Appendix C

Delft3D Hydrodynamic Modeling Technical Memorandum

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memorandum

date	May 8, 2020
to	Heather Adamson, Association of Monterey Bay Area Governments (AMBAG)
cc	Walter Heady and Alyssa Mann, The Nature Conservancy (TNC)
from	Tiffany Cheng, PE, Bob Battalio, PE
subject	Hydrodynamic Modeling (Delft3D) for the Central Coast Highway 1 Climate Resiliency Study

Environmental Science Associates (ESA) has prepared this memorandum for the Association of Monterey Bay Area Governments (AMBAG) to present the application of the Delft3D hydrodynamic model to assess impacts on hydrological patterns and flood extents under future sea level rise (SLR) conditions for preliminary roadway and railway adaptation scenarios developed from the Central Coast Highway 1 Climate Resiliency Study (Study). The results of Delft3D provide an updated assessment of changes in flow patterns (e.g. tidal connectivity, depths and velocities) in and around Elkhorn Slough and inform subsequent refinement of the roadway and railway adaptation scenarios. Contributions to this memo were made by Tiffany Cheng, PE and Bob Battalio, PE. Technical support was provided by Yi Liu and Matt Brennan Ph.D, PE of ESA.

1. Introduction

The construction of the existing transportation infrastructure in and around Elkhorn Slough (e.g. Highway 1 and the railway) have driven large-scale hydrologic and ecological changes to wetland habitats in the system over the last 150 years. Large-scale modifications to the topography and watershed hydrology, such as the relocation of the Slough mouth, construction of the Harbor jetties and Salinas River diversion, have contributed to a decrease in sediment supply to the Slough system and higher tidal velocities through the main channel. In its present condition, the Slough experiences sustained erosion and sediment export, which has led to loss of valuable marsh plain habitat. Rising water levels will likely result in greater marsh erosion, which increases the tidal prism and flow velocities.

The roadway and railway adaptation scenarios proposed in the Study were conceptualized to address both transportation and ecological resilience, specifically investigating restoration actions that could be concurrently planned as part of modifications made to transportation infrastructure. The hydrodynamic modeling conducted within this study is an opportunity to 1) verify that the modifications made to the roadway and railway (e.g. elevating a highway segment on piles or fill) will not impact the existing tidal flow regime in Elkhorn Slough significantly and 2) evaluate any potential benefits yielded by adaptation actions taken. The modeling was also used to identify changes in flood limits associated with an annual high tide level. This report summarizes the application of Delft3D to assess changes in tidal connectivity, water depths and velocities around the study domain for the various roadway and railway adaptation scenarios under future SLR conditions.

2. Model Inputs

ESA utilized Delft3D, a hydrodynamic model, to evaluate potential hydraulic impacts (e.g. changes to flow patterns and flood extents) 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 Ponds (Philip Williams & Associates, 2008). Figure C-1 shows the updated grid extent. Grid cell resolution was refined around the transportation infrastructure to adequately resolve hydraulic impacts around the roadway and railway. Cell resolution varied from approximately 400 ft at the bay boundary to approximately 30 ft within the Slough (Figure C-2).

The model requires topography and bathymetry information for the entire study domain as an input. To most accurately reflect existing conditions, ESA created a merged topo-bathy set based off of a range of different sources (e.g. LiDAR, hydrographic survey, etc.), summarized in Table C-1. All datasets were georeferenced to horizontal datum Universal Transverse Mercator (UTM) Zone 10N and vertical datum North American Vertical Datum 1988 (NAVD88) before being combined. The Struve Pond and Bennett Slough locations lack high-quality survey data; an elevation of -6.5 ft, NAVD (based off of the invert elevation of hydraulic structures located by Highway 1 Reach 2) was assumed for these areas with side slopes to match grade. The elevation in Azevedo Ponds (assumed 4.2 ft NAVD) were based off of the lowest water level values observed at that site. Figure C-3 shows the merged topo-bathy dataset for existing conditions.

Table C-1. Topography and Bathymetry Data Sources

Areas	Dataset	Dates	Source
Upland areas, Main Elkhorn Slough	2017 CoNED Topo-Bathymetric Model (1929-2017) Central Coast of California	Varied; metadata indicates that topography datasets used range from 2008-2015 in collection date, and bathymetry datasets from 1926-2011	United States Geological Survey (USGS)
Parsons Slough	Bathymetry survey	2011, various years	California State University of Monterey Bay (CSUMB)
Moro Cojo Slough	Centerline depths survey	October 2019	Moss Landing Marine Labs (MLML)

Over the last century, numerous hydraulic structures (e.g. culverts, sills) have been installed underneath the transportation infrastructure to assist with controlling flow and inboard water elevations. Culvert modifications or removals have been discussed as a potential near-term and components of long-term adaptation action, depending on ecological goals for the area discussed. ESA collected field survey data for culverts located beneath Highway 1 in the study area and existing hydraulic structure datasets from ESNERR and MLML (summarized in Appendix A of the main report).

Hydraulic structures located through the roadway and railway infrastructure were incorporated into the model (Figure C-4). Culverts were typically modeled using the 'general structures' tool in Delft-3D; in some cases, unidirectional flow was enforced. Model limitations prevented perfect representation of all hydraulic structure characteristics (e.g. the general structures tool only allows rectangular definition of a structure shape, whereas culverts are typically circular); where applicable, ESA exercised professional engineering judgment in the model set up to best approximate existing conditions, as understood from data collected. Tidal gates located by Moro Cojo Slough were incorporated as well in order to accurately represent the hydraulic control for that system. Since the focus of the adaptation study is primarily on the transportation infrastructure and how modifications to these facilities would affect hydrologic patterns, several hydraulic structures located elsewhere (e.g. Elkhorn Road, Moss Landing Wildlife Area) were not included.

3. Model Calibration

A two-week period in December 2012 representing a king tide (extreme high tide with a recurrence between one and six times a year) condition was chosen as tidal boundary condition for the model calibration. Water levels were downloaded for this timeframe from the NOAA Monterey Bay gage

(Station #9413450). The max water surface elevation in this time range was 2.23 m (7.4 ft) NAVD 88. Figure C-5 shows the tidal water levels during this period.

The model was calibrated against observed data collected from the Slough. The Monterey Bay Aquarium Research Institute (MBARI) operates a series of gauges through the main channel and other locations in the Slough, as part of the Land-Ocean Biogeochemical Observatory (LOBO). Observed data from LOBO moorings L01 (Main Channel) and L04 (Parsons Slough entrance) were compared against the model results (Figure C-6). L02 (Kirby Park) and L05 (Parsons Slough) did not have data during the time period. ESA downloaded water level data from the ESNERR Centralized Data Management Office (CDMO) website for locations east of the railway complex, including Azevedo Ponds, North Marsh and South Marsh (Parsons Slough) (Figure C-7).

The model generally reproduces tidal amplitude and peak values well along the main channel of the Slough and at locations where there is full tidal action (e.g South Marsh) and is adequate for the purposes of this study. The calibration in areas with muted tidal signal (e.g. North Marsh and Azevedo Ponds) could be improved in future application of the model. The North Marsh gage was confirmed to be non-operational during the calibration event time period. Limitations in shallow-water bathymetry data, hydraulic structure rating curve data, and model representation of hydraulic structures constrain the calibration quality at Azevedo Ponds. The bed elevation at that location is likely lower than what was assumed; therefore, the representation of hydraulics of tidal flow within the Ponds could be improved with better data. The study focuses on impacts to overall Slough hydrodynamics as a consequence of transportation and ecological modifications by the road and rail infrastructure; further calibration and development would be necessary in order to apply the model specifically for local marsh areas. Also, the modeled hydraulic response of Elkhorn Slough to sea level is provisional pending additional review and vetting of model results. Despite these caveats regarding the appropriate use of the model results in this study, the model is expected to be a useful tool to support future study of Elkhorn Slough.

