

To help disseminate the information prepared in this report, an online map was created using ArcGIS Experience Builder (Esri®) to visualize the outputs (https://experience.arcgis.com/experience/b9c625d22d5443b4b7e81c25cb53ed8a/). This app enables creation of either map centric or non-map centric webpages that can be displayed on a fixed or scrolling screen and organized into single or multiple pages. Experience Builder makes it possible to work not only with ready-to use templates but also implement customized JavaScript codes for specific workflows as desired. Data files are provided in Appendix C.8.

In addition to the results of this study, the online map contains open-source data provided by the Department of Geology and Mineral Industries (DOGAMI), the Oregon Department of Transportation (ODOT), the Oregon Park and Recreation Department, the Federal Emergency Management Agency (FEMA), and the United States Geological Survey (USGS).

The map is designed for engineers, economists, ODOT specialists, planners, the public, and tourists. The purpose of this map is to provide intuitive access to a wide range of available information about Highway 101 potential hazards and potential activities for the restoration of the highway. To this end, the map consists of four main sections: *Vulnerability Analysis Site Summary*, *Highway 101 Detailed Map*, *Adaptation Options*, and *About Project*.

9.1.1 Vulnerability Analysis Site Summary

In the first section, **Vulnerability Analysis Site Summary**, the engine was developed to easily navigate to all potential trouble spots with the tiles on the right. The description and location of the site can be found both by name and ID (Figure 9.1).

Site 40, Sea Lion Point:
Road Length: 2,983 ft (909 meters)
Hazard: Landsliding, cliff erosion ;
Recent Events: Recent failure in 2021; Failure in 1997 by tunnel closed HWY 101 for months
Geomorphology: tall cliffs with landsliding
Shoreline Protection: 0 percent
Unstable Slopes Maintenance Frequency: 5 times or more a year
Estimated annual cost, $: 7000
Estimated repair cost, $: 12419000
Road impact score: 85 , landslide closure 10-60 mile detour
Coastal Vulnerability Index (CVI): 2.082

Figure 9.1: Screenshot of the Vulnerability Analysis Site Summary Section of the webpage.

Clicking on the site, summary information about the site is provided: the road length within the trouble zone; the type of dominate hazards and recent hazard events; geomorphological patterns; level of the shoreline protection; unstable slope maintenance frequency, estimated annual and repair costs, and road impact score; and the enhanced coastal vulnerability index (Section 6.0). A pie chart presents the relative levels of potential hazards (e.g., flooding, erosion, landsliding) as a percentage. The user can change the basemap to any within the standard ArcGIS library (e.g., satellite, topographic, streets, etc.).

9.1.2 Highway 101 Detailed Map

The **Highway 101 Detailed Map** provides more detailed information beyond the vulnerability assessment site summary map, which was meant to be a simpler page with the most critical information. The Highway 101 detailed map was created using a classic template. To make the map more convenient and understandable for the user, the content has been divided into four main groups: Oregon Borders and Roads, Inundation, Erosion, Landslide (Figure 9-2). Layers within each group can be toggled on and off as desired.

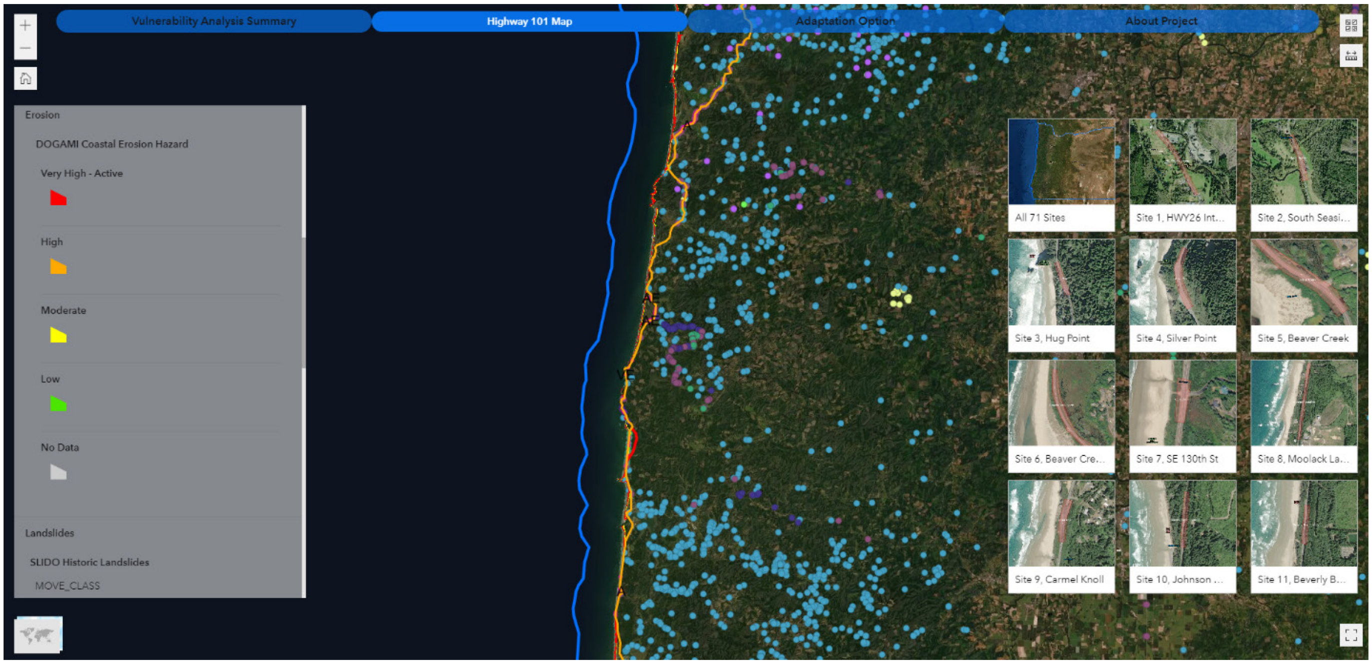


Figure 9.2: Screenshot of the Highway 101 detailed map section.

Oregon Borders and Roads include data provided by ODOT: lanes and shoulders width, pavement condition, the number of lines, information about bridges and annual average daily traffic (AADT). There are also detours for the priority sites, 71 hazard sites, and the Oregon state and county boundaries.

