Final

CENTRAL COAST HIGHWAY 1 CLIMATE RESILIENCY STUDY

Study Report

Prepared for
Association of Monterey Bay Area Governments (AMBAG)

July 2020

Photo Credit: Paul Zaretsky Photography

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ACRONYMS AND ABBREVIATIONS

Acronym/Abbreviation	Definition
AADT	Annual Average Daily Traffic
AMBAG	Association of Monterey Bay Area Governments
BIRIS	Bridge Inspection Records Information System
CalSTA	California State Transportation Agency
Caltrans	California Department of Transportation
CBE	Center for the Blue Economy
CCC	California Coastal Commission
CCWG	Central Coast Wetlands Group
CDFW	California Department
CRMB	Coastal Resilience Monterey Bay
ESA	Environmental Science Associates
ESF	Elkhorn Slough Foundation
ESNERR	Elkhorn Slough National Estuarine Research Reserve
GHG	Greenhouse Gas Emissions
Hwy	Highway
MLW	Mean Low Water
MLLW	Mean Lower Low Water
MLWA	Moss Landing Wildlife Area
MSL	Mean Sea Level
MHW	Mean High Water
MHHW	Mean Higher High Water
MLML	Moss Landing Marine Labs
MP	Milepost
MTP/SCS	Metropolitan Transportation Plan/Sustainable Communities Strategy
OPC	Ocean Protection Council
SCC	California State Coastal Conservancy
SLAMM	Sea Level Affecting Marshes Model
SLR	Sea Level Rise
SR	State Route
TAMC	Transportation Agency for Monterey County
TCR	Transportation Concept Report
TNC	The Nature Conservancy
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled

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CHAPTER 1
Executive Summary

Elkhorn Slough is a major estuary located in Monterey Bay, California that provides valuable habitat area for hundreds of aquatic bird, fish, marine mammal and invertebrate species. With nearly 2,700 acres of a suite of intact habitat types, the Slough is critical to regional biodiversity. Tidal estuarine habitats within the Slough and the ecosystem services they provide are at risk to substantial degradation and losses from sea level rise. With Central California already having lost over 90% of its historical estuarine marsh habitat area (Brophy et al. 2019), every effort is needed to maintain current marsh habitat area in the face of sea level rise. Presently, Elkhorn Slough holds the third largest extent of estuarine marsh in California and is well conserved. However, largely due to the surrounding steep topography, approximately 85% of this marsh is projected to be degraded or converted to tidal flats or open water with sea level rise without concerted restoration and conservation efforts. As sea levels rise, each acre of salt marsh now becomes that much more important to conserve or restore. Ensuring that Elkhorn Slough will perpetually host healthy salt marshes into the future is a high priority for the region (Fountain et al. 2020).

Transportation assets in this region are also vulnerable to sea level rise impacts. The eight-mile stretch of Highway 1 through Elkhorn Slough is a critical transportation asset for the region and beyond. It provides local access to Moss Landing, is essential to freight movement and the economy, and is a major commuting route connecting two regionally important cities, Santa Cruz and Monterey. With 2 feet of sea level rise, major disruptions to Highway 1 transportation function are anticipated. The railway, which runs along the main stem of the Slough for five miles, is also critical to freight movement and envisioned to serve expanded passenger service to meet the needs of a growing population. Extreme tides, known as “King Tides” already cause periodic flooding and disruptions to the railway, which will increase in frequency and severity as sea levels rise.

Maintaining or enhancing both transportation function and the extent of estuarine marsh in Elkhorn Slough are important priorities for the Central Coast and beyond. The Central Coast Highway 1 Climate Resiliency Study (Study) is a unique partnership between the Association of Monterey Bay Area Governments (AMBAG), California Department of Transportation (Caltrans), The Nature Conservancy (TNC), the Center for the Blue Economy (CBE) at the Middlebury Institute of International Studies, and Environmental Science Associates (ESA) to develop and evaluate adaptation strategies for Highway 1 and the railway to improve resilience of transportation infrastructure in a manner that most benefits the surrounding ecosystems throughout Elkhorn Slough.

Integrating regional development and adoption of natural infrastructure and transportation planning can provide better outcomes for both sectors (Marcucci & Jordan, 2013) and Federal Highway Administration guidance and California policy are encouraging this integrated approach (Safeguarding California Plan: 2018 Update, 2018). The project was funded by Caltrans via a Senate Bill (SB) 1 Adaptation Planning grant, a Sustainable Communities Planning grant, with additional funding provided by AMBAG, TNC and the CBE.

The Project Team coordinated with a wide range of local, regional and state stakeholders to gather existing conditions, develop transportation and ecological adaptation concepts, develop adaptation scenarios, and refine and modify the concepts and scenarios with Steering Committee and community input. Throughout the study, an adaptation pathways approach was used in order to explore a variety of strategies that could cultivate transportation and ecological resilience over a range of time horizons (Haasnoot, 2013). A suite of near-term actions (e.g. next ten years) are identified to mitigate flooding impacts to transportation and ecology, in addition to developing long-range adaptation scenarios that could be implemented. The adaptation pathways approach yields deeper insight into what additional steps (e.g. planning, timing, funding) may be necessary to bridge near-term actions to a long-term vision. After assessing a preliminary suite of adaptation scenarios, three revised roadway and railway adaptation scenarios, which were compared against a no action scenario, were evaluated and are described below:

	2-Lane Elevated Highway 1 (C1)	**Improve G12 Inland Corridor as Main Route (C2)**	**4-Lane Elevated Highway 1 (C3)**
	Highway 1 remains 2 lanes and is elevated in place, on piles or fill, as appropriate	Through traffic re-direct inland to the G12 corridor and Highway 1 unmodified for local only access	Highway 1 expanded to 4 lanes and is elevated in place, on piles or fill, as appropriate
Road Features	Highway 1 remains 2 lanes	G12 Widened to 4-lane and Highway 1 traffic diverted	Highway 1 widens to 4 lanes
	Highway elevated on piles or fill	Only local access to Highway 1	Highway elevated on piles or fill
	Road ecotone marsh planting		Road ecotone marsh planting
	Highway operational and access improvements		Highway operational and access improvements
	Express transit service		Express transit service
	Enhanced bicycle and pedestrian facilities	Enhanced bicycle and pedestrian facilities	Enhanced bicycle and pedestrian facilities
Rail Features	Hourly rail service on elevated single track	Hourly rail service on elevated single track	Hourly rail service on elevated single track
	Marsh restoration east of railway	Marsh restoration east of railway	Marsh restoration east of railway

The roadway and railway adaptation scenarios were evaluated using best available locally specific data to inform a series of modeling tools investigating systemic changes to hydrology, transportation, and ecology triggered by sea level rise and adaptation actions. Building upon the results of the hydrodynamic, transportation, and habitat modeling, a probabilistic benefit cost analysis was applied to the scenarios to account for the valuation of ecosystem services and transportation function, and provide perspective on which adaptation scenario provides more in gains than is given up in costs. Further, we provide an examination of when adaptation action needs to be taken to provide resilience benefits to both transportation infrastructure and surrounding ecosystems given probabilities of sea level rise. The major takeaways from each portion of the evaluation are briefly described here.

1.1 Transportation Modeling

AMBAG utilized the Regional Transportation Demand Model (RTDM) to evaluate the proposed transportation improvements in the adaptation scenarios in order to identify the most viable and effective solutions to enable needed transportation function for the study area. The results of the modeling for each scenario were compared to each other and to a no action scenario to analyze the impacts of each under a variety of performance metrics. These performance metrics are indicators of how the adaptation scenarios would perform and how effectively they would serve the needs of this critical transportation corridor with future growth and demand.

The results of the transportation modeling indicate:

- Allowing the roadway to flood (No Action Scenario) would not only increase congestion and delay in the study area, it would also limit access to transportation for disadvantaged communities within the Moss Landing and Elkhorn Slough area.
- Scenario C3 (4-Lane Elevated Highway 1) would best suit the transportation needs of the corridor, allowing for increased capacity on a road that is already overburdened by demand. Widening Highway 1 to four lanes would provide the greatest relief to congestion and delay, leading to less time spent on the roadway and greater ease of travel.
- Scenario C2 (Improve G12 Inland Corridor as Main Route) presents the same problems as a no action scenario in that it limits access for disadvantaged communities, and does not outperform Scenario C3 (4-Lane Elevated Highway 1) under any transportation metric.
- Scenario C1 (2-Lane Elevated Highway 1) does not provide relief to the demand on Highway 1 that already exists in the study area, but does present viable operational improvements that can be implemented to benefit travel time and safety through the corridor.

1.2 Flood Hazards Modeling

The Coastal Resilience Monterey Bay (CRMB) hazard mapping resource was applied to assess the extents of Highway 1 at risk to flooding, resulting in identification of four sections of Highway 1, called Reaches 1, 2, 3 and 4 (Figure 3). Reach 1 is between Struve Pond and Bennett Slough; Reach 2 is between the North Harbor and Bennett Slough; Reach 3 crosses Moro Cojo Slough, and Reach 4 crosses an historical slough, now a swale/drainage through agricultural lands. CRMB are the best available flood hazard mapping for the Monterey region and are being used by municipalities for vulnerability assessments and adaptation planning. We crosswalk CRMB sea level rise curves (2.4 ft by 2060 and 5.2 ft by 2100) with the most recent (2018) California guidance for reference and planning purposes. The CRMB (2014) maps were then updated to better account for micro-topography, overland flow and existing hydraulic control structures, resulting in revised flood water-surface elevations for each Reach for monthly and 100-year recurrence floods from coastal and river sources under existing and future climate-affected sea levels and runoff from the Reclamation Ditch - Gabilan Creek drainage. The refined flood hazard mapping indicates Highway 1 will be impacted by a 100-year flood by 2030 (less than one foot of sea level rise), and by monthly high water by 2050 (about 2 ft of sea level rise).

1.3 Hydrodynamic Modeling

The Delft3D hydrodynamic model was applied to evaluate impacts to overall Slough hydrodynamics as a consequence of sea level rise for the proposed roadway and railway adaptation scenarios. Flood extents, water depths and velocities were analyzed at locations within the study domain to assess changes in local hydrologic conditions.

Hydrodynamic modeling results indicate that a new flood pathway east of the managed ponds in Moss Landing Wildlife Area will develop under 2 to 3 ft of sea level rise (time horizon of 2050 to 2070), with or without roadway modifications. Consequently, Struve Pond and Upper Bennett Slough will be tidally connected to the main channel of Elkhorn Slough. This indicates that improvements made to the roadway (e.g. elevating a segment on piles or fill) will have decreasing control over flooding in this part of the Slough, as sea level rises. Additionally, the model shows overtopping of Potrero Road and Moss Landing Road, resulting in bypassing of tide gates and overland flooding of the low-lying agricultural parcels by Highway 1 and Moro Cojo Slough, assuming 3 ft of sea level rise. Likely, around mid-century, maintaining farming operations in the low-lying agricultural lands near Reaches 3 and 4 will be untenable. These results support ongoing integrated, collaborative efforts around Moro Cojo Slough to plan for future land use under sea level rise.

The hydrodynamic modeling also shows that tidal velocities in the main Slough channel will increase under future sea level rise in all scenarios, which will exacerbate net sediment export and marsh loss within the system. Marsh restoration of the complexes east of the railway (about 700 acres of intertidal areas) proposed within this project will reduce the overall increase in tidal prism associated with sea level rise, thereby reducing marsh loss.

1.4 Habitat Modeling

The Sea Level Affecting Marshes Model (SLAMM) was applied to predict wetland habitat evolution within the Slough for each roadway and railway adaptation scenarios compared to a no action scenario on decadal time steps as sea levels rise. While a majority of Elkhorn Slough is conserved for habitat values, much of the periphery of the estuary is too steep to allow the migration of its extensive marsh habitats as sea levels rise. SLAMM modeling also assessed how much additional wetland habitat could be provided from proposed marsh restoration east of the railway, compared to a no action scenario, which would strengthen habitat resilience through the Slough.

Ecotone levees were incorporated into all scenarios of adapting Highway 1 in place. An ecotone levee utilizes a much more gradual slope (up to 20H:1V) than typically used which creates intertidal habitat area as well as an "ecotone," an area of transition between tidal habitats and upland habitats. This ecotone provides a buffer between the roadway and sensitive estuarine habitats and also provides migration space for tidal marsh habitats to move upwards into as sea levels rise thereby enhancing resilience.

Proposed grading by Reach 2 for levee ecotone creation for Scenarios C1A (2-Lane Elevated Highway 1 with Reach 2 on Piles), C1B (2-Lane Elevated Highway 1 with Reach 2 on Fill), C3A (4-Lane Elevated Highway 1 with Reach 2 on Piles) and C3B (4-Lane Elevated Highway 1 with Reach 2 on Fill) will produce between 72 to 83 acres of estuarine marsh habitat, assuming construction by mid-century. The total number of estuarine marsh habitat acreages will likely be refined and could potentially be greater than this planning study has included. Scenarios C1B (2-Lane Elevated Highway 1 with Reach 2 on Fill) and C3B (4-Lane Elevated Highway 1 with Reach 2 on Fill) result in the greatest area of estuarine marsh habitat from the associated restoration adaptation actions among the different scenarios (607 acres remaining at 2100, compared to 260 acres from the no action scenario).

Adaptation for the railway differed from adaptation of Highway 1. Because the railway is currently within the main stem of Elkhorn Slough, elevating on fill is predicted to subside. We took this as an opportunity for restoration of large extents of tidal habitat in this part of the Slough. The rail would be elevated on trestle, and the existing railway could then be used as grade control to allow elevating the marsh plain of approximately 700 acres to mean higher high water (MHHW) in year 2050 for Parsons Slough, North/ Estrada Marsh and Azevedo Ponds. This approach is supported by the Elkhorn Slough Reserve's strategy for conservation, restoration, and enhancement and was pioneered with the recent construction of Hester Marsh within Elkhorn Slough (Fountain et al. 2020).

According to SLAMM modeling, raising the marsh plain grade to future MHHW at mid-century for Parsons Slough, North/Estrada Marsh and Azevedo Ponds is predicted to have longevity over several decades. Around 290 acres of additional restored estuarine marsh habitat remain at year 2100 (5 ft of sea level rise) as a consequence of proposed marsh restoration. As much of the area of estuarine marsh habitats throughout the Slough are converted to flats and open water under sea level rise, the importance of these marsh complexes and the ecosystem services they provide to the Slough will grow. The cost and difficulty of restoring marshes to higher tidal elevations after mid-century will increase substantially, given that many habitat acres may have already converted to estuarine open water. This highlights the need for adaptation and restoration actions beginning now and by mid-century to minimize loss of marsh habitat, secure resilience and maintain the benefits these habitats provide to people and nature.

The habitat modeling results strongly support action to create and sustain estuarine marsh habitat acreages with any infrastructure adaptation and other restoration projects throughout the Slough. Habitat modeling also urges the need to deploy such adaptation and restoration before mid-century. The model results also confirm that in addition to restoration of existing wetland habitat, present and future land use planning for low-lying agricultural lands by Reaches 3 and 4 will have a significant impact on how much wetland habitat will exist in the future. Strategic land acquisition, in the context of enabling marsh migration, is a critical strategy to sustaining future marsh habitat (Heady et al. 2018). This is further supported by Fountain et al. 2020. The parcels south and southwest of Moro Cojo Slough, if allowed to convert, represent a strong opportunity to mitigate wetland habitat loss (up to 50%) experienced by Elkhorn Slough under future sea level rise.

1.5 Benefit Cost Analysis

Sea level rise presents a significant challenge to maintaining both the transportation system of Highway 1 and the ecological systems of Elkhorn Slough. A major part of that challenge is that the costs of adapting to sea level rise are likely be very large, but the costs of not adapting could be even higher. Decisions must be made about whether to adapt, and if the decision to adapt is made, then a choice must be made of which option should be selected. Benefit cost analysis is a tool to help make these choices. It can show whether the threats from sea level rise are likely sufficient to justify action, and which options have the greatest likelihood of providing more in social benefits than the social costs incurred. Equally importantly, benefit cost analysis works with a common metric of economic values that permits comparison of the changes in both transportation and the environment resulting from sea level rise and the options being considered for response.

The analysis conducted for this study considers:

- The expenditures on transportation system adaptation and wetlands enhancement/ restoration
- The value of time spent in transportation for both passengers and freight
- The economic costs of highway accidents
- Expenditures on motor vehicle operations
- The value of recreation in Elkhorn Slough
- The value of ecosystem services from Elkhorn Slough other than recreation.

Costs and benefits are defined by context. Costs are defined as reductions in economic values, while benefits are defined as gains in economy valuation. Losses and gains are always measured by comparison with a reference scenario. Taking no action with respect to sea level rise risks losses of valuable time, ecosystem services, safety, etc., but saves money for use elsewhere. Adaptation, by contrast, must incur the costs of altering infrastructure and ecosystems but these costs are offset by gains in other social values measured in time, safety, etc. that would be cost. Thus, the costs and benefits of the adaptation scenarios are the inverse of the costs and benefits of taking no action.

The results of this analysis, as shown below, indicate that the option to adapt with a 4-Lane Elevated Highway 1, which includes investments in expanding and restoring wetlands (C3) is the only option whose benefits exceed its costs (adjusted to present value). The No Action and other scenarios, 2-lane elevated highway (C1) or shifting north-south traffic to inland routes (C2/Improve G12 Inland Corridor as Main Route) all show substantially more costs than benefits. The choice of whether to use fill or piles for an elevation of Highway 1 does not affect the benefit cost conclusions.

TABLE 1
SUMMARY OF BENEFIT COST ANALYSIS

Millions of $			C1		C2	C3	
		No Action	On Piles	On Fill		On Piles	On Fill
TOTAL	Costs	-$1,459.02	-$773.91	-$765.10	-$899.02	-$913.34	-$904.54
	Benefits	$858.86	$234.17	$235.87	$149.41	$1,008.95	$1,012.94
Net Present Value		-$600.17	-$539.74	-$529.23	-$749.61	$95.61	$108.40
Cost Benefit Ratio		0.59	0.30	0.31	0.17	1.10	1.12

The analysis also examines how to deal with the large uncertainties surrounding the actual pace and extent of sea level rise in Monterey Bay. The California Ocean

Protection Council recommends using a risk averse approach to planning for sea level rise adaptation. That is, plans should be based on the expectation of large amounts of sea level rise, even if such amounts have low probabilities based on best available science. Planning for worst case (or near worst case) scenarios creates an economic dilemma: moving ahead too soon may mean large expenditures that are ultimately not needed or not needed for many years in the future. Moving ahead too late risks enduring unacceptable losses until action is taken.

Finding a point where the decision to act is more likely to result in net gains requires an analysis of the probabilities of sea level rise. This was done in the benefit cost analysis, with the result that a decision to commit large scale resources should be made no later than the early 2040s, a point at which the data indicates that sea level rise-enhanced storms are more likely than not to begin damaging Highway 1. That decision point will be followed by at least 10 years of project development, evaluation, and construction.

The benefit cost analysis also considered the sensitivity of the analysis to the discount rate (the mechanism for equating distant future benefits with near term costs). It was found that the results were sensitive to the discount rate, with net present values for C3 (4-Lane Elevated Highway 1) approach zero at about a 4% discount rate in contrast to the 3% discount rate used. This indicates that future economic evaluation of Highway 1 adaptation options should include examination of lower cost alternatives, particularly in wetlands restoration, which in the current analysis comprises a large a portion of costs.

1.6 Major Takeaways and Considerations for Future Planning

While not an exhaustive list, summarized below are key takeaways and considerations for future planning drawn from the study process, approach, methodologies and results from the analyses.

Major Takeaways:

- **Choosing not to adapt to sea level rise will result in widespread loss of coastal habitat, significant transportation impacts and economic losses.** Following a no action pathway, or delaying action on climate change adaptation, will result in widespread loss of habitat and biodiversity through the Slough (up to 85% of estuarine marsh habitat) and worsen an existing transportation function problem, to the detriment of the community, region, and the many visitors to Monterey Bay. A no action pathway is not an economically viable option for Moss Landing and Elkhorn Slough.
- **Adaptation of the highway with nature-based elements helps to reduce the loss of marsh habitat.** Marsh habitat is the most at-risk habitat type with sea level rise. Every acre of marsh habitat that can be conserved and restored will be critical to ensure Elkhorn Slough can continue to support healthy wetland habitat. The ecotone proposed for highway adaptation and the marsh restoration for Parsons

Slough, North/Estrada Marsh Complexes and Azevedo Ponds, will make significant contributions to reducing habitat loss in the Slough.

- **Adaptation needs to be in place by 2050 to ensure benefits to transportation and habitats.** The benefits of implementing adaptation actions, such as large-scale marsh restoration, are greater the earlier they happen in the century. The results of the evaluation emphasize the importance of planning for Highway 1 and railway adaptation in the early to mid-2030s and implementing a course of action well before sea levels are predicted to follow the exponential part of the curve in mid- to late- 21st century.
- **Multi-sector cooperation and planning is key.** Integrating transportation and ecosystem resilience planning from the beginning can provide better outcomes for both sectors. It is critical to have a multi-sectoral team of transportation planners, scientists, conservationists, engineers and economists together at the same table, pursuing coequal goals for transportation and ecology, and working to identify pathways to long-term adaptation to achieve multiple benefits.
- **Planning for ecosystem migration is critical to increase future habitat and overall resilience of Elkhorn Slough.** This study revealed the need to also pursue conservation and restoration strategies to ensure migration of coastal habitat with sea level rise. Habitat migration could mitigate approximately half of projected habitat losses with sea level rise.

Considerations for Future Planning (See Section 7.3 Considerations for Future Planning)**:**

- Integrate study results into Regional, Metropolitan and State Transportation Plans and prioritize further planning for this critical transportation corridor.
- Continue planning processes that combine multi-objective and multi-benefit focus in each stage of adaptation planning.
- Future analysis should integrate best available science and modeling, including considering higher sea level rise scenarios when projections are available.
- Integration and consistency with other ongoing and future climate change adaptation planning efforts is critical, including the Moss Landing Community Plan, Local Coastal Plan and Monterey County General Plan.
- The economic benefit cost analysis developed in this project provides a framework for planners to assess when adaptation is needed and should be applied to future efforts.
- Pathways, triggers and strong partnerships must be in place now to ensure effective climate change adaptation for the Moss Landing area and Elkhorn Slough.

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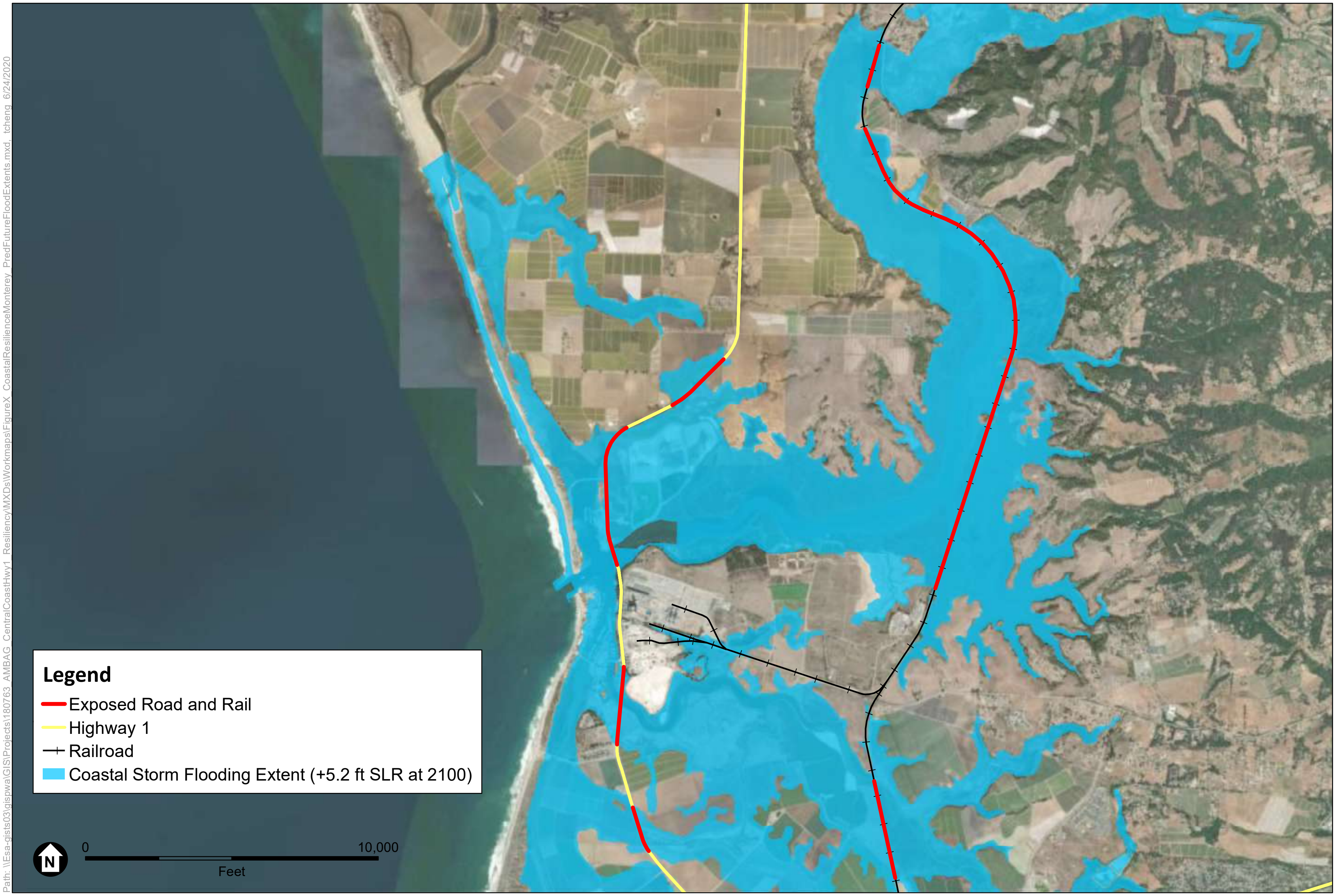
CHAPTER 2

Study Need, Objectives and process

2.1 Study History

The Central Coast Highway 1 Climate Resiliency Study (Study) is a unique partnership between the Association of Monterey Bay Area Governments (AMBAG), California Department of Transportation (Caltrans), The Nature Conservancy (TNC), the Center for the Blue Economy at the Middlebury Institute of International Studies (CBE), and Environmental Science Associates (ESA) on climate change adaptation planning for Highway 1 and the railway through Elkhorn Slough and surrounding ecology. This study seeks to answer the following question: What transportation improvements and nature-based strategies will work in tandem to simultaneously enhance ecological and transportation resilience through the Elkhorn Slough area under future conditions, including sea level rise, through the end of the century? The project seeks to integrate regional development and adoption of natural infrastructure and transportation planning, which can provide better outcomes for both sectors through more responsive regional transportation, shared funding, preservation or enhancement of nature's values and benefits, (i.e. ecosystem services), and streamlining of the project environmental review process (Marcucci & Jordan, 2013). Guidance documents from the Federal Highway Administration and California policy are encouraging this integrated approach, although relatively few demonstrations have been implemented (Webb et al., 2019) (Safeguarding California Plan: 2018 Update, 2018).

Previous flood hazard mapping work for the Coastal Resilience Monterey project show these major transportation assets and large swaths of Slough habitat, which provide invaluable ecosystem services to the region at large, are at risk under future sea level rise, with some areas impacted as soon as 2030 (**Figure 1**). The study, which began in October 2018, leverages previous partner collaborative work and concluded in June 2020, with a final report deliverable summarizing the data collection, development and evaluation of long-term adaptation scenarios and recommendations for future near-term actions. The study is funded through the Caltrans Adaptation Planning Grant Program, part of Senate Bill 1 (SB 1), which intends to advance adaptation planning by local and regional agencies on state transportation infrastructure. The Project Team will work with Caltrans and regional stakeholders to move to the next stages of planning for this critical transportation corridor (see Section 7.3 Considerations for Future Planning) and integrate approach into future Caltrans planning for the region. Additionally, the multi-sectoral planning process, methodology and lessons learned piloted in this study



SOURCE: Coastal Resilience Monterey (2019)

Central Coast Highway 1 Climate Resiliency Study . D180763.00

Figure 1
Coastal Resilience Monterey
Predicted Future Flooding Extents (+5.2 ft SLR at 2100)

can serve as a case study for Caltrans to ensure integration and equal consideration of transportation and ecological goals for adaptation planning in other locations throughout California. The California State Transportation Agency (CalSTA) provided additional funding in Spring 2019, through a Sustainable Communities grant to include adaptation planning for the railway in this study.

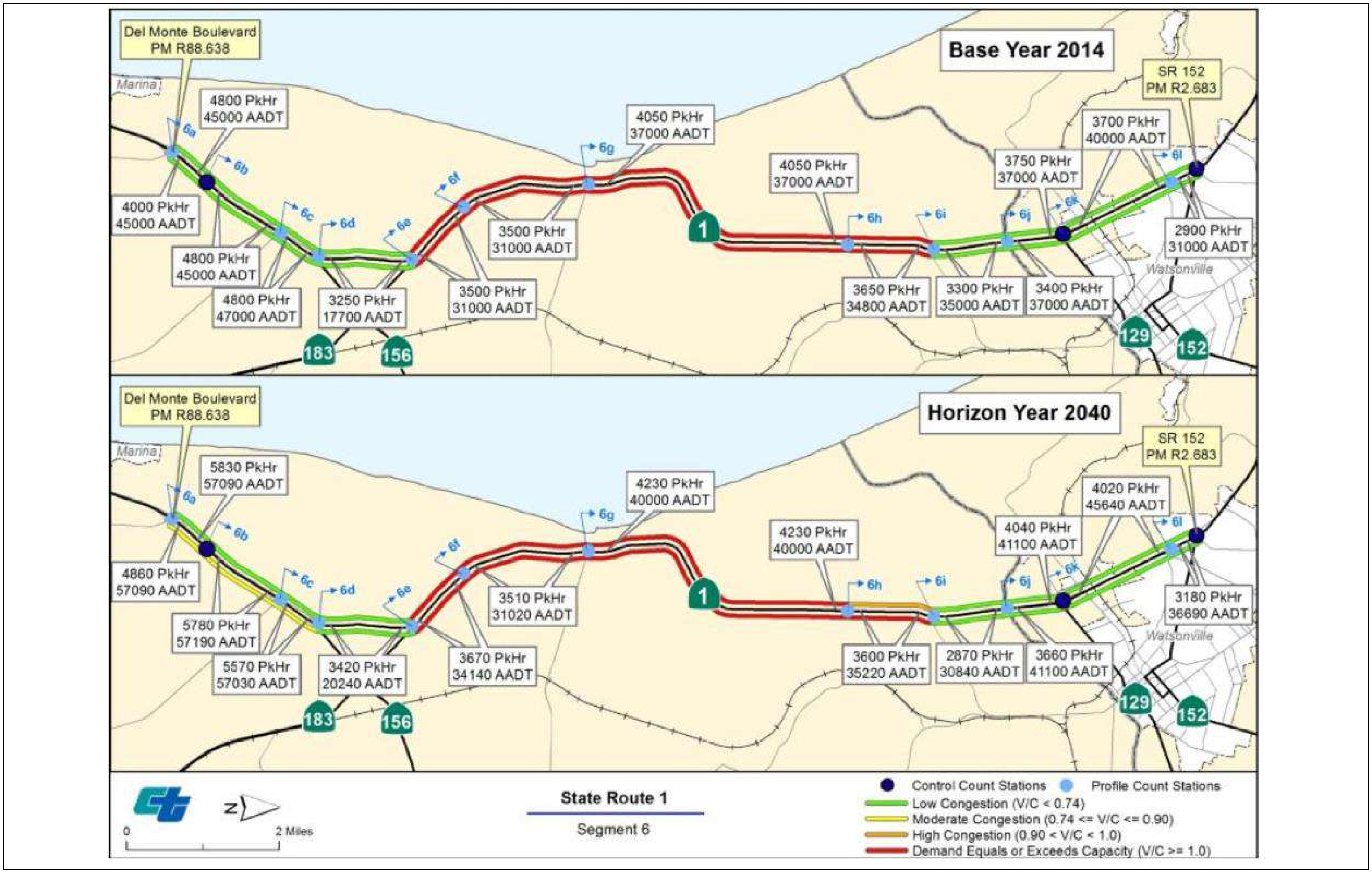
2.2 Study Need

The study is a first step in developing transportation improvements and nature-based strategies that work in tandem to enhance ecological and transportation resilience to sea level rise through the Moss Landing and Elkhorn Slough area under future conditions. The transportation assets the study focuses on are Highway 1 and the railway. The adaptation scenarios from this study are planning-level and informed by, at the time of the study process, the most recent and available locally specific data from Monterey County and relevant stakeholders. This study responds to two major concerns related to transportation infrastructure in this area, both of which are expected to be exacerbated by climate change: (a) inadequate transportation function, and (b) loss of wetland habitat.

Inadequate Transportation Function. Existing transportation demand on Highway 1 near Elkhorn Slough is severely constrained and passengers regularly experience long traffic delays in this corridor. The corridor experiences frequent disruptions to traffic flow, which impact overall safety. The California Highway Patrol Statewide Integrated Traffic Records System (SWITRS)[1] show about 700 reported collisions along the Highway 1 study area between January 1, 2013 and December 31, 2018, a number of which are focused in the northern section of the study area and in the area south of Dolan Road. The highway is a major coastal route for commuters from the Santa Barbara, San Luis Obispo, Monterey and Santa Cruz Counties within Caltrans District 5. **Figure 2** shows existing and future traffic volumes for Highway 1, which indicates the need to improve transportation function in this corridor. Both Highway 1 and the Elkhorn Slough railway will be increasingly impacted by flooding as sea levels rise, with some segments of transportation infrastructure already flooding during present day king tides[2]. Additionally, the North County Land Use Plan, including the Moss Landing Community Plan, has Moss Landing as a critical site for industry, commerce and recreation. As such, it is a priority of the County of Monterey to protect the community in place and maintain vehicular access to the Moss Landing Harbor and Island.

[1] The California Highway Patrol Statewide Integrated Traffic Records System (SWITRS) can be accessed at this address: http://iswitrs.chp.ca.gov/

[2] King tide refers to an ocean and Elkhorn Slough water level that happens about once per year during high astronomical tides, and often elevated by winter weather, as well as climate conditions such as El Niño and abnormally warm ocean waters.



SOURCE: Caltrans Transportation Concept Report (TCR) State Route 1 (SR-1) (2017)

Central Coast Highway 1 Climate Resiliency Study

Figure 2

Existing and Projected Future Travel Demand in Study Area

Loss of Wetland Habitat. Elkhorn Slough is the 7th largest estuary in California at over 3,400 acres, with the third largest extent of salt marsh in the state. The Slough provides critical habitat for more than 135 aquatic bird species, 550 marine invertebrate species, and 102 fish species, including six species that are threatened and endangered. It is also home to southern sea otters, sea lions, harbor seals, and more than 200 different bird species that use the Slough as a resting spot during their annual migration. Over the last 70 years, Elkhorn Slough has lost half of the valuable tidal marsh habitat, approximately 1000 acres, due to human impacts and development (Elkhorn Slough Tidal Wetland Project Team, 2007). Wetland habitats work to improve water quality by filtering polluted waters, provide high carbon sequestration rates, and serve as key nursery habitat for commercially valuable fisheries (Barbier et al. 2011; McLeod et al. 2011; Hughes et al. 2014). Sea level rise is projected to accelerate habitat conversion within the Slough from salt marsh to mudflat to permanently drowned estuarine waters, sharply decreasing habitat for marsh-dependent wildlife species. With sea level rise, salt marsh is the most at-risk habitat type in the Slough. To ensure Elkhorn Slough will continue to host healthy salt marshes, the Elkhorn Slough National Estuarine Research Reserve (NERR) identified three climate adaptation strategies conserve, restore and enhance coastal marsh habitats. These include thick sediment addition, thin sediment addition, and facilitating migration. The addition of sediment can raise the elevation of the marsh, allowing it to keep pace with sea level rise. This approach was demonstrated with the recent construction of Hester Marsh in Elkhorn Slough (Fountain et al. 2020). Marsh migration in areas of the Slough with more gentle slopes will also be critical to ensuring marsh habitat in the Slough. The NERR's plan identifies areas that may be suitable to host future marsh areas, including areas along the Old Salinas River Channel, Tembladero Slough, and the Pajaro River (Fountain et al. 2020).

2.3 Goals & Objectives

The goal of this study is to explore how forward-thinking transportation infrastructure adaptation may enhance ecological function of adjacent ecosystems, enhance habitat resilience to sea level rise and secure resilient and enhanced transportation services for local communities.

The Project Team developed study objectives, which were refined with input from the Steering Committee. The study objectives are to:

- *Evaluate and identify the transportation and ecological needs of the study area*
- *Develop a suite of nature-based adaptation strategies and transportation improvements to enhance the transportation and ecological resilience of the study area under projected future sea level rise conditions and address current and future transportation constraints, such as traffic congestion and safety.*

The study utilizes an adaptation pathways framework to develop adaptation scenarios that will be resilient to future sea level rise and adaptable to future anticipated changes.