4. Model Runs

For modeling purposes, the following adaptation scenarios (except for Scenario A0/B0) were assumed to be constructed by mid-century, which would require the transportation infrastructure and restoration actions to be designed for future SLR at that point in time. Consistent with prior Coastal Resilience Monterey work, which are consistent with the 2013 Ocean Protection Council (OPC) ‘High’ scenario (can be crosswalked to be similar to but lower than the Medium-High Risk Aversion scenario from the 2018 CalNRA-OPC SLR Guidance Update) a SLR amount of 3 ft by 2070 and 5 ft by 2100 was assumed. Table C-2 provides a summary of scenarios, adaptation components and hydrologic conditions evaluated.

Table C-2. Delft3D Model Runs

<table>
<tr><th>Name</th><th>Roadway</th><th>Railway</th><th>Hydrologic Boundary Condition</th></tr>
<tr><td>A0/B0</td><td>No Action Condition</td><td>No Action Condition</td><td>King Tide at present day
King Tide +3 ft SLR at 2070
King Tide +5 ft SLR at 2100</td></tr>
<tr><td>A1A and A3A</td><td>Highway 1 Reaches 1-4 elevated on piles with levee ecotone creation by Moss Landing Wildlife Area.</td><td rowspan="2">Existing railway fill embankment left in place. Marsh restoration assumed east of the railway complex.</td><td>King Tide +3 ft SLR at 2070
King Tide +5 ft SLR at 2100</td></tr>
<tr><td>A1B and A3B</td><td>Highway 1 Reaches 1, 3 and 4 elevated on piles. Reach 2 elevated on fill embankment with levee ecotone creation on either side.</td><td>King Tide +3 ft SLR at 2070
King Tide +5 ft SLR at 2100</td></tr>
<tr><td>B2</td><td>No improvements made to roadway.</td><td>New dual track railway elevated on trestle. Existing railway fill embankment left in place. Marsh restoration assumed east of the railway complex.</td><td>King Tide +3 ft SLR at 2070
King Tide +5 ft SLR at 2100</td></tr>
</table>

The hydrodynamic scenarios focus primarily on the changes in flow patterns, depths and velocities triggered by modifications made to the existing roadway and railway alignments. These include Scenarios A1A, A1B, A3A, A3B and B2. Scenario A2 (Managed Retreat & G12 Widening) was not modeled explicitly because it was assumed that there would be little to no difference in hydrologic patterns from traffic diversion to G12 and leaving the existing Highway 1 alignment in place for local access, compared to the no action scenario. Scenario A4/B1, which assumes a co-located road and rail facility crossing over the Slough, was not modeled explicitly for hydraulic impacts since the proposed location for Slough crossing is at the narrowest point of the channel and we assume the pile supported crossing would be designed to have no impact on overall slough hydraulics. Although there are likely changes to the local flow field and numerous impacts to adjacent wetland habitat from exact pile locations associated with a new roadway/railway facility, the study is planning-level and the analysis would require knowledge from a level of design that is premature for the goals of this current effort.

Grading modifications were made to the topo-bathymetry input for the adaptation scenarios to represent ecological adaptation actions taken. Figure C-7 shows the proposed grading in the topo-bathymetry input for adaptation scenarios with levee ecotone creation (Scenarios A1A, A1B, A3A and A3B). Similarly, for the marsh restoration of complexes east of the railway (e.g. Parsons Slough, North/Estrada Marshes and Azevedo Ponds), the marsh grade plain was modified to reflect raising elevations to future MHHW at mid-century, approximately 8.0’ NAVD. New tidal channels to be graded into the proposed marsh restoration were digitized from historic aerial photos and sized using design guidelines for channel geometry for California estuaries (Philip Williams and Associates, 2004).

5. Results

Modeling results for Scenario A1A (2-lane roadway) and A3A (4-lane roadway), with Highway 1 Reaches 1-4 elevated on piles, show Struve Pond and Upper Bennett Slough with increased tidal action, due to the replacement/removal of the existing highway alignment on fill embankment. The levee on the inner perimeter of Moss Landing Wildlife Area blocks water from flooding the ponds from the direction of the Harbor. Scenarios A1B and A3B, with Highway 1 Reach 2 elevated on fill embankment, show that Struve Pond and Upper Bennett Slough are tidally connected still, because of an alternate flood pathway that develops on the eastern edge of the managed ponds, connecting Elkhorn Slough to those areas (Figure C-8). Both adaptation variations show that this new flood pathway happens regardless of how Reach 2 is elevated, due to water levels exceeding local elevations. Figure C-9 shows the modeled water surface times series for the range of actions modeled. Note that Bennett Slough under existing conditions was modeled with a water surface elevation of +2’ NAVD which is estimated for low runoff conditions and tidal exchange blocked by Highway 1 and other barriers. The no-project (black lines) indicate that Bennett Slough becomes tidal with 3 feet of sea level rise, and high water levels essential match the King Tide elevations while low water levels are elevated due to retarded drainage. At 5 feet of sea level rise, the model predicts that, under no-project conditions, the high water in Bennett Slough matches the King Tides, but the tide range remains limited owing to elevated low tides, again indicating retarded drainage. Therefore, with no-project, flood levels in Bennett Slough will increase markedly with sea level rise and, owing to poor drainage, flooding will persist especially with rainfall (not including in the modeling). Highway 1 on piles results in greater water levels under existing conditions (solid blue line). With higher sea levels, raising Highway 1 on piles results in the same high waters as no-project, but the low tide drainage is improved. For Highway 1 Reach 2 on fill, the model predicts essentially the same water levels as no-project. Struve Pond water levels are expected to be similar to Bennett Slough because Reach One of Highway 1 will be on piles.

Highway 1 Reaches 3 and 4 are assumed to be elevated on piles in all adaptation scenarios except for Scenario B2 (no improvements made to roadway), with the existing fill embankment left in place to provide flexible floodplain management in the future. With the existing fill embankment remaining where it is, it is expected that the model should predict similar flooding pathways and extents to prior modeling. The hydrodynamic modeling shows that with 3 ft of SLR, extreme monthly high water levels in Moss Landing Harbor South overtop Potrero Road and Moss Landing Road, leading to flooding of the low-lying agricultural lands adjacent to Reaches 3 and 4, and Moro Cojo Slough (Figure C-10).

With sea level rise, the model predicts an increase in peak tidal velocities for both no-project and with project scenarios. The effect of sea level rise on the hydrology of Elkhorn Slough requires further study, which is beyond the scope of this project. However, the increase in peak velocities is predicted to be less with the 700 acres of marsh restoration east of the railway: The lower increase in velocities is attributed to the reduction of tidal prism within in the restored marsh areas due to fill placement.

The Highway 1 modifications and marsh restoration east of the railway are not predicted to have any apparent effect on the tidal range of Elkhorn Slough. Figures C-11 and C-12 are plots of water level time series near the mouth and at the upstream end of Elkhorn Slough, respectively. With higher sea levels the tides shift upward but appear to approximately maintain the same tide range in most of the slough as represented in Figure C-11. However, the tide range is predicted to increase markedly with sea level rise at the upstream end of Elkhorn Slough (Figure C-12).

6. Discussion

Several major takeaways from the hydrodynamic modeling performed for the preliminary roadway and railway adaptation scenarios are discussed in this section. The development of a new flood pathway east of the managed ponds in Moss Landing Wildlife Area by mid- to late century indicates that modifications made to the roadway will have decreasing control over flooding in this part of the Slough, as sea level rises. In other words, flood protection provided by the roadway facility for landward areas may not be a significant metric by which to determine how Reach 2 is elevated. Eventually, Struve Pond and Upper Bennett Slough will be tidally connected to the main channel of Elkhorn Slough. In their present condition, both of these areas experience poor water quality from a lack of tidal flushing and runoff from adjacent agricultural operations into these systems. The area by Highway 1 Reach 2 and Moss Landing Wildlife Area represent an opportunity to create additional wetland habitat area and could potentially be developed in conjunction with desired future ecological goals for Struve Pond and Upper Bennett Slough, including taking intentional measures to improve water quality and restore habitat, well before the second half of the century.