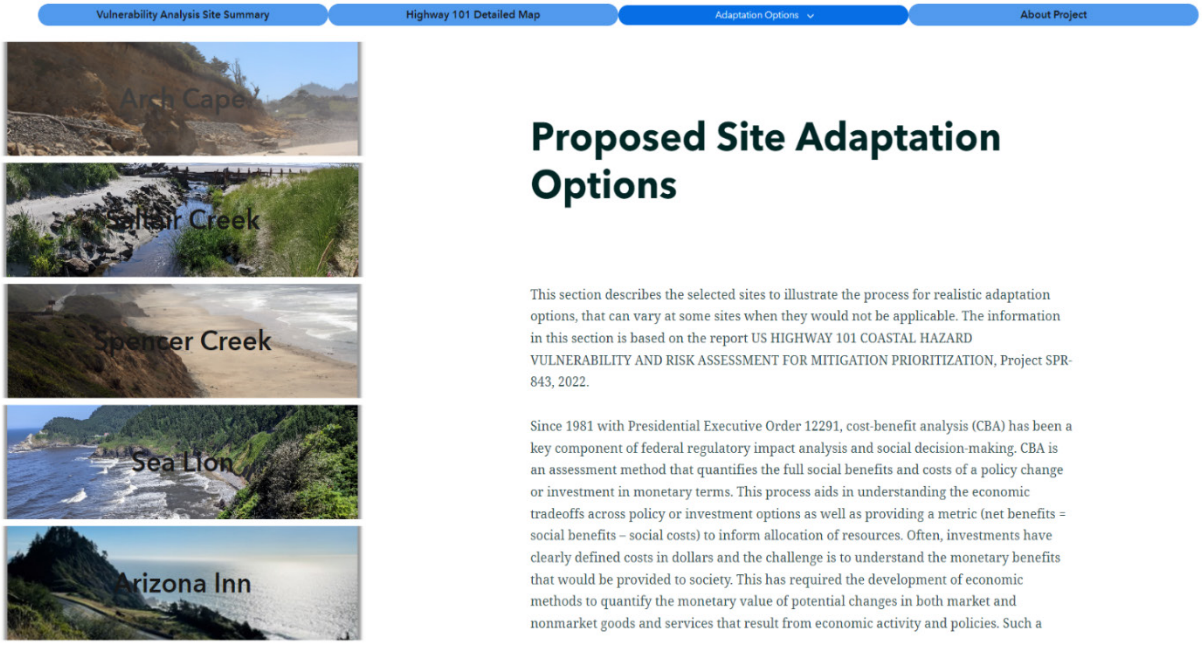
The *Inundation* group layer consists of the information about FEMA flood zones (including the FEMA zones extracted for each site), the road segments and the area that potentially can be flooded if the sea level rise achieves 1ft, 2ft, 4ft, and 5ft based on the DLCD projections for 2050 and 2100.

The *Erosion* group layer represents the DOGAMI coastal erosion hazard zones (very high, high, moderate, low), as well as the nearest points from the highway to the erosion edge.

Landslides include the SLIDO historic landslides and Oregon coast geomorphology classified features.

9.1.3 Adaptation Options

The third section of the map, **Adaptation Options**, contains detailed geographical and economical description of the five proposed sites: Arch Cape, Saltair Creek, Spencer Creek, Beverly Beach, Sea Lion Point, and Arizona Inn. The intent is to summarize the information in Section 7.0 and 8.0 of this report. Besides the descriptions, a 3D interactive map of the reroute option and slideshow are provided for each site to aid with visualization (Figure 9.3).



Proposed Site Adaptation Options

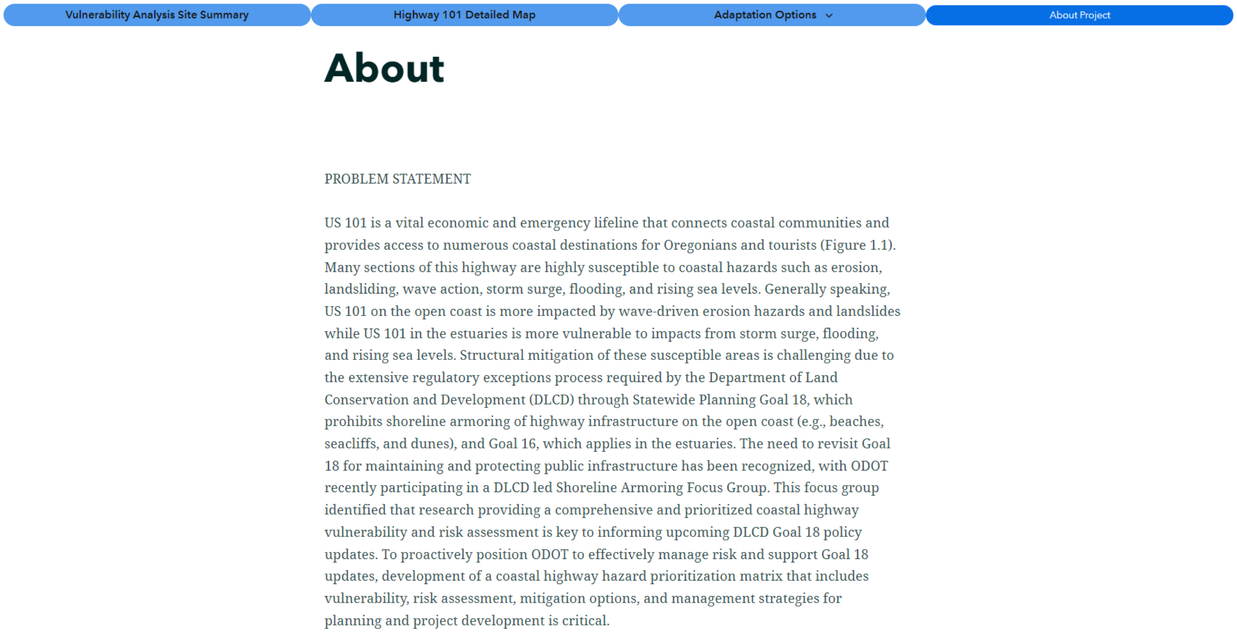
This section describes the selected sites to illustrate the process for realistic adaptation options, that can vary at some sites when they would not be applicable. The information in this section is based on the report US HIGHWAY 101 COASTAL HAZARD VULNERABILITY AND RISK ASSESSMENT FOR MITIGATION PRIORITIZATION, Project SPR-843, 2022.

Since 1981 with Presidential Executive Order 12291, cost-benefit analysis (CBA) has been a key component of federal regulatory impact analysis and social decision-making. CBA is an assessment method that quantifies the full social benefits and costs of a policy change or investment in monetary terms. This process aids in understanding the economic tradeoffs across policy or investment options as well as providing a metric (net benefits = social benefits – social costs) to inform allocation of resources. Often, investments have clearly defined costs in dollars and the challenge is to understand the monetary benefits that would be provided to society. This has required the development of economic methods to quantify the monetary value of potential changes in both market and nonmarket goods and services that result from economic activity and policies. Such a

Figure 9.3: Screenshot of the Adaptation Option section.

9.1.4 About Project Page

The **About Project** page summarizes the purpose and scope of project SPR-843, main outcomes, researchers and ODOT personnel who participated in it, contact information, and other administrative information**.**



About

PROBLEM STATEMENT

US 101 is a vital economic and emergency lifeline that connects coastal communities and provides access to numerous coastal destinations for Oregonians and tourists (Figure 1.1). Many sections of this highway are highly susceptible to coastal hazards such as erosion, landsliding, wave action, storm surge, flooding, and rising sea levels. Generally speaking, US 101 on the open coast is more impacted by wave-driven erosion hazards and landslides while US 101 in the estuaries is more vulnerable to impacts from storm surge, flooding, and rising sea levels. Structural mitigation of these susceptible areas is challenging due to the extensive regulatory exceptions process required by the Department of Land Conservation and Development (DLCD) through Statewide Planning Goal 18, which prohibits shoreline armoring of highway infrastructure on the open coast (e.g., beaches, seacliffs, and dunes), and Goal 16, which applies in the estuaries. The need to revisit Goal 18 for maintaining and protecting public infrastructure has been recognized, with ODOT recently participating in a DLCD led Shoreline Armoring Focus Group. This focus group identified that research providing a comprehensive and prioritized coastal highway vulnerability and risk assessment is key to informing upcoming DLCD Goal 18 policy updates. To proactively position ODOT to effectively manage risk and support Goal 18 updates, development of a coastal highway hazard prioritization matrix that includes vulnerability, risk assessment, mitigation options, and management strategies for planning and project development is critical.