Given the complex nature of climate related impacts to the transportation, ecological and community resources, the study does not suggest a single preferred adaptation scenario for further evaluation. A subset of adaptation scenarios, with Steering Committee and community input, were refined and are presented as potential options for the future. For planning purposes, the study uses best available study sea level rise projections of 2 feet by 2050 and 5 feet by 2100. These values are consistent with the upper range of projected sea level rise indicated in the National Research Council's 2012 report (NRC, 2012) and previous flood hazard mapping from the Coastal Resilience hazard mapping[3]. The sea level rise amounts are similar to but slight lower than the medium-high risk aversion scenario defined by recently updated California policy (CalNRA and OPC 2018; CCC 2018).

2.4 Process and Input

The study planning process included a Project Team, a Steering Committee, community outreach and early coordination with regulatory agencies and major stakeholders in the area through the duration of the study. The Project Team initiated a public planning process to encourage communication and collaboration with a range of local stakeholders, community members, regulatory agencies and others.

i. Project Team

The Project Team is comprised of cross-sectoral, cross-discipline and multifunctional team of practitioners and experts. Members and key roles are described below:

- **The Association of Monterey Bay Area Governments (AMBAG)** – provided grant and contract administration, project management, outreach support and led the transportation modeling
- **The Nature Conservancy (TNC)** – provided science guidance, particularly for the hydrological (Delft3D) and habitat evolution (i.e. SLAMM) modeling, project management, outreach support, and funding and contract management for the SLAMM modeling
- **Center for the Blue Economy (CBE)** – led the development of the economic analysis and Cost Benefit Analysis
- **Environmental Science Associates (ESA)** – lead engineering and planning consulting firm on the project, which included development of the Delft3D and SLAMM

3 Coastal Resilience Hazard Mapping resources for Monterey Bay are described in ESA PWA 2014 (https://maps.coastalresilience.org/california/methods/sea level rise_Monterey.pdf). Hazard maps for Monterey Bay and other locations are available on line at (last visited May 2020): https://maps.coastalresilience.org/

modeling, project management, outreach support and development of the study report

- **WMH Corporation, Inc. (WMH)** – provided highway engineering expertise for the adaptation scenarios development
- **Valle Translations, Inc.** provided interpretation and translation services for the public workshops
- Members from **Caltrans Headquarters**, **Caltrans District 5** and the **Transportation Agency for Monterey County (TAMC)** regularly attended monthly team meetings to provide input on study direction and progress

ii. Steering Committee

A Steering Committee was assembled at the beginning of the study, November 2018, to provide feedback on the project and adaptation scenario development and evaluation. The Committee includes representatives from local and regional transportation agencies, state and federal government agencies, the Moss Landing community, and conservation non-profits and research groups affiliated with Elkhorn Slough. Over the course of the study, the Committee has met four times: February 2019, July 2019, December 2019 and April 2020.

The Steering Committee consists of representatives from:

- California Department of Fish and Wildlife (CDFW)
- County of Monterey
- California Coastal Commission (CCC)
- State Coastal Conservancy (SCC)
- Central Coast Wetlands Group (CCWG)
- Caltrans Headquarters and District 5
- Elkhorn Slough Foundation (ESF)
- Elkhorn Slough National Estuarine Research Reserve (ESNERR)
- Moss Landing Harbor District
- Ocean Protection Council (OPC)
- Point Blue Conservation Science (PBCS)
- Transportation Agency for Monterey County (TAMC)
- U.S. Fish and Wildlife Service (USFWS)

The Steering Committee provided valuable feedback to the Project Team, including information on concurrent local and regional planning studies, existing conditions and constraints and input on adaptation concepts and scenarios.

iii. Community Meetings

As part of the study input process, the Project Team convened community meetings in Moss Landing and Marina for interested members of the public to learn more about the study and provide feedback and comments on the study and adaptation scenarios. The Project Team held two public workshops/meetings:

- *August 2019* – to present and discuss study background, goals and objectives, and initial adaptation concepts
- *February 2020* – to present and discuss the evaluation of adaptation scenarios and gather input for strategies moving forward

The draft study was provided for public comment between mid-May and mid-June 2020. AMBAG also conducted a series of public presentations in the community, including AMBAG Board of Directors, TAMC Committees (Rail Policy, Bicycle and Pedestrian Facilities, Technical Advisory Committee), Monterey County, and others. Additional public outreach events are envisioned upon the completion of the report, which will consider appropriate format and safety precautions related to the global COVID-19 pandemic.

iv. Web Based Outreach

AMBAG hosts a study website to provide project information, including project funding sources and collaborators, to the public. Materials and notes from the public meetings are posted here: https://ambag.org/plans/central-coast-highway-1-climate-resiliency-study

v. Early Agency Coordination

The Project Team conducted additional outreach with and gathered input from members of regulatory and policy state agencies who are expected to have an interest in the adaptation scenarios developed in the Project Team meetings and community meetings, including:

- California Coastal Commission (CCC)
- State Coastal Conservancy (SCC)
- California Ocean Protection Council (OPC)

vi. Virtual Reality Visualization Tool

The Project Team, with Virtual Planet Technologies, is developing a virtual reality experience to visualize sea level rise impacts, adaptation scenarios and communicate results from the study analyses to the stakeholders and the community. The tool is currently in development and is expected to be complete by September 2020.

vii. Technical Approach Methodology

Existing tools were applied with updates (See Section 6 Scenarios Evaluations and Appendices):

- Coastal Resilience Monterey Bay (CRMB, ESA 2014) projections of future flood hazards were updated with refinements of local terrain, hydraulic connectivity overland and via culverts, and refinement of lowland ponding extents.
- An existing Delft3D hydrodynamic model (Philip Williams & Associates, 2008) was updated to a new model version with an expanded and improved computational grid, and verified with prior model results and available hydrographic data.
- Sea Level Affecting Marsh Model (SLAMM) (version 6.7 Warren Pinnacle Consulting, Inc. 2016) was applied using existing habitat maps rolled-up to a smaller set of categories. Locally specific model parameters including sediment accretion and land subsidence rates were supplied by the Elkhorn Slough NERR staff based on field measurements.
- Transportation modeling was accomplished with the AMBAG Regional Travel Demand Model (RTDM) and GIS. The current RTDM’s horizon year is 2040. The model was applied to a range of transportation scenarios to assess transportation function via a range of metrics.
- Economic benefit cost analysis was applied to compare alternative scenarios through the year 2100. The analysis included damages to inundated areas, capital costs for transportation and ecology restoration/enhancement scenarios, and metrics for transportation, recreation and ecology. Concept level planning cost estimates of transportation and ecology investments were developed and used in the economic analysis.
- An adaptive pathway approach including consideration of projected future sea levels and associated hydrologic responses and transportation demand. A suite of adaptation scenarios was considered and publicly reviewed. A subset of these scenarios was analyzed further within a revised adaptation pathway.

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CHAPTER 3
Existing and Potential Future Conditions

3.1 Site Location

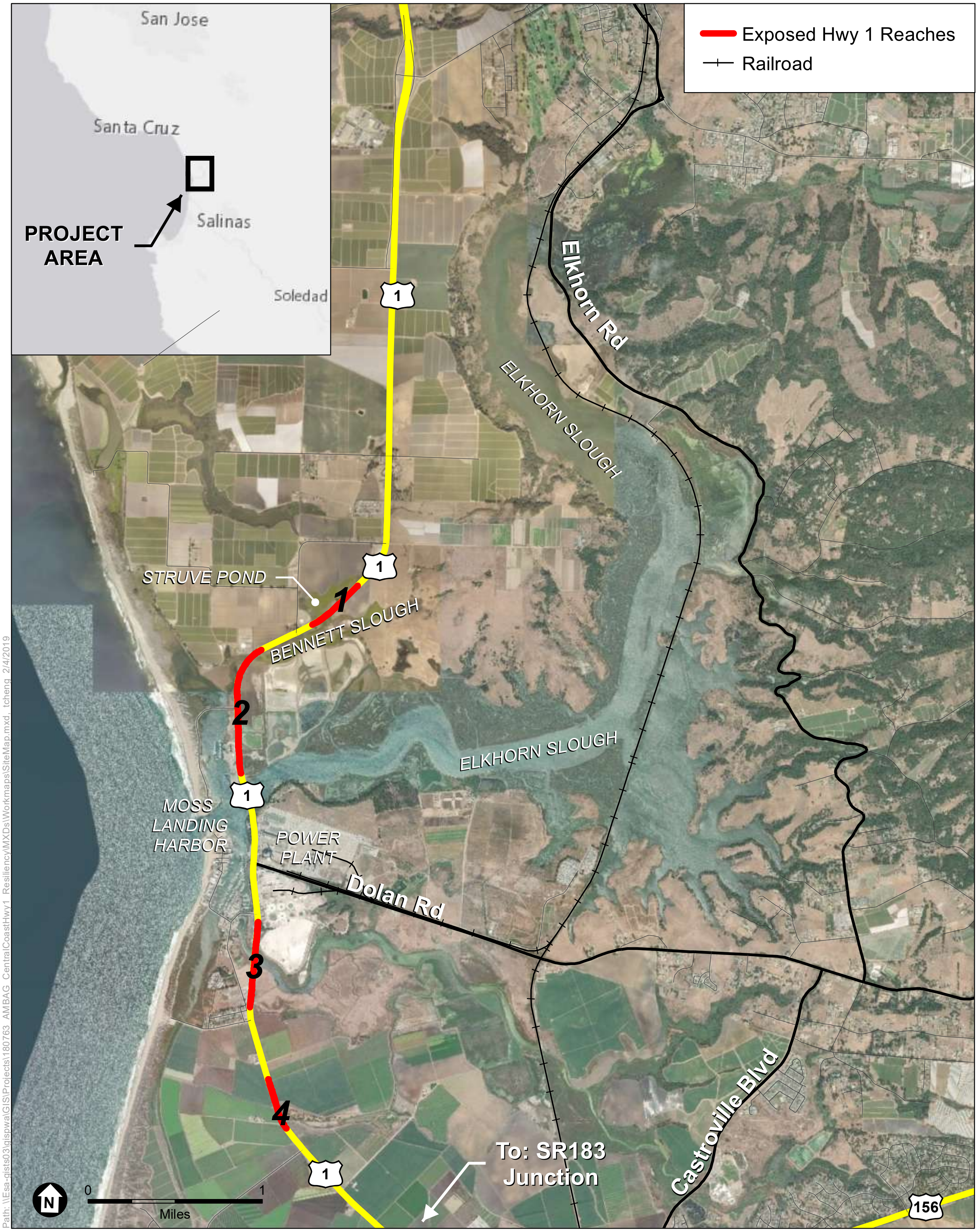
The study area encompasses Highway 1 by Moss Landing, Elkhorn Slough habitats and the railway, and adjacent lands. Moss Landing is located mid-way in Monterey Bay, approximately 16 miles north of the City of Monterey and 25 miles south of the City of Santa Cruz. The study focuses on the eight miles of Highway 1, from MP 94 to MP 102 and five miles of railway located within Elkhorn Slough. **Figure 3** shows the study area and segments of exposed transportation infrastructure at risk from sea level rise.

3.1.1 Surrounding Land Uses and Property Ownership

Figure 4 shows existing land use within Moss Landing and Elkhorn Slough (Caltrans, 2018). The study area consists of a mix of publicly owned and privately owned parcels. Areas north of Struve Pond and Bennett Slough, as well as areas south of Moro Cojo Slough, are used for agriculture. Most commercial land use is located around the Moss Landing Harbor. Known landmarks (e.g. utilities, infrastructure, commercial) within the community and the study area include:

- Moss Landing Harbor District, North and South Harbors, including the Monterey Bay Aquarium Research Institute (MBARI)
- Moss Landing Power Plant
- Moss Landing Marine Labs
- Moss Landing Wildlife Area
- Elkhorn Slough National Estuarine Research Reserve

A number of habitat conservation groups and state and local agencies own land in and adjacent to Elkhorn Slough. **Figure 5** shows protected wetlands and ownership boundaries around the Slough, as of October 2019.

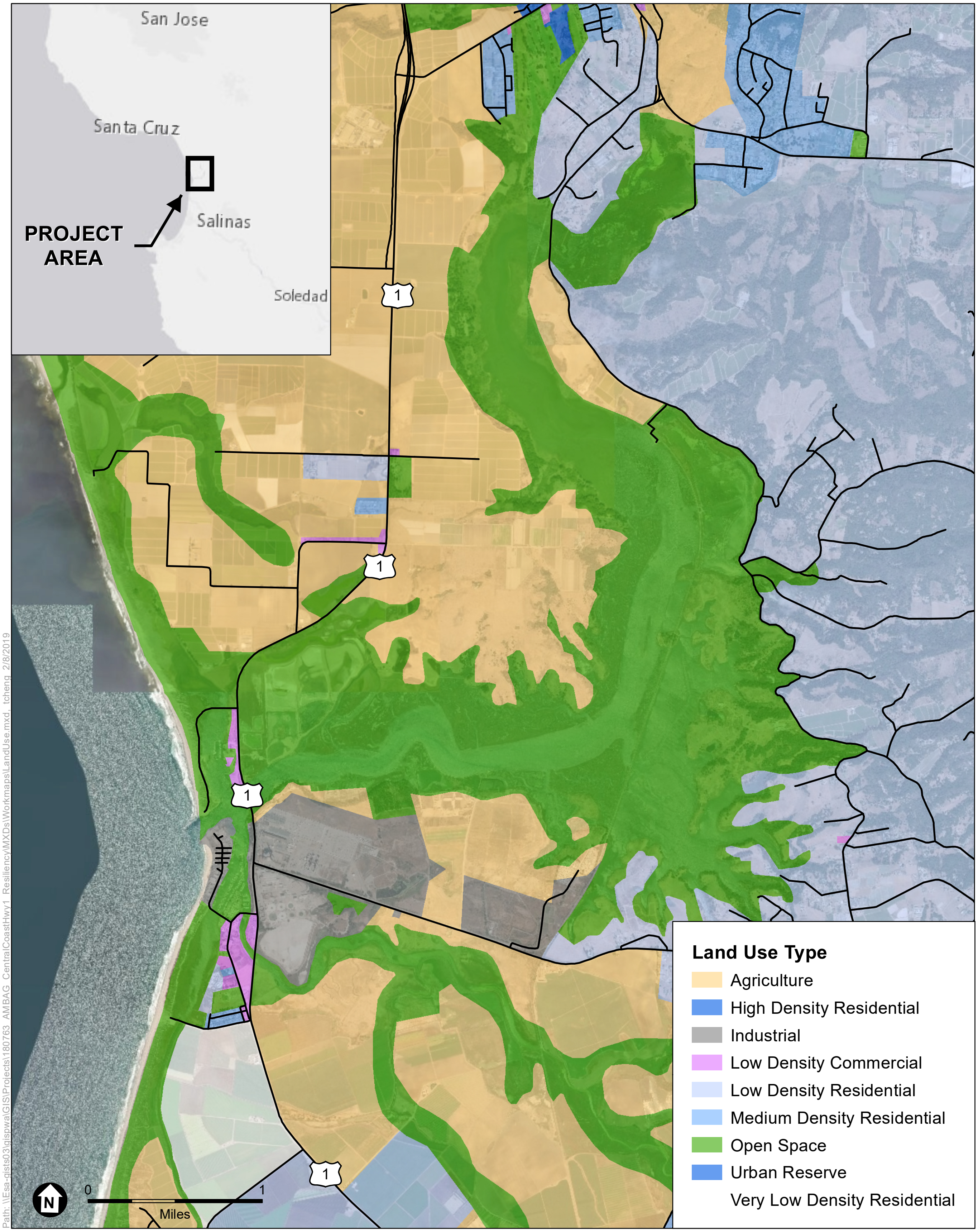


SOURCE: ESRI Imagery, 2019

AMBAG Central Coast Highway 1 Resiliency Study . D180763

Figure 3
Site Map

ESA



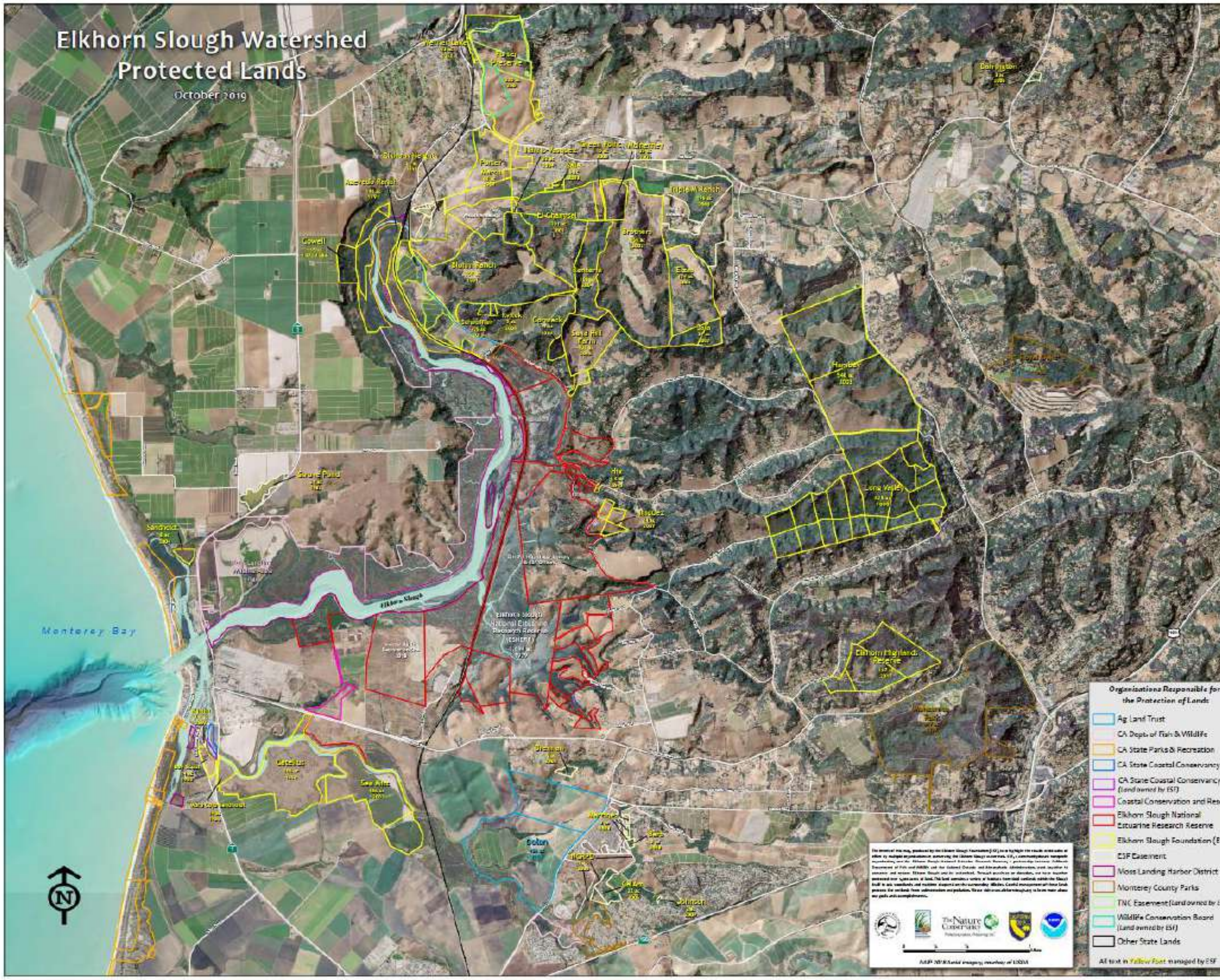
Path: \\Esa-gists03\gispwa\GIS\Projects\180763 AMBAG CentralCoastHwy1 Resiliency\MXDs\Workmaps\LandUse.mxd, tcheng 2/8/2019

SOURCE: ESRI Imagery, 2019, CALTRANS

AMBAG Central Coast Highway 1 Resiliency Study . D180763

Figure 4
Land Use Type

ESA



SOURCE: ESNERR (2020)

Central Coast Highway 1 Climate Resiliency Study
Figure 5
Elkhorn Slough Watershed Protected Lands

3.1.2 Planning and Regulatory Agencies

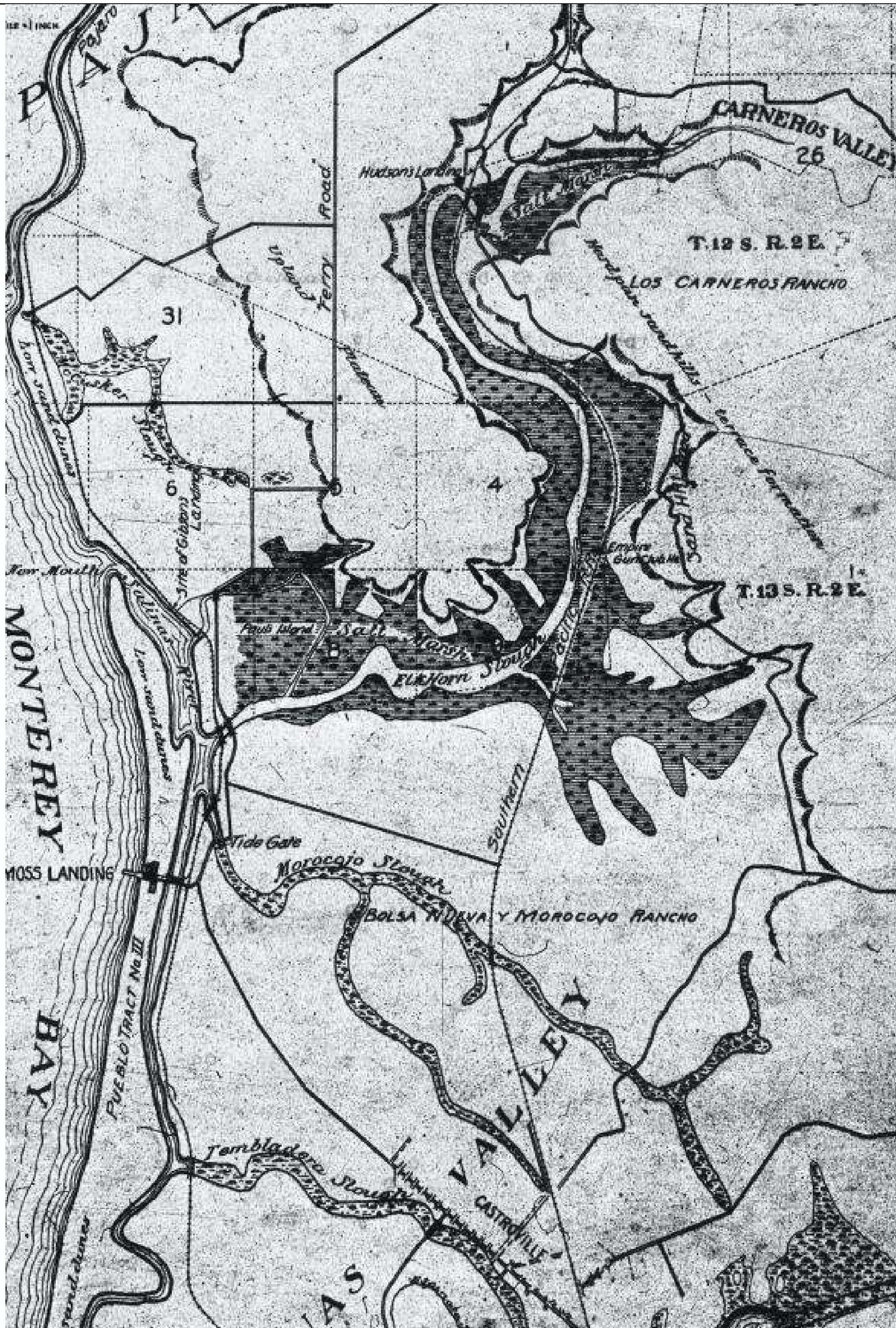
A number of federal, state, and local agencies have planning, operational and/or regulatory authority in the Elkhorn Slough area. The study area is located in the northern coastal portion of Monterey County. Monterey County has land use authority as well as oversees the local roads in the area. Highway 1 is owned and operated by Caltrans. AMBAG is the federally designated Metropolitan Planning Organization as well as the state designated Council of Governments. TAMC serves as the regional transportation planning agency in Monterey County and is planning future passenger rail service on the railway owned by Union Pacific. A number of other local, state and federal agencies/organization oversee the Elkhorn Slough itself. The Elkhorn Slough National Estuarine Research Reserve and Elkhorn Slough Foundation, along with the California Department of Fish and Wildlife and the National Oceanic and Atmospheric Administration, work to conserve, protect, restore the Elkhorn Slough.

3.2 Site History

Present day Moss Landing and Elkhorn Slough were historically part of an interconnected network of estuaries, including Moro Cojo Slough, Tembladero Slough and the Salinas River (**Figure 6**). The area was dominated by wetland habitats, specifically tidally influenced salt marshes and mudflats along the main channels and brackish and/or freshwater marshes along the Slough edges. The historic mouth of Elkhorn Slough was connected to Bennett Slough and located north of the existing jetties and Moss Landing Harbor.

Estuarine habitats in Elkhorn Slough have been largely impacted by human modifications and development over the last 150 years (Elkhorn Slough Tidal Wetland Project Team, 2007). Roadway and railway construction, including levees and bridges, built in marshlands during the 1860s and 1870s led to decreased tidal connections throughout Elkhorn Slough. Specifically, these blocked Upper Bennett Slough and adjacent areas from tidal influence. At the same time, industrialization spurred mass land clearing and increased sediment inputs. Additionally, the diversion of the Salinas River in 1909 drastically reduced freshwater and sediment inputs into Elkhorn Slough. As more land was used for agriculture, farmers installed hydraulic control structures (e.g. dams, culverts, tide gates) to support agricultural operations. This led to significant estuarine habitat loss and subsidence across the Slough. The construction of Moss Landing Harbor in 1947 established a channelized and hydraulically efficient tidal connection between Monterey Bay and Elkhorn Slough, increasing tidal exchange, erosion and discharge of sediments to the ocean (PWA and others, 2008).[4]

[4] See also: Oliver et al., 1988; Philip Williams & Associates, 1992; Broenkow and Breaker 2005; Monismith et al (2005); Sampey, 2006; Nidzieko 2010; Nidzieko and Monismith (2013). Also, Appendix C summarizes hydraulic modeling completed for this study.



Source: Elkhorn Slough Tidal Wetland Strategic Plan (2007)

Central Coast Highway 1 Climate Resiliency Study

Figure 6

Historic Elkhorn Slough

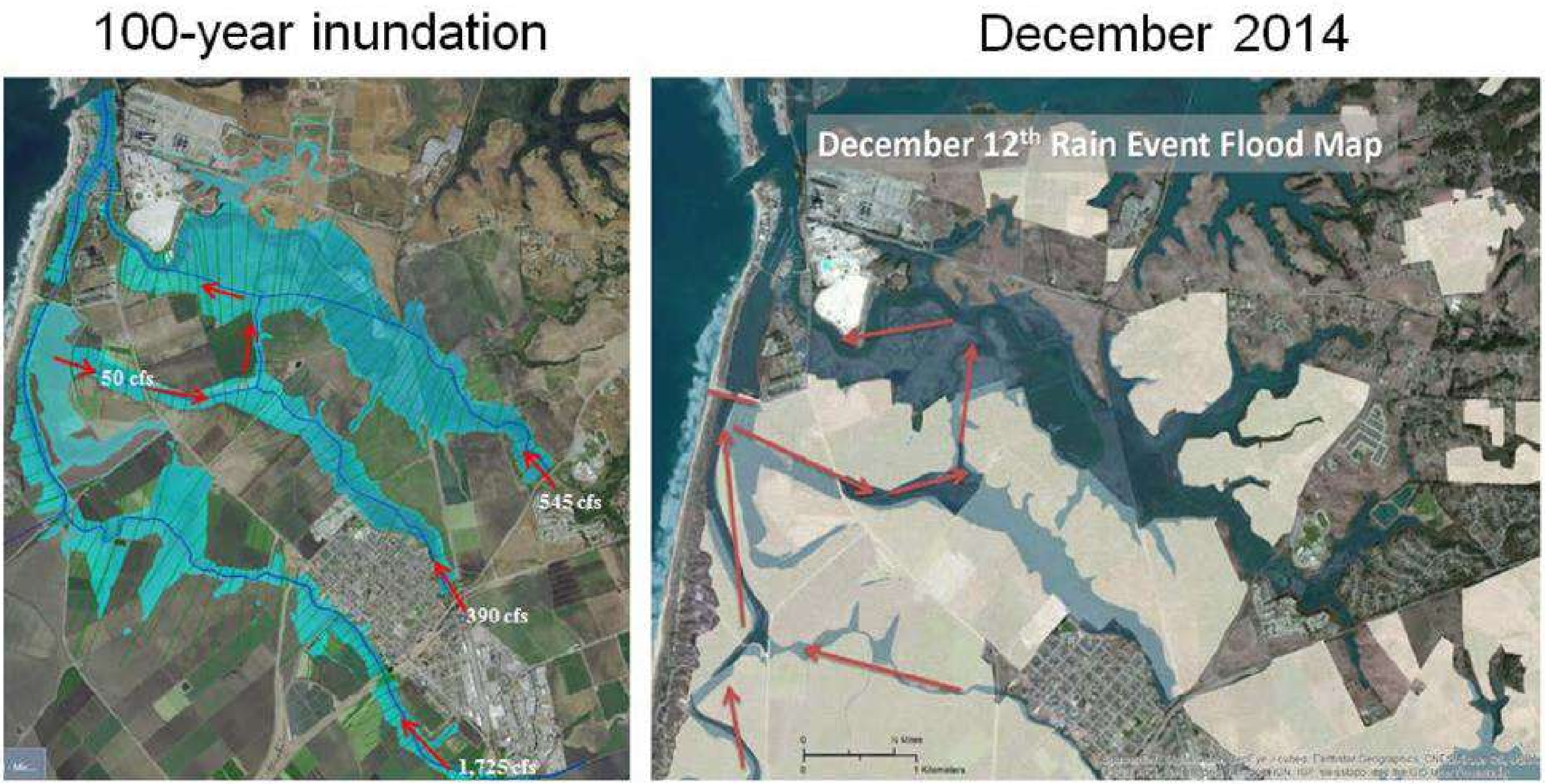
These modifications to establish community use and transportation infrastructure, contributed to changes in the dominant tidal hydrodynamic and geomorphological patterns in Elkhorn Slough. The severe reduction in sediment sources to the Slough, and permanent, deeper, wider opening, have resulted in a net sediment export. These phenomena drive marsh dieback and dramatic changes of estuarine habitats with Elkhorn Slough losing approximately 77% of its healthy vegetated salt marsh during the twentieth century (Van Dyke and Wasson 2005). Since 1971, major conservation efforts spearheaded by the by the Nature Conservancy (TNC), Elkhorn Slough Foundation (ESF), the Elkhorn Slough National Estuarine Research Reserve (ESNERR), California Department of Fish and Wildlife (CDFW), and other groups have led to ongoing conservation, wetland management and marsh restoration projects throughout the Slough, such as the Hester Marsh Restoration.

Modifications to drainages include multiple tide gates and leveed channels, which have modified but not alleviated flood risks, including flood risks to Highway 1. Riverine flooding occurs in the southern section of the study area, affecting Highway Reaches 3 and 4, via the Reclamation Ditch (Gabilan Creek). The 100-year river flood modeling is consistent with flood limits experienced in December 12, 2014 when flood waters flowed across Reach 4 to Moro Cojo Slough and past Reach 3, through Moss Landing Harbor and to Elkhorn Slough as shown in **Figure 7** (CCWG 2017; ESA 2016).

3.3 Topography and Bathymetry

As part of an existing conditions review, ESA gathered latest available topography and bathymetric information for the study area and merged them in ArcGIS 10.6 for a single elevation dataset. The sources ranged from elevation information collected via Light Detection and Ranging (LiDAR) to backscatter to capture shallow estuarine bathymetry within Elkhorn Slough. **Figure 8** shows elevations from the combined dataset. This dataset informed model inputs for the Delft3D hydrodynamic modeling, as part of the evaluation of the adaptation scenarios (Section 6.3).

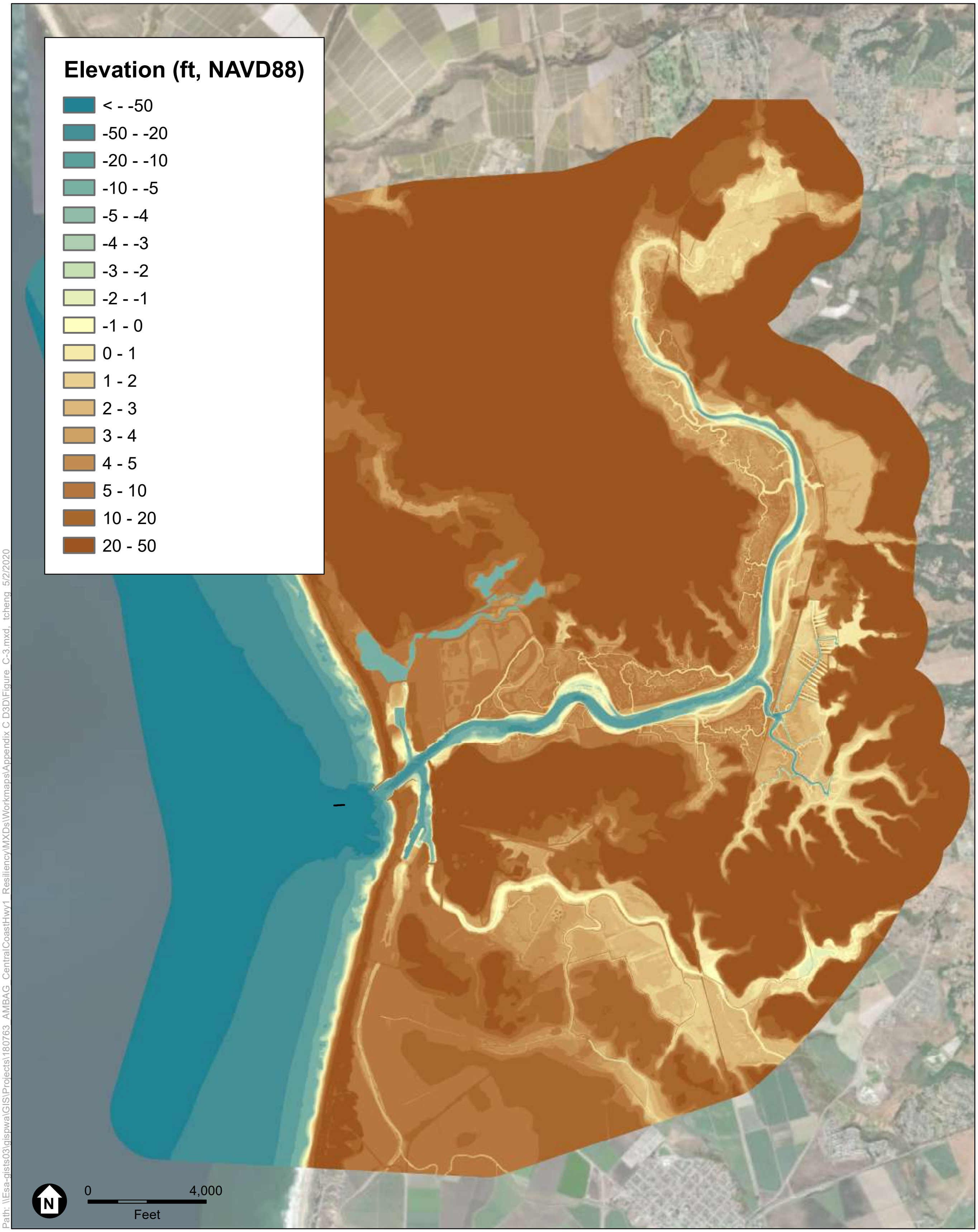
Table 2 lists elevations of key transportation infrastructure and habitats within the study area. Wetland habitats are described in terms of tidal datums, which is a reference elevation of sea level established over the National Tidal Datum Epoch. Tidal datums vary geographically and related to geodetic datums by a conversion factor established by a geodetic survey at the tide gauge location. Mean lower low water (MLLW) is defined as the lowest of the two low tides per day. Mean high water (MHW) represents the average of all daily tidal high water heights. Mean Higher High Water (MHHW) refers to the average height of the daily highest tide. Tidal elevations at the site are defined in Section 3.5.1.



Comparison of Modeled 100-year flowpaths and observed flowpaths during December 2014 flood

SOURCE: ESA (2016)

Central Coast Highway 1 Climate Resiliency Study
Figure 7
Reclamation Ditch (Gabilan Creek) Flood Flow Routing



SOURCE: USGS (2017), CSUMB (2011), CCWG (2019)

Central Coast Highway 1 Climate Resiliency Study

Figure 8
Elevations (Topo-Bathymetry) within Study Domain

TABLE 2
KEY ELEVATIONS OF FEATURES WITHIN STUDY AREA

Location	Min. Elevation (ft, NAVD88[a])
Highway 1	
Reach 1	7.6
Reach 2	8.9
Reach 3	8.8
Reach 4	9.0
Railway	5.5
Elkhorn Slough	Tidal Elevations
Mudflat	MLLW to MHW
Tidal Marsh	MHW to MHHW

NOTES:

a. NAVD stands for North American Vertical Datum (1988), which is a commonly used geodetic vertical datum. Water level (tidal) datums vary geographically and are typically related to land datums using geodetic surveys at tide gauges.

3.4 Transportation

This section describes existing conditions for major transportation infrastructure through Moss Landing and Elkhorn Slough and data sources collected by the Project Team.