The model results for Reaches 3 and 4 support ongoing integrated, collaborative efforts around Moro Cojo Slough to plan for future land use under SLR. Likely, around mid-century, maintaining farming operations in the low-lying agricultural lands near Reaches 3 and 4 will be untenable. These may represent an opportunity area to work with nature and convert land use to wetland habitat; this will be further explored in the SLAMM habitat modeling, which is also a part of the evaluation of the adaptation scenarios.

Large scale trends from decades of study confirm that Elkhorn Slough will continue to experience net sediment export and marsh loss, without commensurate restoration action (Elkhorn Slough Tidal Wetland Strategic Plan, 2007). The adaptation scenarios modeled assume that marsh complexes east of the railway would be restored at the same time; in reality, due to the large area when aggregated, they would be restored separately in phases. Since the restoration consists primarily of raising the site grades to future marsh plain elevations for 700 acres of intertidal areas, the increase in tidal prism associated with sea level rise is reduced. The modeling predicts that tidal velocities increase in all scenarios, including no project and with marsh restoration, but the increase in velocity is reduced with the restoration.

The effect of sea level rise on Elkhorn Slough hydrology is an important question that modeling can investigate, but is beyond the scope of this study. For example, this study did not include morphologic changes (e.g. sediment deposition and erosion, bed elevation changes over time) which may result from hydrodynamic changes. The apparent effects based on this modeling indicate an upward shift in tide range consistent with sea level rise, an increase in tide range in the upper Elkhorn Slough, increase in peak velocities in the main stem of the slough, and expansion of tidal areas into Bennett Slough and Struve Pond near North Harbor and the CDFW Wildlife Area, as well as in Moro Cojo Slough.

7. References

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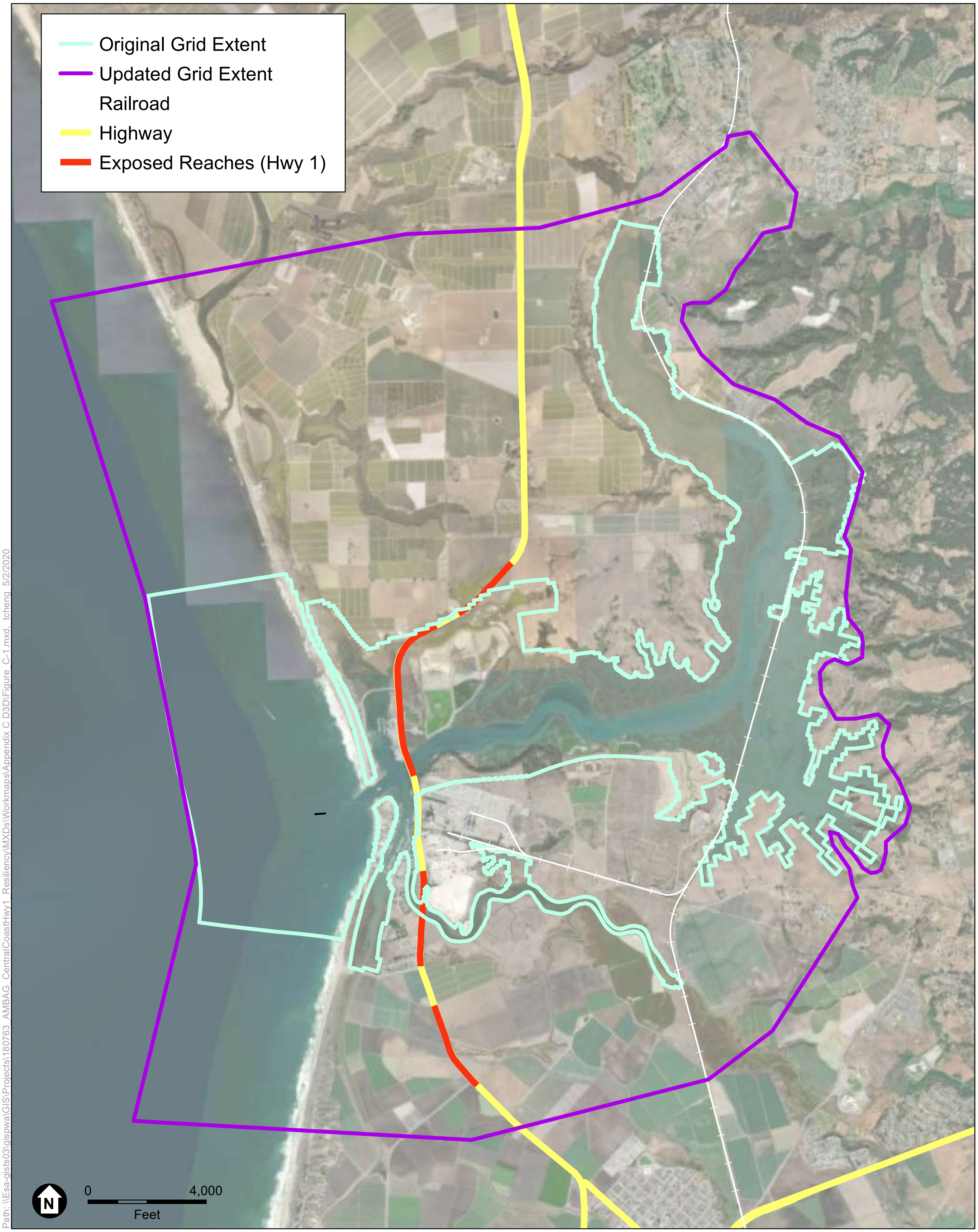
8. Figures



SOURCE: ESA (2011)

Central Coast Highway 1 Climate Resiliency Study

Figure C-1
Updated DELFT-3D Grid Extent

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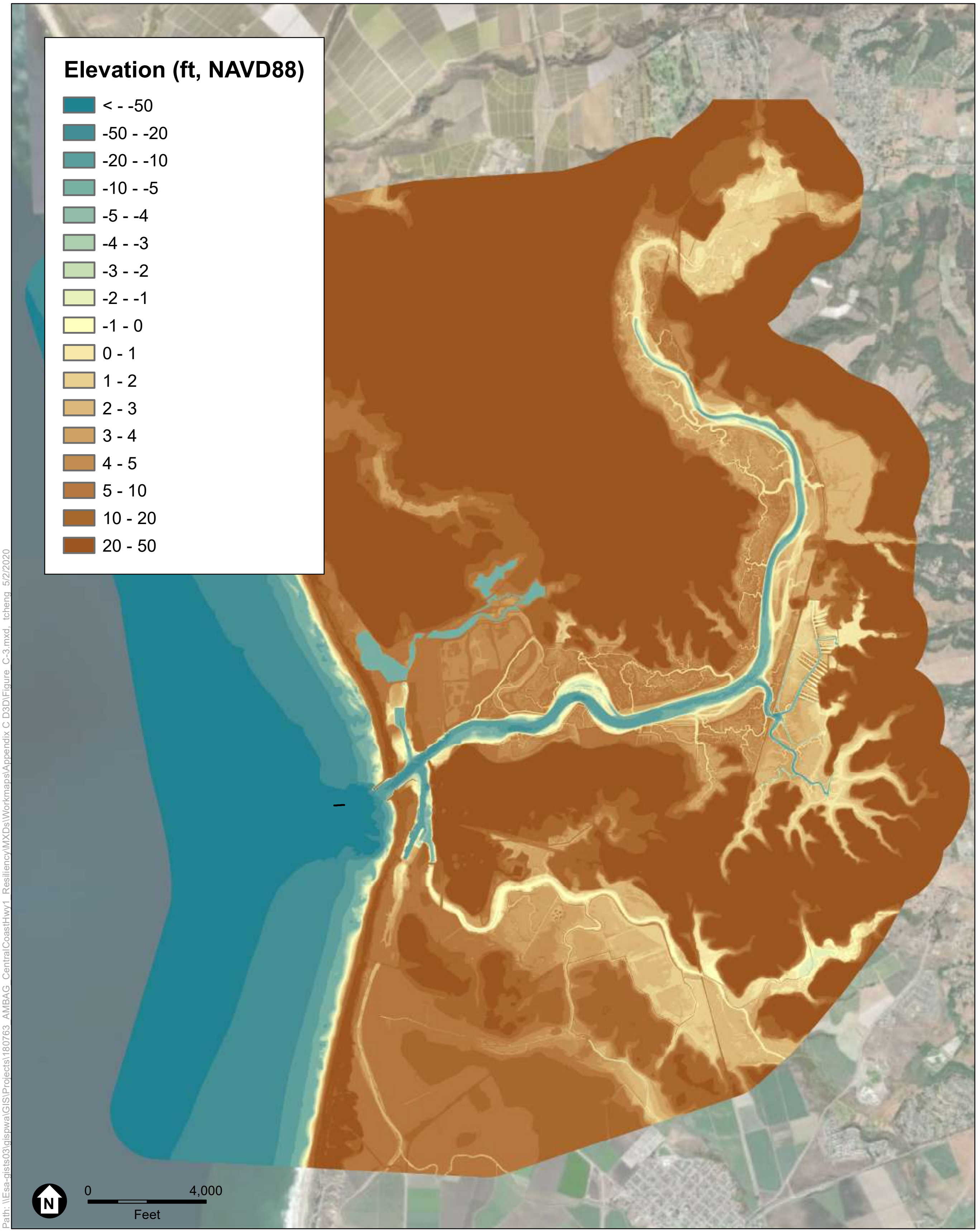
Figure C-2
Cell Resolution in Model Domain