Figure: 9.4: Screenshot of the About Project page.

9.2 COMMUNITY WORKSHOPS

Workshops and other outreach activities with ODOT personnel are ongoing of the project to aid with implementation of this research.

10.0 CONCLUSIONS & RECOMMENDATIONS

10.1 CONCLUSIONS

This research developed methodologies to assess and rank sites based on vulnerability as well as to explore the economic impact of adaptation options. In the vulnerability assessment, 71 problematic sites were identified and ranked. From these, five sites were selected throughout the state as representative sites for the economic analysis. A cost-benefit analysis framework was utilized to compare 3-4 adaptation options per site. This framework quantifies and considers recreational impacts; economic costs of closures; greenhouse gas emissions; changes in population, traffic, and economic activity (GDP); and other factors. The sensitivity to key assumptions such as failure frequency and discount rates were shown. The intent was not to determine specific alternatives, but rather demonstrate the methodology with realistic scenarios. Application of these methodologies will require more detailed study to determine scenarios and more specifics of the adaptation options and assumptions before the analysis can support decision making regarding the most economically advantageous alternatives.

10.2 CAVEATS

While significant effort was made to ensure a robust, rigorous analysis, this study has some limitations:

- Analysis at this statewide scale requires simplification over detailed site-specific analyses. Each site would require a detailed economic impact study as well as a robust investigation of current and future erosional patterns and failures.

- Substantial uncertainty exists in evaluating erosional trends, sea level rise, and other factors as well as the geomorphic response of the seacliffs. Study utilized multiple sources of data to help combat this, but ultimately, the most critical sites should be closely monitored.

- This study did not consider seismic factors such as earthquake induced shaking, landslides and tsunamis which also will impact these coastal areas.

- Sites selected for the detailed economic analysis this study were meant to be representative. Further study is needed to determine which sites should be given highest priority for Goal 18 exceptions for mitigation.

- Many adaption options exist beyond those in this study. The goal was to produce examples of options that could be expanded and further explored.

- Cost-benefit analysis cannot consider all aspects of importance of a site. Some aspects may be highly valuable to a community but not have a tangible cost/benefit value associated with them.

- This study focused on sites relevant to Goal 18. Several sites vulnerable to flooding near estuaries were identified but not prioritized given they are related to Goal 16 rather than Goal 18. Hence, those sites should receive attention and consideration for future studies.

10.3 RECOMMENDATIONS

This research identified several recommendations to help overcome the aforementioned limitations:

- Continue to monitor and implement more rigorous monitoring sensors and surveys at the priority sites identified in this study.

- Institute regular field visits and surveys (e.g., terrestrial laser scanning, UAS) at the priority sites as well as install instrumentation to track changes and identify potential issues prior to significant failures from erosion or flooding.

- Perform more detailed assessments at the sites and expand economic analysis framework to other sites identified in this priority study.

- Develop methods to project economic impacts to communities and the state from short-term closures of Highway 101.

- Ensure that any economic prioritization is conducted using a range of assumptions that reflect current best scientific practices. New guidance on regulatory review issued by OMB in November 2023 is used herein. This guidance also mandates updates to discount rates every three years, so it is important to remain current in assumptions based on federal guidance and changing economic conditions.

- Expand collaborations with other local, state, and federal agencies and communities to quantify economic importance and other important benefits of Highway 101.

- Conduct stakeholder outreach to obtain community input as to the future of Highway 101 and the Goal 18 process. This will likely help identify and potentially quantify additional benefits that were not captured in this assessment.

10.4 OTHER CONSIDERATIONS

While care was taken to identify realistic adaptation options, other adaptation options could be considered. For example, ODOT could consider creative alternatives that still allow residents and tourists to experience and enjoy Highway 101 when desired but reroute the majority of traffic elsewhere. For example, one adaption option could be to maintain a portion of Highway 101 as a one-way scenic route but reroute major highway inland for trucks and through traffic.

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APPENDIX A: SUMMARY OF VIRTUAL SITE VISITS

Table A.1: Summary of findings from virtual site visits to the study sites, ordered south to north, decreasing mile post.

Site ID	Site	Location	SPS present (Y/N)	Type/Condition/Notes
60	Rainbow Rock	124°19' 33" W 42° 05' 05" N	N	N/A
61	Seal Point	124° 21' 35" W 42° 10' 54" N	N	N/A
59	Hooskanaden Landslide	124° 22' 20" W 42° 13' 01" N	N	N/A
58	Pistol River	124° 24' 19" W 42° 17' 02" N	N	N/A
57	Myers Creek	124° 24' 48" W 42° 18' 35" N	N	N/A
56	South side of Hunter Creek	124° 25' 24" W 42° 23' 15" N	Y	OPRD Permit ID 859, Structure 1258; structure type unclear in imagery
55	North side of Hunter Creek	124° 25' 21" W 42° 23' 30" N	N	N/A
54	Nesika Beach	124° 24' 16" W 42° 31' 28" N	Y	Riprap visible in Google Earth StreetView; condition unclear. Notes say “Existing riprap in place. Future problems reflect undermining and collapse of structure.” Not in OPRD SPS layer; only nearby structure in OPRD SPS data layer is well south of site (permit ID 326)
50-53	Ophir Beach	124° 23' 44" W 42° 32' 43" N	N	N/A
49	Sisters Rock to Devils Backbone	124° 23' 43" W 42° 35' 26" N	N	N/A
48	Arizona Inn	124° 24' 06" W 42° 38' 10" N	N	N/A

Site ID	Site	Location	SPS present (Y/N)	Type/Condition/Notes
47	Brush Creek	124° 24' 33" W 42° 39' 14" N	N	N/A
46	Rocky Point to Coal Point	124° 27' 39" W 42° 42' 41" N	N	N/A
45	Port Orford (Gregory Point)	124° 28' 00" W 42° 43' 35" N	N	N/A
70	Hubbard Creek Landslide	124° 29’ 06" W 42° 44’ 27" N	N	N/A
66	Coos Bay - downtown	124° 13’ 03" W 43° 22’ 50" N	Y, but not in OPRD layer	Portions of bay shore built up: piers, bulkhead, maybe some fill. Not in OPRD SPS data layer, although this area is outside of the Ocean Shore Regulation zone.
65	Coos Bay - north slough	124° 13’ 23" W 43° 28’ 45" N	N	N/A
64	Gardner	124° 06’ 39" W 43° 43’ 35" N	N	Appears to be mostly natural river shoreline. Boat ramp and pier roughly in middle of site.
40	Sea Lion Point	124° 07’ 27" W 44° 7’ 36" N	N	N/A
39	Big Creek	124° 06’ 55" W 44° 10’ 30" N	N	Site encompasses Big Creek Bridge.
34	Rock Beach	124° 06’ 54" W 44° 10’ 59" N	N	Site encompasses bridge over Rock Creek (MP 174.40)
35	Ocean Beach	124° 06’ 54" W 44° 11’ 10" N	N	N/A
68	Squaw Creek	124° 06’ 51" W 44° 12’ 29" N	N	N/A
67	Ten Mile Creek	124° 06' 35" W 44° 13' 25" N	N	Ten Mile Creek Bridge within AOI
33	Stonefeld Beach	124° 06' 41" W 44° 14' 20" N	N	N/A
38	Cummins Creek	124° 06' 24" W	N	Cummins Creek Bridge within AOI