3.4.1 Roadway

The study examines a 5 mile stretch of Highway 1 through the community of Moss Landing and Elkhorn Slough, which is segmented into 4 “reaches” which are low-lying and potentially vulnerable to flooding and future inundation. Present day Highway 1 is a 2-lane roadway facility needing major upgrades to improve safety, travel time and overall transportation function. Characterizing existing conditions for the highway is key to identifying relevant opportunities and constraints for developing adaptation strategies. AMBAG and Caltrans District 5 staff provided numerous reports related to existing transportation conditions and the associated opportunities and constraints.

A large portion of residents in the area commute to jobs outside the region via Highway 1. Major sectors in the region that require highway use and reliable connectivity include tourism, agriculture, education, military and the government. The 2040 Metropolitan Transportation Plan/Sustainable Communities Strategy (MTP/SCS) predicts population growth up to 883,300 in the Monterey Bay area, a 16% increase from existing conditions (AMBAG, 2018). Additionally, a significant rise in freight movement in the Central Coast is anticipated (AMBAG, 2012). As the number of roadway users increase in the future, the potential for worse congestion and greater number of collisions also rises. The Caltrans Transportation Concept Report (TCR) (2017) states that the route concept for Segment 6, which is the study area, is to maintain 2 to 5 lanes and minimize and consolidate highway access points.

The Caltrans TCR also recommends increasing shoulder widths as necessary for cyclists. TAMC and the Santa Cruz County Regional Transportation Commission (SCCRTC) are developing a Monterey Bay Sanctuary Scenic Trail, which will pass through Moss Landing. A Class I Bikeway, which provides bicycle and pedestrian travel on a right-of-way separate from a street or highway, is planned for the segment of Highway 1 by the bridge crossing. The bike trail is planned to be 12 feet wide and would start at the intersection of Moss Landing Road and Highway 1, running parallel and west of Highway 1 heading north, and crossing the existing highway bridge (TAMC, 2008), as shown in **Figure 9**.

Caltrans supplied data for Highway 1 between mile posts 90 and 102 in Monterey County. Types of information included –as built drawings, Bridge Inspection Records Information System (BIRIS) files for Elkhorn Slough Bridge, documentation of road or drainage modifications in the last decade, accident data, geotechnical reports, detour route information, road closure/impact data from flood events, boring logs, and descriptions of any planned roadway modifications and schedule. According to Caltrans, there is no record of road closures from flooding nor formal detour routes specified during extreme precipitation events.

3.4.2 Railway

The existing railroad infrastructure (tracks, fill embankment, bridges) was first built in the early 1870s, as an extension of the Southern Pacific Railroad, dividing the main stem of Elkhorn Slough from marshlands to the east (e.g. Azevedo Ponds, North and Estrada Marsh complexes), which reduced tidal exchange. Agricultural land use, including cattle grazing, in the area have led to numerous installations of hydraulic structures underneath the railroad in an effort to control water levels landward of the railway embankment. Details of these hydraulic structures have been collected as part of the existing data collection (Section 3.5.2 Hydraulic Structures).

The existing railway is owned and operated by Union Pacific Railroad. Other existing and future operators include Amtrak and Caltrain. Presently, Amtrak operates the Coast Starlight, which provides rail service from Los Angeles, CA to Seattle, WA, with a stop at Salinas, CA. The Monterey County Rail Extension project developed by TAMC will extend commuter rail service from Santa Clara County to Salinas through the railway corridor through Elkhorn Slough.

Union Pacific was not involved in the development of this study. Several attempts to establish communication with Union Pacific were made through the duration of the study in order to obtain design drawings and other relevant information; no reply was received. The Project Team was able to gather railway dimensions (e.g. widths), elevations and conditions from Google Earth, best available LiDAR and site photos.

Source: Transportation Agency of Monterey County (TAMC) (2020)

Central Coast Highway 1 Climate Resiliency Study

Figure 9

Monterey Bay Sanctuary Scenic Trail

Proposed Bike Trail Alignment

3.5 Hydraulics & Hydrology

3.5.1 Tides

Water levels within Moss Landing Harbor and Elkhorn Slough are driven by ocean water surface fluctuations. Typically, water surface fluctuations are influenced by astronomical tides, which result from gravitational forces between the earth, moon and sun. The National Oceanographic and Atmospheric Administration (NOAA) maintains the Monterey tide gage (NOAA Station #9413450). The station began operations in November 1973. **Table 3** shows the tidal datums at the Monterey tide gauge.

TABLE 3
TIDAL DATUMS AT THE NOAA MONTEREY TIDE GAGE (STATION #9413450)

Datum	Elevation (ft, NAVD88)
Mean Higher High Water (MHHW)	5.20
Mean High Water (MHW)	4.50
Mean Sea Level (MSL)	2.69
Mean Low Water (MLW)	0.95
Mean Lower Low Water (MLLW)	-0.14

Tides from Monterey Bay are modified as they propagate through the Slough, due to bottom bathymetry, friction and interaction with irregular shorelines. Specifically, tidal amplitude and phasing are muted as they travel further up the main channel of the Slough.

ESNERR maintains a system of gauges throughout the Slough, the data from which are accessible via the NERR Centralized Data Management Office. Data collected include hourly measurements of salinity, temperature, water level, pH, turbidity and other parameters. The closest station to Highway 1 is the Vierra Mouth station, approximately 1500 ft east of the bridge, with observations dating back to 2001. The Monterey Bay Aquarium Research Institute (MBARI) also operates the Land/Ocean Biogeochemical Observatory (LOBO) network, which provides additional information about water levels and water quality around the Slough.

Several King Tide events, which refer to the highest predicted high tide event, have occurred since the beginning of the Study, resulting in flooding along the railway (**Figure 10**).

SOURCE: ESF (2019)

Central Coast Highway 1 Climate Resiliency Study
Figure 10
January 2019 King Tide
Railway Flooding

3.5.2 Hydraulic Structures

ESA conducted a culvert survey in November 2018 to verify the location and condition of culverts located under Highway 1 in the study area and collect structure specifications (e.g. diameter, invert elevation, material). Additionally, ESNERR and the Central Coast Wetlands Group (CCWG) provided data for known hydraulic structures throughout the Slough and by the railway embankment. These data were one of the model inputs into the Delft3D hydrodynamic modeling that is part of the evaluation of adaptation scenarios. Further information on hydraulic structure data collected can be found in Appendix A.

3.6 Sea Level Rise

The study requires calculations of damages and changes for a range of future physical conditions driven primarily by sea level rise. This text describes an approach to both build upon prior work, conform to California's most recent (2018) guidance, and support Center for Blue Economy's (CBE) probabilistic economics analysis.

The best available modeling of future coastal hazards for the study area is provided by the Coastal Resilience Monterey Bay mapping (ESA, 2014). This work was accomplished prior to the most recent California guidance (CalNRA & OPC, 2018; CCC 2018; OPC; 2020) as discussed below.

Discrete Sea Level Rise Scenarios

The Coastal Resilience Monterey Bay (CRMB) future hazards mapping (ESA 2014) was used in this study because it is the best available and it is also being used for vulnerability assessments and adaptation planning by nearby communities including Moss Landing (CCWG 2017) and the Moss Landing Harbor District Vulnerability and Adaptation Strategy (CCWG 2019). CRMB projections were developed using the guidance in effect at the time, produced by the National Research Council for the Pacific States (ESA, 2014; OPC, 2013; NRC, 2012) and are thereby consistent with California's 2013 guidance. The time horizons and sea level rise amounts are summarized in **Table 4** (ESA, 2014).

TABLE 4
SEA LEVEL RISE SCENARIOS USED FOR COASTAL RESILIENCE MONTEREY BAY (ESA, 2014; TNC, 2015)

Year	Low SLR	Medium SLR	High SLR
2030	0.1 ft	0.33 ft	0.73 ft
2060	0.5 ft	1.1 ft	2.4 ft
2100	1.3 ft	2.9 ft	5.2 ft

California updated its guidance in 2018 (CalNRA & OPC, 2018; CCC 2018) based on an updated assessment of climate change science (Griggs et al, 2017). This guidance provides probabilities for particular sea level rise amounts and defines sea level rise amounts for selected levels of risk tolerance. This substantial update can be cross-walked with the prior California guidance (OPC, 2013): Sea level rise curves derived from the existing guidance (2018) and prior guidance (2013) are plotted in **Figure 11**.

The updated (2018) Medium-High Risk Aversion sea level rise amounts are similar to the High Sea Level Rise amounts from the prior guidance (2013). Similarly, the 2018 Low Risk Aversion is similar to the Medium Sea level Rise amounts (2013). Consequently, the Project Team used the available hazards from the Coastal Resilience Monterey Bay, high projection sea level rise curves (Section 6.2 Flood Hazards), to develop the adaptation scenarios.

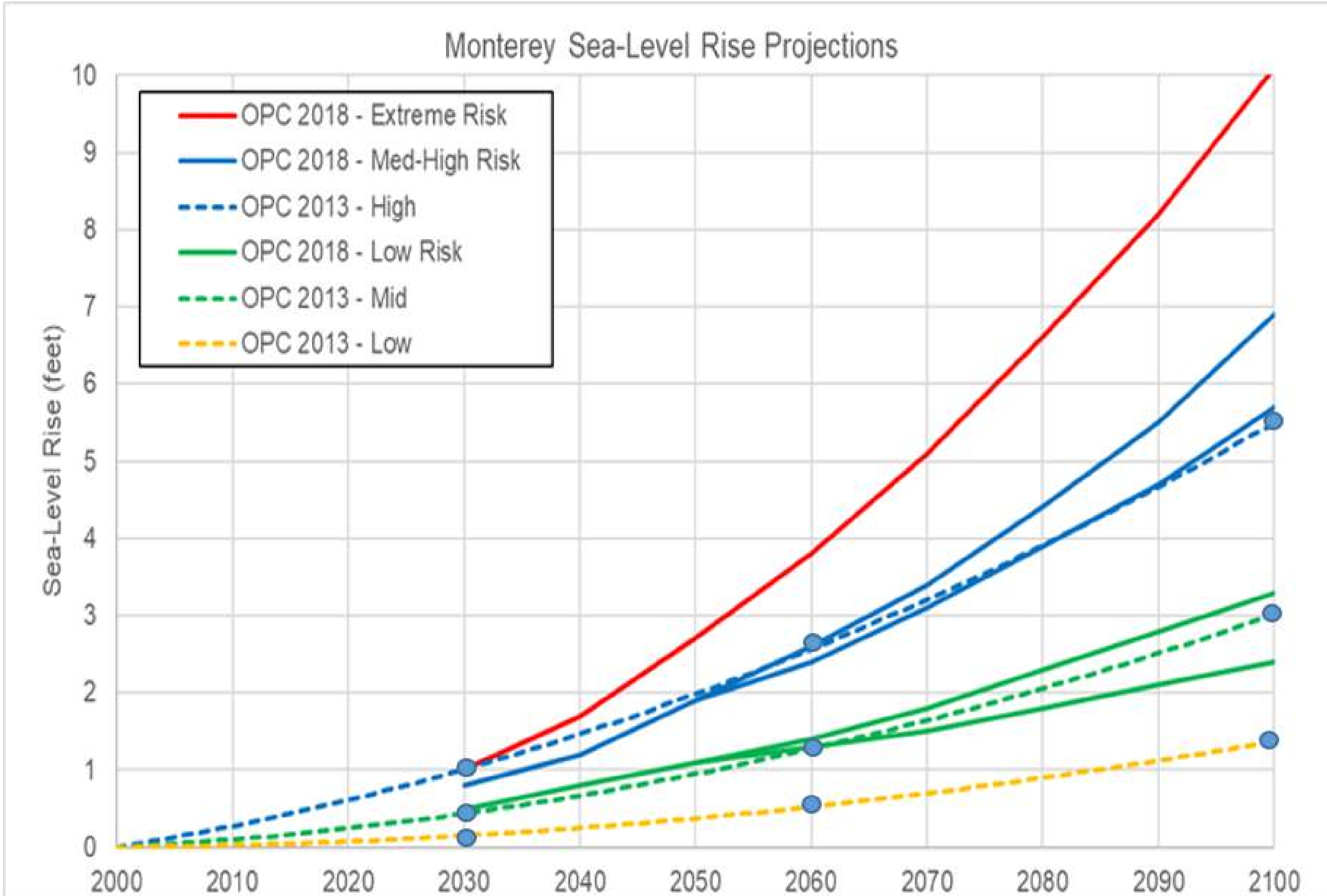
Results from the high sea level rise scenario (**Table 4** High SLR) for discrete time horizons (**Table 4** 2030; 2060; 2100) were then used by CBE to quantify the probabilistic analysis (Section 6.5.3). The probabilities used are consistent with the most recent California guidance (CalNRA & OPC, 2018; CCC 2018). The probabilities are estimates of the likelihood of a particular sea level being reached in any given year: Hence the probabilistic analysis is not constrained by the time horizons in **Table 4**, nor is it constrained by State guidance regarding the appropriate risk-tolerance (e.g. medium-high risk aversion level or the extreme H++ scenario) that otherwise may apply to this Highway 1.

Implications of CRMB Relative to 2018 and 2020 State Guidance

We interpret the 2018 State guidance to indicate a *medium-high risk aversion* scenario is the minimum consideration for significant infrastructure. Consideration of the extreme sea level rise scenario (called *H++*) is also appropriate for major infrastructure. **Table 5** compares the High SLR from CRMB to the medium-high risk aversion and H++ for Monterey (Table G-6 CCC, 2018 based on CalNRA & OPC, 2018). As shown in **Table 5** and **Figure 11**, the CRMB High scenario tracks similarly to the 2018 Medium-High Risk Aversion low emission scenario but diverges from the Medium-High Risk Aversion high emission scenario around 2070, and is 1.7 feet lower than this scenario by 2100. The differences with the H++ scenario are much greater, and diverge sooner.

TABLE 5
COMPARISON OF SEA LEVEL RISE SCENARIOS; COASTAL RESILIENCE MONTEREY BAY (ESA, 2014; TNC, 2015) AND UPDATED CALIFORNIA GUIDANCE (CALNRA & OPC, 2018; CCC, 2018)

	High SLR	**Medium-High Risk Aversion**	**Extreme H++**
Year	**CRMB (2014)**	**CA Guidance (2018)**	**CA Guidance (2018)**
2030	0.73 feet	0.8 feet	1.0 feet
2060	2.4 feet	2.6 feet	3.8 feet
2100	5.2 feet	6.9 feet	10.1 feet



● Blue circles represent scenarios mapped by Coastal Resilience Monterey Bay.

Comparison of sea-level rise scenarios used for Coastal Resilience Monterey Bay (ESA, 2014; TNC, 2015) based on prior State guidance (NRC, 2012; OPC, 2013) and current State Guidance (Griggs et al, 2017; OPC, 2018).
For current state guidance (solid lines), the higher line is the high emission scenario (RCP 8.5) and the lower line is the low emission scenario (RCP 2.6).

SOURCE: Ocean Protection Council (2013), Ocean Protection Council (2018)

Figure 11
Monterey Sea-Level Rise Projections
OPC 2013/2018 Guidance Cross-walk

The State's just-released *Strategic Plan to Protect California's Coast and Ocean 2020–2025* (OPC, 2020) Partners states:

"*Ensure California's coast is resilient to at least 3.5 feet of sea level rise by 2050, as consistent with the State's Sea Level Rise Guidance Document as appropriate for a given location or project.* "

A comparison of the CRMB 2014 sea level rise scenarios with the 2018 Guidance and the 2020 Strategic Plan indicates that higher sea levels should be considered in future study of Highway 1 at Elkhorn Slough. This conclusion is consistent with comments received on the draft report.

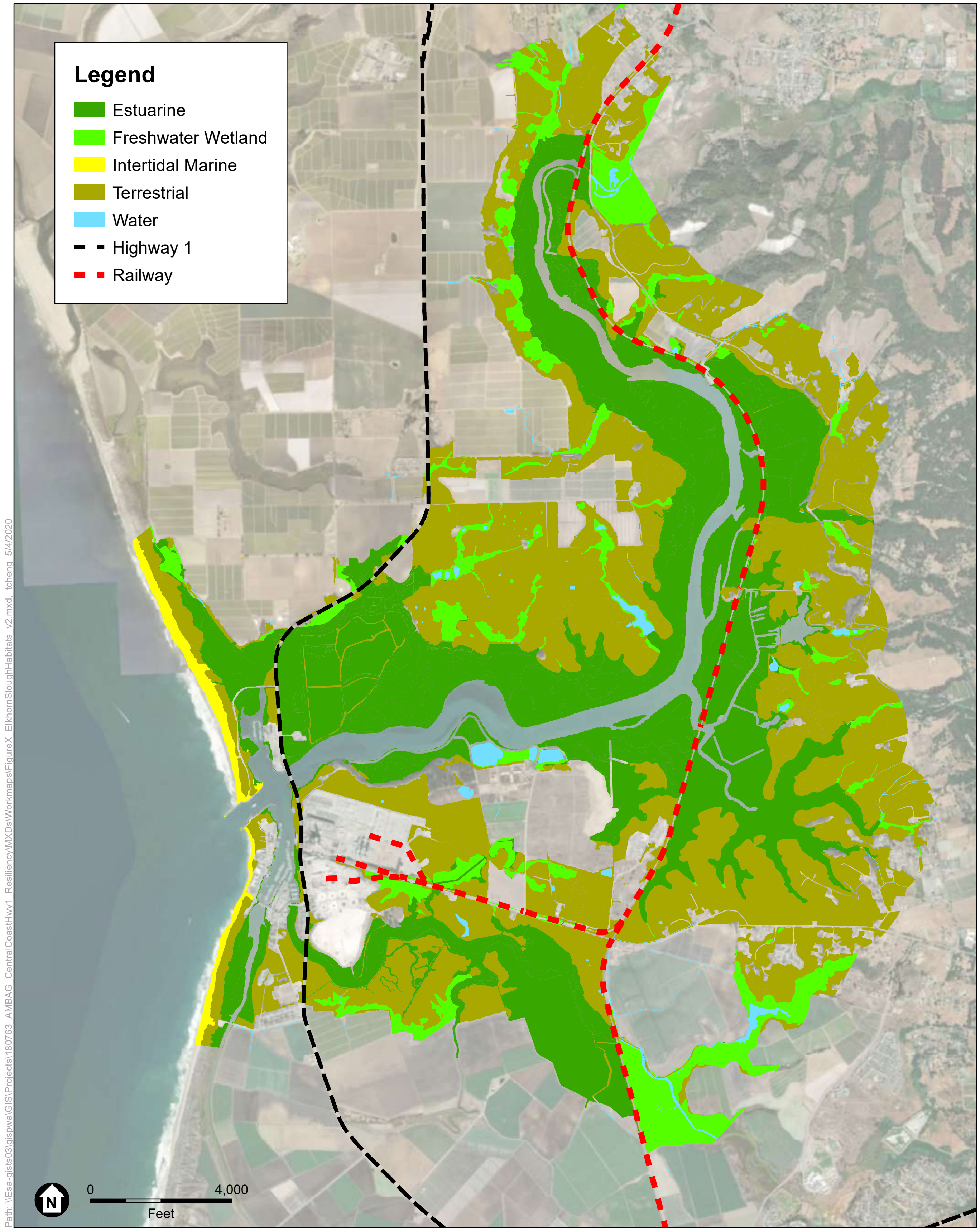
Note however that the infrastructure alternatives were conceptually configured to accommodate a 100-year flood elevation with 3 feet of sea level rise with an additional one foot of freeboard, to be implemented by 2030. These conceptual design criteria are consistent with the 2020-2025 Strategic Plan Objective 1.1 of being resilient with 3.5 feet of sea level rise by 2050.

Additional discussion regarding project parameters and scenarios selected for analysis are provided in Section 5. Adaptation Scenarios Development, Section 5.3.5 Time Horizons and Sea Level Rise Considerations and Section 6.5.3 Benefit Cost Analysis.

3.7 Ecology

Located in Monterey Bay in Central California, Elkhorn Slough is the 7th largest estuary in California. With conservation efforts beginning as early as 1971 and continuing today, the Slough is one of the least developed estuaries of this size, preserving great extents of open space and diverse habitats. With nearly 2,700 acres of a variety of intact habitat types, including a wide range of estuarine habitats (e.g. salt marsh, tidal brackish marsh, mudflat), the Slough is critical to regional biodiversity. **Figure 12** shows simplified general habitat types throughout the Slough. There exists a diversity of different habitat types within each of the major habitat types mapped in **Figure 12.** Estuarine habitats occur on regularly and irregularly flooded areas along the shoreline; different types of wetland habitat can be found across the tidal elevation range (**Figure 13**). Elkhorn Slough contains the 3rd largest tract of tidal marsh in California.

The relatively vast extents and high diversity of habitats throughout Elkhorn Slough provide critical habitat for a diversity and abundance of species. The Slough supports over 500 species of invertebrates, supporting food webs for marine and terrestrial birds, fish, and mammals. Estuarine waters of Elkhorn Slough provide nursery habitat for many imperiled and commercially important species (Hughes et al. 2014; Hughes et al. 2015), which also provide food for birds and mammals. Over 20,000 migratory shore birds use the marshes, mudflats, and waters of Elkhorn Slough as resting and feeding grounds as they migrate along the Pacific Flyway. Elkhorn Slough is an Audubon Important Bird Area supporting high diversity, high abundance of birds, imperiled species, and is of



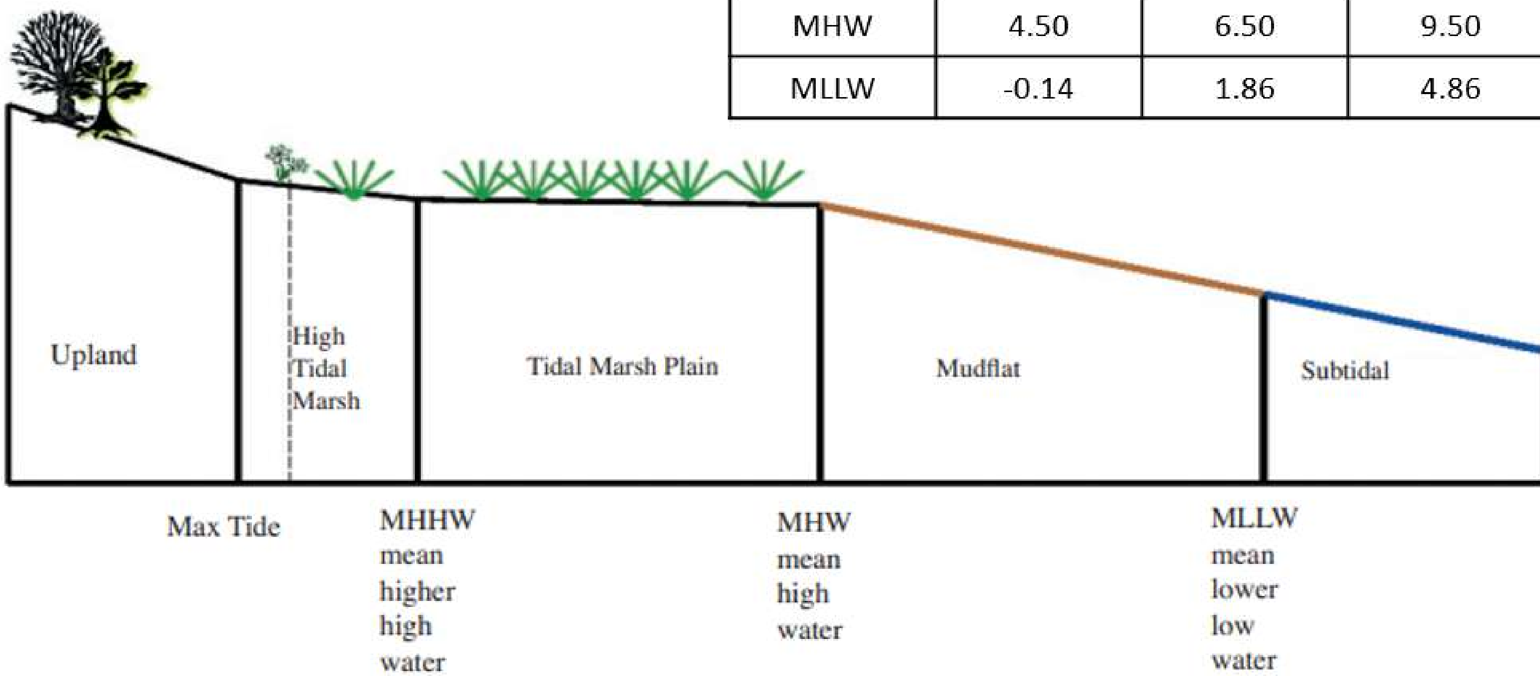
Source: The Nature Conservancy, CA State Coastal Conservancy (2017)

Central Coast Highway 1 Climate Resiliency Study

Figure 12
Study Area Habitat Classification

ESA

	Elevation (ft NAVD)		
	Existing Conditions	**+2 ft SLR [2050]**	**+5 ft SLR [2100]**
Max Tide	7.74	9.74	12.74
MHHW	5.20	7.20	10.20
MHW	4.50	6.50	9.50
MLLW	-0.14	1.86	4.86



Note: Tidal datum elevations from NOAA Monterey (Station #9413450) tide gauge.

SOURCE: Design Guidelines for Tidal Wetland Restoration in San Francisco Bay (PWA and Faber, 2004), Elkhorn Slough Tidal Wetland Project Team (2007)

Figure 13

Vertical Profile of Estuarine Habitat

global importance. Elkhorn Slough has also played a unique role in the recovery and maintenance of southern sea otters with over 100 otters using the Slough year-round.

The great abundance and diversity of life throughout Elkhorn Slough lends the slough to be prized by local community members and visitors from around the world. Tens of thousands of visitors come from around the world to tour the waters, kayak, or walk the shores and hills for spectacular birdwatching and otter viewing opportunities. Elkhorn Slough is a hub and center for scientific research, and provides valuable education opportunities serving thousands of students each year.

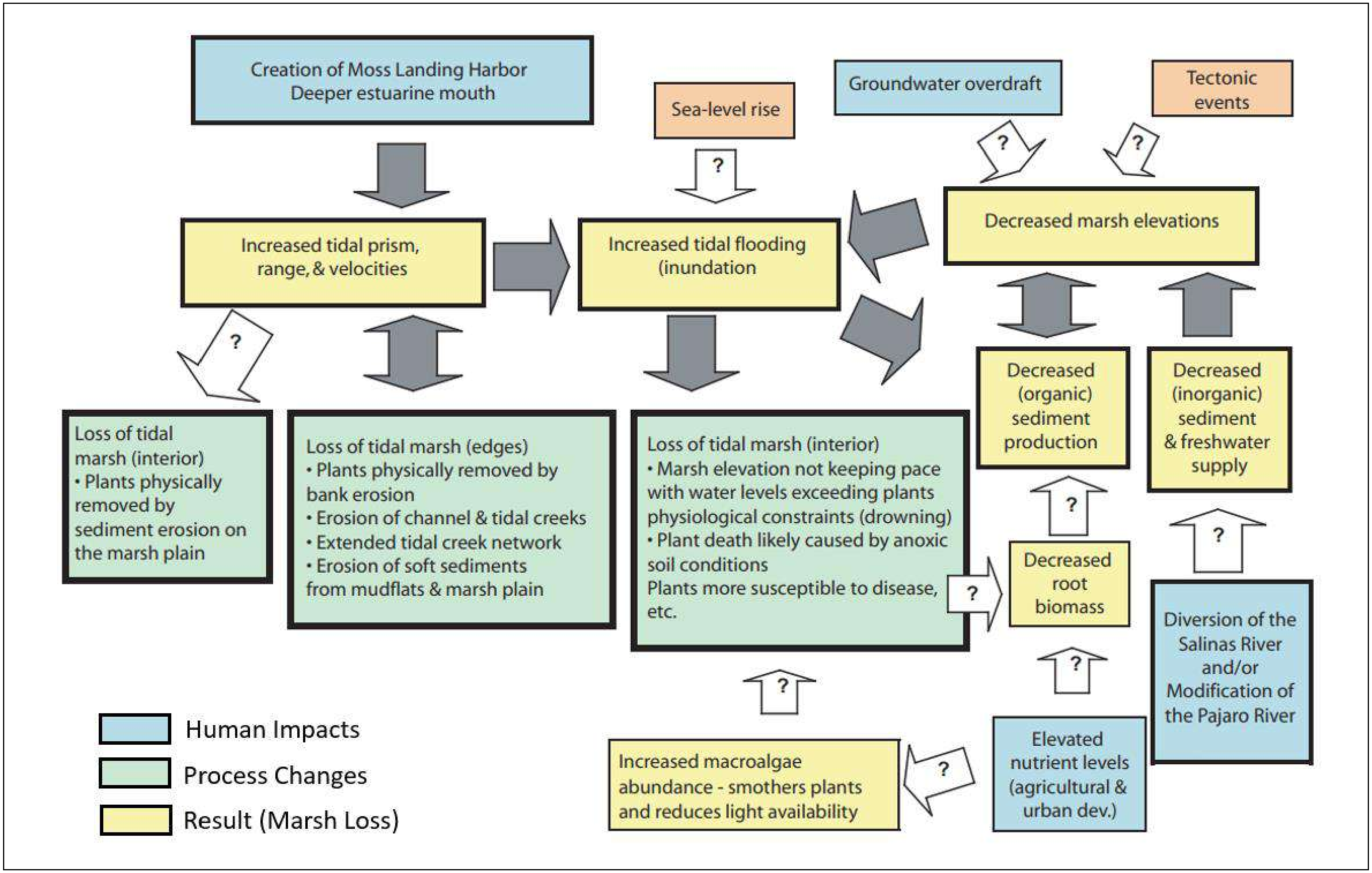
Large-scale human modifications from the construction of transportation infrastructure, development and agricultural operations around the Slough since the late 1800s resulted in a number of adverse habitat impacts, including persistent marsh loss, habitat erosion and degradation, water pollution and eutrophication. Moreover, these changes have altered the hydrology and geomorphology of the system, which in turn impact estuarine habitats (**Figure 14**). The re-location of the Slough mouth and construction of the Moss Landing Harbor jetties have increased tidal velocities in the main channel of the Slough. In conjunction with decreased sediment supply to the Slough over the last century, this has resulted in the Slough experiencing net sediment export and bank erosion along wetland complexes. Modifications to Slough hydrology that increase tidal prism (i.e. the volume of water that is drained during a tidal cycle), including sea level rise, are predicted to exacerbate this trend (Elkhorn Slough Tidal Wetland Project Team, 2007).

Tidal estuarine habitats within the Slough and the ecosystem services they provide are at risk to substantial degradation and losses with sea level rise without concerted action. With Central California already having lost over 90% of its historical estuarine marsh habitat area (Brophy et al. 2019), every effort is needed to maintain the remaining 10% in the face of sea level rise. Presently, Elkhorn Slough holds the third largest extent of estuarine marsh in California, however, approximately 85% of this area is vulnerable to degradation and transfer to open water due to sea level rise unless concerted action is taken. Thus, maintaining or enhancing the extent of estuarine marsh in this well conserved estuary is an important priority.

Extensive efforts have been undertaken by conservation groups, local and state agencies, and community stakeholders to restore marsh habitat in the Slough over the past several decades. This planning-level study seeks to identify opportunities to strengthen ecological resilience as part of improvements to transportation facilities.

Several major wetland complexes are located adjacent to the roadway and railway, with varying histories of human modification and existing management. These are referenced throughout the study report and are described briefly below.

- *Struve Pond/Bennett Slough Wetland Complex:* Struve Pond and Bennett Slough are located adjacent to Highway 1 Reaches 1 and 2, northeast of the Slough mouth. Habitats found here range from salt marsh, tidal flats, tidal brackish marsh and



SOURCE: Elkhorn Slough Tidal Wetland Project Team (2007)

Central Coast Highway 1 Climate Resiliency Study

Figure 14

Conceptual Model of Major Mechanisms of Marsh Loss

Elkhorn Slough

freshwater ponds. Highway construction in the early 1930s led to the existing configuration where culverts were installed underneath the road embankment between Struve Pond and Upper Bennett Slough, and between Lower and Upper Bennett Slough. Subsequent construction of the Moss Landing Harbor mouth in 1947 and Jetty Road significantly reduced tidal exchange to this area.

- *Moss Landing Wildlife Area (Salt Ponds):* The managed salt ponds portion of the Moss Landing Wildlife Area is approximately 153 acres of former salt marsh that were diked/leveed for salt production. The ponds are currently managed by California Department of Fish and Wildlife (CDFW) and act as valuable nesting and breeding habitat for the Western Snowy Plover, wintering waterfowl and shorebirds.
- *Azevedo Ponds:* The Azevedo Ponds wetland complex (20 acres total) are a series of three wetland areas (North, Middle and Southern) located on the eastern side of Elkhorn Slough. These wetlands are separated from the main channel by the railway fill embankment and experience limited tidal exchange due to the installation of hydraulic control structures.
- *North/Estrada Marsh Complexes:* The North/Estrada Marsh complexes are historic salt marsh and tidal creek habitat located on the eastern side of Elkhorn Slough. They are presently separated from the main channel of the Slough by the existing railway embankment, which reduces tidal exchange to the site. Conversion of the wetlands to pasture land has resulted in subsidence through the complex. The installation of tide gates in 1986 introduced tidal connectivity back to the wetlands. Currently, the area is characterized by mudflat and estuarine open water habitat, with salt marsh along the fringes.
- *Parsons Slough:* The Parsons Slough wetland complex (429 acres) is located in the southeastern area of Elkhorn Slough. Prior to human modification, this area was characterized by estuarine marsh and tidal creeks. The wetland has experienced subsidence due to diking and draining from historic conversion of the habitat for grazing. Since the average elevation of the complex cannot support marsh vegetation, large portions of the complex are comprised of unvegetated mudflat, with tidal marsh and subtidal creek habitats distributed along the fringes.

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CHAPTER 4

Strategies for Resilience – Using Adaptation Pathways

4.1 Adaptation Pathways

The adaptation scenarios developed within this study are presented in a pathways approach to account for uncertainty around climate change decision-making. An adaptation pathways approach enables consideration of multiple possible futures and allows for analysis of the robustness and flexibility of a range of adaptation scenarios (Haasnoot, 2013). Determining a sequence of short-, medium- and long-term actions can assist stakeholders in identifying opportunities and/or constraints that may arise in the future. Additionally, by considering a wide swath of potential futures, planners can identify when an option or pathway will shut down future options and adjust as needed. An adaptation pathways framework was used throughout the study process to develop and communicate the adaptation scenarios internally and externally.

Based on projected future hazards using the high sea level rise scenario, Highway 1 and the Railway in the vicinity of Elkhorn Slough/Moss Landing are at risk of flooding as early as 2030 and likely flooded so frequently by 2050 as to lose functionality (Section 6.2 Flood Hazards), indicating substantial capital investment as early as 2030 is desired to initiate planning, environmental and regulatory review, design and construction. The hazard maps also indicate that much of the developed areas and agricultural areas would be frequently inundated after about 3 feet of sea level rise, which could occur by year 2070. Hence, the adaptation pathways and study scenarios were focused on substantial action to maintain transportation function for at least 3 feet of sea level rise, which is expected to be resilient through 2070 for the CRMB high sea level rise scenario used for planning (Section 3.6 Sea Level Rise). Also, another round of substantial capital investment would be needed for sea levels greater than 3 feet higher than today, but with potentially very different land uses and needs. Given these probable impacts and an Adaptation Pathway approach the phases considered in this study are:

- Phase 1 - Up to 2030: Near term/Maintenance Strategy (0-10 years) (See Section 4.3 Near-Term Actions)
- Phase 2 - 2030 to 2070: Accelerated (as early as 2030) long-term capital investment (Beyond 20-30 years) to upgrade transportation infrastructure to be resilient for at least 3 feet of sea level rise

- Phase 3 - 2070 and beyond: Long-term capital investment for more than 3 feet of sea level rise, to be determined

The above phasing led to an adaptation pathway framework identified in Section 6.4 Refined Roadway and Railway Scenarios, shown schematically in **Figure 34**.

It is acknowledged that other adaptation pathways are worthy of evaluation and may be preferred. Reviewers noted that it may not be feasible to initiate roadway rehabilitation by 2030, and it may not be economically viable for a large investment to have a functional life of potentially less than 50 years and or 3 feet of sea level rise.

It is also acknowledged that planning documents are just beginning to address the future challenges of sea level rise (Section 4.2 Community Climate Change Adaptation Planning), and there are many elements that need further attention. For example, it is unlikely that the existing railway can maintain function with near-term sea level rise but no planning document to address adaptation to sea level rise is available. Regional rail planning by TAMC/Santa Cruz Regional Transportation Commission for expanded rail service including passenger rail service has been ongoing, as part of the Monterey County Rail Extension Project. Also, future transportation demand projections extend 30 years into the future, and do not consider the effects of sea level rise (See Sections 6.3.2 Preliminary Transportation Modeling and 6.5.2 Transportation Modeling for Revised Scenarios). In addition, the existing Local Coastal Plan does not include expansion of Highway 1 along its existing alignment (Monterey County Resource Management Agency, 1988). An update to the Moss Landing Community Plan and Local Coastal Plan is under development (Monterey County Resource Management Agency, 2017). Therefore, it is expected that additional analysis including revised scenarios and parameters will be needed to effectively adapt.