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

Central Coast Highway 1 Climate Resiliency Study

Figure C-3
Merged Topo-Bathymetry Dataset

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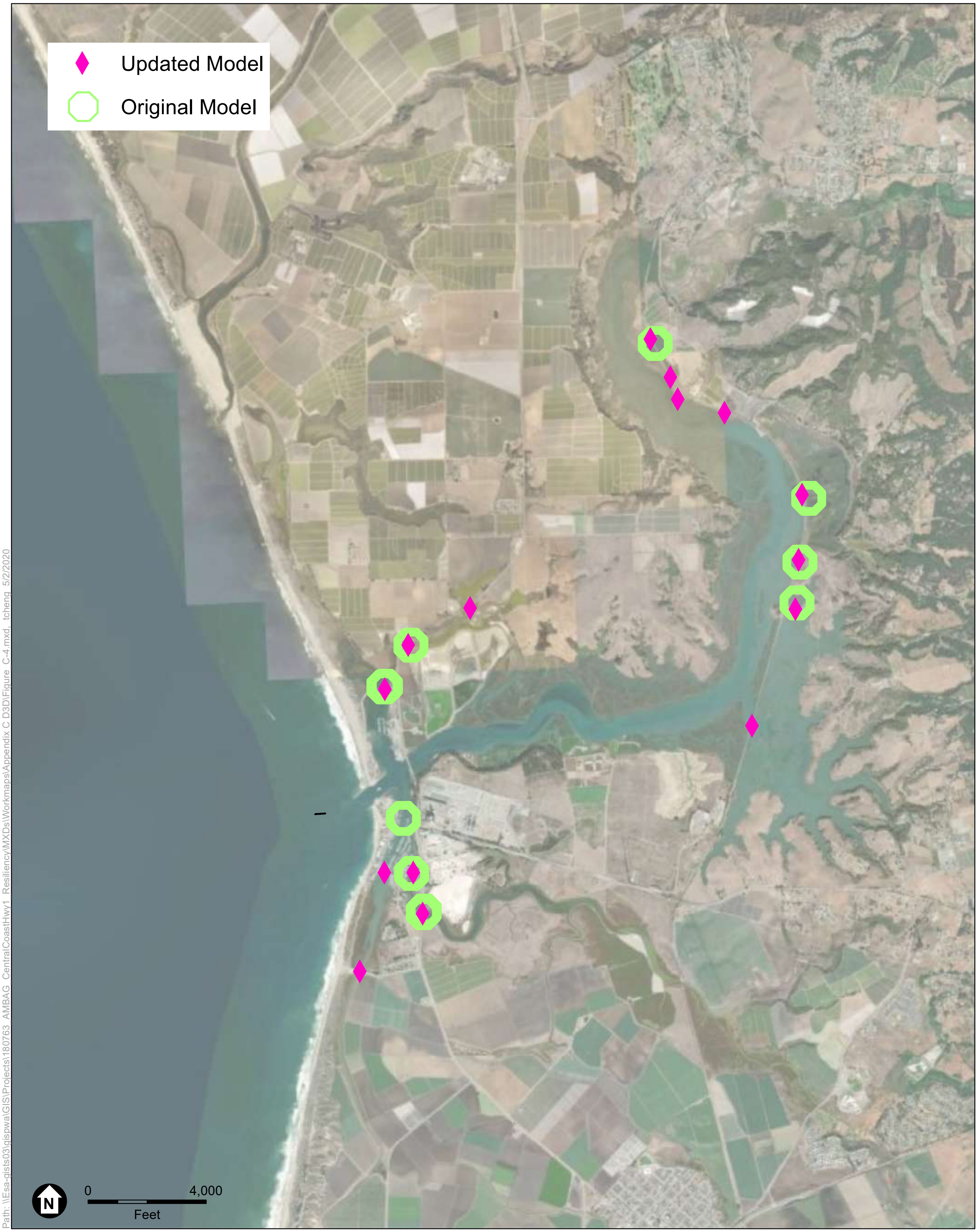

Path: \\Esa-gists03\gispwa\GIS\Projects\180763 AMBAG CentralCoastHwy1 Resiliency\MXDs\Workmaps\Appendix C D3D\Figure C-4.mxd, tcheng 5/2/2020

SOURCE: Moss Landing Marine Labs, Elkhorn Slough National Estuarine Research Reserve