Site ID	Site	Location	SPS present (Y/N)	Type/Condition/Notes
		44° 15' 55" N		
37	Gwynn Creek	124° 06' 29" W 44° 16' 13" N	N	Gwynn Creek culvert within AOI
36	Yachats River	124° 06' 00" W 44° 18' 26" N	Y	OPRD Permit ID 854, Structure 1239: riprap noted in front of houses north of bridge; appears to be affording protection to houses, rather than to highway. Bridge over Yachats River within AOI.
30	Big Creek	124° 05' 22" W 44° 22' 14" N	Y	OPRD Permit ID 731, Structure 1009; and Permit ID 698, Structure 968. Notes include statement: "Existing riprap @ bridge abutments." Riprap visible along both north and south stream banks in Google Street View. Site contains bridge over Big Creek (MP 160.15) in AOI.
31	SW Wakonda Beach Rd	124° 05' 18" W 44° 23' 14" N	Y	OPRD Permit 706, Structure 325; and Permit 712, Structure 995; and Permit 718, Structure 999; and Permit 95, Structure 724. Notes include statement: "some riprap." Riprap is visible in GE imagery; appears to be affording protection to houses, rather than to highway.
32	Annice Creek	124° 05' 11" W 44° 23' 32" N	Y	OPRD Permit 0 (?), Structure 1228; and Permit 0, Structure 1227. Notes include statement: "Existing riprap @ bridge abutments." Riprap visible in Google Earth protecting structures (hotel and house?) just north of Little Creek.
29	SW Whitecap Dr	124° 05' 07" W 44° 24' 14" N	N	There is an OPRD-permitted structure (Permit ID 21), ~70 m south of this site, but not identifiable in Google Earth imagery.
63	Alsea Bay	124° 04' 20" W 44° 25' 22" N	Y	Protected by seawall
28	Seal Rock 2	124° 05' 00" W 44° 29' 23" N	N	N/A
27	Seal Rock 1	124° 05' 00" W 44° 29' 34" N	N	N/A

Site ID	Site	Location	SPS present (Y/N)	Type/Condition/Notes
5	Beaver Creek	124° 04' 17" W 44° 31' 24" N	N	N/A
6	Beaver Creek North	124° 04' 29" W 44° 31' 33" N	N	N/A
7	SE 130th St	124° 04' 24" W 44° 32' 36" N	N	N/A
8	Moolack landslide	124° 03' 42" W 44° 41' 55" N	Y	OPRD Permit ID 214, Structure 900; and Permit ID 845, Structure 1212; and Permit ID 845, Structure 1211. Riprap in front of a house and a motel (Moolak Shores?). Since the main threat is landslide/erosion, not clear if this riprap is providing any protection to highway.
9	Carmel Knoll	124° 03' 37" W 44° 42' 30" N	N	N/A
12	Beverly Beach South	124° 03' 28" W 44° 43' 34" N	N	N/A – Bridge over Spencer Creek is just north of site
11	Beverly Beach North	124° 03' 24" W 44° 44' 04" N	N	N/A
10	Johnson Creek landslide	124° 03' 22" W 44° 44' 21" N	N	Johnson Creek culvert under HWY 101 @ south end of site
14	Cape Foulweather landslide	124° 04' 01" W 44° 46' 08" N	N	N/A
13	Whale Cove	124° 04' 05" W 44° 47' 13" N	N	N/A
41	North Depoe Bay	124° 03' 49" W 44° 49' 10" N	N	N/A
15	Boiler Bay	124° 03' 32"° W 44° 49' 46" N	Y	Riprap; appears in Google Earth imagery to be in poor condition. (Follow-on note: site visit conducted in 2022 confirmed poor condition of riprap; appears to not be providing any protection to cliff.)

Site ID	Site	Location	SPS present (Y/N)	Type/Condition/Notes
62	Fogarty Creek	124° 03' 04" W 44° 50' 20" N	Y	OPRD Permit ID 844, Structure 1210. Attributes in Potential Trouble Spots layer include statement: "erosion undermines riprap structure during extreme storms." Bridge over Fogarty Creek is also within site; riprap is just north of bridge.
42	Siletz Bay South	124° 01' 04" W 44° 53' 36" N	N	N/A. Small bridge at north end of site. Bridge over Siletz River is north of site.
43	Siletz Bay Central	124° 00' 23" W 44° 54' 25" N	N	N/A.
44	Siletz Bay North	124° 00' 52" W 44° 55' 27" N	N	N/A
17	Blue Heron Cheese	123° 50' 40" W 45° 28' 03" N	N	N/A
18	Tillamook Cheese Factory	123° 50' 43" W 45° 29' 00" N	N	N/A
19	Saltair Creek	123° 56' 43" W 45° 36' 19" N	N	N/A. Appears to be culvert under Hwy (Saltair Creek)
20	South Nehalem	123° 56' 38" W 45° 36' 48" N	Y	OPRD SPS layer includes text: Sea View Condos; was linked Permit ID 772.
21	Manhatten Beach Wayside	123° 56' 27" W 45° 38' 13" N	N	N/A. (Small bridge at southern end of site. Some protection at railway site)
25	Neahkahnie Mountain	123° 57' 26" W 45° 44' 35" N	N	N/A
26	Arch Cape Tunnel	123° 58' 02" W 45° 47' 54" N	N	N/A. Tunnel at MP 35.90 – 35.97
3	Hug Point	123° 57' 37" W 45° 50' 50" N	N	N/A. (Permit ID 196, Structure ID 832 in ORPD SPS layer is south of site.)
4	Silver Point	123° 57' 45" W 45° 51' 25" N	N	N/A
1	HWY26 interchange	123° 55' 22" W 45° 56' 48" N	N	N/A

Site ID	Site	Location	SPS present (Y/N)	Type/Condition/Notes
2	South Seaside	123° 55' 35" W 45° 58' 23" N	N	N/A

APPENDIX B:
SITE ANALYSIS TABLES

Table B.1. Trouble Spot Analysis for sites (Flooding Parameters)