4.2 Community Climate Change Adaptation Planning

Local and regional planning is currently ongoing to address sea level rise and climate change at Moss Landing and Elkhorn Slough. Representatives from organizations working or worked on these various planning efforts served on the Steering Committee to ensure consistency and expert perspectives were integrated into this study where possible. The below provides a brief summary of ongoing (or recently completed) planning at the time of study:

- *Moss Landing Community Plan* - the Moss Landing Community Plan and Coastal Implementation Plan, which are components of the Monterey County Local Coastal Program, are currently being updated. As this planning effort was advancing in parallel with this study, representatives from Monterey County served on the Steering Committee through the entire duration of the study to ensure consistency with any developments.

- *Elkhorn Slough Tidal Wetland Program (TWP)* – The Elkhorn Slough TWP is led by ESNERR and convenes a number of stakeholders and scientists to develop and implement strategies to conserve and restore estuarine habitats within the Slough. The TWP has recommended various approaches for restoration efforts, including restoring subsided marsh by sediment placement and increasing tidal connectivity to wetlands behind water control structures. Recent projects undertaken by TWP have included the Hester Marsh restoration and Parsons Slough Project.
- *Moss Landing Harbor Sea Level Rise Vulnerability and Adaptation Strategy Assessment* - CCWG conducted a vulnerability assessment for the Moss Landing Harbor District and identified critical coastal infrastructure at risk by 2030, 2060 and 2100 and a range of adaptation strategies for the Moss Landing community. The report predicts that monthly tidal flooding by 2060 will be significant, with major impacts to the infrastructure and commercial areas in the North and South Harbors. Additionally, large areas of intertidal marsh and beach habitat are projected to convert to subtidal habitats by mid-century. Beach and dune nourishment are identified as a potential mitigation/adaptation measure to address vulnerabilities to the existing infrastructure at Moss Landing Harbor.

4.3 Near-Term Actions

Since the adaptation scenarios developed in this study are meant to be implemented in the long-term (several decades from present day), a range of near-term (i.e. the next few years to decades) maintenance/operational actions and ecological enhancements are identified to increase transportation and habitat resilience in the interim. These are informed by a review of the existing condition of transportation infrastructure, strategies identified by community climate change adaptation planning, and ongoing conservation efforts around Moss Landing and Elkhorn Slough. These proposed actions include:

- Raising the roadway facility in low-lying areas by regrading, reconstruction
- Outer coast dune enhancements to protect Moss Landing Harbor from wave overtopping
- Increasing hydraulic conveyance (e.g. culvert replacement and modifications) to decrease flooding impacts
- Operational restrictions on railway when water levels are elevated
- Strategic planning for marsh restoration projects throughout and around Elkhorn Slough
- Land acquisition for marsh migration and restoration

Some of these actions, such as planning for marsh restoration around the Slough, have been in progress for decades prior to this study. Other actions are being considered in other community plans, such as coastal dune enhancement and restoration (Central Coast Wetlands Group, 2017). They are included to further underline the importance of continuing these efforts to preserve valuable coastal habitat as sea levels rise. Other actions, such as restricting the use of the railway during king tides and storm events which is presently accomplished by Union Pacific[5], will need to be implemented more often as water levels rise and the frequency of disruption to transportation service increases. It is also important to note that these actions are not without cost and could impact and alter ecological function in the Slough, which was not covered in the scope of this study.

5 Personal communication, ESNERR

CHAPTER 5
Adaptation Scenario Development

The following adaptation elements were developed as potential actions to enhance both the resilience of transportation infrastructure as well as surrounding habitats, in particular tidal marsh, under future sea level rise conditions. These scenarios were developed based on the understanding of existing flood hazards to roadway and railway infrastructure and surrounding ecology, as well as recent planning around floodplain management for distinct areas by Highway 1. These formed the first stage of adaptation scenario development and evaluation over Fall and Winter 2019. With Steering Committee and community input, a subset of these adaptation scenarios was further refined and evaluated through Spring 2020. This section provides a summary of this process.

It is important to note the very low elevation of Highway 1, the railway, and estuarine marsh habitats throughout the study area, and the overwhelming vulnerability of each, to modest sea level rise. This gives rise to two important realizations. Firstly, the application of ad hoc natural infrastructure to existing Highway 1 and existing railway will not provide flood protection benefits to those transportation infrastructures, nor habitat benefits. Highway 1 and the railway are in true need of adaptation – here we explore adaptation that benefits surrounding habitats. Secondly, the overwhelming potential impact to estuarine marsh habitats throughout the Elkhorn Slough area is sea level rise, and that while we explore how transportation adaptation will help mitigate degradation or loss of these important habitats, it is clear that concerted investment in other strategies such as restoration, managing in place for resilience, conservation, and investing in future potential habitat will be necessary to maintain the area and function of tidal habitats throughout the Elkhorn Slough area (Heady et al. 2018).

5.1 Transportation Adaptation and Improvement Elements

The existing transportation function of the roadway and railway are impacted by disruptions posed by flooding and constraints in capacity. The highway is also in need of other upgrades to address current issues related to safety, congestion and overall transportation function. The section below describes changes to the infrastructure that would strengthen resilience to sea level rise and improve transportation function.

5.1.1 Elevate Infrastructure on Fill and/or Piles

To adapt the transportation infrastructure to rising sea levels, the existing roadway and railway could be elevated via two methods: 1) raised fill embankment and 2) piles. An embankment entails placing and compacting a volume of earthen material (fill) in order to raise the grade of a roadway above adjacent ground surface. Embankments typically have steeper side slope ranging from 2H:1V to 4H:1V[6] extending out on either side. Where space allows, traditional engineered side slopes can be graded to a much gentler slope (up to 20H:1V) to allow for additional habitat area creation and resilience. Piles (pylons) refer to structures that support bridge or highway overpasses, typically elevating them over water. **Figure 15** shows a conceptual cross-section for a 2-lane roadway elevated on fill and/or piles.

Current planning by Moss Landing includes a Class I bike trail, as part of the Monterey Bay Sanctuary Scenic Trail Plan. The bike path trail would start at the intersection of Moss Landing Road/Highway 1 and run parallel and to the west of Highway 1 heading north and cross Elkhorn Slough west of the existing highway bridge (**Figure 9**). The proposed roadway sections, whether elevated on fill or pile, include space (approx. 12 ft) for bike and pedestrian use. Since its construction in the late 1800s, the railway through Elkhorn Slough has operated on tracks elevated on fill embankment. The present railway floods under king tide conditions, with disruptions to service until water levels return to normal[7]. To avoid more frequent disruptions to this transportation function as sea levels rise, the grade of the fill embankment could be raised higher to keep pace with water levels. Alternatively, the railway could be raised on trestle, which is an open cross-braced framework used to support an elevated structure (e.g. bridge). **Figure 16** shows a conceptual cross-section for a railway elevated on fill and/or trestle.

A key constraint for fill embankments is the weakness of the existing soils. The soil weakness will result in settlement of the fill, requiring additional fill volume to compensate for the loss of elevation. Also, fill placement will need to be carefully implemented to avoid failure and deformation of the underlying soils and embankment, and uneven settlement (called *differential settlement*) or mass movements during earthquakes. This weak soils constraint on the embankment option can likely be addressed across existing uplands but is considered not likely to be feasible for the existing railway because it is largely in the Elkhorn Slough.

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6 This notation refers to the slope of an embankment, in terms of horizontal and vertical distance (ex. 2H:1V indicates that for every 2 units of horizontal distance traveled, the elevation of a slope changes 1 unit.)

7 Personal communication, ESNERR

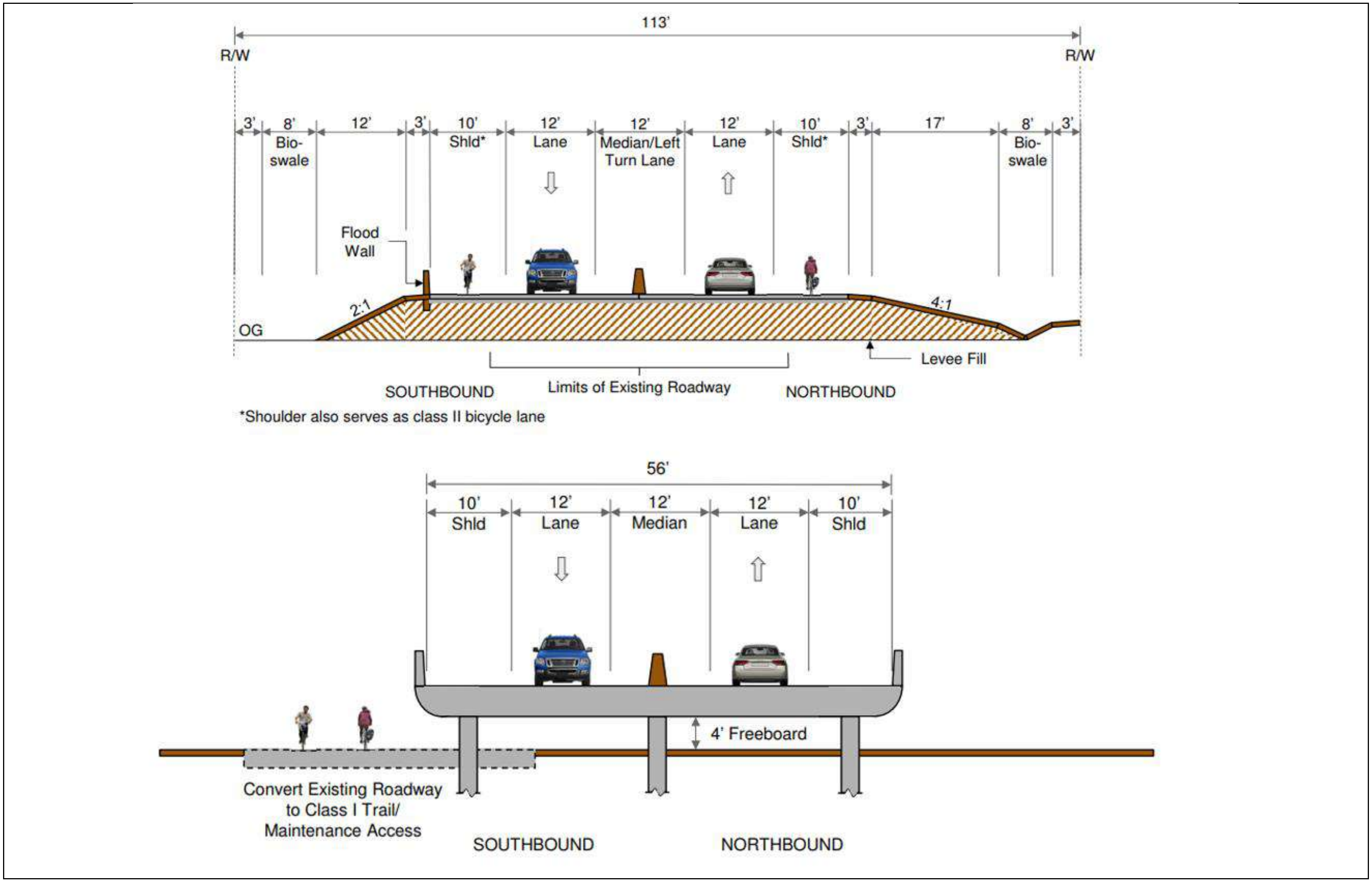


Figure 15

2-Lane Roadway Elevated on Fill (Top) or Piles (Bottom)
Conceptual Schematic

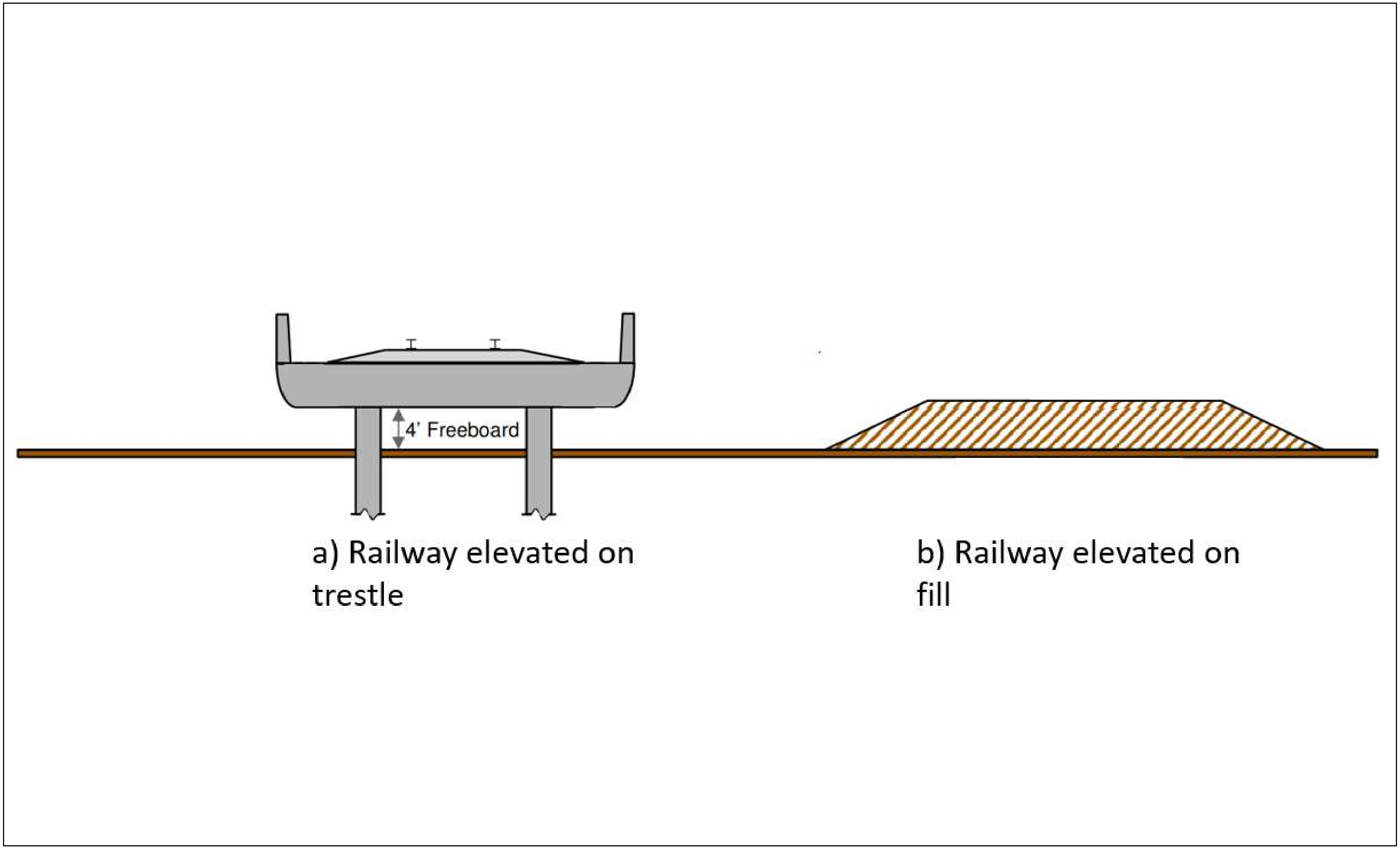


Figure 16

Railway Elevated on Trestle (Left) or Fill (Right) Conceptual Schematic

5.1.2 Widening the Roadway

The existing transportation function of the roadway does not meet the transportation demand, resulting in frequent slowdowns, delay and traffic accidents. Widening the highway facility to 4-lanes to address congestion and other transportation function parameters through the study area is included as an adaptation element. The Caltrans TCR (2017) states that the future vision for Highway 1 would be widened to 4 lanes through the Moss Landing area. Widening to a 4-lane highway would require building out a significant part of the existing alignment in multiple phases, which would have large impacts on the adjacent habitat. The roadway footprint associated with a 4-lane highway is approximately 20 acres larger compared to a 2-lane highway. **Figure 17** shows the conceptual cross-section for a 4-lane highway elevated on fill and/or piles. These sections also include future planning for a bike/pedestrian path.

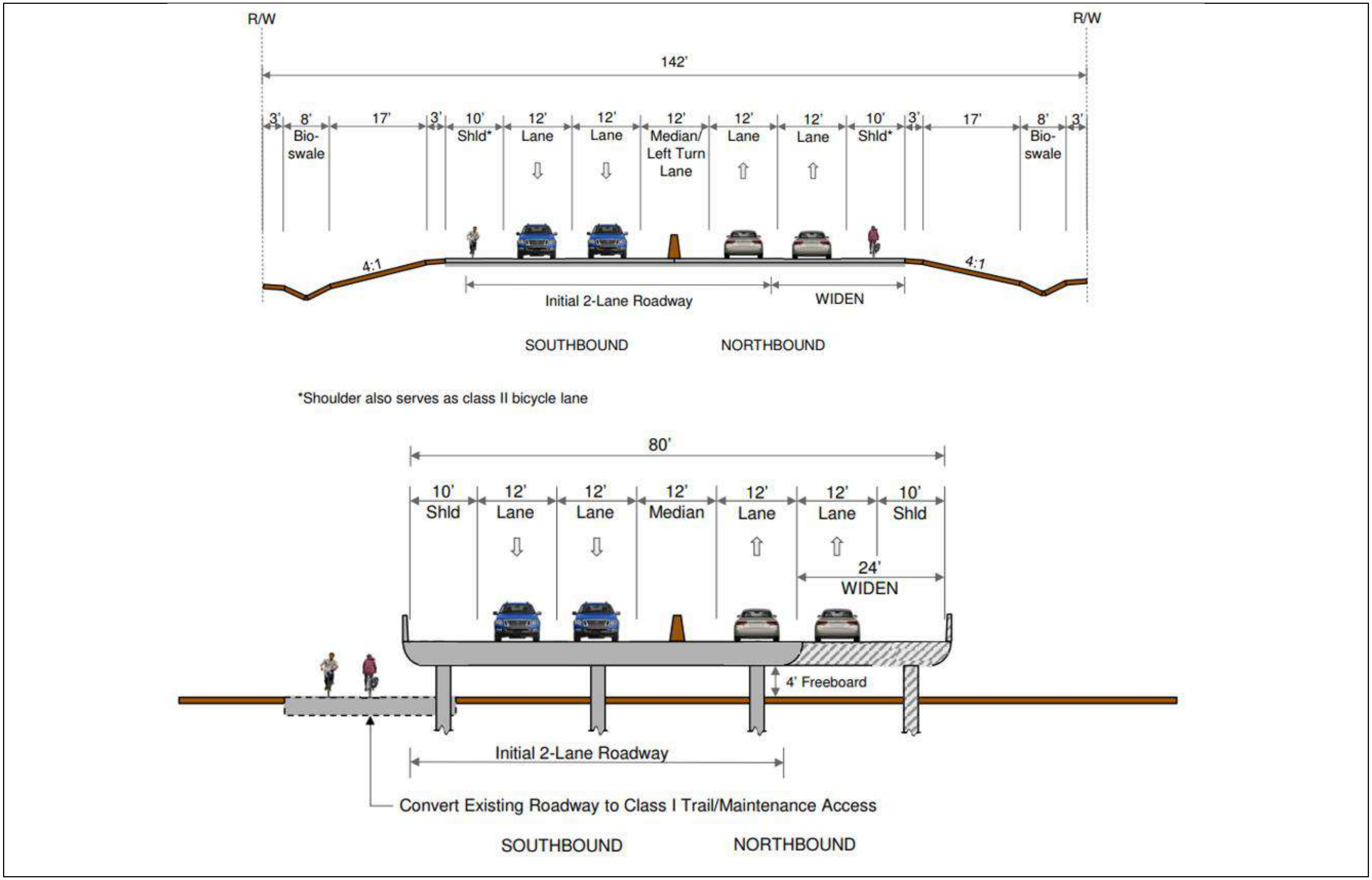
5.1.3 Co-located Roadway and Railway Facilities

Constructing a new alignment east of the existing roadway was included as adaptation concept to examine potential opportunities for long-term transportation and ecological resilience. This facility proposed co-locating road and rail infrastructure in a single facility and would be located approximately 1.3 mi east from the Slough mouth. The current railway crosses through the Slough, adjacent to 4.7 mi of wetland habitat. Selecting a different alignment at the narrowest point of the Slough channel for a co-located facility could alleviate transportation impacts to marsh complexes east of the existing railway alignment, but would also likely result in significant negative impacts to ecology. This roadway concept included 4-lanes, consistent with the Caltrans TCR (2017). This adaptation strategy received significant concern from Steering Committee members and members of the public, as it creates substantial impacts on the ecosystem. Other alignments were considered, but the impacts of rerouting over the Slough are adequately captured by the scenario analyzed in the study.

Figure 18 shows the conceptual cross-section for a co-located 4-lane roadway and dual track railway.

5.2 Ecological Adaptation Elements

The following ecological adaptation elements would be deployed in combination with specific transportation adaptation actions to create habitat area, mitigate habitat loss, and increase ecosystem and transportation sea level rise resilience. These elements were developed in close coordination with the Steering Committee and stakeholder groups around Elkhorn Slough through Summer 2019.



Central Coast Highway 1 Climate Resiliency Study

Figure 17

4-Lane Roadway Elevated on Fill (Top) or Piles (Bottom)
Conceptual Schematic

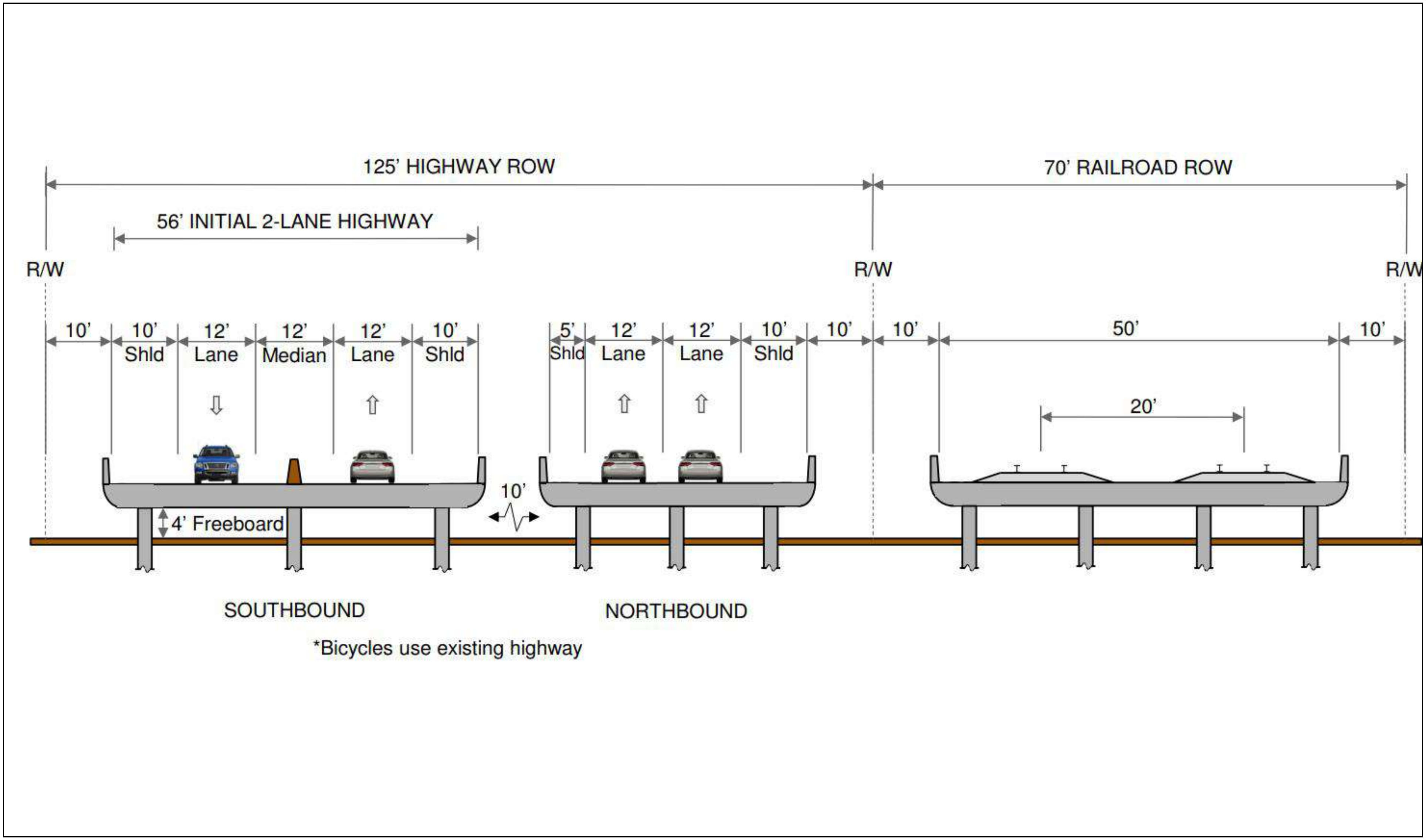


Figure 18

Co-located 4-Lane Roadway and Dual-Track Railway Facility
Conceptual Schematic

5.2.1 Levee Ecotone Creation

Levee ecotone[8] creation entails grading a gentle slope (up to 20H:1V) down from a levee (in this case, the roadway crest) into tidal elevations, where space allows (**Figure 19**). Ecotones can be vegetated and provide space for marsh migration as sea levels rise to facilitate the maintenance of marsh habitats. Similarly, the gentle slope allows marshes to accrete sediments and "grow" vertically to keep pace with rising seas. Tidal marsh can slow wave action and reduce overtopping during flood conditions. These provide sea level rise resilience for both the habitats created and the assets landward of the ecotone.

5.2.2 Increased Tidal Connectivity and Hydraulic Flow

Increased hydraulic flow and tidal connectivity by elevating transportation on piles or improving culvert function can restore benefits such as the delivery of oxygen and nutrient rich waters and beneficial sediment transport to areas that have been historically degraded due to levees or failed culverts restricting flow. When combined with levee ecotones, increased flow can create these benefits while maintaining habitat elevation, area, and room to migrate upwards.

5.2.3 Marsh Restoration

Several marsh complexes, including Parsons Slough, North/Estrada Marsh Complexes and Azevedo Ponds, are located east of the existing railway embankment. Due to the historic installation of tide control structures underneath the rail, North/Estrada Marshes and Azevedo Ponds experience muted tides and water quality issues. The railway overtops in present day king tide conditions. With increasing water levels, the habitats in these areas are at risk to be permanently drowned. Restoration of these complexes, which entails sediment deposition to raise the marsh grade plain and creation of new tidal channels, would boost maintenance of valuable wetland habitat acreages and ecosystem services these habitats provide under future sea level rise.

5.3 Preliminary Roadway and Railway Adaptation Scenarios

Preliminary roadway and railway adaptation scenarios were developed based on the suite of transportation and ecological adaptation elements described above. Since the study area spans a large extent of Moss Landing and Elkhorn Slough, development of the adaptation scenarios was informed by existing floodplain management, community planning and system-wide and local hydraulic ecological conditions. In particular,

[8] "ecotone" refers to a transition between two or more ecology communities, and in this case from wetlands to uplands along a slope, and where wetlands can migrate upward with sea level rise.

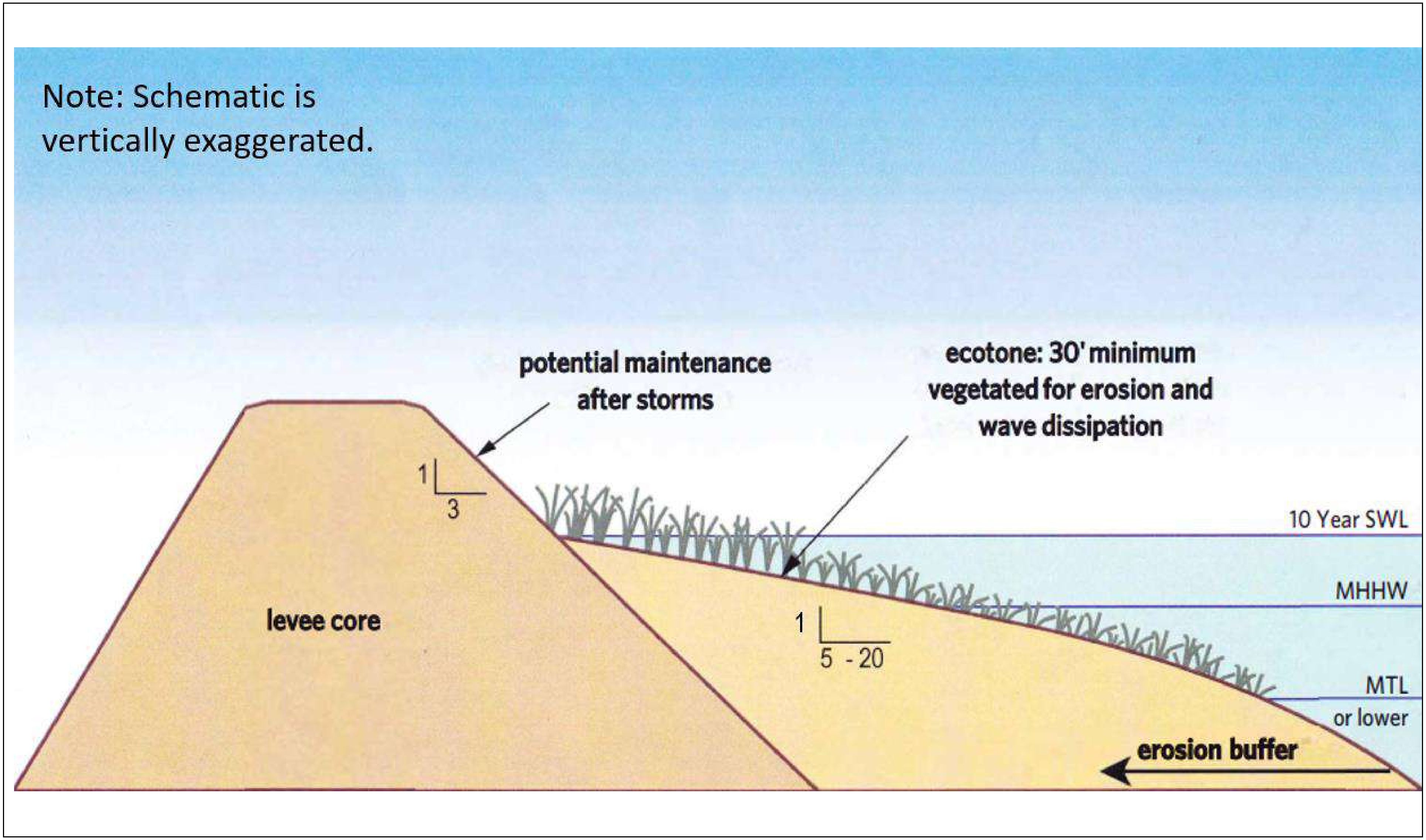


Figure 19

Levee Ecotone Schematic

additional focus was placed on which segments of the roadway would be elevated on fill embankment or piles, since these influence local flow patterns (e.g. tidal connectivity) that indirectly influence habitat quality. The initial list of adaptation scenarios in **Table 6** constituted a broader array of potential options, which were further narrowed through analysis, modeling and stakeholder input, which are described in Section 6, Table 9. This study does not select a preferred scenario among the narrowed scenarios, but instead provides robust, yet initial, analysis of potential opportunities and constraints. Any future actions that may be selected would presumably require additional planning, environmental review, permitting and include mitigation. Other options and solutions, such as other alternate alignments of the highway, were considered but ultimately it was determined that the initial list of adaptation scenarios analyzed provided a well-rounded view of the effectiveness of the various adaptation strategies.

5.3.1 Reaches 1 and 2

The construction of the transportation corridor and other human activities around Elkhorn Slough have largely shaped existing hydrology and hydraulics in the area. Struve Pond and Upper Bennett Slough are currently blocked off from tidal connection due to re-location of the Harbor mouth and construction of the existing Highway 1 facility. Reconnaissance of the existing highway show that there are a number of hydraulic structures, in varying condition, underneath the embankment which control tidal connectivity and flood patterns in the area. ESA verified that the culvert underneath Highway 1 Reach 2 connecting Lower and Upper Bennett Slough was crushed and seemed to convey little to no flow. Both Struve Pond and Upper Bennett Slough have been identified as areas with poor water quality, due to the lack of flushing and runoff from adjacent agricultural lands and the roadway.

Highway 1 Reaches 1 and 2 are located adjacent to the western portion of the Moss Landing Wildlife Area (MLWA), an 872-acre property with large amounts of salt marsh habitat. The portion of the wildlife area next to the roadway is managed to provide habitat to Western Snowy Plover in spring and summer and flooded in the fall and winter to provide wintering waterfowl habitat. CDFW provided locations and heights of perimeter and internal berms in the pond system. Additionally, CDFW confirmed that the artificial salt ponds at this location would continue to be managed in this way over the next several decades and the opportunity to create additional habitat area between the western edge of the wildlife area and Highway 1 Reach 2 would be beneficial. Therefore, in design development for Highway 1 Reach 2, the Project Team assumed that the ponds would remain in place and that the space between Highway 1 and MLWA would be available for levee ecotone creation. **Figure 20** shows the locations and extents of the levee ecotone creation corresponding to Reach 2 elevated on fill or piles.