Central Coast Highway 1 Climate Resiliency Study

Figure C-4
Hydraulic Structure Locations

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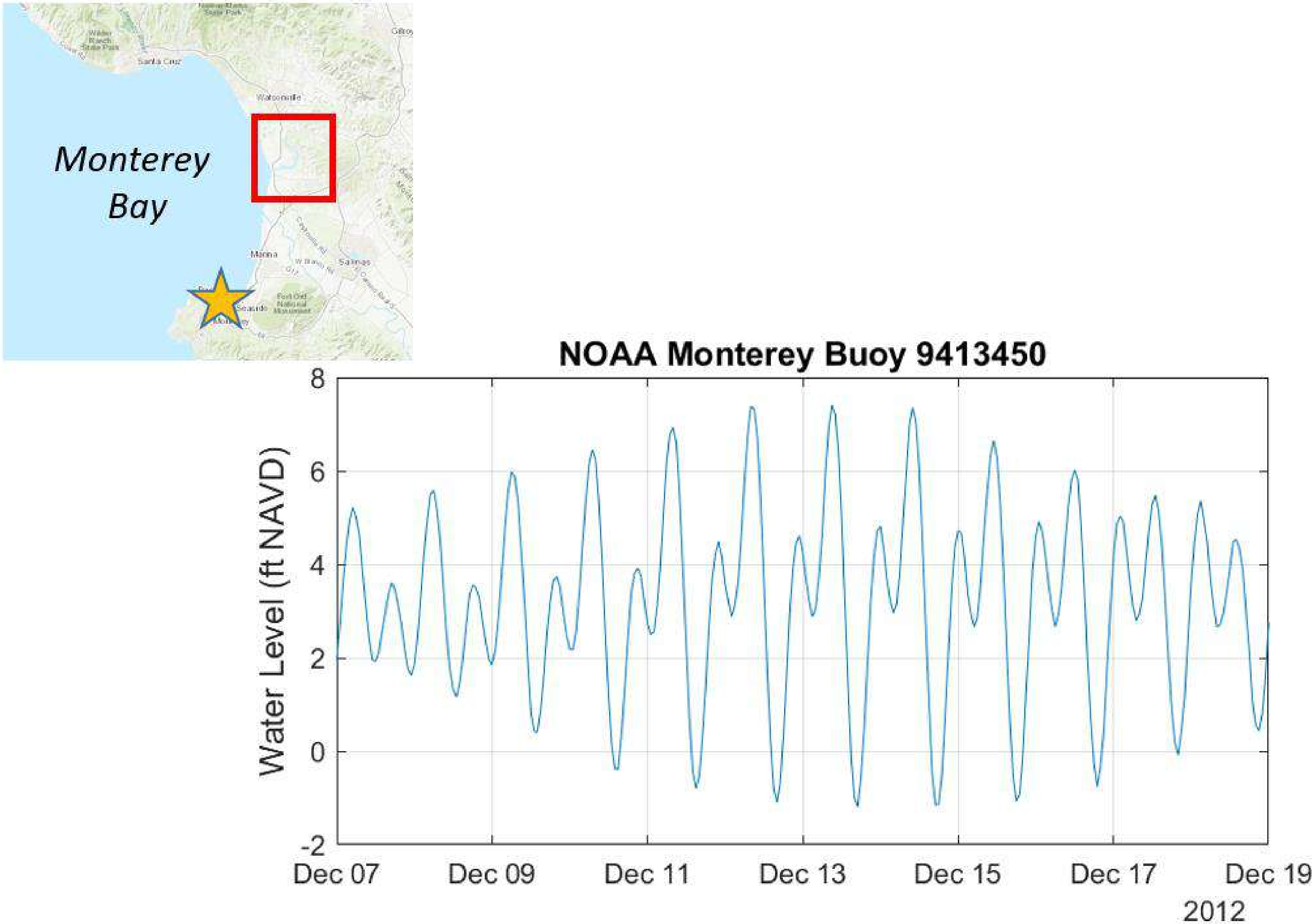
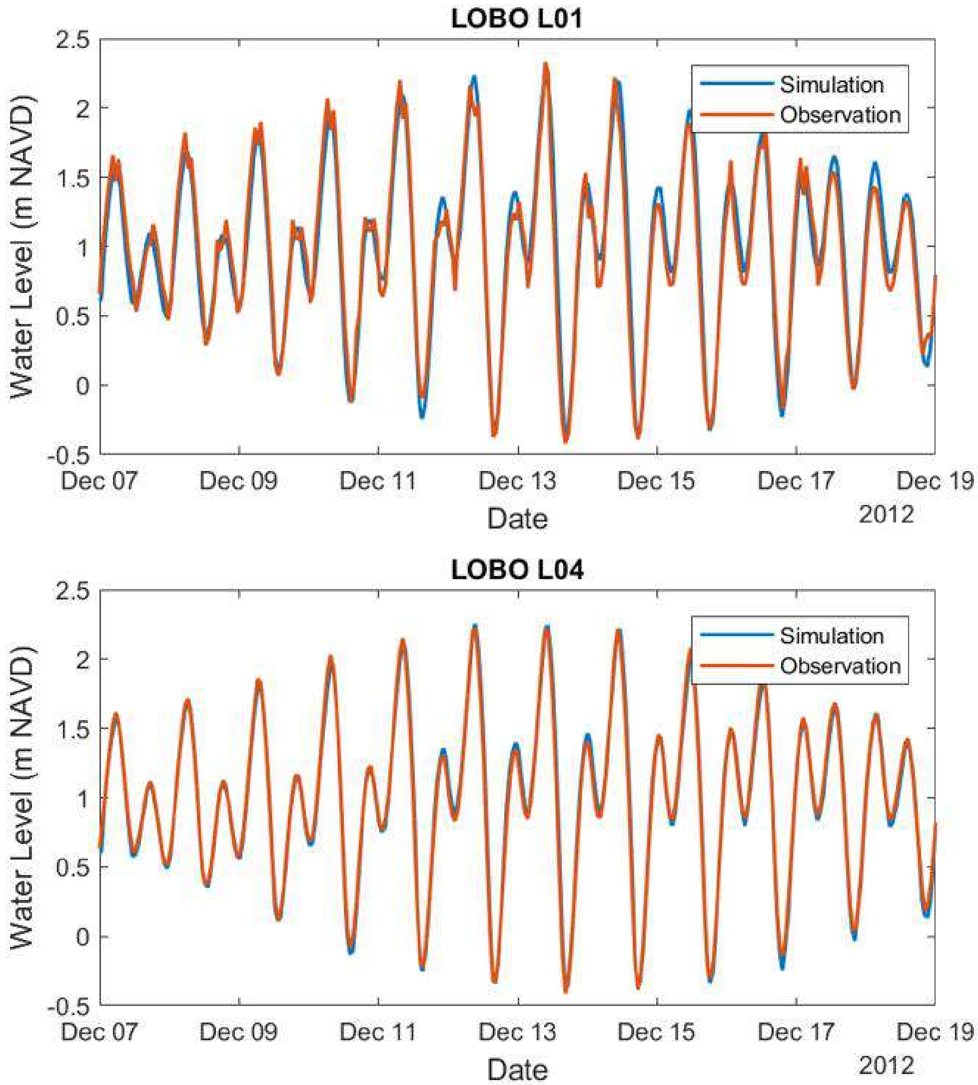


SOURCE: NOAA Tides and Currents (2019)

Central Coast Highway 1 Climate Resiliency Study. D180763.00

Figure C-5
King Tide Water Level Time Series
Model Calibration



SOURCE: Monterey Bay Aquarium Research Institute (2019)