Trouble Spot ID	Floods	Flooded Length (m)	SLR Inundation Length, 2050 (m)	SLR Inundation Length, 2100 (m)	SLR Inundation Depth, 2050 (m)	SLR Inundation Depth, 2100 (m)	Intersects NOAA High Tide Flooding Layer	Highway Elevation (m)
1	4	477	0	0	0.000	0.000	Y	10.63
2	4	373	0	8	0.000	0.042	Y	3.44
3	0	0	0	0	0.000	0.000	N	15.90
4	0	0	0	0	0.000	0.000	N	40.85
5	2	134	0	0	0.000	0.000	N	4.99
6	2	324	0	0	0.000	0.000	N	4.73
7	3	0	0	0	0.000	0.000	N	6.31
8	0	0	0	0	0.000	0.000	N	15.61
9	0	0	0	0	0.000	0.000	N	20.60
10	0	0	0	0	0.000	0.000	N	24.27
11	0	0	0	0	0.000	0.000	N	21.04
12	0	0	0	0	0.000	0.000	N	16.32
13	0	0	0	0	0.000	0.000	Y	30.28
14	0	0	0	0	0.000	0.000	N	115.36
15	0	0	0	0	0.000	0.000	N	21.42
16	2	17	17	20	0.989	1.277	Y	3.63
17	3	1294	27	648	1.030	1.317	Y	0.77
18	3	0	0	0	0.000	0.000	N	5.38
19	3	0	0	0	0.000	0.000	N	5.59
20	2	0	0	0	0.000	0.000	N	5.66
21	2	31	0	0	0.000	0.000	Y	3.42
22	0	0	0	0	0.000	0.000	Y	8.21
23	0	0	0	0	0.000	0.000	Y	7.62
24	4	243	1000	1000	5.029	5.029	Y	3.36
25	0	0	0	0	0.000	0.000	N	146.80

Trouble Spot ID	Floods	Flooded Length (m)	SLR Inundation Length, 2050 (m)	SLR Inundation Length, 2100 (m)	SLR Inundation Depth, 2050 (m)	SLR Inundation Depth, 2100 (m)	Intersects NOAA High Tide Flooding Layer	Highway Elevation (m)
26	0	0	0	0	0.000	0.000	N	40.54
27	0	0	0	0	0.000	0.000	N	11.94
28	0	0	0	0	0.000	0.000	N	15.43
29	0	0	0	0	0.000	0.000	N	11.26
30	2	31	25	30	0.989	1.276	N	2.08
31	1	23	0	0	0.000	0.000	N	6.95
32	1	0	0	0	0.000	0.000	N	5.85
33	1	0	0	0	0.000	0.000	Y	24.39
34	2	35	0	0	0.000	0.000	N	4.23
35	1	0	0	0	0.000	0.000	N	22.78
36	2	59	0	0	0.000	0.000	Y	2.17
37	0	0	0	0	0.000	0.000	Y	11.94
38	2	29	0	0	0.000	0.000	N	3.55
39	0	37	0	0	0.000	0.000	Y	3.06
40	0	0	0	0	0.000	0.000	Y	43.58
41	0	0	0	0	0.000	0.000	Y	18.70
42	2	75	82	90	1.001	1.289	Y	2.02
43	2	149	0	0	0.000	0.000	Y	4.23
44	2	64	0	0	0.000	0.000	Y	2.21
45	0	0	0	0	0.000	0.000	Y	35.72
46	0	0	0	0	0.000	0.000	Y	18.73
47	0	0	0	0	0.000	0.000	N	60.76
48	0	0	0	0	0.000	0.000	N	51.35
49	0	0	0	0	0.000	0.000	Y	49.76
50	1	0	0	0	0.000	0.000	N	8.16
51	1	0	0	0	0.000	0.000	N	12.20

Trouble Spot ID	Floods	Flooded Length (m)	SLR Inundation Length, 2050 (m)	SLR Inundation Length, 2100 (m)	SLR Inundation Depth, 2050 (m)	SLR Inundation Depth, 2100 (m)	Intersects NOAA High Tide Flooding Layer	Highway Elevation (m)
52	1	0	0	0	0.000	0.000	N	11.48
53	1	0	0	0	0.000	0.000	N	10.38
54	0	0	0	0	0.000	0.000	Y	16.29
55	2	30	0	0	0.000	0.000	Y	2.21
56	0	0	0	0	0.000	0.000	Y	5.01
57	0	78	0	0	0.000	0.000	Y	2.82
58	0	24	0	0	0.000	0.000	Y	2.80
59	0	0	0	0	0.000	0.000	N	44.84
60	0	0	0	0	0.000	0.000	N	35.17
61	0	0	0	0	0.000	0.000	N	96.90
62	3	14	0	0	0.000	0.000	N	3.13
63	1	477	32	118	0.282	0.515	Y	3.20
64	2	1734	1005	1939	1.013	1.300	Y	0.85
65	3	0	8	13	0.980	1.267	Y	4.15
66	3	3372	647	2652	0.117	0.404	Y	2.35
67	2	48	0	0	0.000	0.000	Y	2.73
68	0	0	0	0	0.000	0.000	N	19.21
69	0	0	0	0	0.000	0.000	N	32.56
70	0	0	0	0	0.000	0.000	N	23.38
71	3	162	134	817	1.003	1.290	Y	0.99

Table B.1. Trouble Spot Analysis for sites (Erosion Parameters)

Trouble Spot ID	Erosion Rate (2002-2016) (m/year)	Erosion Rate (2008-2016) (m/year)	Erosion Rate Source	Geo-morph-ology Class	Projected Distance from Seacliff Edge to Highway (Average, 2050) (m)	Projected Distance from Seacliff Edge to Highway (Average, 2100) (m)	Current Distance to Seacliff Highway (m)	Shoreline Protection Condition	Shoreline Protection Length (%)	Qual-itative Field Change Analysis	Percent-age of Transects	DSAS Max Neg Rate	DSAS source	TWL_10	OVER-TOP	TWL Int.
1	-0.005	-0.005	Assumed	2	999	999	4500	-1	999	4	0.00	0.00	Assumed	-99	-99	
2	-0.005	-0.005	Assumed	2	999	999	675	-1	999	4	0.00	0.00	Assumed	-99	-99	
3	-0.102	-0.009	AirLidar	4	43	42	12	4	0	1.5	0.00	0.00	DSAS	6.81	2	
4	-0.036	-0.021	AirLidar	4	198	198	59	4	0	1	42.86	-0.27	DSAS	5.87	2	
5	-0.005	-0.005	Assumed	3	35	35	9	4	0	3	0.00	0.00	Assumed	7.83	1	
6	-0.015	-0.015	DSAS	2	48	47	13	4	0	1.5	5.41	-0.10	DSAS	8.73	1	
7	0.000	0.000	DSAS	3	18	18	4	4	0	3	0.00	-0.01	DSAS	10.25	1	
8	-0.087	-0.089	AirLidar	1	57	54	5	3	17	2	68.42	-0.65	DSAS	9.95	1	
9	-0.030	-0.021	AirLidar	1	16	14	5	4	0	3	50.00	-0.30	DSAS	10.12	1	
10	0.000	0.007	AirLidar	1	10	10	26	4	0	2	51.52	-0.41	DSAS	8.3	2	
11	-0.030	-0.046	AirLidar	1	20	20	12	4	0	2	42.62	-0.27	DSAS	8.05	2	
12	-0.060	-0.057	AirLidar	1	-65	-68	0	4	0	4	75.86	-0.36	DSAS	9.25	2	
13	-0.080	-0.080	DSAS	1	9	9	3	4	0	3	33.33	-0.20	DSAS	10.73	2	
14	-0.045	-0.044	AirLidar	0	429	427	130	4	0	1	80.00	-1.12	AirLidar	11.8	2	
15	-0.065	-0.039	AirLidar	2	32	31	9	4	0	1.5	22.22	-0.16	DSAS	7.75	2	
16	-0.050	-0.050	DSAS	3	999	999	0	4	100	2	9.38	-0.08	DSAS	9.75	1	
17	-0.005	-0.005	Assumed	3	999	999	3000	-1	999	3	0.00	0.00	Assumed	-99	-99	
18	-0.005	-0.005	Assumed	3	999	999	3000	-1	999	3	0.00	0.00	Assumed	-99	-99	
19	-0.120	-0.120	DSAS	3	999	999	50	4	0	3	54.55	-0.32	DSAS	6.62	1	
20	-0.130	-0.130	DSAS	3	48	43	14	4	100	2	20.00	-0.24	DSAS	8.28	1	
21	-0.210	-0.210	DSAS	3	70	62	22	4	0	2	60.61	-0.53	DSAS	7.4	2	