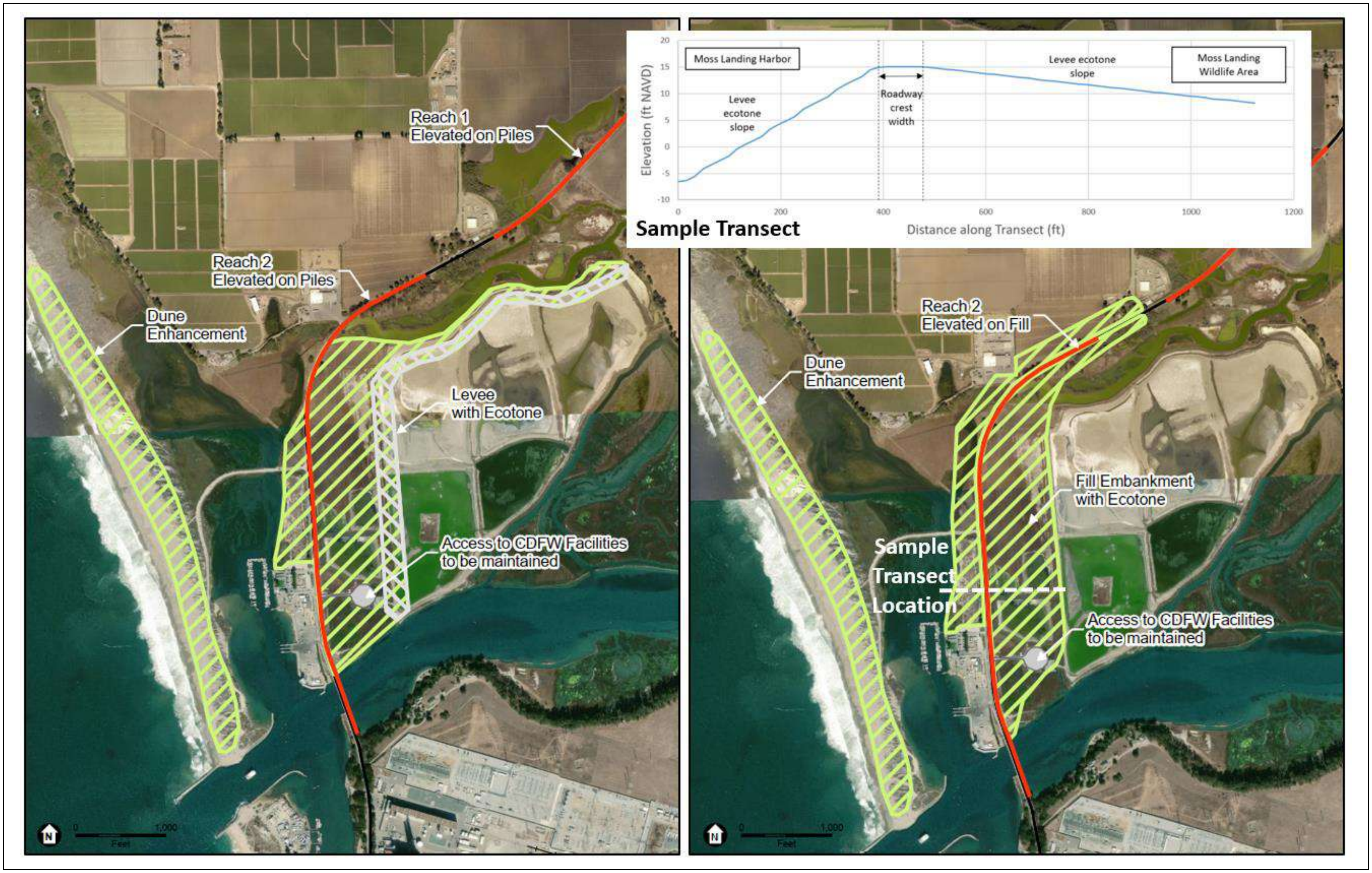


Figure 20

Levee Ecotone Creation (Conceptual)

Reach 2 Elevated on Piles (Left) or Fill (Right)

5.3.2 Reaches 3 and 4

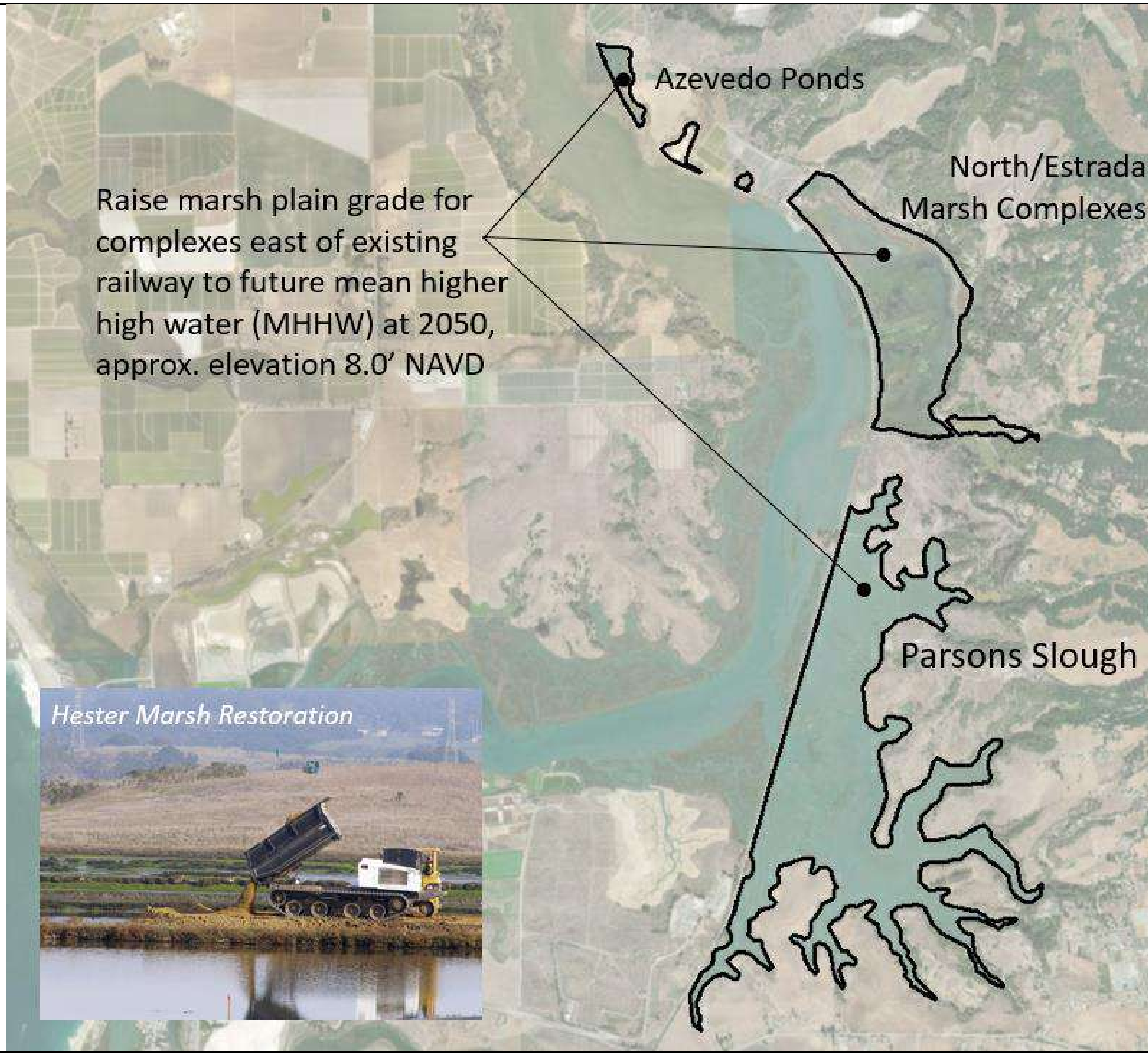
Highway 1 Reaches 3 and 4 are located south of the Elkhorn Slough bridge crossing, upstream of tide gates, and near low-lying agricultural lands. The Moro Cojo Management Enhancement Plan (2013) lists conservation strategies for Moro Cojo Slough, including acquisition of key lands, including viable farmlands, to protect and restore marsh habitat. Implementation of the Plan include acquisition of parcels adjacent to the Slough, creation of pond and freshwater habitat, and extensive coordination with local landowners. Discussions with Central Coast Wetland Group (CCWG) and other Moro Cojo Slough stakeholders indicate that these efforts will continue as part of the overall management plan for Moro Cojo Slough system. For consistency with this current planning, the study assumes that Reaches 3 and 4 would be elevated on piles in the future, in order to allow for tidal connectivity as the adjacent lands flood under future sea level rise. The existing roadway embankment is assumed to be left in place to provide more flexibility in floodplain management into the future (e.g. hydraulic control mechanism for inland areas)

5.3.3 Railway

Due to concerns around subsidence within the Slough, elevating the railway on a raised fill embankment was removed from consideration. Improvements to the railway would assume that the facility would be elevated on trestle. The existing railway embankment serves as a hydraulic control mechanism for the inboard marshes and may potentially aid in sediment retention. The study assumes that the existing facility would be left in place and a new facility offset from the existing railway alignment would be constructed. For all adaptation scenarios, restoration of the marsh complexes east of the railway (e.g. Azevedo Ponds, North/Estrada Marsh, Parsons Marsh) by raising marsh elevations is assumed (**Figure 21**). These would be similar to recent efforts in other locations within the Slough, such as Hester Marsh Restoration, where 65 acres of salt marsh was restored by raising the existing marsh plain grades.

5.3.4 Alternate Routes to the Existing Roadway Alignment

Alternatives to modifying the existing roadway alignment, such as re-routing to an inland alignment, were developed as potential adaptation scenarios. A number of various routes were considered, such as Elkhorn Road and San Juan Road, but those were considered to be not as viable as other options. Elkhorn Road is a small narrow road that is also potentially impacted by flooding. San Juan Road provides a connection from Highway 1 to U.S. 101 but travels more east-west instead of north-south and would cause more out of direction travel. Input from the Steering Committee informed the development of a managed retreat scenario where traffic is diverted from Highway 1 to the existing G12 corridor that runs along San Miguel Canyon Road. TAMC completed the G12: Pajaro to Prunedale Corridor Study in 2019 to address safety and congested traffic conditions along the G12 corridor. The study identified mid-term and long-term improvements with other planned regional improvements, including



Source: Elkhorn Slough Foundation (2018)

Figure 21

Proposed Salt Marsh Restoration Areas

improved bicycle and pedestrian facilities, roundabouts, traffic signals, lane modification improvements and more to improve safety and multimodal use of the roadway and transportation facilities. The study did not recommend widening the corridor to 4 lanes.

Managed retreat is a concept to strategically relocate built assets where coastal erosion and flooding risks, impacts or costs are significant enough to warrant moving those assets to a safer location. Landward shore migration and increasing hazards associated with sea level rise will likely warrant managed retreat of important built assets in many locations along the California coastline.

5.3.5 Time Horizons and Sea Level Rise Considerations

Typically, major transportation infrastructure projects are designed to last for a specific project lifetime, or be able to withstand future conditions. Roadway and railway facilities constructed by mid-century (e.g. 2050) would be designed for a sea level rise amount corresponding to a time horizon in late-century (e.g. 2070, 2100), or later. For the purposes of planning-level design and evaluation, it is assumed that the roadway and railway elevations would be in place by 2050 and designed for a 2070 time horizon (equivalent to 3 ft of sea level rise for the planning scenario). All reaches of Highway 1 and the railway were assumed to be elevated to accommodate 3 ft of sea level rise with an additional foot of freeboard[9]. For roadway segments elevated on piles, an additional height of 4 ft was added to account for the roadway deck width. Similarly, the proposed marsh restoration east of the railway would be designed for future elevations. The marsh plain grade is assumed to be raised to future MHHW at mid-century, which is approximately 8.0’ NAVD.

Table 6 describes the preliminary roadway and railway adaptation scenarios in detail, including locations and specifications of adaptation actions. A number of associated access improvements (e.g. intersection improvements, frontage roads) must be made in tandem with elevating and widening the roadway. **Figures 22** through **27** show locations of planned access improvements for each of the preliminary adaptation scenarios.

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[9] Freeboard is defined as the distance between the water line and top of a structure or mass above the water (e.g. roadway deck).

TABLE 6
PRELIMINARY ROADWAY AND RAILWAY ADAPTATION SCENARIOS

<table>
<tr><th rowspan="2">Scenario</th><th rowspan="2">Short Name</th><th colspan="2">Roadway</th><th colspan="2">Railway</th></tr>
<tr><th>Transportation</th><th>Ecology</th><th>Transportation</th><th>Ecology</th></tr>
<tr><td>A0/B0</td><td>No Action</td><td>No action</td><td>No action</td><td>No action</td><td>No action</td></tr>
<tr><td>A1A</td><td>2-Lane Elevated Highway 1 with Reach 2 on Piles</td><td>2-lane roadway with operational improvements, including access improvements and bike/ pedestrian trail. Reaches 1-4 would be elevated completely on piles, with +3 ft allowance for sea level rise and 1’ of additional freeboard.</td><td>A levee ecotone would be constructed on the inboard side of Reach 2, with a crest along the inner perimeter of MLWA and sloping downwards (underneath the elevated highway) to Moss Landing Harbor (North). This would provide additional future wetland habitat under sea level rise.</td><td rowspan="6">A new dual track railway facility would be constructed adjacent to the existing railway fill embankment and elevated on trestle. The existing railway fill embankment would be left in place, to potentially aid in sediment retention for the inboard marsh complexes.</td><td rowspan="8">Marsh complexes east of the existing railway fill embankment, including Azevedo Ponds, North/Estrada Marsh and Parsons Marsh, would be restored to keep pace with sea level rise. Existing marsh grade plain for these areas would be raised to future MHHW at mid-century, which is approximately 8.0’ elev. NAVD. To increase tidal connectivity to these areas, new tidal channel openings North/Estrada Marsh complexes and the larger Azevedo Pond would be created.</td></tr>
<tr><td>A1B</td><td>2-Lane Elevated Highway 1 with Reach 2 on Fill</td><td>2-lane roadway with operational improvements, including access improvements and bike/ pedestrian trail. Reaches 1, 3 and 4 would be elevated completely on piles and Reach 2 would be elevated on fill embankment, with +3 ft allowance for sea level rise and 1’ of additional freeboard.</td><td>Levee ecotones would be constructed on both sides of Reach 2, gently sloping to match grade at Moss Landing Harbor and Moss Landing Wildlife Area. This would provide additional future wetland habitat under sea level rise.</td></tr>
<tr><td>A2A</td><td>Managed Retreat/ Widening G12 (4-Lanes)</td><td>Traffic from existing Highway 1 would be diverted to the G12 corridor. Salinas Road and San Miguel Canyon Road would be widened to 4-lanes with a number of intersection improvements.</td><td>No action</td></tr>
<tr><td>A2B</td><td>Managed Retreat/ Widening G12 (6-Lanes)</td><td>Traffic from existing Highway 1 would be diverted to the G12 corridor. Salinas Road and San Miguel Canyon Road would be widened to 6-lanes with a number of intersection improvements.</td><td>No action</td></tr>
<tr><td>A3A</td><td>4-Lane Elevated Highway 1 with Reach 2 on Piles</td><td>4-lane roadway, including access improvements and bike/pedestrian trail. Reaches 1-4 would be elevated completely on piles, with +3 ft allowance for sea level rise and 1’ of additional freeboard.</td><td>Same as A1A</td></tr>
<tr><td>A3B</td><td>4-Lane Elevated Highway 1 with Reach 2 on Fill</td><td>4lane roadway, including access improvements and bike/pedestrian trail. Reaches 1, 3 and 4 would be elevated completely on piles and Reach 2 would be elevated on fill embankment, with +3 ft allowance for sea level rise and 1’ of additional freeboard.</td><td>Same as A1B</td></tr>
<tr><td>A4/B1</td><td>Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway</td><td colspan="3">A co-located 4-lane roadway facility and dual track railway facility would be constructed inland (east) of the existing roadway alignment. The roadway would be elevated on piles and railway on trestle. The new alignment would cross approximately the Slough below Struve Rd/Highway 1. The roadway and railway facilities would diverge after the Slough crossing. The new roadway would continue south and rejoin the existing highway by Castroville. The new railway would reconnect the existing railway by Dolan Road and Moro Cojo Slough.</td></tr>
<tr><td>B2</td><td>Dual Track Railway</td><td>No planned transportation improvements to roadway facility.</td><td>No planned ecology adaptation actions by roadway facility.</td><td>A new dual track railway facility would be constructed adjacent to the existing railway fill embankment and elevated on trestle. The existing railway fill embankment would be left in place, to potentially aid in sediment retention for the inboard marsh complexes.</td></tr>
</table>

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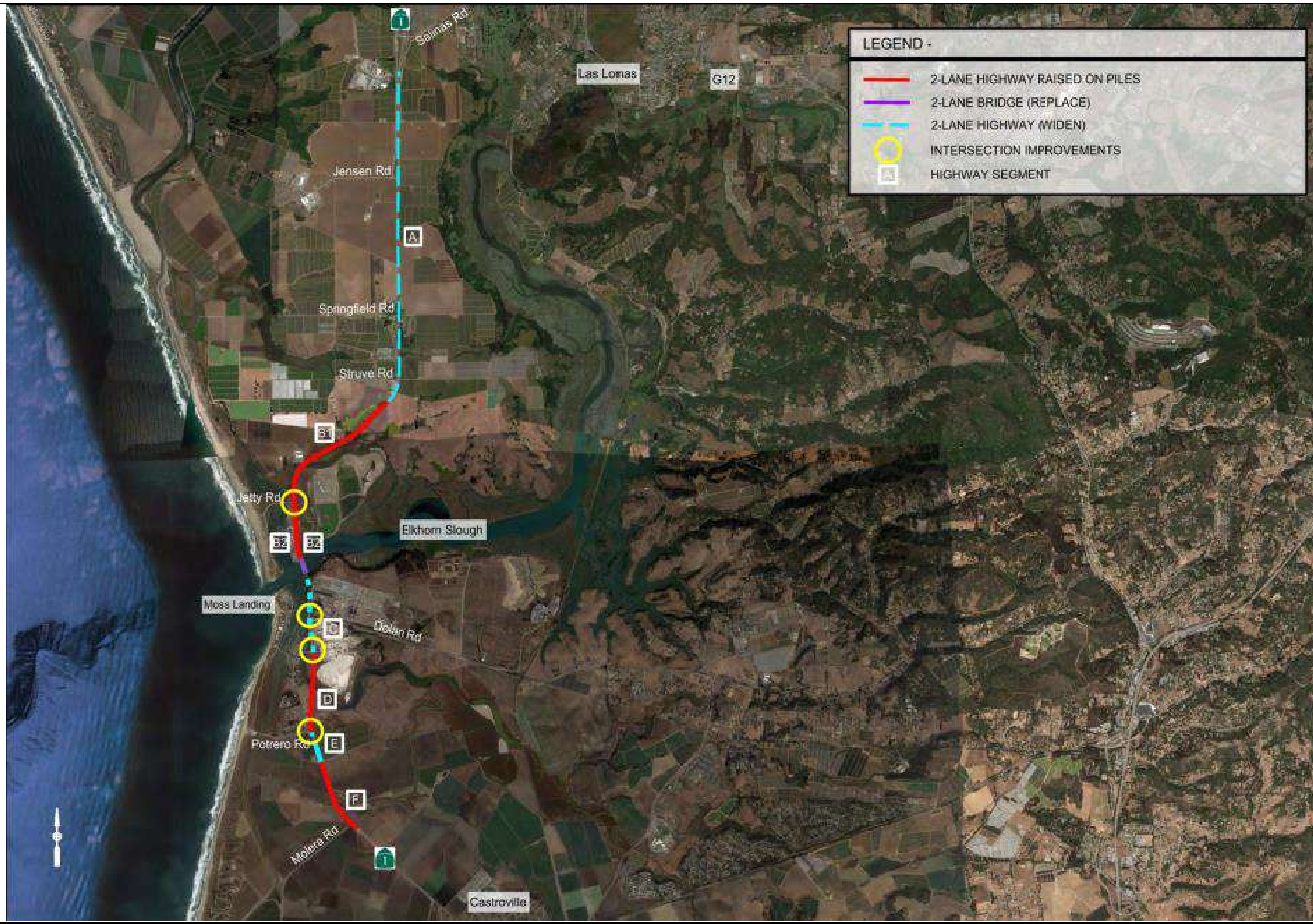
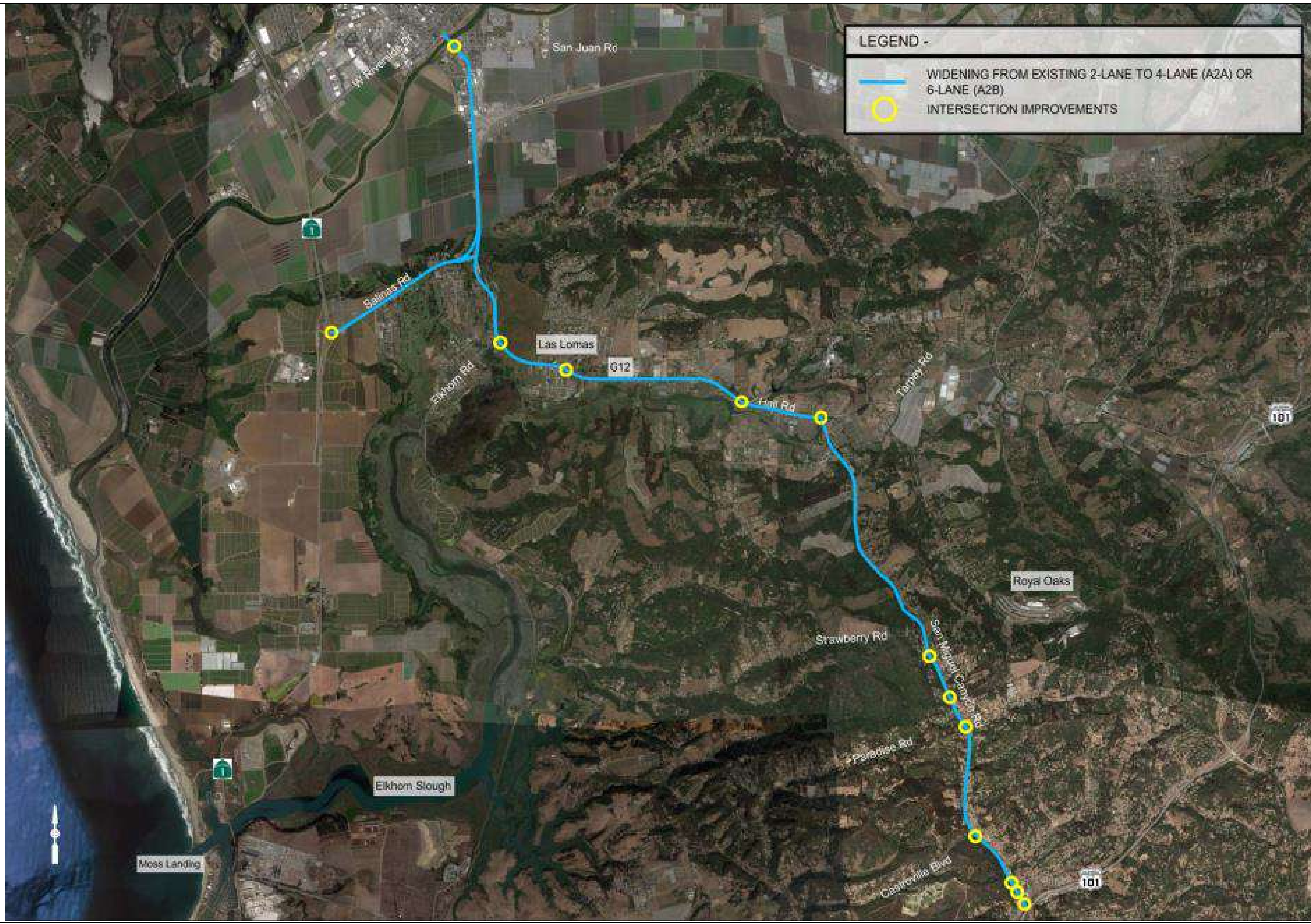


Central Coast Highway 1 Climate Resiliency Study

Figure 22

Scenario A1 (Conceptual)

2-Lane Highway with Operational Improvements

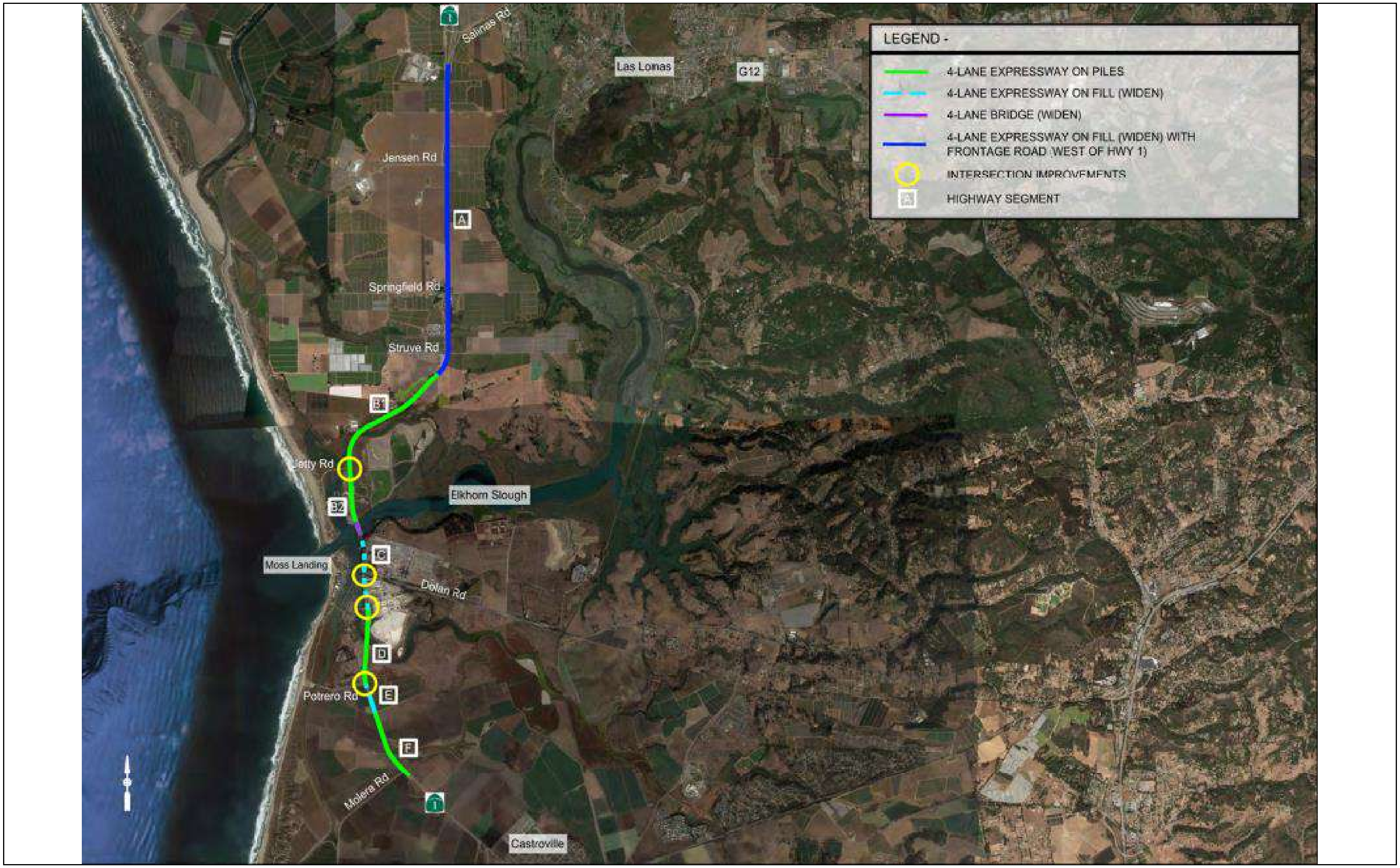


Central Coast Highway 1 Climate Resiliency Study

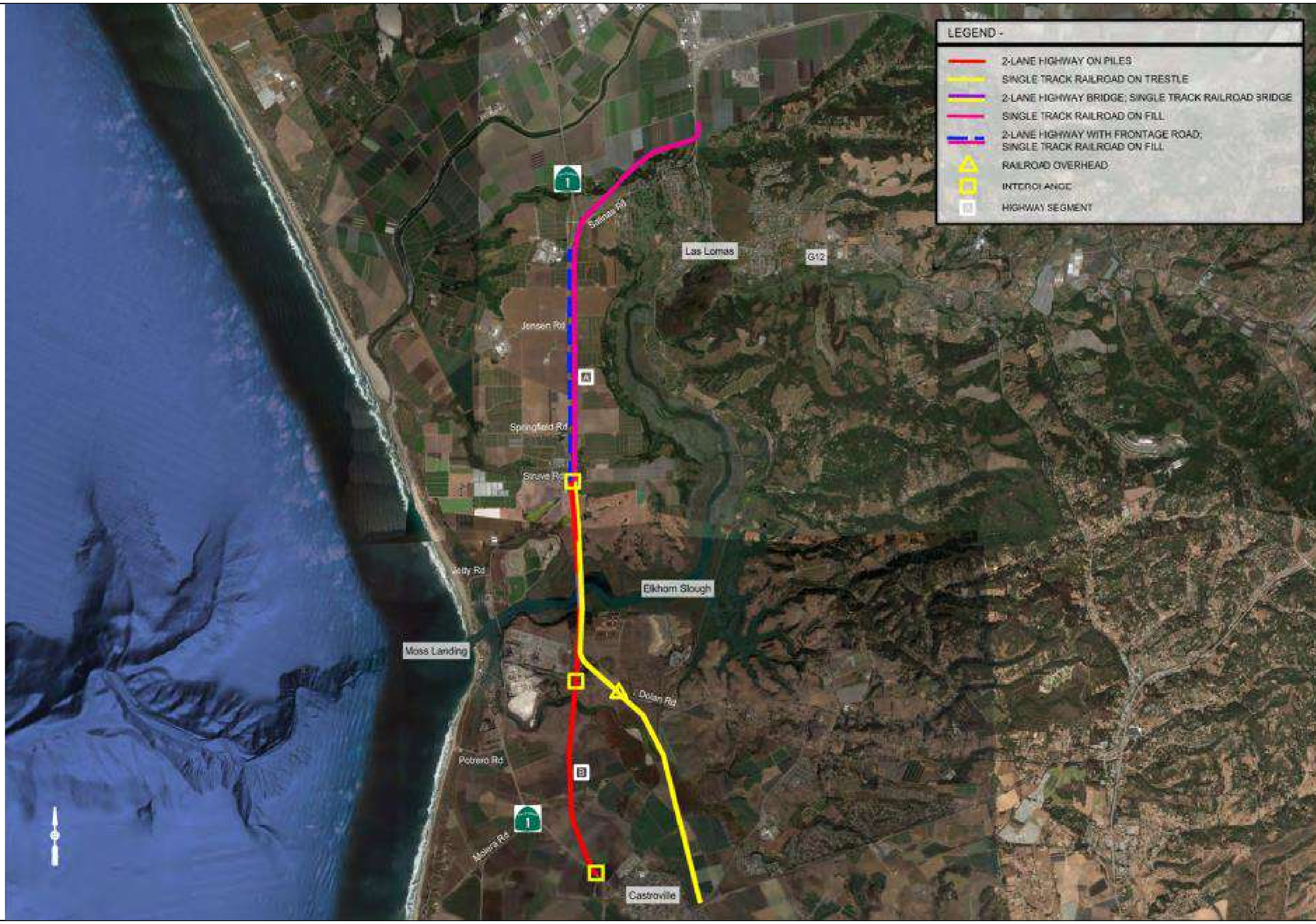
Figure 23

Scenario A2 (Conceptual)

G-12 Widening to 4- or 6- Lanes



Central Coast Highway 1 Climate Resiliency Study
Figure 24
Scenario A3 (Conceptual)
4-Lane Highway (Existing Alignment)

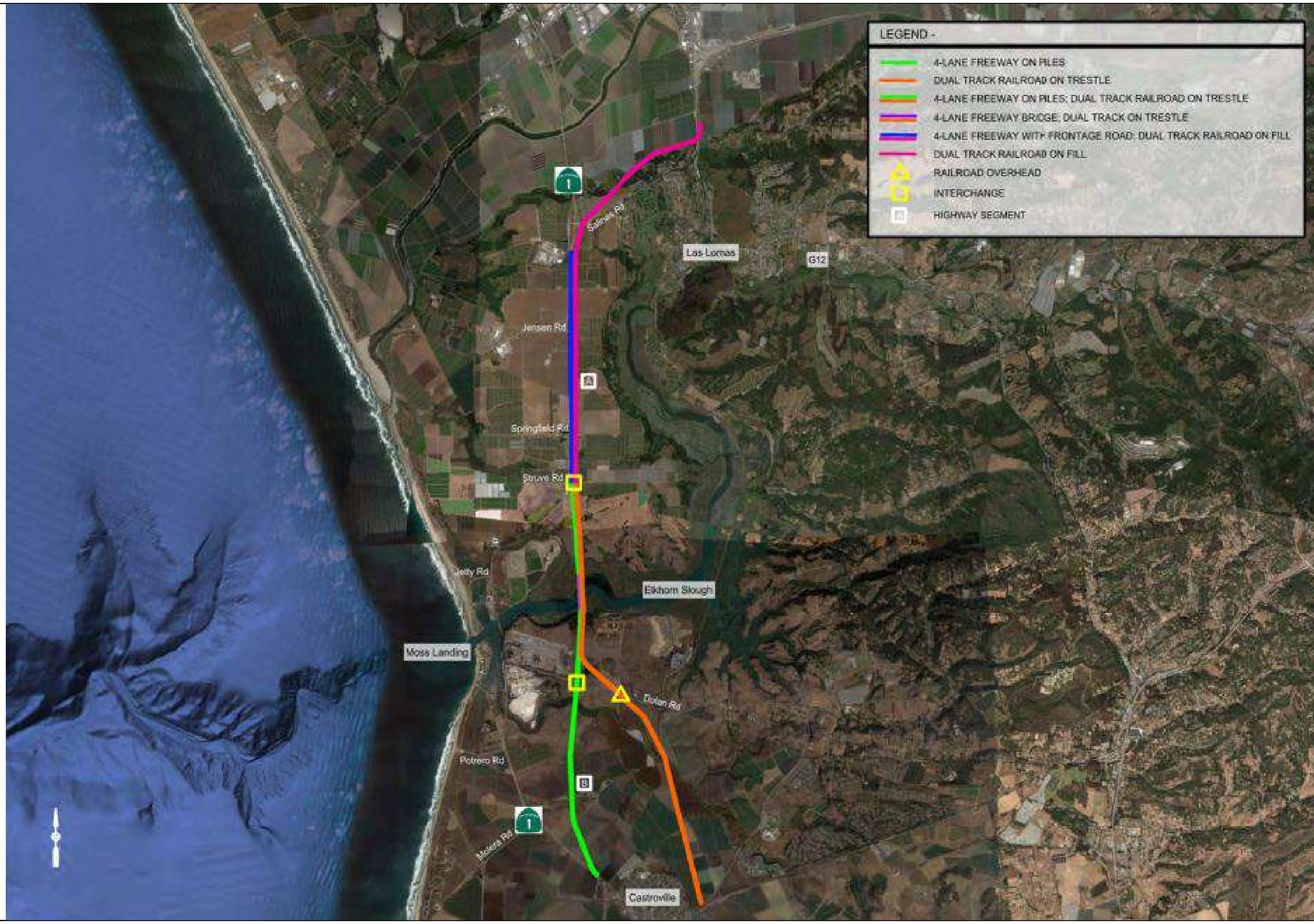


Central Coast Highway 1 Climate Resiliency Study

Figure 25

Scenario A4/B1 – Phase 1 (Conceptual)

Co-located Roadway and Railway Facility (New Alignment)

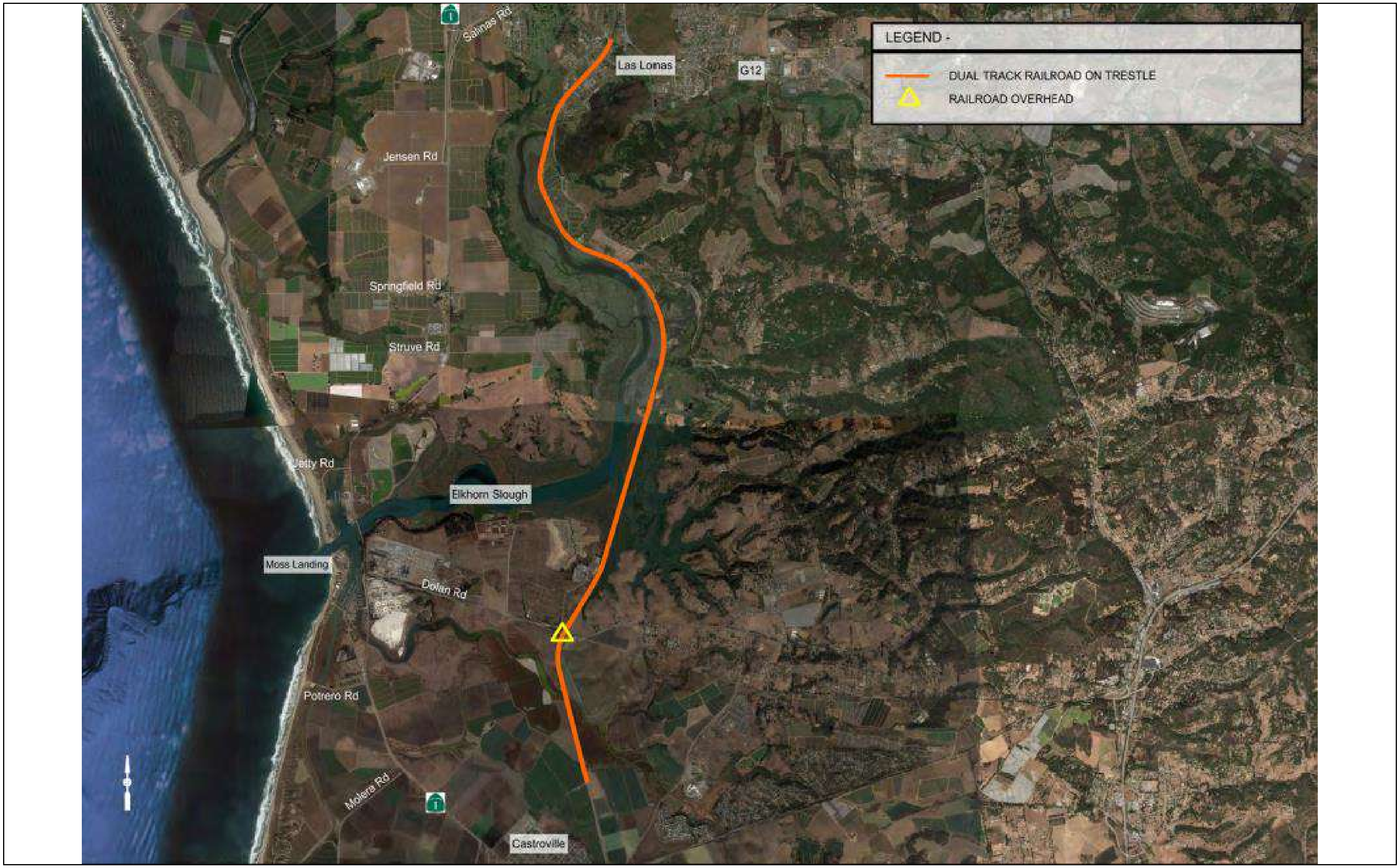


Central Coast Highway 1 Climate Resiliency Study

Figure 26

Scenario A4/B1 – Final Phase (Conceptual)

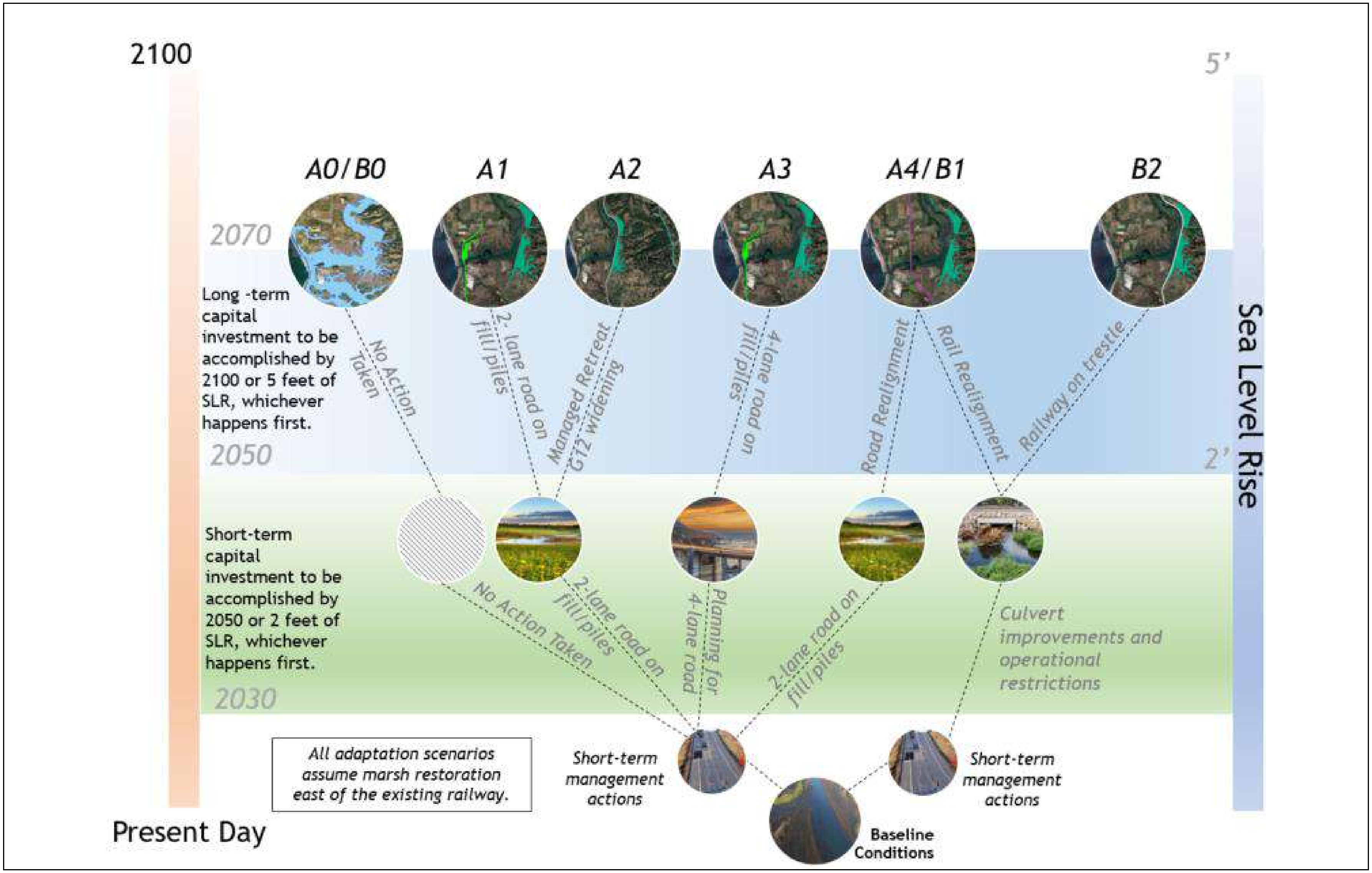
Co-located Roadway and Railway Facility (New Alignment)



Central Coast Highway 1 Climate Resiliency Study
Figure 27
Scenario B2 (Conceptual)
Dual-Track Railroad on Trestle

5.3.6 Adaptation Pathways Approach

The various transportation and ecological components of the adaptation scenarios will require significant capital investment and time for planning, design, regulatory review processes and construction. As discussed in Section 4, the study utilizes an adaptation pathways approach to outline timing of recommended near-term actions, short-term capital and long-term capital investments and place the adaptation scenarios into context with existing climate change adaptation planning efforts and predicted sea level rise amounts for the Monterey Bay Area region. **Figure 28** shows the adaptation pathways diagram for the range of preliminary roadway and railway adaptation scenarios. The preliminary adaptation scenarios, represented by circular nodes, are located at the 2070 time horizon to indicate that the transportation and ecology components are designed for future sea level rise conditions.