Central Coast Highway 1 Climate Resiliency Study. D180763.00

Figure C-6
King Tide Event 12/7/12-12/19/12
Model Calibration

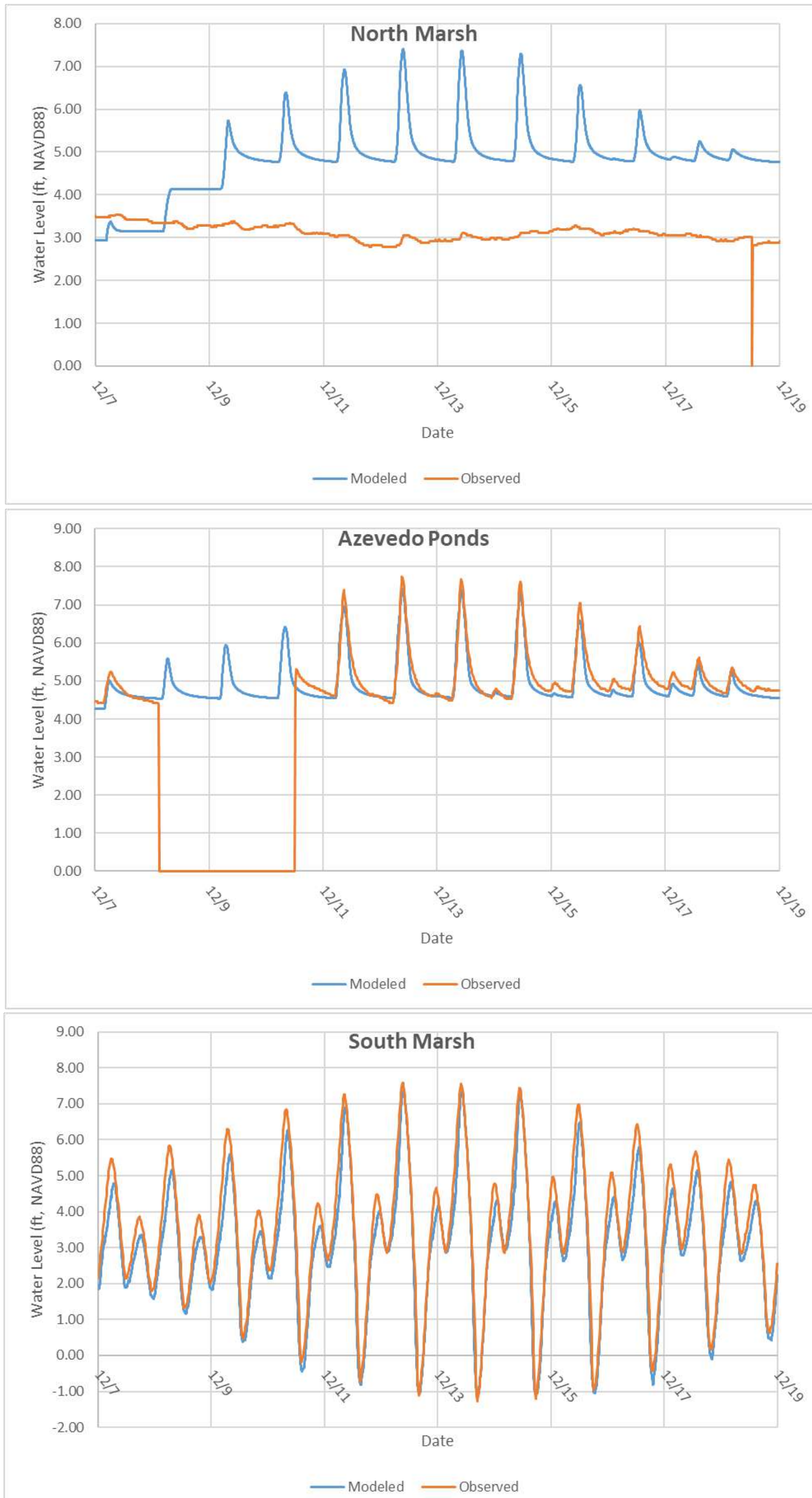


Figure C-7

Model Calibration for Locations East of the Railway

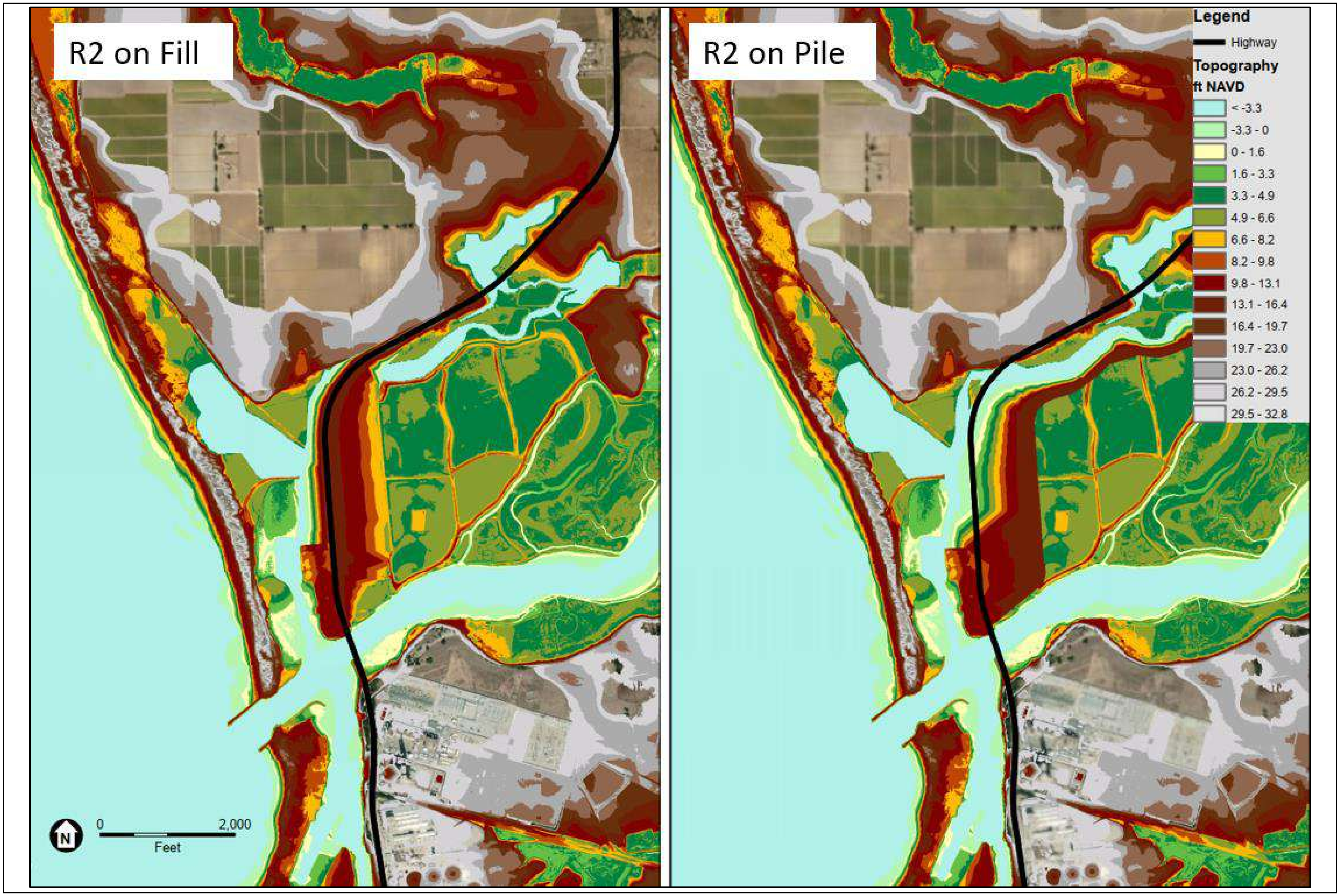


Figure C-8
Terrain Modifications for Levee Ecotone

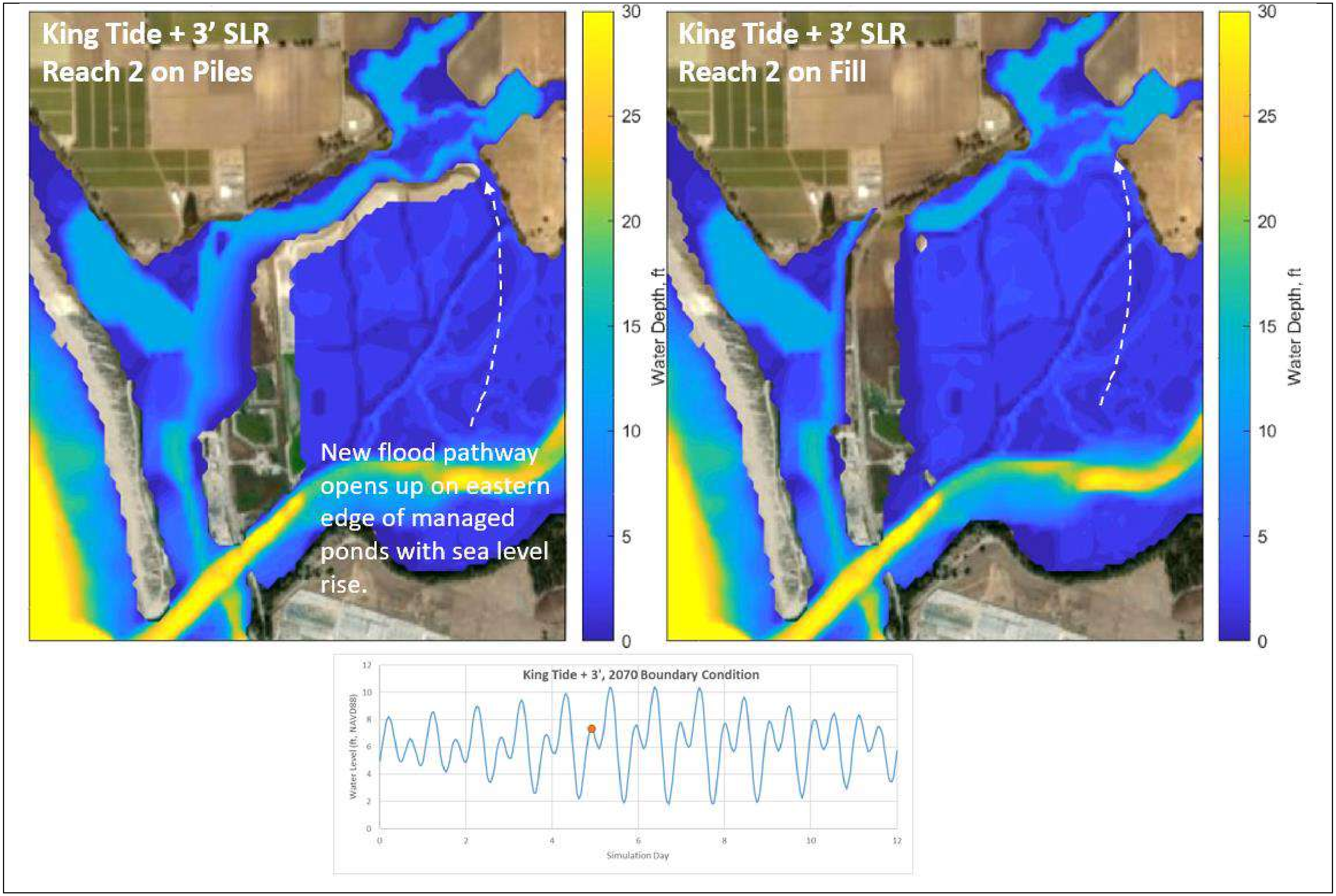