Trouble Spot ID	Erosion Rate (2002-2016) (m/year)	Erosion Rate (2008-2016) (m/year)	Erosion Rate Source	Geo-morph-ology Class	Projected Distance from Seacliff Edge to Highway (Average, 2050) (m)	Projected Distance from Seacliff Edge to Highway (Average, 2100) (m)	Current Distance to Seacliff Highway (m)	Shoreline Protection Condition	Shoreline Protection Length (%)	Qual-itative Field Change Analysis	Percent-age of Transects	DSAS Max Neg Rate	DSAS source	TWL_10	OVER-TOP	TWL Int.
22	-0.005	-0.005	Assumed	2	11	11	2	-1	999	2	0.00	0.00	Assumed	-99	-99	High
23	-0.005	-0.005	Assumed	2	14	14	3	-1	999	2	0.00	0.00	Assumed	-99	-99	
24	-0.005	-0.005	Assumed	4	999	999	3000	-1	999	4	0.00	0.00	Assumed	-99	-99	
25	-0.024	-0.032	AirLidar	1	15	14	3	0	100	1	20.00	-0.10	Assumed	12.67	1	>500
26	-0.046	-0.011	AirLidar	1	-12	-12	8	4	0	3	71.88	-0.22	DSAS	8.52	1	
27	-0.045	-0.041	AirLidar	1	15	13	3	4	0	1.5	3.45	-0.09	DSAS	8.3	2	
28	-0.010	-0.013	AirLidar	1	10	10	2	4	0	1.5	0.00	-0.01	DSAS	8.3	2	
29	0.011	-0.013	AirLidar	2	20	19	5	4	0	1.5	0.00	-0.02	DSAS	7.07	2	
30	-0.005	-0.005	Assumed	2	23	23	6	3	50	1	0.00	0.00	Assumed	8.28	1	
31	-0.033	0.030	AirLidar	2	48	50	13	3	22	1.5	3.08	-0.06	DSAS	9.03	1	
32	-0.014	-0.035	AirLidar	2	78	76	22	3	10	1	5.55	-0.09	DSAS	7.89	1	
33	-0.027	-0.084	AirLidar	1	7	4	1	4	0	1	12.00	-0.17	DSAS	10.47	2	
34	-0.033	-0.033	DSAS	2	17	16	4	4	0	0	17.65	-0.15	DSAS	9.4	2	
35	0.017	0.022	AirLidar	1	87	88	25	4	0	0	16.67	-0.30	DSAS	9.4	2	
36	-0.060	-0.060	DSAS	2	33	30	9	3	10	1	42.86	-0.10	DSAS	6.86	2	
37	-0.034	-0.098	AirLidar	2	4	0	0	4	0	1	15.39	-0.13	DSAS	8.75	2	
38	-0.061	-0.061	DSAS	2	20	17	5	4	0	1	38.71	-0.11	DSAS	8.75	2	
39	-0.006	-0.004	AirLidar	2	21	21	5	4	0	1	42.42	-0.47	DSAS	8.55	2	
40	-0.023	-0.038	AirLidar	0	-16	-16	14	4	0	2	65.38	-0.15	DSAS	16.77	2	
41	-0.245	-0.026	AirLidar	2	21	19	5	4	0	1.5	0.00	-0.14	Assumed	13.57	1	
42	-0.005	-0.005	Assumed	3	999	999	1000	-1	999	1	0.00	0.00	Assumed	-99	-99	
43	-0.005	-0.005	Assumed	3	999	999	1000	-1	999	1	0.00	0.00	Assumed	-99	-99	

Trouble Spot ID	Erosion Rate (2002-2016) (m/year)	Erosion Rate (2008-2016) (m/year)	Erosion Rate Source	Geo-morph-ology Class	Projected Distance from Seacliff Edge to Highway (Average, 2050) (m)	Projected Distance from Seacliff Edge to Highway (Average, 2100) (m)	Current Distance to Seacliff Highway (m)	Shoreline Protection Condition	Shoreline Protection Length (%)	Qual-itative Field Change Analysis	Percent-age of Transects	DSAS Max Neg Rate	DSAS source	TWL_10	OVER-TOP	TWL Int.
44	-0.005	-0.005	Assumed	3	21	21	1000	-1	999	1	0.00	0.00	Assumed	-99	-99	
45	-0.049	-0.048	AirLidar	1	-9	-9	19	4	0	2	41.99	-0.74	DSAS	8.47	2	High
46	-0.030	-0.033	AirLidar	1	-22	-27	11	4	0	2	83.43	-0.37	DSAS	8.47	2	High
47	-0.010	-0.063	AirLidar	0	17	17	19	4	0	2	21.99	-0.58	DSAS	8.36	2	High
48	-0.328	-0.294	AirLidar	1	71	71	79	4	0	3	95.35	-0.46	DSAS	8.36	2	High
49	-0.027	-0.028	AirLidar	1	22	22	36	4	0	2.5	75.00	-0.35	DSAS	8.36	2	High
50	-0.071	-0.129	AirLidar	2	6	6	6	4	0	2	0.00	-0.02	DSAS	8.52	2	Mod.
51	-0.071	-0.129	AirLidar	2	14	14	8	4	0	2	93.10	-0.54	DSAS	8.52	2	Mod.
52	-0.071	-0.129	AirLidar	2	8	5	20	4	0	2.5	93.10	-0.54	DSAS	7.47	2	Mod.
53	-0.071	-0.129	AirLidar	2	-3	-3	12	4	0	2	4.17	-0.09	DSAS	7.47	2	Mod.
54	-0.017	0.004	AirLidar	1	-23	-28	6	2	50	2	55.84	-0.36	DSAS	11.38	2	Mod.
55	-0.500	-0.500	Estimate	0	37	17	14	2	50	2	79.38	-2.07	DSAS	7.65	2	Mod.
56	-0.100	-0.100	Estimate	1	13	9	3	3	40	1	79.38	-2.07	Assumed same as north	7.44	2	Mod.
57	-0.038	-0.038	DSAS	1	22	21	6	4	0	2	8.91	-0.16	DSAS	8.29	2	High
58	-0.042	-0.033	AirLidar	1	69	67	20	4	0	1.5	24.88	-0.35	DSAS	8.29	2	High
59	-0.180	-0.349	AirLidar	2	66	65	67	4	0	3	79.79	-0.76	DSAS	8.29	2	High
60	-0.021	-0.035	AirLidar	1	94	92	27	4	0	1	0.00	-0.09	DSAS	9.04	2	Mod.
61	-0.019	-0.024	AirLidar	0	58	57	16	4	0	1	87.50	-0.41	DSAS	9.04	2	High
62	-0.005	-0.005	Assumed	2	18	18	4	3	22	1	0.00	0.00	Assumed	11.55	1	Mod.
63	-0.005	-0.005	Assumed	2	999	999	1	0	100	1.5	0.00	0.00	Assumed	7.29	2	High
64	-0.005	-0.005	Assumed	2	999	999	6	-1	999	0	0.00	0.00	Assumed	-99	-99	