Central Coast Highway 1 Climate Resiliency Study

Figure 28

Preliminary Roadway and Railway Adaptation Scenarios

Adaptation Pathways Diagram

CHAPTER 6

Scenarios Evaluation

This section describes the process and methods used for evaluating the adaptation scenarios and major conclusions stemming from analyzing the preliminary set of roadway and railway adaptation scenarios. These, in conjunction with input from the Steering Committee and community workshop, informed refinement of a subset of the adaptation scenarios for full evaluation with the economic benefit cost analysis. Finally, this section presents the results of the benefit cost analysis on the refined subset of adaptation scenarios as well as interpreting the uncertainty of future sea level risk in relation to benefits and costs for planning purposes.

6.1 Evaluation Methods

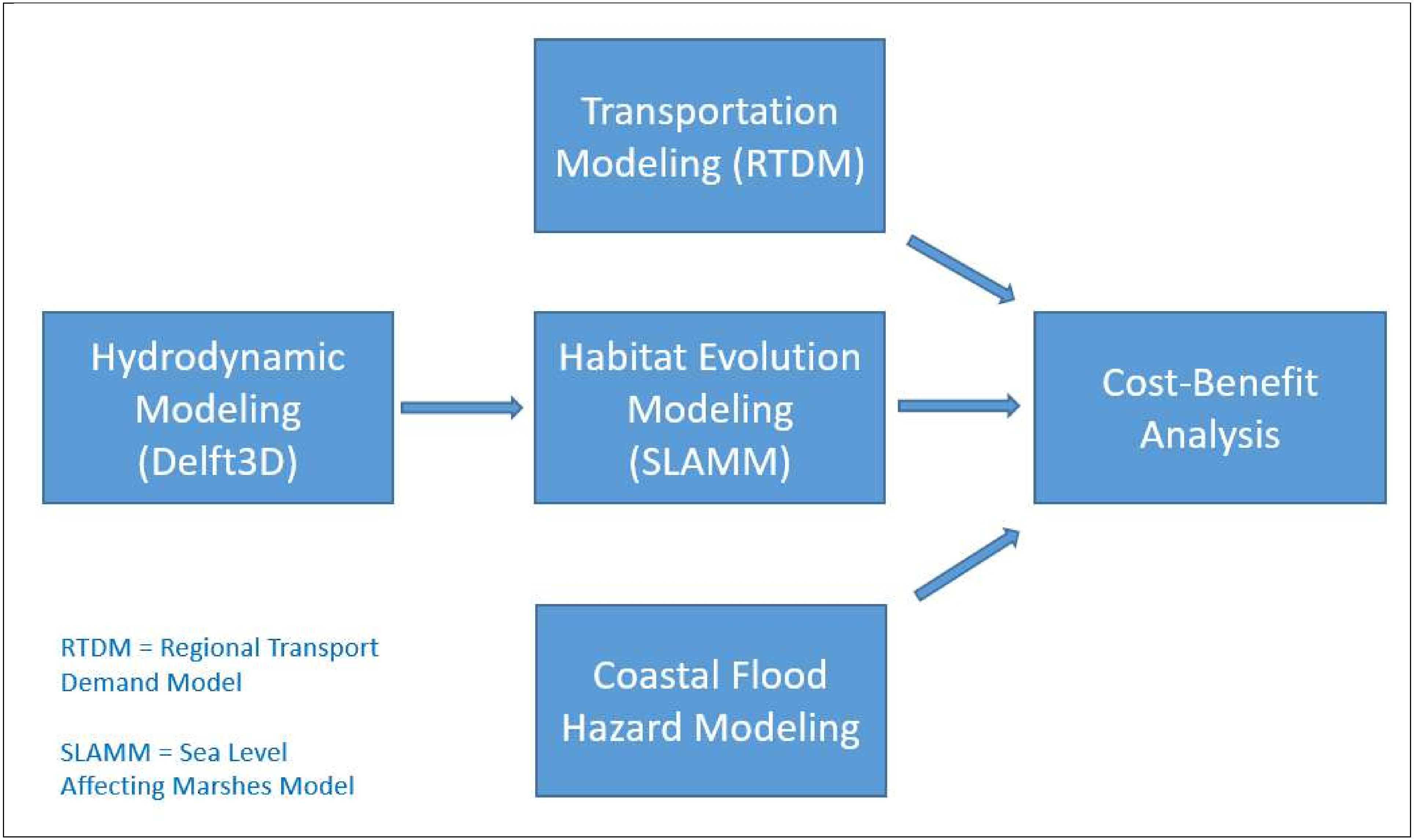
The dual nature of the study necessitates the use of several models to establish the performance of the adaptation scenarios with respect to transportation and ecological parameters. Flood hazard modeling for existing and future sea levels was conducted using Coastal Resilience methods, with refinements for existing and future conditions. Hydrodynamic modeling and habitat evolution modeling were conducted for the adaptation scenarios in order to establish impacts to wetland habitats. Transportation modeling was conducted to assess future transportation function as a result of adaptation and improvements. Outputs from these modeling processes informed the economic benefit cost analysis portion of the scenarios evaluation. **Figure 29** shows the overall study process and workflow.

6.2 Flood Hazards

Flood hazard maps for Monterey Bay were developed as part of the Coastal Resilience Program[10]. Flood and erosion hazard maps developed with funding from the State of California are available for viewing online, and geographical information system files are available for download, together with technical report documentation[11]. ESA, the original developer of the maps and supporting methodology, modified the hazard maps

10 Coastal Resilience Program, an approach and on line decision support tool (last visited May 2020): https://coastalresilience.org/about/

11 Coastal Resilience Mapping Portal (last visited May 2020): https://maps.coastalresilience.org/



Central Coast Highway 1 Climate Resiliency Study
Figure 29
Study Process for Evaluation of Adaptation Scenarios

for this project. Modifications consisted of refinements to flood elevations at the highway reaches by more precise computation of overland flood routing and potential groundwater levels with sea level rise, and consideration of the effects of highway adaptation scenarios. Also, a representative elevation for each highway reach was selected as the “flood threshold,” and compared to the computed water levels in order to identify the amount of sea level rise that would initiate flooding and hence degradation of the road and its transportation function under no project, future conditions. The results are summarized in **Table 7** below.

TABLE 7
FLOOD THRESHOLDS, SEA LEVEL RISE AND TIME HORIZONS DEVELOPED IN THIS STUDY FOR THE FOUR REACHES OF EXISTING HIGHWAY 1.

Coastal and Fluvial Storm have 100-year recurrence intervals and indicate that the storm event was modeled in addition to sea level rise. Monthly refers to the maximum monthly water level, also called Extreme Monthly High Water.

Reach	Minimum Elevation (ft, NAVD)	Coastal Storm Threshold	Fluvial Storm Threshold	Monthly Inundation Threshold
1	7.6	2030 [WSE* 7.3 ft with sea level rise** = 0.7ft]	N/A	By 2050 [Bennett Slough WSE 7.6 ft with 2 ft sea level rise]
2	8.9	2030 [0.7 ft sea level rise]	N/A	2060 [2.4 ft sea level rise]
3	8.8	2040 [1.3 ft sea level rise]	2040 [1.3 ft sea level rise]	2065 [2.6 ft sea level rise]
4	9.0	2045 [1.4 ft sea level rise]	2040 [1.3 ft sea level rise]	2070 [2.8 ft sea level rise]

* WSE = water surface elevation in feet, NAVD
** sea level rise = sea level rise in feet relative to existing conditions

6.3 Evaluation of Preliminary Roadway and Railway Scenarios

6.3.1 Hydrodynamic Modeling (Delft3D)

ESA utilized Delft3D, a hydrodynamic model, to evaluate potential hydraulic dynamics (e.g. changes to flow patterns and flood extents though time) associated with each of the adaptation scenarios. Delft3D models hydrodynamics, sediment transport and morphology, and water quality for fluvial, estuarine and coastal environments. This application provides hydrodynamics using a two-dimensional, depth-averaged configuration.

ESA updated an existing application of Delft3D, which was developed to evaluate management actions for Elkhorn Slough, to encompass the full study area, including: Struve Pond, Bennett Slough and adjacent roadway area, Moro Cojo Slough, North/ Estrada Marsh Complexes and Azevedo Pond. Grid cell resolution was refined to 30 ft around the transportation infrastructure to adequately resolve hydraulic impacts around the roadway and railway. ESA incorporated the most recent and up-to-date elevation (topography/bathymetry) data provided by National Oceanic and Atmospheric Administration (NOAA), California State University, Monterey Bay (CSUMB) and Central Coast Wetlands Group (CCWG). Hydraulic structures located through the roadway and railway infrastructure were modeled, based on data provided by ESNERR and MLML. More technical detail on model development and results can be found in Appendix C.

Modeling results for Scenario A0/B0 (No Action) confirm that with no adaptation actions, the roadway and railway infrastructure will be flooded under future sea level rise. Previous flood hazard modeling work conducted, Coastal Resilience Monterey, show Reaches 1 and 2 by Struve Pond and Bennett Slough flooding with 2.4 ft of SLR, assumed to occur by 2060; the hydrodynamic model results for Scenario A0/B0 are consistent with this conclusion and show flooding in those areas and through most of the existing railway, assuming 3 ft of sea level rise at 2070. Although Scenario A2 (Managed Retreat/Widening G12) was not explicitly modeled, the results from the revised flood hazard mapping for Scenario A0/B0 (No Action) indicate that the local access to the Moss Landing community would only be available until 2050 (2 ft of sea level rise), assuming conversion of the existing Highway 1 to a local road and managed retreat.

Modeling results for Scenario A1A (2-Lane Elevated Highway 1, Reach 2 Elevated on Piles), show lower Bennett Slough and Struve Pond with increased tidal action, which may improve historic water quality issues in those areas (e.g. pollution from agricultural and road runoff). Scenarios A1A (2-Lane Elevated Highway 1, Reach 2 Elevated on Piles) and A1B (2-Lane Elevated Highway 1, Reach 2 Elevated on Fill) also show flooding of Struve Pond and Bennett Slough via an alternate pathway behind Moss Landing Wildlife Area. This indicates that modifications made to the roadway may have decreasing control over flooding in this part of the Slough, as sea levels rise and new flood pathways develop. These modeling results are predicted to be similar for Scenario A3 (4-Lane Elevated Highway 1) in both variations (Reach 2 on fill and piles), from a hydraulic standpoint.

Scenario A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) was not explicitly modeled for a number of reasons. Firstly, since the new alignment would likely only span a short section of the Slough channel and was assumed to not have major impacts on the overall hydrodynamic patterns of the Slough, in comparison to modifications made to the existing roadway and railway. Further, as the existing Highway 1 would need to remain under this scenario to provide local access for residents and businesses, the new alignment would not alleviate any environmental stress from Elkhorn Slough’s ecosystems but would instead be completely additive in impact. Input from the Steering Committee made it clear that the new alignment would cut through, thereby removing or degrading several different types and locations of intact, sensitive terrestrial, estuarine, and marine habitats supporting species protected under State and Federal Endangered Species Acts. Finally, similar to Scenario A2 (Managed Retreat/Widening G12 4-6 Lanes), the results of Scenario A0 (No Action) represents Highway 1 being maintained to support local transportation assuming conversion of the existing Highway 1 to a local road. Results indicate that the local access to the Moss Landing community would only be available until 2050 (2 ft of sea level rise) into the future, and thus the new alignment would also fail to support the local community.

Preliminary results for all adaptation scenarios assuming marsh restoration show that flow velocities by the areas of marsh restoration and inner Slough are lower compared to Scenario A0/B0 (No Action) under future sea level rise, which may be beneficial for retaining sediment within the Slough. Given that the Slough has been experiencing a net export of sediment (i.e. losing sediment), pursuing marsh restoration and using the existing railway embankment as a dike could help support the resilience of these habitats under future conditions.

6.3.2 Preliminary Transportation Modeling

AMBAG evaluated the transportation improvements in the adaptation scenarios using the AMBAG Regional Travel Demand Model (RTDM) and GIS. The current RTDM's horizon year is 2040. There are no transportation models for the AMBAG region that go beyond 2040. The 2015 existing network in the travel demand model represents existing conditions.

AMBAG evaluated eight scenarios containing a variety of roadway, transit, rail and active transportation improvements. All 2040 scenarios include future population, housing and employment growth in the region. The initial eight scenarios plus the existing conditions are described below.

- Scenario A0/B0 (No Action) was separated into two sub-scenarios, A0A/B0A and A0B/B0B, and modeled for comparative purposes to see what would happen when Highway 1 was unavailable. Scenario A0A/B0A (No Action Without Highway) presents a future 2040 scenario without Highway 1. This reflects what would happen if Highway 1 were to flood and be completely unavailable, and traffic was rerouted to the G12 corridor or other roadways. Transit stops would no longer exist along the Highway 1 corridor. No changes to the rail corridor.
- Scenario A0B/B0B (No Action with Highway) is the same as the existing 2015 network with no improvements to Highway 1 or the rail in the study area. In this scenario it is assumed that Highway 1 would often be unavailable due to flooding.
- Scenario A1 (2-Lane Elevated Highway 1) has a two-lane Highway 1 elevated, either on fill or piles, with access point modifications. Access to Highway 1 would be

improved with grade separation at the Dolan Road and Potrero Road intersections. Highway access at the north end of Moss Landing Road would no longer exist. The bus and rail components would remain the same as existing conditions.

- Scenario A2A (Managed Retreat/Widening G12 4-Lanes) removes Highway 1 from the study area and widens the G12 corridor to four lanes from U.S. 101 to Salinas Road. Monterey-Salinas Transit bus routes would be terminated in Castroville. Existing Highway 1 would remain for local access to Moss Landing. No changes would be made to the rail corridor. Scenario A2B (Managed Retreat/Widening G12 6 Lanes) is identical to scenario A2A, but the G12 corridor is widened to six lanes instead of four. This was separated into two sub-scenarios to compare the 4-lane and 6-lane options.
- Scenario A3 (4-Lane Elevated Highway 1) is similar to scenario A1, but Highway 1 is widened to 4 lanes. Additionally, access at Struve Road would be improved by grade separation, and there would be southbound access to the north end of Moss Landing Road. Bus and rail would remain the same as existing.
- Scenario A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) presents a realignment of both Highway 1 and rail. Highway 1 is widened to four lanes, and relocated east of the current alignment, and the double-tracked railway is moved west of its current alignment through the middle of the slough. Additionally, new interchanges would be created at Highways 1 and 83, Dolan Road, Struve Road, and Salinas Road. Bus would no longer run on Highway 1, but rail service would increase its frequency to every 30 minutes.
- Scenario B2 (Dual Track Railway) is similar to scenario A0B/B0B, but rail service is increased to every 30 minutes. Highway 1 and bus service remain the same.

The County of Monterey is currently planning a bicycle and pedestrian route through the study area as part of the Monterey Bay Sanctuary Scenic Trail. The Moss Landing segment includes 0.85 of a mile pedestrian and bicycle path, a 386-ft long bridge to span Elkhorn Slough and will link Moss Landing to the north Moss Landing Harbor. This bicycle and pedestrian route is assumed to be in place for all of the scenarios evaluated.

For each scenario, the RTDM was utilized with specific network and transit components, and the output was analyzed quantitatively. The evaluation criteria listed below were applied to each scenario, and the results were compared relative to each scenario. The goal of this process was to identify scenarios that best met the purpose and need of the Central Coast Highway 1 Resiliency Study.

Figure 30 is a matrix of how each scenario performed relative to each scenario for each of the performance measures.

Performance Measures for Central Coast Highway 1 Climate Resiliency Study

PM ID	DESCRIPTION	2015 Existing	2040 A0A/B0A	2040 A0B/B0B	2040 A1	2040 A2A	2040 A2B	2040 A3	2040 A4/B1	2040 B2
1	VMT Total[1]	N/A	=	=	=	=	—	—	—	=
2	Congested VMT[2]	N/A	—	—	—	=	=	+	+	—
3	Average Travel Time[1]	N/A	+	=	=	+	+	—	—	=
4	VHT Total[1]	N/A	=	=	=	=	=	=	=	=
5	Vehicle Delay[2]	N/A	—	—	—	—	=	+	+	—
6	Freight Delay (VHT)[1]	N/A	=	—	—	=	=	=	=	—
7	GHG (CO2) Emissions from all land use and VMT per capita (lbs)[2]	N/A	=	=	=	=	=	=	=	=
8	Collisions/Accidents (Annual projected number of injury and fatal collisions per thousand VMT)[2]	N/A	=	=	=	=	=	=	=	=
9	Multimodal Trips/Mode Share (Transit, Bike, Ped)[1]	N/A	+	=	=	+	+	—	—	=
10	Disadvanted Communities Accessibility[2]	N/A	—	+	+	—	—	+	+	+
11	Impact to Natural Resources[2]	N/A	+	+	+	—	—	—	—	—

\+ Scenario would result in positive benefits

= Scenario would result in neutral benefits

— Scenario would result in negative impacts

[1]Regionwide

[2]Project Area

Central Coast Highway 1 Climate Resiliency Study

Figure 30

Transportation Performance Matrix

Preliminary Roadway and Railway Adaptation Scenarios

The following performance measures were developed as the best set of metrics using data available to inform the technical analysis of the adaptation scenarios:

Roadway

Vehicle miles traveled (VMT) is the total distance traveled by all vehicles in a given area over a given period of time. It is calculated by the number of vehicles multiplied by the miles traveled in a given area or on a given highway during the time period. In general, daily VMT remains consistent for each of the scenarios, apart from Scenarios A2B (Managed Retreat/Widening G12 6 Lanes), A3 (4-Lane Elevated Highway 1), and A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway), where it increases. A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) has the highest daily VMT, while Scenario A0A/B0A (No Action Without Highway) has the lowest.

Congested VMT (CVMT) is the total vehicle miles traveled at level of service, E and F (volume/capacity ≥ 0.86 for functional class 2 and where volume/ capacity ≥ 0.90 for functional classes 3-7) divided by total vehicle miles traveled in the peak periods. CVMT is highest for scenarios A0A/B0A (No Action Without Highway), A0B/B0B (No Action With Highway), A1 (2-Lane Elevated Highway 1), and B2 (Dual Track Railway). Scenarios A2A (Managed Retreat/Widening G12 4 Lanes) and A2B (Managed Retreat/Widening G12 6 Lanes) have roughly equal CVMT, while Scenarios A3 (4-Lane Elevated Highway 1) and A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) have the lowest CVMT of the scenarios.

Vehicle hours traveled (VHT) is an aggregate of vehicle miles traveled divided by vehicle speed for all trips in the region. VHT remains consistent for each of the scenarios, showing no significant increase or decrease.

Vehicle Delay: This performance measure shows hours of delay for passenger vehicles in the study area. Vehicle delay is closely correlated with CVMT, with scenarios A0A/B0A (No Action Without Highway), A0B/B0B (No Action With Highway), A1 (2-Lane Elevated Highway 1), B2 (Dual Track Railway), and A2A (Managed Retreat/Widening G12 4 Lanes) having the highest numbers for vehicle delay. Scenarios A3 (4-Lane Elevated Highway 1) and A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) have the lowest vehicle delay, while scenario A2B falls in the middle.

Freight Delay: This measure estimates the daily truck hours of delay. Over the next several decades, the Central Coast region can expect to see significant increases in freight movement due to population increases and a continued expansion of the region's agricultural production. A focus on enhancing the efficiency and safety of the region's goods movement system is critical to supporting the economic health of the region and the quality of life for its residents. Hours of truck delay are increased in scenarios A0B/B0B (No Action With Highway), A1 (2-Lane Elevated Highway 1), and B2 (Dual Track Railway), while the remaining scenarios have consistent levels of freight delay with each other.

Collisions/Accidents: This performance measure evaluates the safety of the transportation system by using data on injuries and fatalities to calculate a per capita rate of injury or fatality. It is an annual projected number of injury and fatal collisions per thousand VMT. This is a particularly difficult measure to project because it assumes that fatalities and injuries are held constant for every vehicle mile traveled. The percentage of collisions and accidents per thousand VMT remains consistent across each scenario.

Historical collision data for the study roadways and intersections were derived from the California Highway Patrol Statewide Integrated Traffic Records System (SWITRS). Data was collected on the Highway 1 study area for a six-year period between January 1, 2013 and December 31, 2018. Based on the collision data, there were roughly 700 reported collisions along the Highway 1 study area. A number of collisions are focused in the northern section of the study area and in the area south of Dolan Road. This suggests that improvements in these areas should be implemented in the near term to address these issues.

General/Multimodal

Average Travel Time: This performance measure shows average commute travel time in minutes. Average travel time is consistent for Scenarios A0B/B0B (No Action With Highway), A1 (2-Lane Elevated Highway 1), and B2 (Dual Track Railway). Scenarios A0A/B0A (No Action Without Highway), A2A (Managed Retreat/Widening G12 4 Lanes), and A2B (Managed Retreat/Widening G12 6 Lanes), show improved average travel times, while Scenarios A3 (4-Lane Elevated Highway 1) and A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) have longer average commute travel times.

Multimodal trips: This is defined as the percentage of total trips that are shared ride, walk, bike, transit, school bus, or other. Scenarios A0B/B0B (No Action With Highway), A1 (2-Lane Elevated Highway 1), and B2 (Dual Track Railway) have similar percentages of multimodal trips, while Scenarios A0A/B0A (No Action Without Highway), A2A (Managed Retreat/Widening G12 4 Lanes) and A2B (Managed Retreat/Widening G12 6 Lanes) have greater percentages of multimodal trips. Scenarios A3 (4-Lane Elevated Highway 1) and A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) show a decrease in the percentage of multimodal trips.

Social Equity

Disadvantaged Communities: This performance measure evaluates the percent of low income populations and racial and ethnic minority groups that are located within one-half mile of a transit stop for all communities in the vicinity of the adaptation scenarios. Census data was used to identify Census tracts that contained greater than 65% of households with an income of less than $75,000 per year, as well as tracts where 65% or more of the population is non-white. Much of population within the study area is both low income and home to communities of color. This performance measure was calculated using GIS.

Scenarios A0B/B0B (No Action With Highway), A1 (2-Lane Elevated Highway 1), A3 (4-Lane Elevated Highway 1), A4/B1(Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway), and B2 provide the greatest accessibility to transit for disadvantaged communities. Scenarios A0A/B0A (No Action Without Highway), A2A (Managed Retreat/ Widening G12 4 Lanes), and A2B (Managed Retreat/Widening G12 6 Lanes), in which transit along the existing Highway 1 corridor is removed, inhibit accessibility for disadvantaged communities.

Environment

Impacts to Natural Resources: This performance measure shows the total acres of natural resource areas, wetlands, critical habitats, open space areas, and farmlands consumed by each scenario. This was calculated using GIS using data from the U.S. Fish & Wildlife Service, California Department of Fish & Wildlife, Farmland Mapping and Monitoring Program and the California Protected Areas Database. Further ecological impacts are presented in the habitat modeling section (Section 6.5.1) for the adaptation scenarios. Scenario A4/B1 (Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway) has the largest impact on natural resources, consuming substantially more acreage than the other scenarios. Further ecological impacts are also discussed in the ecological modeling section. Scenarios A2B (Managed Retreat/Widening G12 6 Lanes), A3 (4-Lane Elevated Highway 1), and B2 (Dual Track Railway) are roughly equal in their negative impact to natural resources, while Scenario A2A would be slightly less. Scenarios A0A/B0A (No Action Without Highway), A0B/B0B (No Action With Highway) and A1 (2-Lane Elevated Highway 1) would result in little impact on natural resources compared to existing conditions.

Cost

Costs vary by scenario. A summary of the cost estimates, which include right-of-way acquisition and mitigation costs, are shown below in **Table 8**. A detailed cost breakdown is included in Appendix F.

TABLE 8
CONCEPTUAL TRANSPORTATION COST ESTIMATES FOR PRELIMINARY ADAPTATION SCENARIOS

Scenario	Draft Cost Estimate (2019 dollars)
A1 (2-Lane Elevated Highway 1)	$240 million
A2A (Managed Retreat/Widening G12 4 Lanes)	$190 million
A2B (Managed Retreat/Widening G12 6 Lanes)	$280 million
A3 (4-Lane Elevated Highway 1)	$445 million
A4/B1(Co-Located 4-Lane Elevated Highway 1 and Dual Track Railway)	$1.8 billion
Scenario B2 (Dual Track Railway)	$470 million

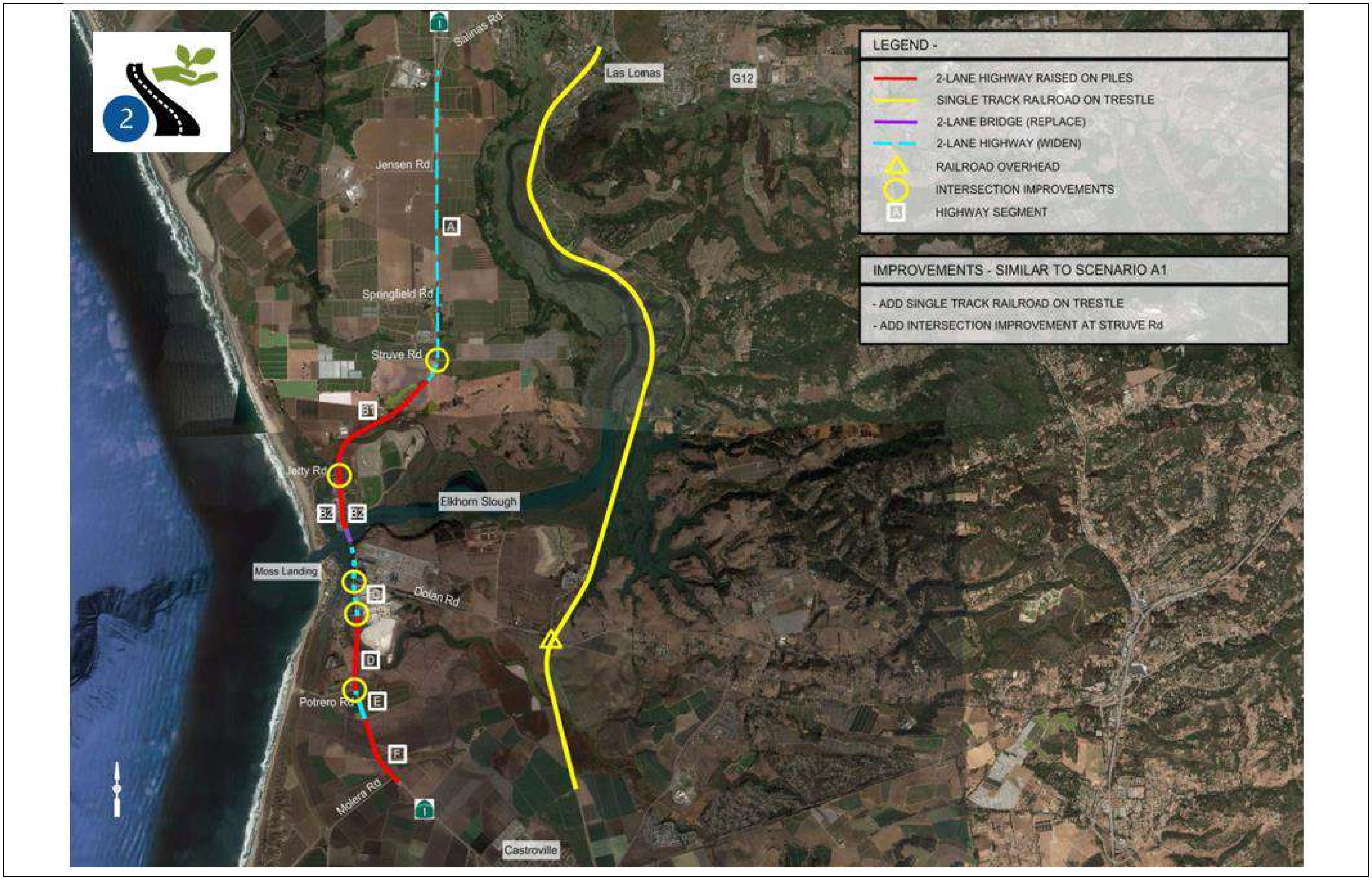
6.4 Refined Roadway and Railway Scenarios

Results from the hydrodynamic and transportation modeling for the preliminary adaptation scenarios were presented at the December 2019 Steering Committee meeting. Based on input from the Steering Committee, the set of preliminary adaptation scenarios were narrowed to three refined scenarios for the habitat modeling and full benefit cost analysis. Additional discussions regarding double tracking the railway resulted in the assumption that the railway did not need to be double tracked through the Elkhorn Slough area. The railway is assumed to be double tracked outside of the study area but remain as a single track in each of the revised adaptation scenarios. **Table 9** describes the revised adaptation scenarios.

In Scenarios C1 and C3, Highway 1 is assumed to be elevated to accommodate 3 ft of sea level rise (corresponding to a 2070 time horizon) with an additional foot of freeboard. Scenarios C1 and C3 have variations where Highway 1 Reach 2 is either elevated on fill embankment (Scenarios C1A, C3A) or piles (Scenarios C1B, C3B). Adjustments to access improvements and revised adaptation pathways diagram are shown in **Figure 31** through **Figure 34**.

TABLE 9
REVISED ROADWAY AND RAILWAY ADAPTATION SCENARIOS

	2-Lane Elevated Highway 1 (C1)	**Improve G12 Inland Corridor as Main Route (C2)**	**4-Lane Elevated Highway 1 (C3)**
	Highway 1 remains 2 lanes and is elevated in place, on piles or fill, as appropriate	Through traffic re-direct inland to the G12 corridor and Highway 1 unmodified for local only access	Highway 1 expanded to 4 lanes and is elevated in place, on piles or fill, as appropriate
Road Features	Highway 1 remains 2 lanes	G12 Widened to 4-lane and Highway 1 traffic diverted	Highway 1 widens to 4 lanes
	Highway elevated on piles or fill	Only local access to Highway 1	Highway elevated on piles or fill
	Road ecotone marsh planting		Road ecotone marsh planting
	Highway operational and access improvements		Highway operational and access improvements
	Express transit service		Express transit service
	Enhanced bicycle and pedestrian facilities	Enhanced bicycle and pedestrian facilities	Enhanced bicycle and pedestrian facilities
Rail Features	Hourly rail service on elevated single track	Hourly rail service on elevated single track	Hourly rail service on elevated single track
	Marsh restoration east of railway	Marsh restoration east of railway	Marsh restoration east of railway

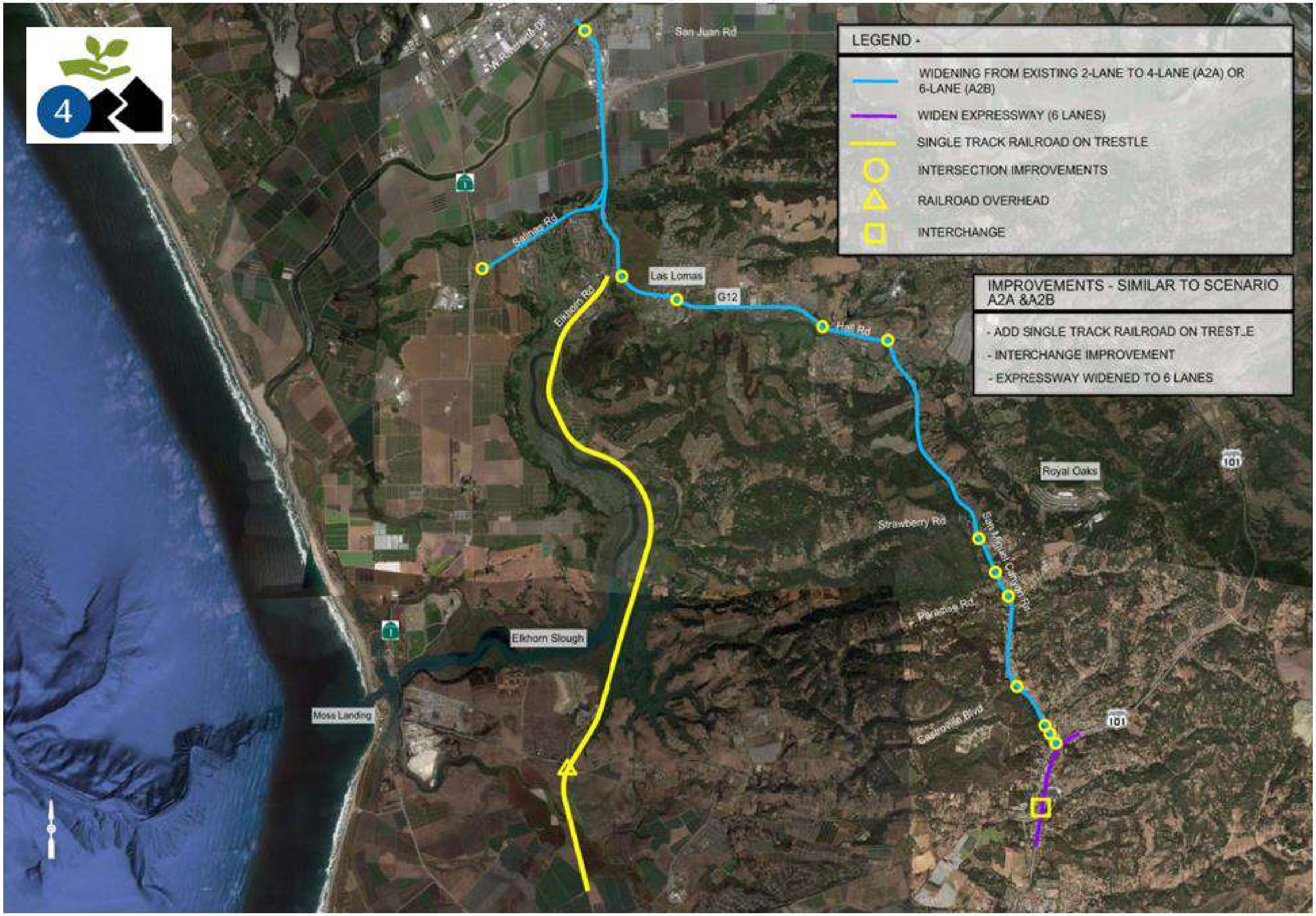


Central Coast Highway 1 Climate Resiliency Study

Figure 31

Scenario C1 (Conceptual)