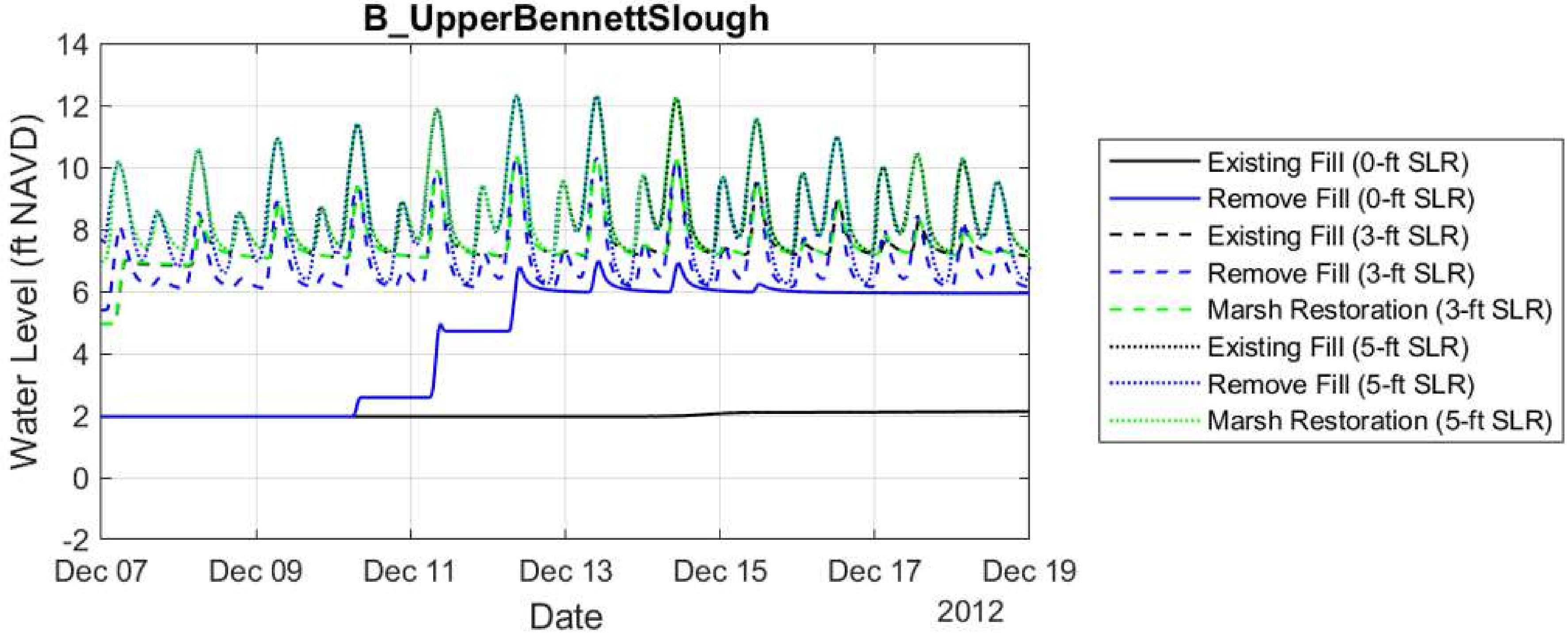


Figure C-9

Highway 1 Reach 2 Elevated on Piles and Fill, +3 ft SLR



Bennett Slough Water Levels during King Tide sequence for 0, 3' and 5' of sea-level rise. No project A0 "Existing Fill" is in black, Highway One on piles A1A/A3A "Remove Fill" is in blue, and Highway One on Fill A1B/A3B "Marsh Restoration" is in green.