Trouble Spot ID	Erosion Rate (2002-2016) (m/year)	Erosion Rate (2008-2016) (m/year)	Erosion Rate Source	Geomorphology Class	Projected Distance from Seacliff Edge to Highway (Average, 2050) (m)	Projected Distance from Seacliff Edge to Highway (Average, 2100) (m)	Current Distance to Seacliff Highway (m)	Shoreline Protection Condition	Shoreline Protection Length (%)	Qualitative Field Change Analysis	Percentage of Transects	DSAS Max Neg Rate	DSAS source	TWL_10	OVER-TOP	TWL Int.
65	-0.005	-0.005	Assumed	1	999	999	1	-1	999	1	0.00	0.00	Assumed	-99	-99	
66	-0.005	-0.005	Assumed	0	999	999	7	2	999	1	0.00	0.00	Assumed	-99	-99	
67	-0.005	-0.005	Assumed	2	999	999	4	4	0	0	0.00	0.00	Assumed	9.55	2	
68	-0.036	-0.083	AirLidar	1	999	999	27	4	0	1	80.00	-0.63	AirLidar	9.32	2	
69	-0.063	-0.100	AirLidar	1	999	999	17	4	0	0	80.00	-0.46	AirLidar	13.09	2	
70	-0.040	-0.058	AirLidar	1	28	28	33	4	0	3	80.00	-0.21	AirLidar	8.47	2	Mod.
71	-0.005	-0.005	Assumed	4	999	999	170	-1	999	1.5	0.00	0.00	Assumed	-99	-99	

Table B.2. Trouble Spot Analysis for sites (Landslide Parameters)

Trouble Spot ID	Proximity to landslide (SLIDO) (m)	Un Stable Slopes Dist _M	US Count	US_ DTR LENGTH	Annual Cost ($)	US_ REPAIR COST ($)	Failure Hazard Score	Road Impact Score	Frequency of Repair	US_ HAZ SCORE	Landslide Susceptibility
1	0	3	5	60	9110	23338	9	85	50	164	1
2	0	3	2	60	3527	566715	9	85	50	214	1
3	-1	34	4	28	2332	201477	100	85	50	278	4
4	-1	4	4	28	6562	2190659	86	85	0	160	4
5	411	437	0	0	0	0	0	0	0	0	1
6	517	519	0	0	0	0	0	0	0	0	2
7	73	2593	0	0	0	0	0	0	0	0	3
8	-1	2	11	37	277711	27115947	97	85	94	359	4
9	-1	2	6	37	44709	3547352	81	85	81	306	4
10	-1	9	2	37	20000	3599109	27	85	75	252	4
11	-1	5	2	37	16481	943910	27	85	81	252	4
12	-1	4	1	37	0	0	9	27	0	95	3
13	-1	2	2	37	0	0	9	27	0	95	3
14	-1	6	2	37	0	0	27	3	56	145	3
15	128	4725	0	0	0	0	0	0	0	0	3
16	393	7604	0	0	0	0	0	0	0	0	2
17	1313	2434	0	0	0	0	0	0	0	0	1
18	272	1099	0	0	0	0	0	0	0	0	1
19	386	6	2	111	0	0	9	100	0	168	1
20	191	34	1	111	0	0	9	100	0	168	1
21	281	1	3	111	0	0	9	100	0	156	1
22	0	0	22	111	20318	2964931	27	100	56	230	4
23	17	8	4	111	715	286031	100	100	69	243	3
24	65	181	0	0	0	0	0	0	0	0	4

Trouble Spot ID	Proximity to landslide (SLIDO) (m)	Un Stable Slopes Dist _M	US Count	US_ DTR LENGTH	Annual Cost ($)	US_ REPAIR COST ($)	Failure Hazard Score	Road Impact Score	Frequency of Repair	US_ HAZ SCORE	Landslide Susceptibility
25	0	5	4	28	5267	123150174	92	85	63	229	3
26	-1	6	2	28	548	668532	27	3	0	77	4
27	381	2805	0	0	0	0	0	0	0	0	1
28	145	3241	0	0	0	0	0	0	0	0	3
29	0	11849	0	0	0	0	0	0	0	0	2
30	252	8361	0	0	0	0	0	0	0	0	2
31	604	9905	0	0	0	0	0	0	0	0	1
32	1937	10775	0	0	0	0	0	0	0	0	1
33	0	3	8	154	9755	5708426	100	27	100	270	3
34	65	65	3	154	0	177493	81	27	69	224	2
35	0	1	6	154	2082	8502925	100	27	100	274	3
36	11	1391	0	0	0	0	0	0	0	0	1
37	319	465	0	0	0	0	0	0	0	0	2
38	436	449	0	0	0	0	0	0	0	0	3
39	662	662	0	0	0	0	0	0	0	0	2
40	0	10	10	154	6550	12419074	100	85	100	274	3
41	154	3572	0	0	0	0	0	0	0	0	2
42	331	625	0	0	0	0	0	0	0	0	2
43	555	468	0	0	0	0	0	0	0	0	2
44	162	2629	0	0	0	0	0	0	0	0	3
45	0	6	1	187	229245	10871877	9	100	100	245	4
46	0	4	4	187	181597	8248750	27	100	100	263	3
47	0	1	14	187	61794	27034785	100	27	100	267	3
48	-1	6	6	187	376220	7153993	27	100	100	201	4
49	0	3	3	187	397601	8256652	9	27	100	172	4

Trouble Spot ID	Proximity to landslide (SLIDO) (m)	Un Stable Slopes Dist _M	US Count	US_ DTR LENGTH	Annual Cost ($)	US_ REPAIR COST ($)	Failure Hazard Score	Road Impact Score	Frequency of Repair	US_ HAZ SCORE	Landslide Susceptibility
50	136	88	1	187	0	0	9	3	0	48	2
51	189	4	1	187	0	0	9	3	0	48	3
52	188	283	0	0	0	0	0	0	0	0	2
53	225	421	0	0	0	0	0	0	0	0	2
54	125	1897	0	0	0	0	0	0	0	0	2
55	483	1672	0	0	0	0	0	0	0	0	2
56	242	1432	0	0	0	0	0	0	0	0	3
57	0	240	0	0	0	0	0	0	0	0	3
58	0	371	0	0	0	0	0	0	0	0	3
59	-1	0	3	18	490178	300517800	9	85	100	247	3
60	0	9	4	18	3135	3071570	93	27	100	267	3
61	0	2802	0	0	0	0	0	0	0	0	3
62	514	3585	0	0	0	0	0	0	0	0	2
63	0	10603	0	0	0	0	0	0	0	0	3
64	1368	1661	0	0	0	0	0	0	0	0	2
65	28	7	1	154	1376	160838	9	3	50	121	2
66	393	10	1	154	0	0	9	100	25	215	1
67	0	803	0	0	0	0	0	0	0	0	2
68	0	4	6	154	1909	268243	100	27	75	249	2
69	21	21	1	154	0	0	9	27	0	83	3
70	0	5	2	187	0	0	9	27	0	83	3
71	0	1	9	20	0	31599	9	85	0	141	2