2-Lane Elevated Highway 1 and Single-Track Railway

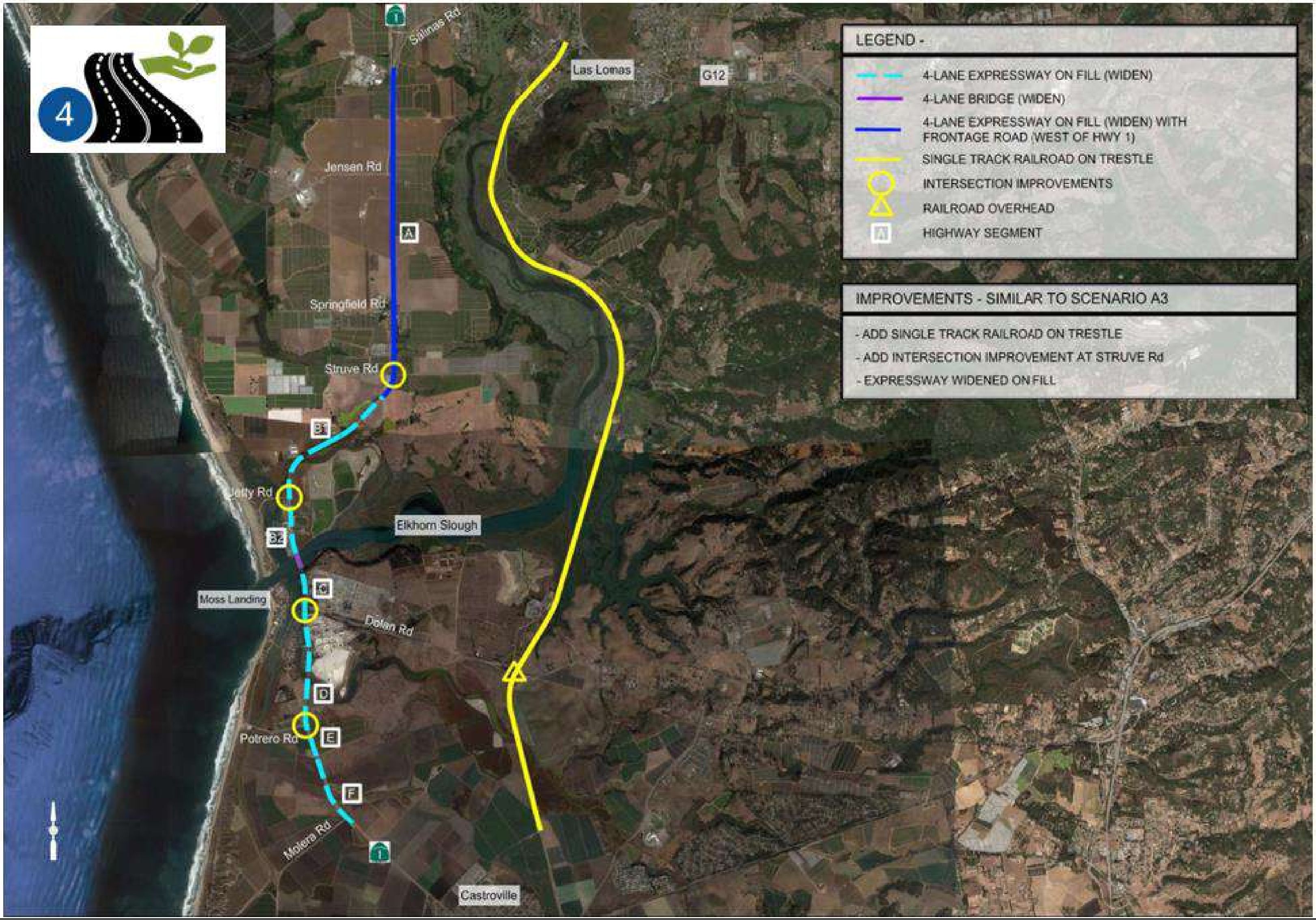


Central Coast Highway 1 Climate Resiliency Study

Figure 32

Scenario C2 (Conceptual)

Improve Inland G12 Corridor as Main Route and Single Track Railway

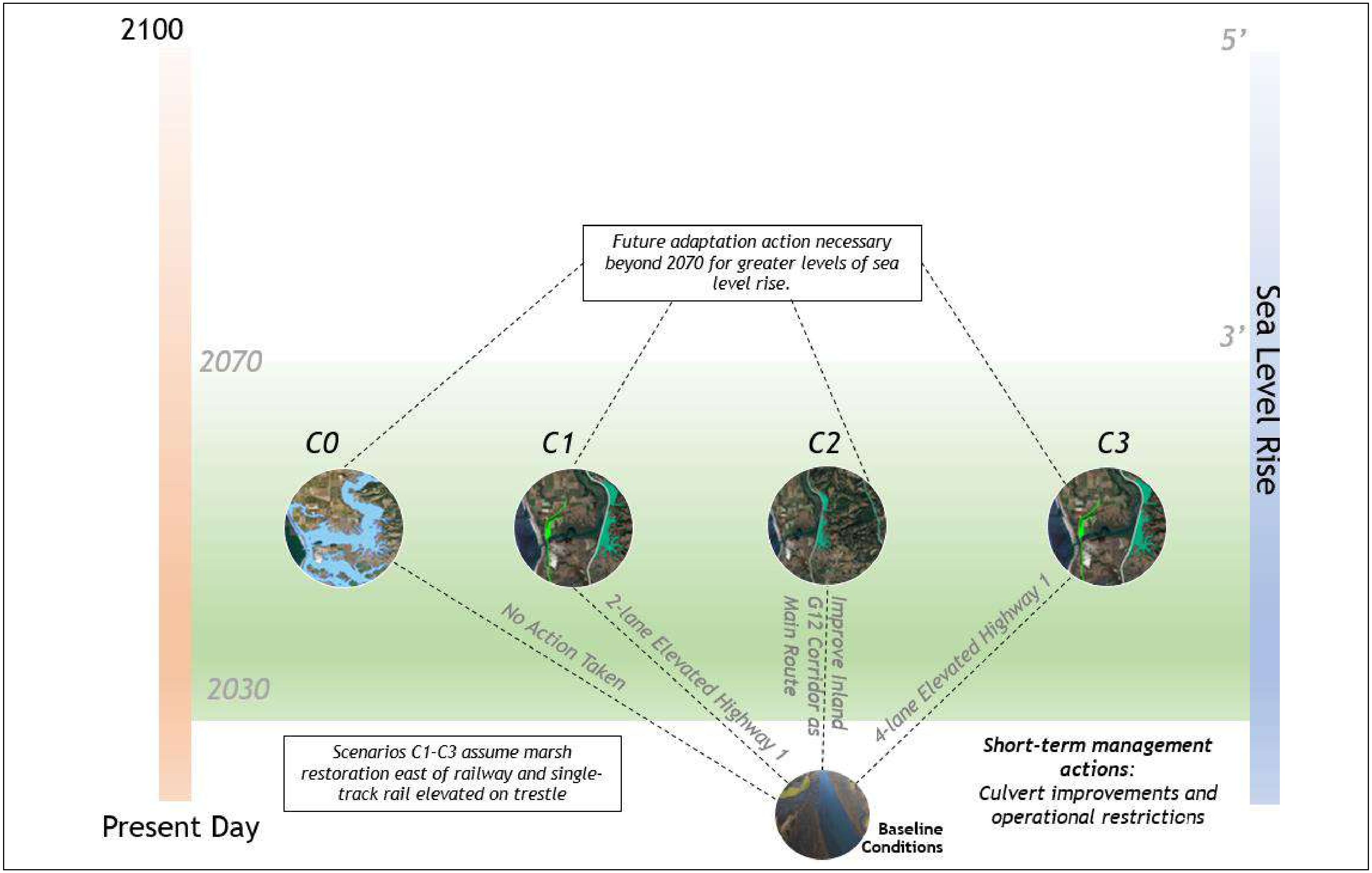


Central Coast Highway 1 Climate Resiliency Study

Figure 33

Scenario C3 (Conceptual)

4-Lane Elevated Highway 1, Single Track Railway



Central Coast Highway 1 Climate Resiliency Study

Figure 34

Refined Roadway and Railway Adaptation Scenarios
Adaptation Pathways Diagram

6.5 Further Evaluation of Refined Roadway and Railway Scenarios

6.5.1 Habitat Modeling (SLAMM)

Much of the estuarine habitats of Elkhorn Slough are vulnerable to impacts from sea level rise without restoration efforts due to the steep surrounding topography precluding the inland migration of the current extent of estuarine marsh (**Figure 8**). This highlights several important points. Firstly, much of the projected loss is due to accelerated sea level rise, independent of transportation infrastructure. This study compares ecological responses among transportation adaptation to seek the best alternative for nature, which is to say the alternative that minimizes habitat loss due to sea level rise. Secondly, it is clear that transportation adaptation alone will not prevent the loss of estuarine habitat in Elkhorn Slough. This highlights the clear need for concerted actions in other strategies such as further conservation, managing conserved lands in place, and investing in conserving and restoring non-habitat areas projected to be inundated by sea level rise will be necessary to maintain the iconic and important habitats of Elkhorn Slough (Heady et al. 2018). Here we use the Sea Level Affecting Marshes Model (SLAMM)[12] developed by Warren Pinnacle Consulting to project habitat changes in response to sea level rise for each of the selected adaptation scenarios. Estuarine plants that define estuarine habitats live in discrete zones defined by relative elevation, hydrology, salinity, and other forces (Figure 12). SLAMM models dominant processes involved in wetland conversion as sea levels rise based on existing or modeled topography. The adaptation scenarios we considered each differ in topography, bathymetry, and certain other parameters that giver rise to different ecological outcomes as modeled by SLAMM.

A no action scenario (Scenario C0) was run from present day (2020) until 2100 to use as a baseline for evaluating the performance of the different adaptation scenarios. Scenarios C1A (2-Lane Elevated Highway 1, Reach 2 on Piles), C1B (2-Lane Elevated Highway 1, Reach 2 on Fill), C2 (Improve G12 Inland Corridor as Main Route), C3A (4-Lane Elevated Highway 1, Reach 2 on Piles) and C3B (4-Lane Elevated Highway 1, Reach 2 on Fill) were evaluated using SLAMM from 2050 (time of adaptation) to 2100. Habitat acreages and maps were output for every decade for each adaptation scenario and no action. In order to highlight the direct effect of transportation adaptation and ecosystem restoration on ecosystem changes throughout Elkhorn Slough and facilitate the evaluation of differences among transportation adaptation strategies the following results and acreages refer to model outcomes assuming that human assets including agriculture and developed areas will be defended and wetland habitats are allowed only to migrate into existing habitat areas including terrestrial upland habitats. Technical detail on model input development and process is provided in Appendix D.

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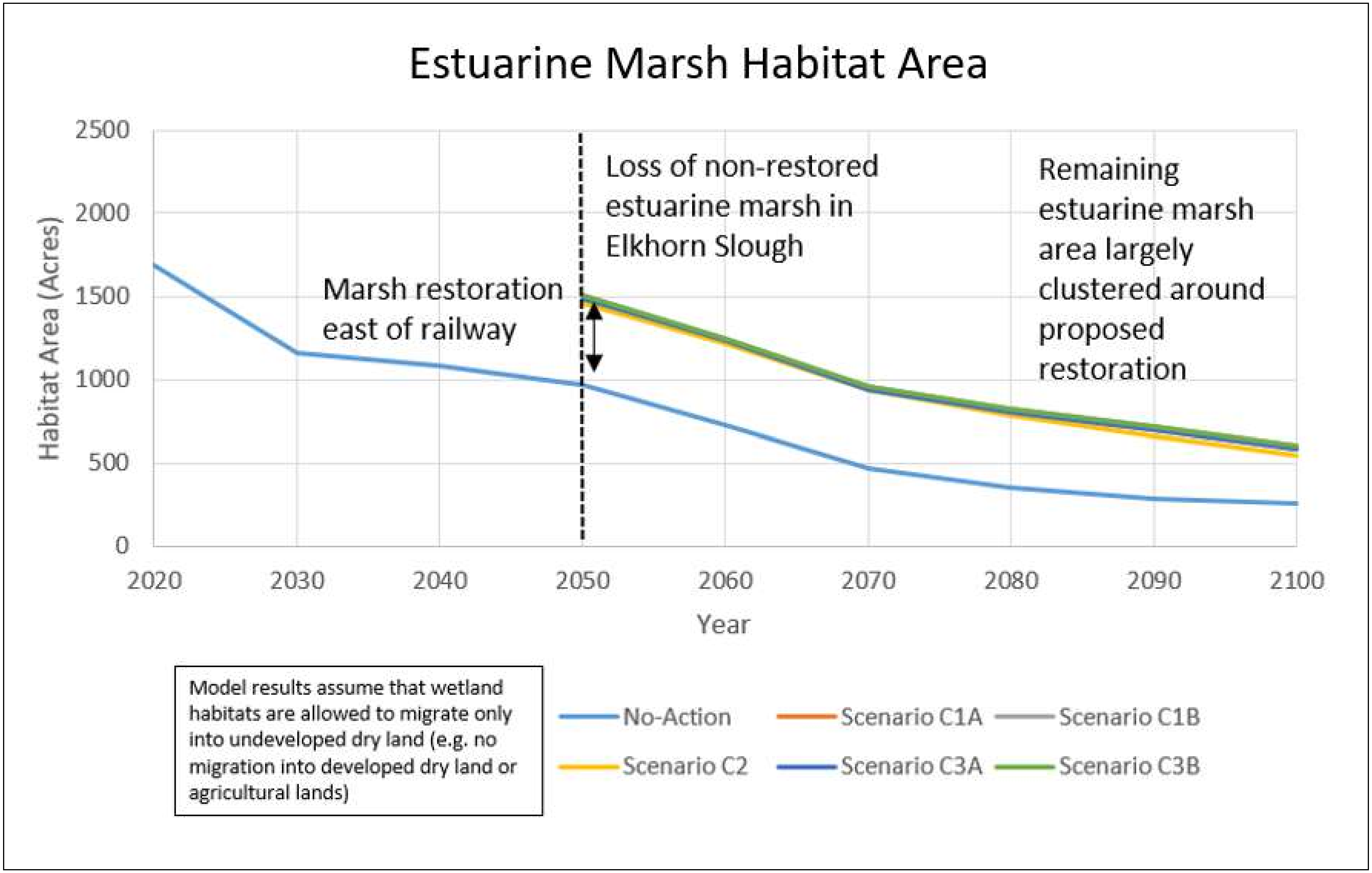
[12] More information on SLAMM can be accessed at this address: http://warrenpinnacle.com/prof/SLAMM/

Levee Ecotone

The levee ecotone by Reach 2, in Scenarios C1A (2-Lane Elevated Highway 1, Reach 2 on Piles), C1B (2-Lane Elevated Highway 1, Reach 2 on Fill), C3A (4-Lane Elevated Highway 1, Reach 2 on Piles) and C3B (4-Lane Elevated Highway 1, Reach 2 on Fill), result in the creation of transitional marsh habitat under future sea level rise conditions. Scenarios C1A (2-Lane Elevated Highway 1, Reach 2 on Piles) and C3A (4-Lane Elevated Highway 1, Reach 2 on Piles) result in approximately 72 acres of estuarine marsh habitat creation by Reach 2 and Moss Landing Wildlife Area at 2050, assuming Reach 2 is elevated on piles. 52 acres of estuarine marsh remain at 2100 assuming this configuration. Scenarios C1B (2-Lane Elevated Highway 1, Reach 2 on Fill) and C3B (4-Lane Elevated Highway 1, Reach 2 on Fill) result in approximately 83 acres of estuarine marsh habitat creation by Reach 2 at 2050, assuming Reach 2 is elevated on fill, with 70 acres remaining at 2100. For Scenarios C1B (2-Lane Elevated Highway 1, Reach 2 on Fill) and C3B (4-Lane Elevated Highway 1, Reach 2 on Fill), the difference in roadway "footprint" for a 2-lane and 4-lane highway in Reach 2 is approximately 0.5 acres. Therefore, the habitat acreage numbers reported for these two scenarios in that particular location are similar. It should be noted that the model does not capture impacts to habitats as a consequence of construction of a new 4-lane highway facility. Construction of a 4-lane highway will have significant impacts on habitat adjacent to the existing roadway alignment. Any construction impacts would be evaluated in the future if a project were to move forward as part of the project development process.

Marsh Restoration

Marsh restoration east of the railway was included in all three adaptation scenarios evaluated. The adaptation scenarios assume that the existing railway embankment, which acts as a hydraulic control for estuarine water levels on its inland side, will remain in place as a new railway is elevated on trestle. Marsh restoration, which includes creating new tidal openings to the marsh complexes east of the railway, would assist with equalizing the water levels on either side of the embankment, which would improve stability and support sediment retention in the newly restored marshes. With marsh restoration, the total acreage of estuarine marsh habitat at 2050 is approximately 1500 acres, compared to 971 acres for Scenario C0 (No Action) at the same time horizon. The total acreage of mudflat habitat at 2050 for the adaptation scenarios is approximately 1250 acres, compared to 1634 acres for Scenario C0 (No Action) at the same time horizon. The mudflat acreage is lower at mid-century for the adaptation scenarios because the proposed restoration would elevate areas that historically converted to mudflat to be restored to estuarine marsh. The remaining estuarine marsh predicted at 2100 (approx. 550 acres) is about 40% of the total restored acreage at 2050. At 2100, marsh restoration results in approximately 800 acres of mudflat habitat, compared to 639 acres for Scenario C0 (No Action). **Figure 35** and **36** show the habitat trends across adaptation scenarios for estuarine marsh and tidal flats.



Central Coast Highway 1 Climate Resiliency Study

Figure 35

Predicted Estuarine Marsh Habitat Trends

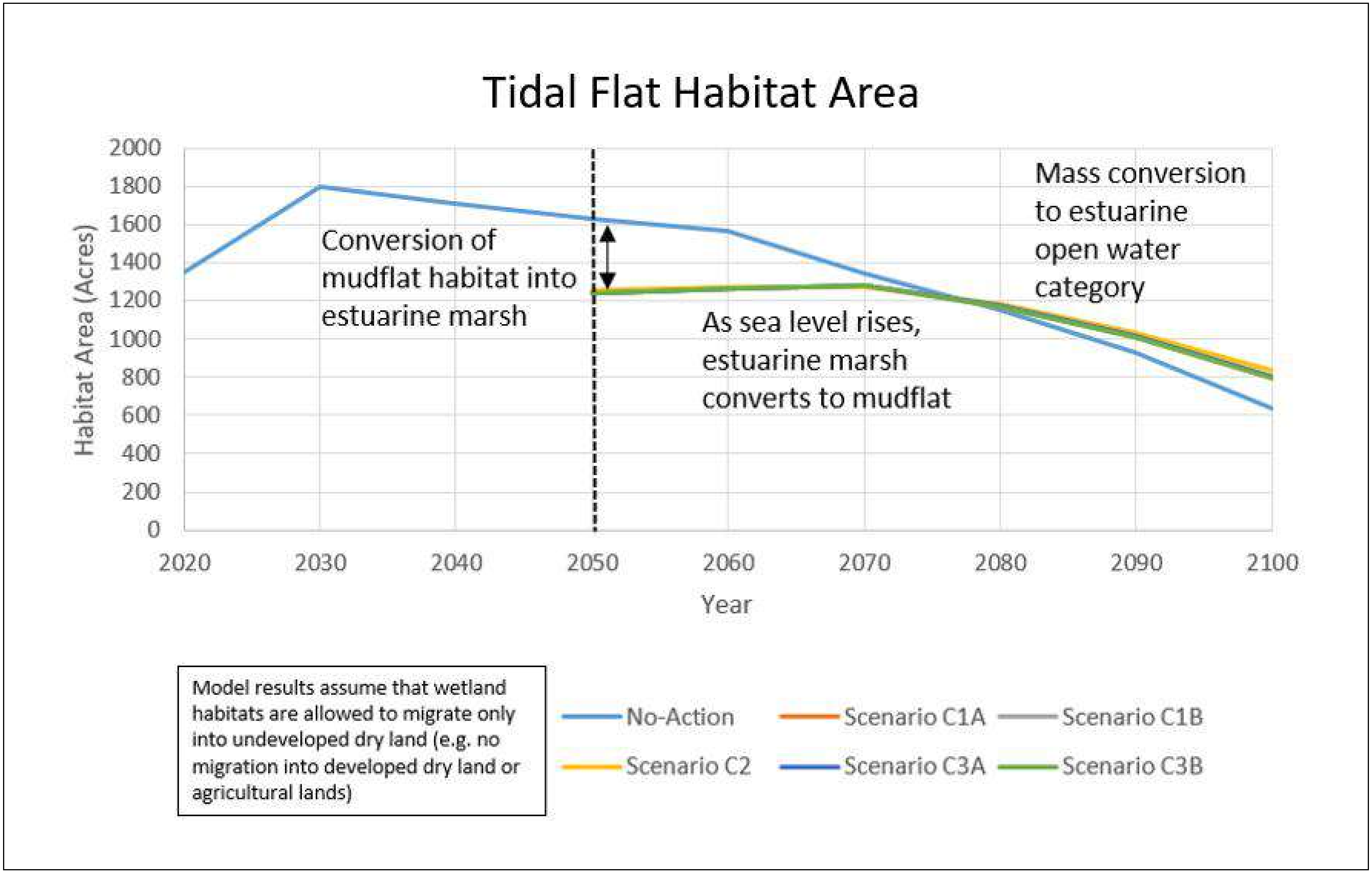


Figure 36

Predicted Tidal Flat Habitat Trends

The results of the habitat modeling project that without marsh restoration, up to 85% of existing estuarine marsh habitat in Elkhorn Slough will be convert to mudflat and estuarine open water habitat types by 2100 (5 ft of sea level rise). Up to 50% of existing mudflat habitat will be lost by 2100. These projected habitat losses are result of the steep surrounding topography not allowing the inland migration of the current extent of estuarine habitat (Figure 8) coupled with accelerated rates of sea level rise. However, marsh complexes modeled to be restored to an elevation of 8' NAVD (future MHHW at 2050) were predicted to persist through the end of the century and help mitigate these losses.

Model results show that estuarine marsh acreages amongst the adaptation scenarios trend similarly, with loss of marsh areas west of the railway and by the main channel stem. At 2100, the estuarine marsh remaining is primarily those that were assumed restored at mid-century.

Low Elevation Non-Habitat Areas and Rising Seas

There are considerable areas of non-habitat within the region that are low elevation (**Figure 8**) and predicted to be inundated by sea level rise (**Figure 1**). When habitat migration is allowed into non-habitat areas, the model predicts that as sea levels rise and inundate the low-lying agricultural lands by Highway 1 Reaches 3 and 4 and Moro Cojo Slough they could be restored to wetland habitat (approx. 1100 acres). This indicates the vulnerability of these land uses to sea level rise. As the productivity and value of these land uses as agriculture decreases, the opportunity of these lands to revert into wetland habitats increases with the potential to mitigate estuarine habitat loss.

6.5.2 Transportation Modeling for Revised Scenarios

AMBAG evaluated the transportation improvements included in Scenarios C1 (2-Lane Elevated Highway 1), C2 (Managed Retreat/Widening G12 4 Lanes), and C3 (4-Lane Elevated Highway 1) using the RTDM and GIS. All 2040 scenarios include future population, housing and employment growth in the region. The three scenarios are described below.

- Scenario C1 (2-Lane Elevated Highway 1) is based on Scenario A1 from the previous round of scenario evaluations, with additional access point modifications and increased bus and rail services. Access to Highway 1 would be improved at the Struve Road, Jetty Road, Dolan Road, Moss Landing Road and Potrero Road intersections. Monterey-Salinas Transit Routes 27, 28, 78, and 79[13] would operate with a bus rapid transit type service at 30-minute frequencies between Santa Cruz and Monterey/Salinas and passenger rail service would operate at an hourly frequency.

[13] More information on the Monterey-Salinas Transit Routes can be accessed here: https://mst.org/maps-schedules/route-list/

- Scenario C2 (Improve G12 Inland Corridor as Main Route) is a managed retreat from Highway 1, widening the G12 corridor to four lanes. The Highway 11/156 interchange would be improved, and Highway 11 would be widened to six lanes from San Miguel Canyon Road to the SR 156 interchange. Highway 1 would operate as a local access road between Springfield Road and Moss Landing Road. MST routes 27 and 28 would end in Castroville, but passenger rail would operate on an hourly service from Salinas north to San Jose.
- Scenario C3 (4-Lane Elevated Highway 1) is similar to scenario C1, but Highway 1 is widened to 4 lanes. Additionally, a frontage road would extend from Struve Road to Salinas Road on the west side of Highway 1, with no access to the highway at Jensen Road. MST Routes 27, 28, 78, and 79 would operate with a bus rapid transit type service at 30-minute frequencies and passenger rail service would operate at an hourly frequency.

The County of Monterey is currently planning a bicycle and pedestrian route through the study area as part of the Monterey Bay Sanctuary Scenic Trail. The Moss Landing segment includes 0.85 of a mile pedestrian and bicycle path, a 386-ft long bridge to span Elkhorn Slough and will link Moss Landing to the north Moss Landing Harbor. This bicycle and pedestrian route is assumed to be in place for all of the scenarios evaluated.

For each conceptual scenario, the RTDM was utilized with specific network and transit components, and the output was analyzed quantitatively. The evaluation criteria listed below were applied to each of the three scenarios, and the results were compared relative to each scenario.

Figure 37 is a matrix of how each scenario performed relative to each scenario for each of the performance measures.

Roadway

VMT: In general, daily VMT remains consistent for each of the scenarios, increasing from a 2040 No Action scenario.

CVMT: CVMT is highest for Scenario C1 (2-Lane Elevated Highway 1), lowest for Scenario C3 (4-Lane Elevated Highway 1), and Scenario C2 (Improve G12 Inland Corridor as Main Route) falls between C1 (2-Lane Elevated Highway 1) and C3 (4-Lane Elevated Highway 1).

VHT: VHT is roughly equal for Scenarios C1 and C2 (Improve G12 Inland Corridor as Main Route), while C3 has the lowest VHT.

Vehicle Delay: Scenario C2 (Improve G12 Inland Corridor as Main Route) has the highest amount of delay, Scenario C3 (4-Lane Elevated Highway 1) has the lowest, and Scenario C1 (2-Lane Elevated Highway 1) falls between the C2 (Improve G12 Inland Corridor as Main Route) and C3 (4-Lane Elevated Highway 1).

Performance Measures for Central Coast Highway 1 Climate Resiliency Study

PM ID	DESCRIPTION	2040 No Action	2040 C1	2040 C2	2040 C3
1	Vehicle Miles Traveled Total[1]	=	—	—	—
2	Congested Vehicle Miles Traveled[2]	—	—	=	+
3	Average Travel Time[1]	+	=	=	—
4	Vehicle Hours Traveled Total[1]	=	=	=	+
5	Vehicle Delay[2]	—	=	—	+
6	Freight Delay (Vehicle Hours Traveled)[1]	=	=	=	+
7	Greenhouse Gas Emissions (CO2) Emissions from all land use and Vehicle Miles Traveled per capita (lbs)[1]	=	=	=	=
8	Collisions/Accidents (Annual projected number of injury and fatal collisions per thousand Vehicle Miles Traveled)[2]	=	=	=	=
9	Multimodal Trips/Mode Share (Transit, Bike, Ped)[1]	+	—	=	=
10	Disadvantaged Communities Accessibility[2]	—	=	—	=
11	Impact to Natural Resources[2]	+	+	—	—

+ Scenario would result in positive benefits

= Scenario would result in neutral benefits

— Scenario would result in negative impacts

[1] Regionwide

[2] Study Area

Figure 37

Transportation Performance Matrix

Revised Roadway and Railway Adaptation Scenarios

Freight Delay: Hours of truck delay are relatively equal for Scenarios C1 (2-Lane Elevated Highway 1) and C2 (Improve G12 Inland Corridor as Main Route), and Scenario C3 (4-Lane Elevated Highway 1) has the lowest amount of freight delay.

Collisions/Accidents: The percentage of collisions and accidents per thousand VMT remains roughly consistent across each scenario.

General/Multimodal

Average Travel Time: Average travel time is consistent for Scenarios C1 (2-Lane Elevated Highway 1) and C2 (Improve G12 Inland Corridor as Main Route), while Scenario C3 (4-Lane Elevated Highway 1) has the longest average commute time.

Multimodal trips: Scenarios C2 (Managed Retreat/Widening G12 4 Lanes) and C3 (4-Lane Elevated Highway 1) have similar percentages of multimodal trips, while Scenario C1 (2-Lane Elevated Highway 1) has the lowest percentage.

Environment

Impacts to Natural Resources: In addition to the ecological analysis described in the previous section, the RTDM also includes an analysis of impacts to natural resources, which is summarized in the following. Scenario C1 (2-Lane Elevated Highway 1) provides the lowest impact on natural resources, while Scenarios C2 (Improve G12 Inland Corridor as Main Route) and C3 (4-Lane Elevated Highway 1) have a larger impact. Construction impacts were not included in this evaluation but would be evaluated in the future when a project would move forward into project development.

Social Equity

Disadvantaged Communities: Scenarios C1 (2-Lane Elevated Highway 1) and C3 (4-Lane Elevated Highway 1) provide the greatest accessibility to transit for disadvantaged communities. Scenario C2 (Improve G12 Inland Corridor as Main Route), in which transit along the Highway 1 corridor is removed, inhibits accessibility for disadvantaged communities.

Cost

Planning level cost estimates were prepared for each scenario. A summary of the cost estimates, which include right-of-way acquisition and mitigation costs are shown below in **Table 10**. A detailed cost breakdown is included in Appendix F.

TABLE 10
CONCEPTUAL TRANSPORTATION COST ESTIMATES FOR REVISED ROADWAY AND RAILWAY ADAPTATION SCENARIOS

	Scenario	Draft Cost Estimate (2019 dollars)
	C1 (2-Lane Elevated Highway 1)	$570 million
	C2(Improve G12 Inland Corridor as Main Route)	$680 million
	C3 (4-Lane Elevated Highway 1)	$750 million

Based on the transportation evaluation of these three adaptation scenarios, Scenario C3 (4-Lane Elevated Highway 1) is the best performing scenario in terms of the transportation, mobility and accessibility needs in the corridor. Many of the components of the Scenario C3 (4-Lane Elevated Highway 1) are longer term and require a large amount of funding to be secured in order to be implemented. Some of the operational improvements components from Scenario C1 (2-Lane Elevated Highway 1) could be considered as shorter term improvements in the corridor. Additional information from the benefit cost analysis would provide additional information from an economic perspective on the transportation investments.

6.5.3 Benefit Cost Analysis

Comparing Benefits and Costs

A benefit cost analysis was undertaken to examine the economic consequences of selecting one of the four scenarios defined above. Benefit cost analysis helps answer three essential questions about making complex investment decisions:

- Will we get back more in benefits than we give up in expenditures and other costs from a particular option?
- Of those options that have a positive return, which should be selected?
- In the case of decisions being driven by highly uncertain processes like climate change, how can we assure the greatest chance of a positive return?

Benefit cost analysis addresses these questions because it uses economic theory and methods to measure different types of changes arising from a decision to a common monetary metric. It is then possible to compare the economic consequences of changes in the transportation system with changes in ecosystems on the same basis so that a complete picture is available.

Benefit cost analysis compares positive and negative changes in economically valuable goods and services. A gain in something of value is a benefit; a reduction in value is a cost. With projects such as those dealing with climate change, the comparison is made between the consequences of taking no action to address climate change and the consequences of one or more identified adaptation scenarios. Taking no action to address climate change generally results in a set of expected damages and consequent losses, which are the costs of a no action scenario. Taking action avoids these losses to some extent. These avoided costs thus become the benefits of an adaptation scenario. At the same time, the expenditures on adaptation which are costs in evaluating an adaptation scenario are benefits in the no action scenario since those expenditures are available for other uses.

The benefits and costs in this analysis can be briefly summarized as follows. Details concerning sources and calculations are provided in Appendix E.

Expenditures on the planning, development, and construction of the highway projects. Estimates of these expenditures were provided by WMH, the highway engineering partner in the study team. These expenditures are spaced out over 10 years from the point where a decision is made to proceed with a particular adaptation strategy. The ten years includes project design, evaluation and permitting, and construction.

- *Expenditures for ecotones and marsh restoration projects*. These estimates were provided by ESA and were spread over three years, coinciding in this analysis with the three-year construction period for highway projects estimated by WMH. Separate analyses are done for options to elevate Highway 1 on pile or fill. (See Section 5.2 Ecology Adaptation Action Elements.)
- *Changes in the value of travel time*. These were estimated as changes in hours of delay as estimated by the AMBAG transportation model for the Area of Interest (AOI). The estimates of hours of delay include assumptions in the AMBAG model that a bus rapid transit system would be established for Highway 1 during commute hours and that hourly passenger rail service from Salinas to San Jose would be available. The delay hours are thus net of a shift in travel modes. The value of the time of delay is set as a proportion of the average hourly wage, which was estimated as the average wage for Santa Cruz and Monterey counties. The proportion, which varies from 50% to 100%, depends on the purpose of the trip. The proportion of trips by purpose is derived from trip data in the AMBAG model.
- *Changes in value of traffic safety*. Using data from the California Highway Patrol, the number of accidents by type (from property damage to fatality) per vehicle mile

traveled in the study area was estimated for the period 2013-2019. The accident rates were then multiplied by the estimated vehicle miles traveled (VMT) for each scenario to get the total number of accidents by type. These were then multiplied by estimates of the economic value of accidents by type from the National Highway Transportation Safety Administration.

- *Changes in vehicle operating costs*. Changes in routes may increase or decrease expenditures on fuel and other per mile costs. The changes in VMT estimated for each scenario were multiplied by 16 cents per mile which was based on an adjusted Department of Transportation estimate of vehicle operating costs for the average fleet. The DOT estimate was adjusted upward for inflation in motor fuels and down for increases in vehicle efficiency to arrive at the 16 cents number.
- *Changes in the Value of Ecosystem Services* Estuaries like Elkhorn Slough are some of the most productive ecosystems providing habitat services to a diversity of species as well as abundant ecosystem services to people (Barbier et al. 2011). However, putting dollar amounts to habitat and ecosystem services is challenging. Estimating the changes in ecosystem service values as a result of large changes such as those examined here is even more challenging since not only must a monetary value be estimated but there must be a quantifiable relationship between the quality, quantity, or access the services as a result of the change in the ecosystems. Even though Elkhorn Slough is intensively studied, the requisite information is not currently available.

  Ecosystem Services: Recreation One ecosystem service that has been valued is recreation. Around 45,000 people visit the Slough every year for kayaking, motorboat tours, bird watching, and hiking. The value to these visitors of their recreational experience may be altered depending on the adaptation option selected. The value of these recreational experiences was estimated through a survey of visitors conducted in 2019 by the Center for the Blue Economy. The results of this survey showed that visitors to Elkhorn Slough value their recreational experience, over and above whatever was spent on that experience (such as travel, rentals, tours, etc.) at $3.2 million per year. (Colgan, 2020)

  Other Ecosystem Services. In addition to recreation, Elkhorn Slough provides a variety of other ecosystem services including habitat for juvenile commercial fish species, flood protection, cleaning waters, and carbon sequestration. The estimation of the value of each of these services individually is a complex task that was beyond the scope of the current project. To estimate these values, information on the purchase price of the lands that make up the current ownerships around Elkhorn Slough was provided by the Elkhorn Slough NERR. This information was then matched to the habitat types on each parcel based on the information from the SLAMM model (Section 6.5.2) for 2020 and the sales price (adjusted for inflation) to estimate a per acre price for each habitat. Average per acre prices for each habitat type were calculated and these prices were used to estimate changes in wetlands values based on the SLAMM estimates of habitat changes for each scenario described above.

Some types of changes in the economic values from ecosystems or other aspects of an area may not be easily quantified or monetized and included in benefit cost analyses. Examples include the research and education activities in the Slough, as well as the historic character of the region. These values should be assessed in future assessments of transportation and sea level rise adaptation options even if they are not included in benefit cost analyses.

An important feature of a benefit cost analysis is that it compares benefits which will be received over many years in the future with costs that are incurred up front in a project. Making this comparison requires that costs incurred and benefits received in the future be discounted; that is adjusted for the fact that expenditures committed to one purpose might earn a higher return if invested at some interest rate. That interest rate is called *the discount rate*. For this analysis a discount rate of 3% was used along with a project period of 50 years beyond the completion of construction. The result of discounting is called *the present value*. All economic values were discounted to present value in 2020; this includes the expenditures on project development and construction for scenarios C1-C3.

Comparing the cost and benefits commonly uses two measures. The benefit cost ratio is calculated as the present value of benefits *divided by* the present value of costs. If the result is greater than 1 the project returns more in benefits over its life than the costs. The other measure is the net present value - the present value of benefits *minus* the present value of costs. As a general rule, projects that have a benefit cost ratio greater than 1 should be considered economically viable; of these options, the one with the greatest net present value of benefits is the economically "best" option. The results of this analysis are shown in **Table 11**.

In **Table 11**, a negative number is shown in red. Post construction effects may be positive or negative and negative effects could be designated as either costs or benefits depending on the scenario being examined. Costs and benefits of the no action scenario and the adaptation scenarios are reversed; that is the costs in no action are the post-construction effects and the benefits are not spending funds on the highway.