Figure C-10

Bennett Slough Water Levels with King Tide and SLR

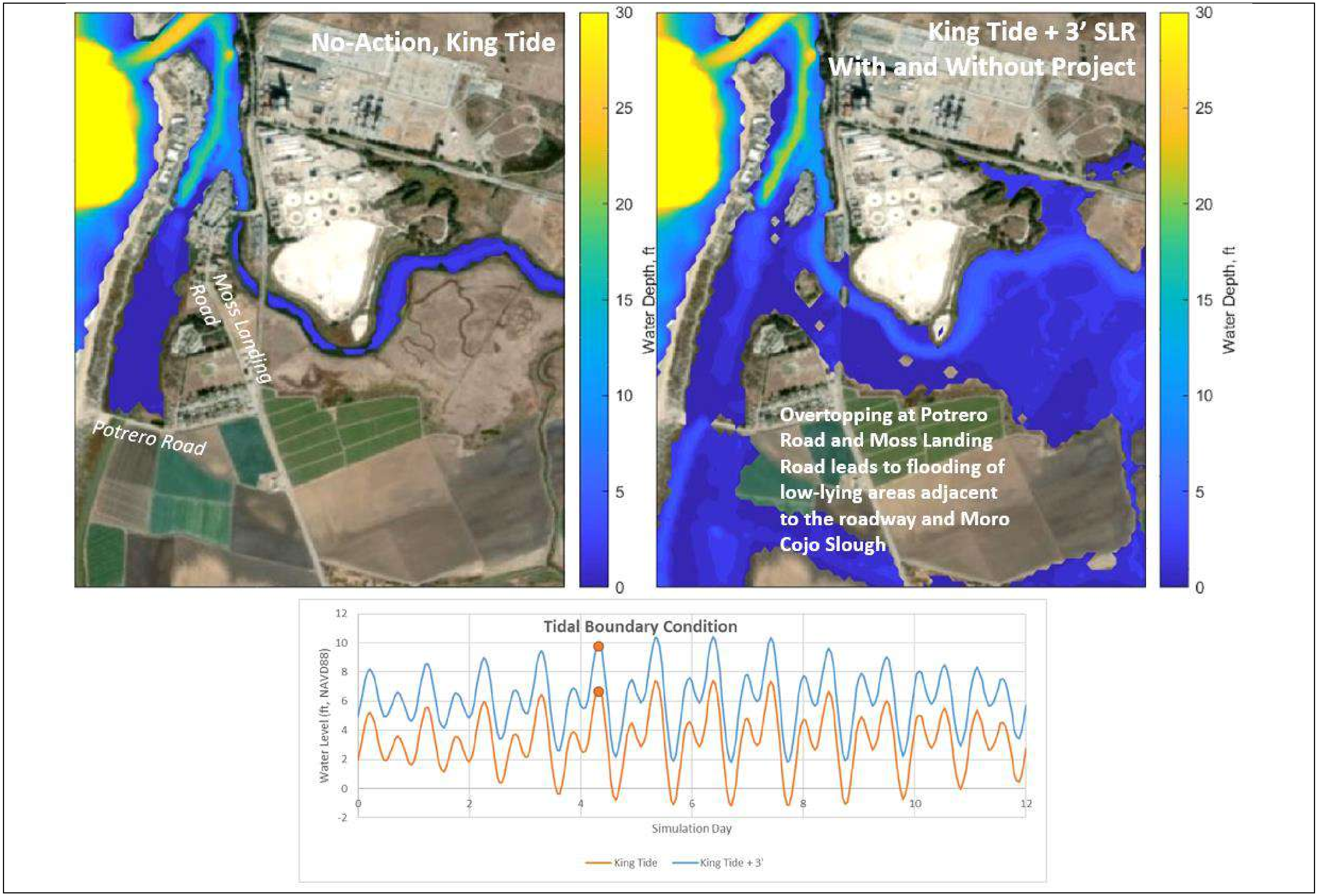
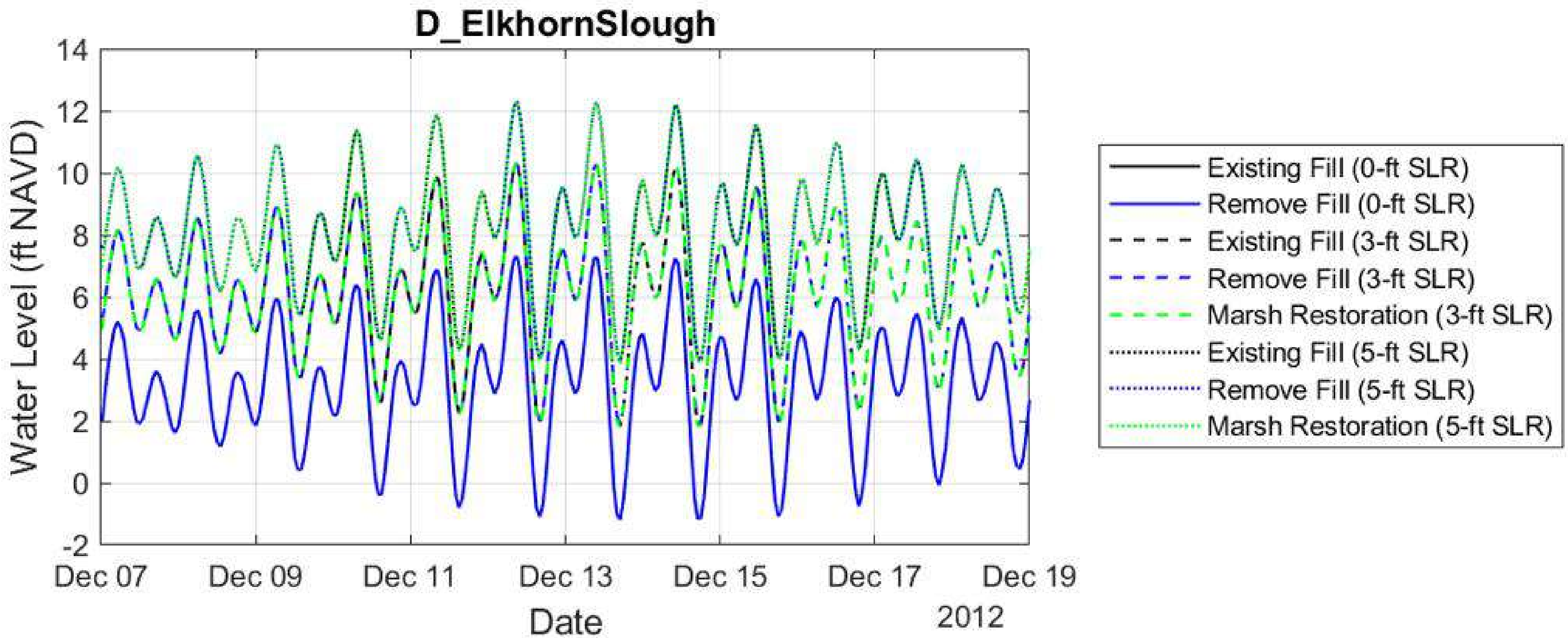


Figure C-11

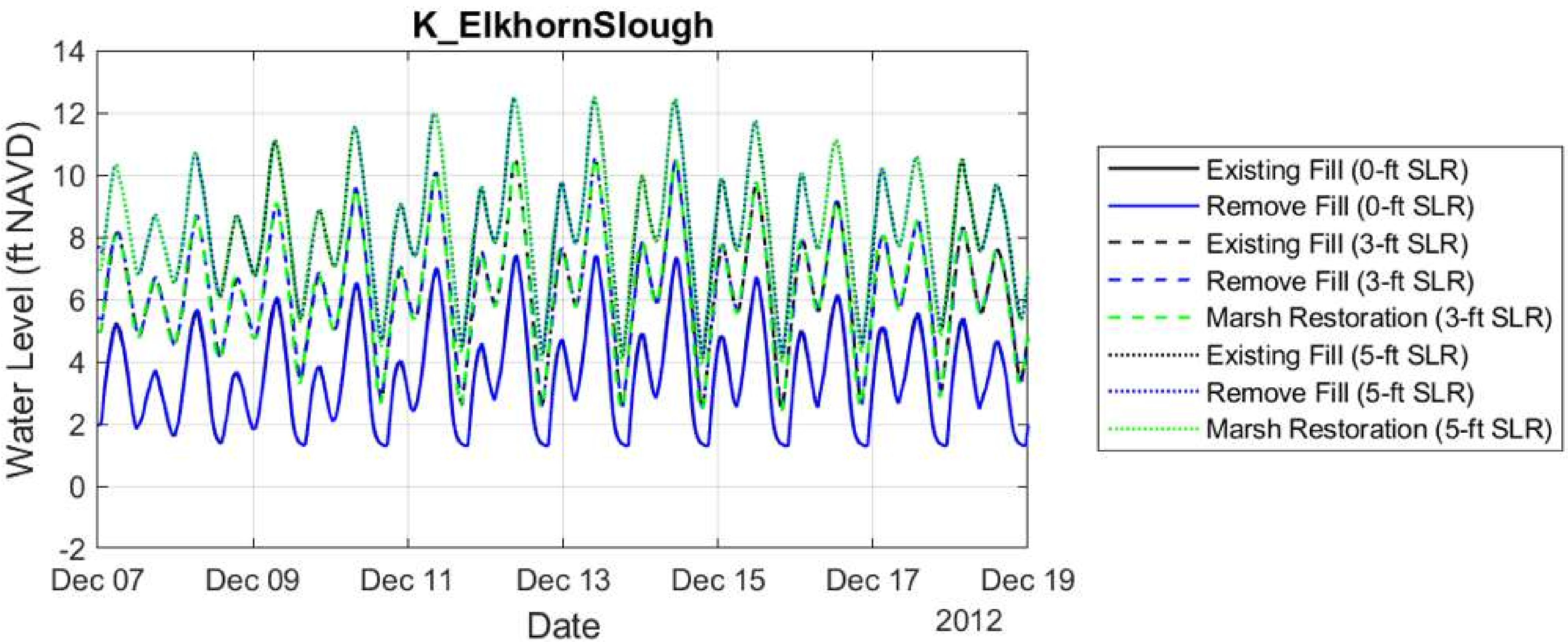
Highway 1 Reaches 3 and 4 by Moro Cojo Slough, EC and +3 ft SLR



Downstream end of Elkhorn Slough showing no apparent change in tide range with sea-level rise of 3 and 5 feet, and showing no apparent effect of project actions to modify Highway One and restore marsh east of railway.

Figure C-12

Elkhorn Slough Main Channel Water Levels Near Mouth



Upstream End of Elkhorn Slough showing increased tide range with sea-level rise, but no effect of potential project actions to modify Highway One and restore marsh east of railway.

Figure C-13

Elkhorn Slough Main Channel Water Levels Near Upstream End