APPENDIX C:
DATA DELIVERABLES

Please contact ODOT Research Coordinator Kira Glover-Cutter (kira.m.glover-cutter@odot.oregon.gov), the Principle Investigator Mike Olsen (michael.olsen@oregonstate.edu), or the general ODOT Research inbox (odotnewresearch@odot.oregon.gov) to obtain this appendix. This appendix describes the digital data products delivered with the project to ODOT for critical analysis steps. These include:

C.1 SITE ANALYSIS GIS GEODATABASE

Values for all parameters and final scores for each site were compiled into a geodatabase feature class for use in GIS (*AppC1a_SiteVulnerabilityAnalysis_HWY101_GIS.zip*). An accompanying spreadsheet (*AppC1a_SiteVulnerabilityAnalysis.xlsx*) containing these data is also provided for all sites. These data can also be accessed via the webGIS described in Section 9.1 and also provided in Appendix B. The fields and methods used to compute these values are described in this report.

C.2 HAZARD VULNERABILITY ASSESSMENT MATRIX

The hazard vulnerability matrix spreadsheet (*AppC2_VulnerabilityIndexMatrix_FINAL.xlsx*) contains the information, classification thresholds, and weightings used for the parameters used in the vulnerability analysis that is described in Tables 3.4, 3.6, and 3.7.

C.3 PYTHON SCRIPT AND TABLES

A custom python script (*HWY101_CVI_calculation.py*) was developed to implement the analysis workflow (Figure 3-6). This script inputs the hazard vulnerability matrix (App. C.2) and the Site Analysis table (App. C.1). For each site, it converts each parameter to the range of 0-4 following the classification thresholds in the hazard vulnerability matrix. These values are then multiplied by the weights for each parameter as outlined in the hazard vulnerability matrix. The results are then summed to compute the ECVI score for each site following Equation 3.3b.

In addition to the code, simplified versions of *SiteAnalyses_example_for_script.xlsx* and *VulnerabilityIndexMatrix_example_for_script.xlsx* are provided for use with the script. These files have been adapted for running the script compared with the previous versions in App. C.1 and C.2, which are focused on readability. For example, characters such as “-“, “>”, “<”, have been removed from the *VulnerabilityIndexMatrix_example_for_script.xlsx* to avoid errors when running the script.

C.4 AIRBORNE LIDAR ANALYSIS FOR SHORT TERM EROSION RATE ASSESSMENT

This spreadsheet (*AppC2_AirborneLidar_ErosionRateCalculationsV3.xlsx*) contains statistics and the associated airborne lidar (short-term) erosion estimates described in Section 4.1. The spreadsheet contains several tabs:

- *Overall*: main sheet containing erosion rates computed between the different survey dates (2002, 2009, 2014, and 2016) for all applicable sites. It contains summary change statistics that have been normalized by time. Some sites have been broken down into smaller sections based on natural breaks in the seacliffs.

- *2002-2016*: simplified sheet with erosion rates computed between 2002 and 2016 for the applicable sites.

- *2008-2016*: simplified sheet with erosion rates computed between 2008 and 2016 for the applicable sites.

C.5 DSAS GIS ANALYSIS FOR LONG TERM EROSION RATES

A zip file (*AppC5a_DSAS_Highway101_coastal_sites.zip*) contains a GIS personal geotadabase that includes the inputs and outputs of the DSAS analysis described in Section 4.2 to compute the long-term erosion rates. It contains several data layers connected by IDs (e.g., SiteID, TransectID, and BaselineID), including:

- *Transects*- This feature class contains polyline transects spaced at 10 m intervals for each site where erosion rates are computed.

- *Shorelines*- This feature class contains polyline digitized shorelines of each site (e.g., cliff toe or cliff top, depending on which is more visible at each site) for each aerial photograph epoch (i.e., 1967 and 2018). This data layer also includes uncertainty tags.

- *Baseline*- This feature class contains a reference polyline from which all shoreline measurements are compared to for computing shoreline change rates.

- *Transect intersect*- This feature class contains points located at the intersections of the shoreline and transects. These features are used by DSAS in computing the shoreline change rates for each transect.

- *Transect Rates*: This feature class contains the output shoreline change results for each transect.

In addition, a spreadsheet (*AppC5b_DSAS_AnalysisSummary.xlsx*) contains a summary of the DSAS Analysis results is included. This sheet summarizes the core statistics for all transects at each site. Readers are referred to the DSAS user manual for the definitions of the output fields.

C.6 EROSION RATE MODELING RESULTS

This spreadsheet (*AppC6_ErosionRateModelingResults.csv*) contains the output of the erosion rate modeling described in Section 5.0. It contains the retreat magnitudes and locations of cliff toes through time for each transect at each site for each epoch of interest (e.g., 2030, 2040, 2050, …, 2100).

C.7 ECONOMIC ANALYSIS SPREADSHEET

The evaluation of different adaptation options under different future scenarios described in Chapter 8.4 are based on net present value calculations from this Excel spreadsheet. The file contains 10 sheets, the first being a README sheet with relevant descriptions and key parameters, the second a summary of TPAU SWIM model output used in the analysis, the third describing the calculation of site-specific benefits from avoiding highway closures, the fourth describing the costs of the alternative options over time, and sheets 5 to 10 illustrating the NPV calculations for each site and scenario. Note that on sheets 5 to 10, the current outcomes are based on the assumption of a 2% discount rate. Cell B4 in each sheet can be changed via drop-down menu to update results and graphs for alternative assumptions (1%, 3%).

C.8 WEBGIS

As described in Section 9.1 a *WebGIS* Online Map was created to facilitate data sharing and communication of the research results. A backup of the code for each webGIS is provided as a digital deliverable to ODOT.

APPENDIX D:
TPAU RESULTS

Please contact ODOT Research Coordinator Kira Glover-Cutter (kira.m.glover-cutter@odot.oregon.gov), the Principle Investigator Mike Olsen (michael.olsen@oregonstate.edu), or the general ODOT Research inbox (odotnewresearch@odot.oregon.gov) to obtain this appendix. This appendix contains files provided by ODOT TPAU to support the economic analysis:

- *AppD1_CommodityFlows_SPR843revised.xlsx*: A spreadsheet containing commodity information (both northbound and southbound) for all identified vulnerable sites.

- *AppD2_SPR843_DetourCostTechMemo.pdf:* A technical memo providing a summary of estimated user costs associated with the closure of five locations on US 101.

- *AppD3_TPAU_SWIMMResults*: This folder contains zip files with the output from SWIM for the selected sites described in Section 7.0 for the detailed economic analysis. Each site has a *Deliverable* zip file which contains summary information and plots of volume trends, population growth, etc. Each site also has a *SupportDocs* zip file containing the input files used in the SWIM analysis.