The results of the benefit cost analysis indicate the following:

- Scenario C0 (No Action) has the highest costs even without offsetting these costs with the savings on infrastructure reconfiguration in the adaptation scenarios. Taking no action results in large losses to travelers in delay and safety and there are large losses in the value of wetlands. To calculate the benefits of taking no action (the saving of money for other uses) the least expensive (Scenario C2) construction option is used. But even if the most expensive option (Scenario C3) were selected, losses would still outweigh gains if no action is taken

TABLE 1
SUM OF BENEFITS AND COSTS BY OPTION WITH NET PRESENT VALUE AT 3% DISCOUNT RATE AND BENEFIT COST RATIO

			C1		C2	C3	
		No Action	On Piles	On Fill		On Piles	On Fill
Highway	Costs		-$443.67	-$443.67	-$677.24	-$583.10	-$583.10
	Benefits	$443.67					
Ecotone + Restoration	Costs		-$330.24	-$321.43	-$221.78	-$330.24	-$321.43
	Benefits	$321.43					
Travel Delay Passenger	Costs	-$102.99					
	Benefits		-$115.13	-$115.13	-$159.00	$511.10	$511.10
Travel Delay Freight	Costs	-$100.97					
	Benefits		-$103.85	-$103.85	-$80.78	$43.27	$43.27
Travel Safety	Costs	-$776.02					
	Benefits		$534.56	$534.56	$644.91	$644.91	$644.91
Vehicle Operating Costs	Costs						
	Benefits	$93.76	-$217.15	-$217.15	-$335.30	-$335.30	-$335.30
Recreation	Costs	-$81.64					
	Benefits		$86.86	$86.86	$22.39	$99.98	$99.98
Wetlands	Costs	-$397.40					
	Benefits		$48.88	$50.59	$57.19	$44.99	$48.98
TOTAL	Costs	-$1,459.02	-$773.91	-$765.10	-$899.02	-$913.34	-$904.54
	Benefits	$858.86	$234.17	$235.87	$149.41	$1,008.95	$1,012.94
Net Present Value		($600.17)	($539.74)	($529.23)	($749.61)	$95.61	$108.40
Cost Benefit Ratio		0.59	0.30	0.31	0.17	1.10	1.12

- Of the action options, only Scenario C3 (4-Lane Elevated Highway 1) has a benefit cost ratio greater than 1 and thus also has the highest net present value. Only this option reduces the costs of traffic delays sufficiently to offset the total costs of the highway construction and marsh restoration.
- Scenario C1 (2-Lane Elevated Highway 1) does have the greatest present value of wetlands benefits but these are not sufficient to offset the continuing costs of delay.
- Scenario C2 (Improve G12 Inland Corridor as Main Route) has even greater delay costs even with the lane expansion of San Miguel Canyon Road (G12) and Route 101. The social costs of C2 exceed the benefit of saving on construction expenditures in C2, making C2 the most economically costly option.
- The choice between highway construction on fill or on piles would slightly favor construction on fill based on net present value, but the difference between the two is only about $12.8 million in present value terms. More detailed evaluation of these scenarios may clarify which is preferable.

Managing the Uncertainty of Sea Level Rise

The estimates of benefits and costs provided here depend in large part on the timing of the investment in adaptation, which in turn is dependent on the extent and pace of sea level rise. Although there are many projections of possible rates of sea level rise, there are still too many factors in play in the climate, oceans, and human efforts to reduce climate change to know exactly how much sea levels will rise. Thus, any decision to take action to adapt Highway 1 to sea level rise must be made with little confidence about the economic value of outcomes.

There are high stakes in making the decision and getting the timing right. Deciding to proceed with an adaptation option too soon, risks diverting funds that could address other needs. Committing the funds too late risks enduring potentially large losses from damages to the highway and to Elkhorn Slough before responses can be implemented. Understanding the nature of the sea level rise guidance provided by the Ocean Protection Council and considering alternative interpretations can provide guidance on the best timing for initiating the process of selecting an adaptation option.

The Ocean Protection Council guidance for sea level rise-related planning (Ocean Protection Council 2017) was based on sea level rise projections developed at Rutgers University (Sweet et al. 2017; Kopp et al. 2014). These projections were based on models that combined the effects of changes in ocean temperatures, ice melt in Greenland and Antarctica, glacial melt, and runoff from the land, as well as local changes in land elevation. The projections recognize the fundamental uncertainties in the pace and extent of climate change and sea level rise by calculating not a single forecast, but a range of forecasts ordered by the likelihood of each forecast occurring.

The OPC guidance used for this study is based on what the OPC describes as the "medium to high risk aversion" scenario with an assumption of high emissions levels. For Monterey Bay (based on the Monterey tide gauge), that scenario recommends assuming sea level rise listed in **Table 12**:

TABLE 2
OCEAN PROTECTION COUNCIL GUIDELINES SEA LEVEL RISE AT MONTEREY FOR MEDIUM-HIGH RISK AVERSION HIGH EMISSIONS SCENARIO

	OPC Guidance	
Year	**Feet**	**Centimeters**
2050	1.9	58
2060	2.6	79
2070	3.4	104
2080	4.4	134
2090	5.5	168
2100	6.9	210

This scenario is not a "worst case" scenario but assumes little progress is made globally in restraining greenhouse gas emissions over the next thirty years and thus climate change and sea level rise will be very significant.

The curves shown in **Figure 11** (Section 3.6) depict a relatively smooth upward progression out to 2100. But these are not an accurate depiction of the actual data from which the OPC guidance is derived. Each of the decadal points is actually estimated as the probability of that value occurring based on 10,000 iterations of a probability model incorporating sea temperatures, glacial melt, and runoff from the land. A more accurate representation of the sea level rise projection is given in **Figure 38,** which shows two histograms of possible sea level rise in 2050 and 2100 for Monterey.

In these graphs the extent of sea level rise (in centimeters, where 1 foot = approximately 35 centimeters) is shown on the horizontal access and the probability of that level occurring in that year is shown on the vertical axis. It can be seen from these figures that the values for sea level rise specified by the Ocean Protection Council guidance (58 centimeters in 2050, and 210 centimeters in 2100) are at the far-right end of the probability distribution. In fact, the OPC guidance for the Medium-High Risk/High Emissions estimates have only a 0.5% chance of happening in the specified years, indicated by the yellow arrows.

This is a risk averse position to take. The OPC guidance recommends to plan for high sea level rise projections even if the probability is low, which is a reasonable approach to critical public infrastructure decisions. But taking this approach means particular care

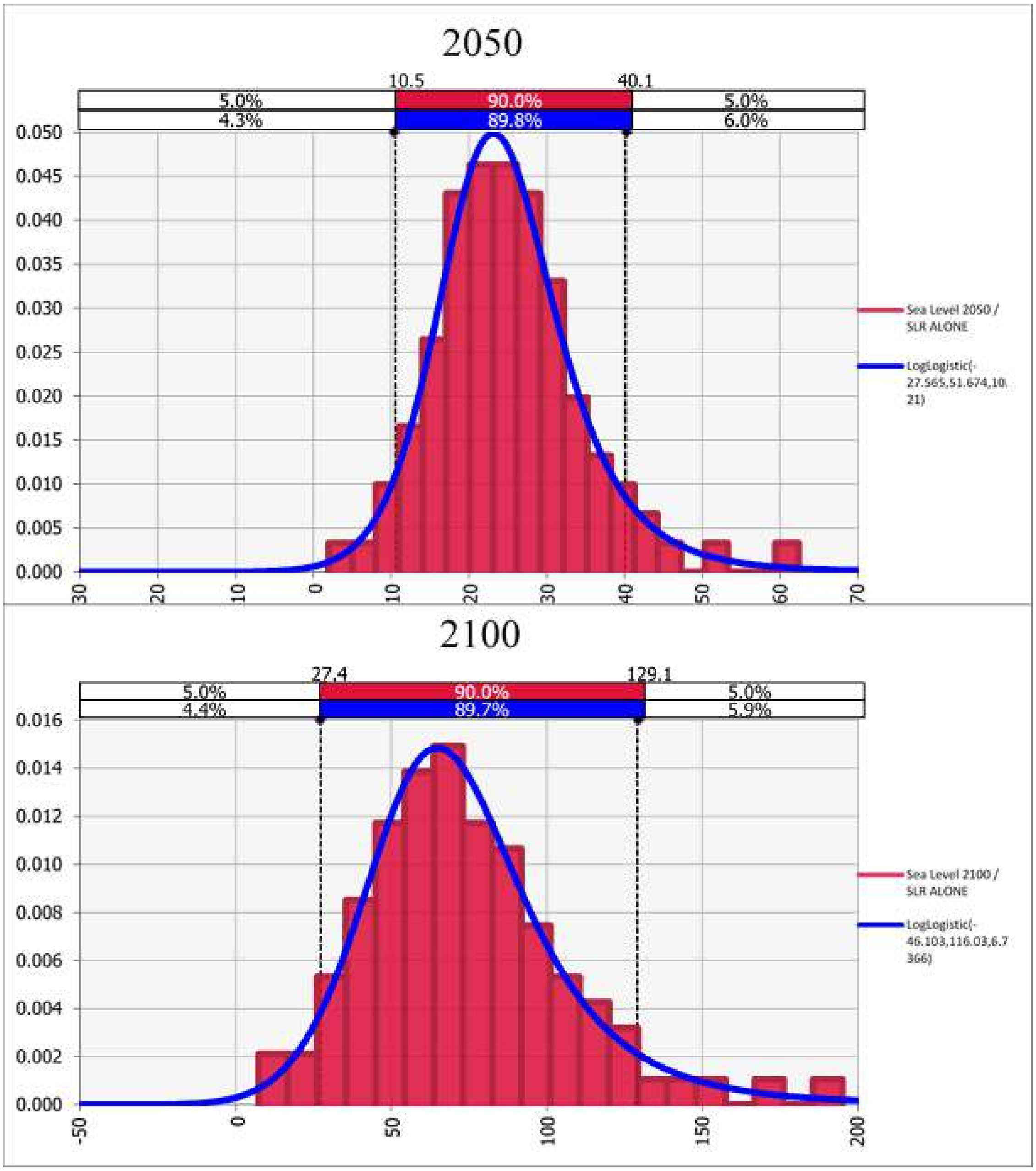


Figure 38

Histograms of Projected Sea Level Rise for Monterey
2050 (top) and 2100 (bottom)

must be taken in the timing of committing to an adaptation approach. The concept of the expected net present value (or the risk-adjusted net present value) shows why. If the 0.5% probability of sea level rise in the medium-high risk/ high emissions scenario were applied to the estimates of benefits and costs from **Table 11** to calculate the expected net present value the result would be very small values (**Table 13**)[14].

TABLE 3
COMPARISON OF NET PRESENT VALUE AND EXPECTED NET PRESENT VALUE AT OPC GUIDANCE PROBABILITIES

		Expected Net Present Value	Net Present Value
	No Action	($3.00)	($600.17)
C1	On Piles	($2.70)	($539.74)
	On Fill	($2.65)	($529.23)
C2		($3.75)	($749.61)
C3	On Piles	$0.48	$95.61
	On Fill	$0.54	$108.40

Table 13 shows, in effect, that, from today's perspective, Scenario C0 (No Action) would probably result in very small losses and Scenario C3 (4-Lane Elevated Highway 1) would probably have very small gains. This implies that the choice of when to commit to an adaptation option has important implications for realizing economic gains. Act too soon and the expected present values could become negative if sea level rise falls below expectations (which they are likely to do on a purely probability basis). Act too late and there is a probability of damages and costs occurring before action is taken.

14 To understand the expected present value, consider what you would do if someone offered to flip a coin; if it comes up heads you would be paid $1.00. If it comes up tails, you would be paid nothing. What amount would you take in place of making the bet? The answer should be 50 cents, or 0.5 (the probability of heads or tails) times $1.00. In the current context, if the state invested ~$100 million in scenario C3, they could expect to get back about $100 million (depending on the assumption about how Highway 1 is to be elevated) over and above the amount expended. But that is the "sure bet" amount. In reality, the probability of sea level rise high enough to produce the projected costs and benefits based on the risk averse assumptions suggested by the Ocean Protection Council would return only ~$0.5 million above the ~$100 million expenditure. This would be a return of about 0.5%, which is less than the 3% discount rate; from a strictly economic perspective Caltrans would be better off buying a bond.

One way to address this risk decision is to evaluate when, based on the probabilities underlying the OPC guidance, the probability of taking action has a better chance of producing positive results than not. Or what is the probability of sea level rise occurring that should trigger the initiation of the 10-year planning and development process assumed for this analysis?

A reasonable rule would be to plan to make a decision about which option to propose at the point where the probability that damage will occur exceeds 50%. For this purpose, we identified two alternative trigger points:

- *Trigger A* The ESA modeling of sea level rise effects on Elkhorn Slough and Highway 1 indicates that tides will be high enough on the extreme monthly high water basis to regularly flood the highway in the stretch just north of the Highway 1 bridge over Elkhorn Slough at about two feet (70 centimeters) of sea level rise. This would cause significant disruptions more than a dozen times a year.
- *Trigger B* Disruptions to the traffic on Highway 1 are likely to be caused by a combination of sea level rise and storms before regular tidal inundation becomes a problem. The ESA modeling of floods indicates that the combination of threats from sea level rise and storms will begin to affect the highway at 0.72 feet or 22 centimeters.

Table 14 shows the probabilities of reaching the 22-centimeter and 70-centimeter levels using the probability distributions in the OPC Medium High Risk Averse/High Emissions scenario.

TABLE 4
PROBABILITY OF REACHING POSSIBLE TRIGGER SEA LEVELS

	Probability of Sea Level Rise of:	
	Trigger B 22 centimeters	**Trigger A 70 centimeters**
2020	0%	0%
2030	0%	0%
2040	19%	0%
2050	60%	0%
2060	82%	1%
2070	92%	5%
2080	95%	16%
2090	97%	32%
2100	97%	49%

Table 14 shows that waiting until regular tidal flooding of Highway 1 is likely to delay initiation of adaptation actions too late. Even by 2100, the probabilities never exceed 50%. The probabilities suggest that it would be into the 22nd century before the project had a high probability of returning sufficient benefits. During the interim, the probabilities also indicate that periodic and likely significant disruptions from sea level rise-enhanced storms will be accumulating damages to travelers and to Elkhorn Slough.

On the other hand, **Table 14** also indicates that some time during the 2040-2050 decade the likelihood of storm caused disruptions will exceed 50% and so planning that targets a decision to select an adaptation option early in the 2040s would have the best chance of choosing an option whose benefits are likely to exceed its costs.

Sensitivity Analysis

All benefit cost analyses are based on a combination of empirical analysis, models (simplified representations of complex systems) and assumptions. Details of these inputs to the analysis are provided in other chapters of this report and in Appendix E. One important assumption in all benefit cost analyses is the choice of the discount rate. The discount rate equates benefits received in the future with costs incurred in the present. Highway and other infrastructure projects typically require large expenditures up front and then generate benefits over many years or decades into the future. But people generally prefer to have benefits sooner rather than later. The discount rate adjusts for this preference by recognizing that benefits received in the future (say 50 years from now) will be perceived as worth less today.

A low discount rate reduces the value of future benefits less than a high discount rate. This analysis uses a 3% discount rate, which is considered a low discount rate. Lower discount rates are considerate appropriate for issues involving climate change. But as the benefit cost ratios are relatively small (around 1.1) the results may be sensitive to the choice of discount rates.

Table 15 shows the net present value of the alternatives analyzed at discount rates from 0% to 9%. This table illustrates the effects of using higher or lower discount rates. It confirms the conclusions from the results shown in Table 11. Even at 0% discount rates neither the no action nor the C1 or C2 adaptation options pass the benefit cost test. C3 does have positive net present values at 3% but not at 5%. A discount rate of about 3.9% produces approximately equal net present value benefits and costs.[15] This rate is above current long-term financing rates for public bonds in California indicating that investing in adaptation of Highway 1 is a good investment. But current rates are very low by historical standards because of the weak economic conditions prevailing at the time of this study. Future studies of adaptation may use higher discount rates.

[15] The discount rate at which net present value equals 0 is known as the internal rate of return.

TABLE 5
NET PRESENT VALUES AT ALTERNATE DISCOUNT RATES

Discount Rate	No Action	C1 Piles	C1 Fill	C2	C3 Piles	C3 Fill
0%	($1,928.53)	($443.68)	($436.99)	($657.48)	$699.43	$715.64
1%	($1,316.55)	($499.51)	($490.59)	($694.52)	$429.42	$444.22
3%	($600.17)	($539.74)	($529.23)	($749.61)	$95.61	$108.40
5%	($244.71)	($533.47)	($522.93)	($786.59)	($77.35)	($65.91)
7%	($61.38)	($508.97)	($498.87)	($811.80)	($165.66)	($155.20)
9%	$36.00	($478.43)	($468.85)	($829.38)	($208.55)	($198.82)
3.9%	($410.29)	($540.43)	($529.81)	($768.06)	$3.61	$15.73

This analysis also shows that the results of the benefit cost analysis for scenario C-3 are discount rate sensitive and that at higher discount rates it may be necessary to alter the C-3 scenario to either reduce costs or increase benefits. A likely candidate for reassessment would be the restoration of the wetlands near the railroad tracks in the northern end of the Slough; at an estimated $221 million, this comprises about one fifth of the cost of C-3. At an estimated $317,000 per acre this would be a very expensive restoration project. The timing and extent of this restoration, particularly if sea level rise is kept below the levels assumed here, may be altered to reduce costs. This marsh restoration, along with other restoration planned or envisioned by the Elkhorn Slough partnership agencies, could also result in comparable wetland benefits at lower cost.

Conclusions

The benefit cost analysis shows the following:

1. The costs of doing nothing about the effects of sea level rise on Highway 1 are likely to far exceed the benefits of saving money by doing nothing if sea levels rise to the relatively high levels assumed here.
2. Of the three major reconfigurations of the transportation network examined, only the C3 scenario (4-lane Highway 1) provides sufficient social benefits in the form of reduced delay, increased safety, and increases in wetland ecosystem service values to yield a positive net present value. The wetlands investments in this scenario including ecotones on the sides of the highways and a restoration of the marshlands north of the railroad tracks yield positive net present values when combined with the widened highway.
3. Transforming Highway 1 into a local road and shifting through traffic to the north and east along Highway G12 has substantial negative net present value. The 2-lane elevated Highway 1 can offset the effects of possible sea level rise, but the economic

losses from delays, even after new travel options in the form of bus and rail are included, result in overall negative present values.

4. The extent of sea level rise remains unknown. Using guidance from the California Ocean Protection Council, the scenarios evaluated in this study reflect a high level of risk aversion, meaning a high amount of sea level rise with a current low probability. The low probability means that the risk-adjusted ("expected") positive net present value of the 4-lane scenario are very small (less than $1 million). For this reason, a decision to make a large investment in Highway 1 adaptation should be timed so that the probability of adequate economic returns on that investment are clear.

5. The probabilities of the sea level rise scenario assumed for this study indicate that a decision of which adaptation option to actively pursue should be made by the early 2040s when the probability of sea level rise-enhanced storm damages to Highway 1 becomes more likely than not. Planning and evaluation of options for any large-scale adaptation of Highway 1 (assumed to be 10 years in this study) should proceed so that transportation adaptation is completed sometime between 2040 and 2050.

6. Further benefit cost evaluations of options should be undertaken as planning proceeds in order to fully understand the combined consequences of adaptation options for transportation in the region and the unique ecological values of Elkhorn Slough. Those further analyses should consider at least the following:

   - Additional options for wetlands restoration in Elkhorn Slough, many of which are currently being planned or envisioned by the partner organizations who own and manage Elkhorn Slough and its adjacent lands. More research on Elkhorn Slough ecosystems and their economic benefits should be undertaken to refine the estimates of these benefits used here.

   - Information about recreational users not covered in detail in the 2019 survey cited here should be gathered, particularly for the large population of bird watchers who come to the Slough.

   - Changes in transportation and the spatial distribution of economic activity resulting from the 2020 corona virus pandemic. It is possible that substantial changes in the location of residences and work locations of the type made necessary by public health considerations in early 2020 may persist into the future. The result could be reductions in commuting and in service-work related trips. These will become clearer as the time when a decision is needed draws closer.

   - The effects of discount rates appropriate to the time when decisions will be made on the economic evaluation should be included in future analysis.

   - Climate change implications of the alternatives should be examined. The shifts in traffic, vehicle miles traveled, and mode of transportation will result in increases or decreases in greenhouse gas (GHG) emissions. These changes are a function, however, not only of the total amount of travel but of the technologies of travel.

It is clear that the future automobile and truck fleets will use substantially different technologies with much lower GHG emissions than the current fleet. This means that projections based on the current fleet must incorporate different energy use factors. This requires much more complex modeling that could be done for this study. Other California agencies, including Caltrans, will have this capacity.

- Another climate change related issue is carbon sequestration, which has economic value based on the prices paid in carbon markets or on estimates of the "social cost" of carbon. Elkhorn Slough is known to sequester carbon at fairly high levels, and this potential has increased with the recent Hester Marsh restoration project. But estimating the extent of carbon sequestration in the proposed wetlands enhancement and restoration in this project was beyond the resources available so no economic value was included in the benefit cost analysis. Future studies should include this economic value of information on the effects of options being considered on carbon sequestration is available.

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CHAPTER 7

Near-Term Actions to Advance Adaptation Strategies Moving Forward

7.1 Near-Term Actions and the Need to Begin Planning Now

The study presents a range of roadway and railway adaptation strategies over time in order to facilitate action now towards meaningful climate change adaptation for the transportation infrastructure and habitats of Elkhorn Slough. Near-term actions for transportation and ecological resilience, such as replacements/modifications of existing hydraulic structures, operational restrictions for use of railway during high water conditions and continuing marsh restoration efforts around the Slough, were presented in Section 4. The efficacy of these interim strategies will diminish as sea level rises, simply because it will become necessary to adapt infrastructure to a new normal.

According to sea level rise, flooding response, ecological response, and benefit cost modeling, adaptation implemented not later than 2050 is critical to the resilience of transportation infrastructure and particularly to minimize habitat loss and the services ecosystems provide. Given the scope of the adaptation required, action toward implementation (e.g. planning, environmental review, design, approvals) must be initiated in the near term. The consequences of taking no action to improve either would be extremely costly and result in devastating losses in habitat area and disruption to commuter function. The hydrodynamic modeling (Delft3D) conducted show that new flood pathways develop in the study area by 1) Moss Landing Wildlife Area, Struve Pond and Bennett Slough, as well as 2) Highway 1 Reaches 3, 4 and Moro Cojo Slough under a future extreme monthly high water and additional sea level rise of 2 to 3 feet (2050 to 2070 timeframe). With a coastal storm, the flood hazard modeling results show that portions of the roadway alignment (Reaches 1 and 2) will be impacted even earlier (2030 to 2040). Modifications made to the roadway will have decreasing control over flood protection for landward areas, which underlines the importance of defining triggers for adaptation actions now.

The habitat modeling (SLAMM) portion of the evaluation projects that without restoration up to 85% of existing estuarine marsh habitat in the Slough will be degraded or transferred to open water under sea level rise at 2100. The main drivers of this change to habitat is due to topography preventing the migration of habitats with sea level rise (Figure8). About half of existing tidal flat habitat will be permanently submerged at that time horizon. Marsh restoration of the complexes east of the railway at mid-century would help mitigate some of this habitat area loss, providing an additional 290 acres of wetland habitat at 2100. The cost and difficulty of conducting a large-scale restoration would drastically increase as water levels rise. The modeling also shows opportunity areas by Highway 1 and Moss Landing Wildlife Area to create between 72 to 83 acres of estuarine marsh habitat at mid-century using a levee ecotone approach. At a synoptic scale, the agricultural lands by Highway 1 Reaches 3 and 4 and Moro Cojo Slough could potentially mitigate a greater portion of estuarine habitat loss (up to 460 acres), if allowed to convert to wetlands. These results underline the importance of strategic land acquisitions in supporting marsh migration and sustaining future marsh habitat acreages.

Overall, the results of the economic assessment and transportation evaluation indicate that Scenario C3 would be considered economically justified and meet the transportation, mobility and accessibility needs in the corridor. However, many of the components of the Scenario C3 are very long term and require a large amount of funding to be secured in order to be implemented. Some of the operational components from Scenario C1 could be considered in the near-term for improvements in the corridor. In this time frame, additional analysis could be conducted to see how adverse impacts on wetland habitat from construction of a new highway facility could be minimized. It may be possible that demographic changes and patterns in using the transportation infrastructure could shift significantly in the future, as climate change drives larger impacts in the wider Monterey Bay area. The nuances of this conclusion point towards the limitations of existing data in being able to perfectly predict options for the future, thus underscoring the value of an adaptation pathways approach.

This study will not be the last to investigate the dual issues of transportation and ecological resilience for Moss Landing and Elkhorn Slough. New information (e.g. technology shifts in transportation, planned large-scale ecological action, projected commuter use of the corridor and other factors) may become available and should be incorporated into the adaptation planning for the future of the roadway, railway and adjacent habitats, as part of an adaptive management approach. Overall, the analyses performed in this study confirm that planning and action in the next decade to prepare for future sea level rise will be critical and must be taken sooner rather than later and that the benefits of doing so earlier will be greater.

7.2 Potential Future Funding Sources

This section lists potential sources of federal and state funding and potential matching local funds to support adaptation strategies investigated in this study.

<u>Federal Funding Sources</u>

- Federal Highway Administration
- U.S. Army Corps of Engineers

  - Section 204 Beneficial uses of dredged material
  - Section 206 Aquatic system restoration
- National Oceanic and Atmospheric Administration
- Environmental Protection Agency
- Federal Emergency Management Agency (FEMA)
  - Building Resilient Infrastructure and Communities (BRIC)
  - Hazard Mitigation Grant Program
  - Pre-Disaster Mitigation Program
- U.S. Fish and Wildlife Service
  - National Coastal Wetlands Conservation Program

State Funding Sources

- California State Coastal Conservancy
- California Department of Water Resources
  - Integrated Water Resource Management Program
- California Department of Fish and Wildlife
  - Wetland Restoration for Greenhouse Gas Reduction Program
- Wildlife Conservation Board
- Climate Ready Grants
- Senate Bill 1 (SB 1) - SB 1 Competitive Programs

Local/Regional Matching Funds

The transportation and ecological adaptation actions constitute large capital investments, encompassing further study, planning, design and construction. Revenue streams at the local/regional level will have to be developed in order to leverage state and federal funds. Cost-sharing amongst project beneficiaries may also be a potential strategy.

7.3 Considerations for Future Planning

The study team provides the following considerations for future planning.

- **Integrate study results into Regional, Metropolitan and State Transportation Plans and prioritize further planning for this critical transportation corridor.** Recommend that the adaptation pathways developed in this study be prioritized for further planning, including the nature-based elements, in the Regional and Metropolitan Transportation Plans.

- **Future analysis should integrate best available science and modeling, including considering higher sea level rise scenarios.** About 3 feet of sea level rise will result in a marked change in land uses and habitat conversion owing to extensive inundation. The California 2018 guidance indicates this amount of sea level rise may happen between year 2050 (extreme H++ scenario) and 2100 (low-risk aversion scenario 17% exceedance risk). The often used 2018 guidance for moderate-high risk aversion and the locally used CRMB (2014) High SLR scenario based on earlier California guidance both indicate the 3' threshold to be reached around 2070. Finally, the California Strategic Pan (2020) envisions action to develop resilience for 3.5 feet of sea level rise by 2050. Future planning and analyses will need to be consistent with California guidance on sea level rise, which may require consideration of specific sea-level rise scenarios such as the Medium-High Risk Aversion and Extreme Risk Aversion (Cal-NRA and OPC 2018; CCC 2018) applied to major infrastructure projects. These low-risk-tolerance scenarios may result in relative benefits and costs that differ from those resulting from the probabilistic analysis. Given the complexities surrounding transportation adaptation, we further highlight the need for planning to begin now so that adaptation may be in place by 2050.
- **Integration and consistency with other ongoing and future climate change adaptation planning efforts.** We note the importance of integration and consistency with the County's ongoing local planning effort for the Moss Landing community, the Elkhorn Slough Reserve's climate resilience planning, the Moss Landing Harbor and other local and regional planning efforts, to inform the next stage of planning for this transportation corridor. Sea level rise is a major driver to future conditions, with effects dominating other changes such as modifications to Highway 1 and the railway. Communities and facilities are finding adaptation planning difficult and future adaptations for Moss Landing and the Moss Landing Harbor would affect transportation planning. This information is not yet available and should be considered in future transportation adaptation efforts.
- **The economic benefit cost analysis developed in this project provides a framework for planners to assess when adaptation is needed and should be applied to future efforts with transparency.** Economic benefit cost analysis using published probabilities associated with future sea levels (e.g. Sweet et al. 2017; Kopp et al. 2014, Griggs et al. 2017; CalNRA and OPC 2018) inform economic performance of decisions based on best available probabilities. The implication is that societal risk tolerance is not well represented by economics analysis, likely due to discounting of future valuations and difficulty with monetizing societal values, such as the value of wetlands. However, the work presented here provides a framework for planners to assess when to break ground on adaptation and therefore when to begin planning based on their knowledge of planning times, risk aversion, project life, and resiliency

goals. Such an approach should be applied in future efforts to most efficiently plan and implement with transparency.

- **Continue multi-objective and multi-benefit focus in the next stage of adaptation planning.** Interaction with public and stakeholders indicated a keen interest in addressing risks to transportation and coastal resources. However, all scenarios reviewed and the few scenarios analyzed raised concerns. All scenarios entailed significant investment, losses and changes. Therefore, further attention to multi-objective adaptation planning in the Moss Landing, Elkhorn Slough vicinity is needed to develop multi-benefit adaptation to rising sea levels.
- **Pathways, triggers and strong partnerships must be in place now to ensure effective climate change adaptation.** Further study and analysis in the next decade will be necessary in order to investigate the impacts of both scenarios at a more detailed level and to take into account updated information on climate change, sea level rise, and changes in transportation usage. Pathways to partnerships and processes supporting integrated approaches around climate change adaptation, including triggers for collective action, must be in place now in order for communities and ecosystems to successfully adapt to future sea levels. The process and findings presented in this study will hopefully serve as a critical link to the future of the transportation and ecology in Moss Landing and Elkhorn Slough.

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CHAPTER 8

References

Association of Monterey Bay Area Governments (AMBAG). 2012. Central Coast California Commercial Flows Study. Prepared by: Cambridge Systematics. Seaside, CA.

Association of Monterey Bay Area Governments (AMBAG). 2018. Moving Forward Monterey Bay 2040: Metropolitan Transportation Plan/Sustainable Communities Strategy. Seaside, CA.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs, 81(2), 169–193. https://doi.org/10.1890/10-1510.1.

Broenkow WW, Breaker LC. 2005. A 30-Year History of Tide and Current Measurements in Elkhorn Slough, California. Moss Landing, CA: Moss Landing Marine Laboratories. 55 p.

Brophy L. S., C. M. Greene, V.C. Hare , B. Holycross, A. Lanier, W.N. Heady, K. O'Connor, H. Imaki, T. Haddad, R. Dana. 2019. Insights into estuary habitat loss in the western United States using a new method for mapping maximum extent of tidal wetlands. PLOS ONE *PloS one*, *14*(8):), e0218558. https://doi.org/10.1371/journal.pone.0218558

California Coastal Commission (CCC), 2018, California Coastal Commission Sea level Rise Policy Guidance: Interpretive Guidelines for Addressing Sea level Rise in Local Coastal Programs and Coastal Development Permits, adopted on August 12, 2015; updated 2018. https://documents.coastal.ca.gov/assets/slr/guidance/2018/0_Full_2018AdoptedSLRGuidanceUpdate.pdf

Caltrans. 2017. Transportation Concept Report: State Route 1. San Luis Obispo, CA.

Central Coast Wetlands Group. 2013. Moro Cojo Slough Management and Enhancement Plan. Moss Landing, CA.

Central Coast Wetlands Group. 2017. Moss Landing Community Coastal Climate Change Vulnerability Report. Moss Landing, CA.

Central Coast Wetlands Group. 2019. Moss Landing Harbor Sea Level Rise Vulnerability and Adaptation Strategy Report. Moss Landing, CA.

Deltares. 2019. User Manual of Delft3D-FLOW – Simulation of Multi-dimensional Hydrodynamic Flows and Transport Phenomena, Including Sediments. Delft, The Netherlands. First published 2003.

Elkhorn Slough Tidal Wetland Project Team. 2007. Elkhorn Slough Tidal Wetland Strategic Plan. A report describing Elkhorn Slough's estuarine habitats, main impacts, and broad conservation and restoration recommendations. 100 pp. Moss Landing, CA.

ESA, 2014. Monterey Bay Sea Level Rise Vulnerability Assessment Technical Methods Report, Prepared for the Monterey Bay Sanctuary Foundation. http://maps.coastalresilience.org/california/methods/SLR_Monterey.pdf

Fountain, M., Jeppesen, R., Endris, C., Woolfolk, A., Watson, E., Aiello, I., Fork, S., Haskins, J., Beheshti, K., Wasson, K. Hester Marsh Restoration. Annual Report 2019. Elkhorn Slough National Estuarine Research Reserve. Available from https://www.elkhornslough.org/tidalwetland-program/

Fountain, M.; Endris, C.; Woolfolk, A.; Wasson, K.Wasson, K. 2020. Salt marsh conservation, restoration and enhancement opportunities in and around Elkhorn Slough in the face of sea level rise. Elkhorn Slough Technical Report Series 2020:2. Available at http://www.elkhornslough.org/research-program/technical-report-series/.: http://www.elkhornslough.org/research-program/technical-report-series/

Grant Application Guide: Sustainable Communities and Strategic Partnerships. 2019. California Department of Transportation. https://dot.ca.gov/programs/transportation-planning/regional-planning/sustainable-transportation-planning-grants

Griggs et al, 2017. Griggs, G, Árvai, J, Cayan, D, DeConto, R, Fox, J, Fricker, HA, Kopp, RE, Tebaldi, C, Whiteman, EA (California Ocean Protection Council Science Advisory Team Working Group), 2017. Rising Seas in California: An Update on Sea Level Rise Science. California Ocean Science Trust, April 2017. http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea level-rise-science.pdf

Haasnoot, M., Kwakkel, J.H., Walker, W.E. and ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global environmental change, 23(2), pp.485-498.

Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D.J., Strauss, B.H. and Tebaldi, C., 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's future*, *2*(8), pp.383-406.

Marcucci, D. J., & Jordan, L. M., 2013. Benefits and Challenges of Linking Green Infrastructure and Highway Planning in the United States. Environmental Management, 51(1), 182–197. https://doi.org/10.1007/s00267-012-9966-7

Monismith S, Paytan A, Jones N, Bela M, Nidzieko N, Misra G, Street J. 2005. Hydrodynamics and Sediment Dynamics in Elkhorn Slough. Stanford University, California: Dept of Civil and Environmental Engineering & Dept of Geologic and Environmental Sciences. 83 p.

Monterey County Resource Management Agency. 1988. Monterey County Coastal Implementation Plan (PART 2: Regulations for Development in the North County Land Use Plan Area (Chapter 20.144)). https://www.co.monterey.ca.us/home/showdocument?id=37937

Monterey County Resource Management Agency. 2017. Moss Landing Community Plan: Revised Working Draft. Salinas, CA.

Nidzieko, N.J. 2010. Tidal asymmetry in estuaries with mixed semidiurnal/diurnal tides. Journal of Geophysical ResearchOceans 115(C8). doi:10.1029/2009JC005864.

Nidzieko, N. J.,Monismith, S. G. (2012) Contrasting Seasonal and Fortnightly Variations in the Circulation of a Seasonally Inverse Estuary, Elkhorn Slough, California; Estuaries and Coasts, DOI 10.1007/s12237-012-9548-1, Sept. 2012.

National Resource Council (NRC), 2012. “Sea Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.” Prepublication. National Academy Press: Washington, D. C.

Natural Resources Agency and Ocean Protection Council, 2018. State of California Sea Level Rise Guidance 2018 Update. http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf

Ocean Protection Council (OPC), 2013. State of California Sea Level Rise Guidance Document, Developed by the Coastal and Ocean Working Group of the California Climate Action Team (CO-CAT), with science support provided by the Ocean Protection Council’s Science Advisory Team and the California Ocean Science Trust, March 2013 update: http://www.opc.ca.gov/webmaster/ftp/pdf/docs/2013_SLR_Guidance_Update_FINAL1.pdf

Oliver JS, King J, Hornberger M, Schwartz D. 1988. Erosion of Wetland Habitats by Increasing Tidal Currents from Harbor Construction and Breaching Dikes in Elkhorn Slough, California. Moss Landing: Moss Landing Marine Laboratories. 23 p.

Philip Williams & Associates. 1992. Elkhorn Slough Tidal Hydraulics Erosion Study. San Francisco, CA: Prepared for the US Army Corps of Engineers. 31 p.

Safeguarding California Plan: 2018 Update (p. 249), 2018. https://resources.ca.gov/CNRALegacyFiles/docs/climate/safeguarding/update2018/safeguarding-california-plan-2018-update.pdf

Sampey J. 2006. A bathymetric analysis of equilibrium potential within Elkhorn Slough, California: California State University Monterey Bay.

Sweet, W., Horton, R., Kopp, R. and Romanou, A., 2017. Sea level rise.

TNC, 2015. The Nature Conservancy, Coastal Resilience Website, mapping portal, Monterey, California. https://maps.coastalresilience.org/network/, last visited December 2018.

Transportation Agency for Monterey County (TAMC). 2008. Monterey Bay Sanctuary Scenic Trail Master Plan.

Transportation Agency for Monterey County (TAMC). 2018. Prepared by: Omni-Means, Ltd. *G12: Pajaro to Prunedale Corridor Study – Existing Conditions Report*. Salinas, CA

Webb, B., Dix, B., Douglass, S., Asam, S., Cherry, C., & Buhring, B, 2019. Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide. US Department of Transportation, Federal Highway Administration.

CHAPTER 9
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